Final Report
Team 13: Smart Prosthetics for the Upper Extremity

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Executive Summary

Myoelectric prostheses allow the user to open and close their artificial hand (or gripper) by tensing muscles. Current myoelectric prosthetics do not provide sufficient feedback to allow the user to determine properties of the object they are grasping with their gripper. Thus, our assignment is to further develop a myoelectric device to be used for research purposes which provides various types of feedback to the user and can be used by an able-bodied person.

The previous design developed by our sponsor Professor Gillespie provides force feedback which requires the bicep to resist an applied torque about the elbow but this torque does not provide rich feedback so that the user may identify the firmness of an object. A major cause of this shortfall is that the signals collected from operation of the device are noisy. Because the signal is of poor resolution, the force-feedback is not predictable or dependable.

Based on the problems of the previous design and our knowledge of necessary characteristics for prostheses, we developed design requirements, wants, and specifications. In particular we are required to have a skin-safe, working prototype by April 16, 2009 which can be used by able-bodied persons to collect data. The prototype must facilitate easy calibration and provide force feedback to the bicep. Key wants include improving the means by which force measurements are collected from the gripper so that the force feedback is applied correctly. In addition, various forms of haptic (or touch) feedback should be developed to provide rich feedback. Also, the gripper must be easy to use.

Using brainstorming, functional decomposition, and benchmarking methods, we created a number of design concepts (Appendix D). Then, with scoring matrices, we chose the best concepts to be skin-stretching feedback, vibrotactile feedback, use of force-sensing resistors (FSRs), use of strain gauges, and manufacturing of a custom aluminum exoskeleton. Finally, we eliminated the use of FSRs and opted to use only the strain gauges as sensors.

Our fully evolved, final design incorporates key concepts to create a custom exoskeleton which conveys vibrotactile feedback to the user when the gripper first comes in contact with an object and conveys skin-stretching feedback while the object being gripped is deforming. The prototype was manufactured using machining processes including milling, drilling, and buffing and assembled with various fasteners and epoxy.

Our prototype permits researchers to turn each feedback system on and off to test which feedback method(s) works best. For example, skin-stretch and force feedback together may convey more information to the user than skin-stretch and vibrotactile feedback. In addition, the learning curve for the device may change with the use of additional forms of feedback. Validation testing showed that test subjects may use the device to differentiate between foams of varying density. 76% of users found our two added feedback systems conveyed more information about the object than the force feedback did. Signal data collected showed that strain gauges are suitable for our purposes.

Our prototype fulfills our specifications and requirements as requested. Future work could focus on weight reduction (by using lighter materials, for example), improved fit (perhaps with more adjustability), and further development of the computer code. In addition, other forms of feedback should be investigated.

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Introduction

The purpose of this project is to create a variety of feedback systems for a myoelectric-controlled prosthesis which will be testable by able-bodied individuals. In addition to the already developed force feedback which requires the bicep to resist an applied torque about the elbow, we will develop haptic (touch) feedback systems. The project consists of developing our own prosthesis for integrating and testing the various feedback systems as well as improving data acquisition for these and similar systems. Most important to note is that we are developing a device purely for research purposes. Sometime in the future, our developments may be used to create a prosthetic for a trans-radial amputee but, for now, our device is designed for an able-bodied person and used for information purposes.

Myoelectric prostheses are controlled by picking up electromyogram (EMG) signals from the surface of the skin to command the gripper. The difficulty with this system, and prostheses in general, is that the operator must rely on visual feedback when performing tasks. For example, the user is unable to differentiate between objects of differing stiffness unless he can see whether or not the object is being deformed. In addition, since he is also unable to feel how much force is being applied to the object, he cannot feel how stiff one deforming object is as compared to another. Our goal is to create a variety of complementary systems for providing haptic feedback to the user.

Project Requirements

We used the Quality Function Deployment (QFD) method to determine which requirements and engineering specifications we should focus on. We took a combination of pre-existing requirements and requirements that we defined, and determined which ones were the most important. When using QFD, it is possible to delineate the difference between a requirement that must be met and a requirement that is optional but still desirable or, in other words, a want.

We have identified six “musts”. To fulfill our obligation to ME 450 and our sponsor, a functional prototype must be fabricated by April 16, 2009. The prototype must be usable by an able-bodied person because its intended use is to collect data in a lab setting. The design must facilitate easy and accurate calibration to maximize the quality of control and feedback. The primary goal for the use of this design is to validate and further develop a revolutionary haptic feedback system; therefore, being able to successfully collect data from a series of experiments is crucial. The forces sensed at the gripper must be reflected through the bicep as it is the muscle controlling the design via a myoelectric sensor. Finally, the materials used in the manufacture of the prosthetic must be skin safe. Each of these requirements is considered a must, because missing any of them will severely limit the ultimate success of the project.

As a result of utilizing QFD, we prioritized our remaining wants and there are three in particular that stand out. For the use of the prosthetic to feel as natural as possible, the gripper must be easy to control. The new design should improve the measurement of force from the gripper to improve the feedback implementation featuring a torque applied to the elbow joint. Additional and varied forms of feedback should be developed and implemented in concert with one another, to increase the amount of information being relayed to the user. By making the haptic feedback as rich as possible, it is more likely that the user will be able to master its use and realize the potential of the technology.

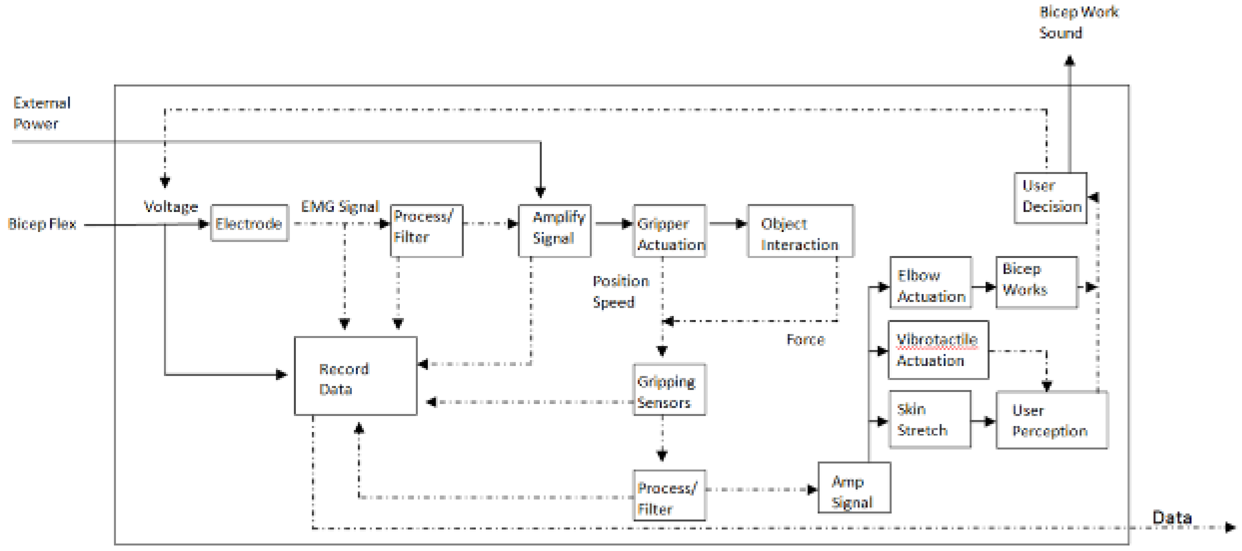
Engineering Specifications

To satisfy the requirements which we denoted as musts and wants that were mentioned above, we generated ten specifications, of which five were selected as a result of their relative importance. Gripper control response time or latency is important for the ease of use of the gripper. EMG voltage difference sensitivity is related to control latency and has a large effect on the usability of the gripper. The voltages from the electrodes are very sporadic and seemingly random so proper filtering and processing of this signal is a necessity. The torque required to flex the elbow has implications on the ease of use also. Since forces introduced via friction and other sources of energy dissipation interfere with the haptic feedback mechanism, ease of use will be affected. The feedback motor acceleration should accurately reflect the interaction forces at the gripper and the torque on the elbow needs to be scaled properly to the information coming from the sensors on the gripper.

Concept Generation

With our engineering specifications, we began to generate design concepts. First, we created the functional decomposition diagram shown in Figure 1 below. This exercise assisted in analyzing the flow of signals (information) and energy. We also collaborated with Alicia Davis at the University of Michigan Prosthetics and Orthotics Center, Rob Wagner of Wright and Fillipis, and John Carpenter of Touch Bionics to learn more about current concepts in the prosthetics field.

Figure 1: Functional Decomposition



With our research and functional decomposition, we brainstormed and developed 55 design concepts. We found that our concepts can be classified with six categories: feedback, gripper,

exoskeleton, EMG signal acquisition, unit control methods, and computer controls/data acquisition. An outline of these concepts can be viewed in Appendix D, page 75.
We worked with our sponsor, Professor Gillespie, and his laboratory technician, John Baker, to create a focused scope for our project. With this focus, we chose five main concepts: use of force-sensing resistors (FSRs), use of strain gauges, skin-stretching feedback, vibrotactile feedback, and the manufacturing of a custom polypropylene exoskeleton.

Concept Selection and Specifications

From the list of concepts generated, we decided to focus on the feedback, sensors, and exoskeleton categories because we felt that these areas provided the most opportunity for improvement. We then created a scoring matrix for each category and compared alternative solutions to the current prototype. From the scoring matrix, we were able to determine the top concepts for each of the categories.

Feedback

Feedback can be provided to the user through a variety of methods including force, subcutaneous, and tactile. Force feedback to the elbow is required as specified by the sponsor. Therefore, the scoring matrix was used to determine additional types of force feedback that could be implemented. Skin-stretching, vibration, and a pressure sleeve were the additional methods of feedback we felt could be utilized. The scoring matrix resulted in a tie between skin-stretching and vibration. Therefore, we decided to analyze each as a concept.

Concept #1 – Skin-Stretching Feedback

Our first concept is to implement the sensation of the user’s skin being stretched as the gripper is deforming an object. Once the gripper begins to deform an object, the motor would begin to rotate and pull the silicone strap towards the elbow. The relationship between gripper arm displacement and the angular displacement of the servomotor shaft must be tuned to optimize effectiveness.

The skin-stretch system consists of a hobby servomotor and a silicone cuff strapped to the forearm. The servomotor will be used to pull on the silicone strap attached to the users forearm so the torque needs to be high enough to create perceivable feedback. The motor must have a small volume and a weight less than 10 N due to packaging and usability concerns. The motor is mounted to the underside of the brace near the elbow joint. The cuff is 254 mm long and 50.8 mm wide, and is adjusted with a Velcro™ strap to ensure proper fit and tightness for all users.

The main advantage to this concept is that it provides the user with an added method of haptic feedback. This feedback can provide a variety of information using the speed, direction, and displacement of the skin-stretch. The disadvantages to this concept are that it will add a mechanical assembly to the forearm which will add weight and limit space for other components. It will also require more time to integrate than other feedback methods. Additionally, skin irritation is possible.

Concept #2 – Vibrotactile Feedback

Our second concept is to utilize vibration motors to provide vibrotactile feedback. One to three vibration motors would be placed on the forearm of the user and used to indicate the first instance and impulse magnitude of contact between the gripper digit and the artifact being manipulated.

The vibration feedback system will receive electronic signals to actuate vibration motors. The intensity of the feedback will be scaled to the speed of impact, either by varying the number of actuators used or the frequency of vibration of a single actuator. The upper limit of the frequency will be 200 Hz and as many as three actuators could be employed to provide the feedback.

This concept would provide another sensation of feedback to the user. Advantages of the concept are that it would be relatively cheap, simple to implement, and compact. The disadvantages are that the vibration could create too much noise for the EMG sensors to work properly and that it is not as intuitive to the user as other feedback methods.

Sensors

The types of sensors that we analyzed using a scoring matrix were strain gauges, force sensitive resistors (FSRs), potentiometers, and optical encoders. The scoring matrix showed a tie between the use of strain gauges and FSRs. Considering the different applications that they could be used for in the current prototype, we treated each one as a separate concept.

Concept #3 – Force Sensitive Resistor

Our third concept is to place two FSRs on the inside of the gripper that will be used to indicate the first instance of contact between the gripper digit and the artifact being manipulated. One FSR will be placed on the inside tip of one gripper digit and the other will be placed on the middle, inner face of the opposing digit. Using two FSRs at the specified locations will ensure that a FSR is in contact with any object subject to manipulation.

The FSR’s resistance decreases as pressure is applied to the pad. The range of sensitivity will be from 0-6.89 kilopascals. The signal will saturate quickly, but the sensitivity will be greater than that of an FSR with a greater range. The signal coming from the FSRs will be amplified to reduce the effect of signal noise introduced by the internal resistance of the wires used to transfer the information.

The advantage to using FSRs is that they will allow for better implementation of force feedback to the user. The disadvantage is that the FSR requires additional wiring to and around moving components, increasing the chances for electrical failure.

Concept #4 – Strain Gauge

The strain gauge would be placed on the outside of the gripper and would be used to indirectly measure the force that the gripper is applying to an object. The reaction force on the gripper from the object will create a strain within the gripper digit that the strain gauge will measure.

The strain gauge must have no dimension greater than 12.7 mm in order to mount it to the gripper digit within its dimensions. The sensitivity of the strain gauge must be selected to match the geometry of the gripper arm and the forces inducing strains on the surface of that arm. This can be determined by the area moment of inertia of the arm, the maximum gripping force, and the material of the arm. The strain gauge signal will be amplified to improve the signal to noise ratio to ensure a consistent and accurate feedback control signal.

The advantages of this concept are that it improves the measure of force from the gripper and it will be relatively simple to implement. Also, strain gauges are inexpensive and would provide for better resolution and real-time signal collection. One disadvantage is that since they are on the outside of the gripper digit they will be more susceptible to damage.

Exoskeleton

Concept #5 – Custom arm brace

Our fifth concept is to make a custom one-piece brace using polypropylene, elbow hinges and Velcro™ straps. The brace will have a bar for the user's hand to rest on as shown in Figure 2, page 9.

The primary advantage is that it will be easier to mount assemblies to it than to the store-bought arm brace, through the integration of custom mounting plates. This will allow us to integrate various types of force feedback to the user. Other advantages are that it could adjust to fit a wide variety of users and would be more compact than the brace bought from the store. The disadvantages are that it would require more time to make than buying one from the store and we would need the technical assistance of the University of Michigan Prosthetics and Orthotics Center.

Chosen Concept: The Alpha Design

Our chosen concept is to integrate each of our five concepts with the current prototype. The main advantage is that by using elbow actuation, vibration, and skin-stretching we are able to convey different types of sensory information to the user. The elbow actuation will tell the user when they are gripping an object, the vibration will tell the user when the grippers just touched an object, and the skin-stretching will allow the user to feel how much deformation the gripper is causing. The disadvantage to the implementation of three feedback methods is that it is less intuitive and may be too complicated for users.

The FSRs will control the vibration motors and the elbow actuation since these feedback methods are given via contact with objects. The FSRs in conjunction with the internal position sensing of the gripper motors will control the skin-stretching method of feedback, in particular, the speed at which the skin is stretched and the amount that it is stretched. The strain gauge will be used to control the elbow actuation by giving the system an indirect measure of the forces applied at the faces of the gripper digits. The disadvantage of using these types of sensors is that they will be more susceptible to damage since they are placed on the outside and inside of the gripper.

How the Alpha Design Works

The components are strapped to the arm using the brace. Control for the gripper is provided via EMG electrodes on the bicep, the gripper is attached to the brace at a point beyond an able-bodied user's hand, and the feedback systems are placed about the elbow as shown at right in Figure 2.


Figure 2: Isometric View of the Alpha Design

The operator's command signal is picked up from the bicep using dry EMG surface electrodes. The signal is processed and then activates the gripper's Dynamixel AX-12+ servomotors. When the gripper comes in contact with an object, the FSRs detect the slight pressure, and the signal is picked up, processed, and sent to the vibration motors. The purpose of these motors is to indicate the moment of contact and it only operates for one half second.

The skin-stretch system indicates to the user how much force is being applied to the object. The skin-stretch will convey object stiffness information to the user. For example, if they experience the skin-stretch for a long time, they will know that they have been deforming the object for that amount of time.

Engineering Design Parameter Analysis

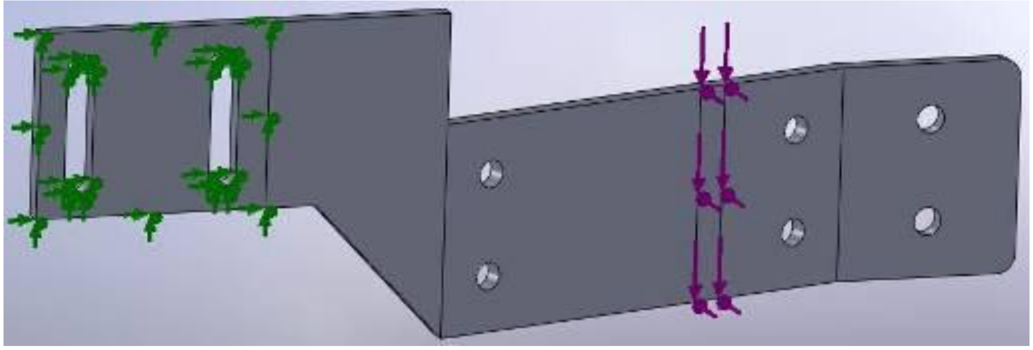
To select specific components for our prototype and determine that the brace was structurally sound, we performed analysis for the strain gauges, skin-stretch mechanism, elbow capstan drive mechanism, and elbow brace.

Strain gauges

We have selected the Vishay 125BZ-WK strain gauge. It is 7.4 by 3.3 mm in size, with a fully encapsulated K-alloy and high endurance lead wires. Smaller gauges are unsuitable for our design while larger gauges would not provide accurate readings since they would cover more than the highest strain area [3, 4, 5]. We will be testing the usability of strain gauges as signaling devices with our prototype.

We performed an FEA for the gripper digits to confirm the location of highest strain. The gripper fingers are made of aluminum. The slotted holes are fixed to restrict the motion of the gripper digit. The point at which the loading is applied is approximately 50 mm from the fixed constraint boundary conditions. The loading consists of a 16 N force directed outward and a 10 N force directed downward. These forces were determined by considering the maximum torque output of the gripper servomotors, and the maximum weight of an object that can be lifted with the gripper. These boundary and loading conditions can be seen in Figure 3.

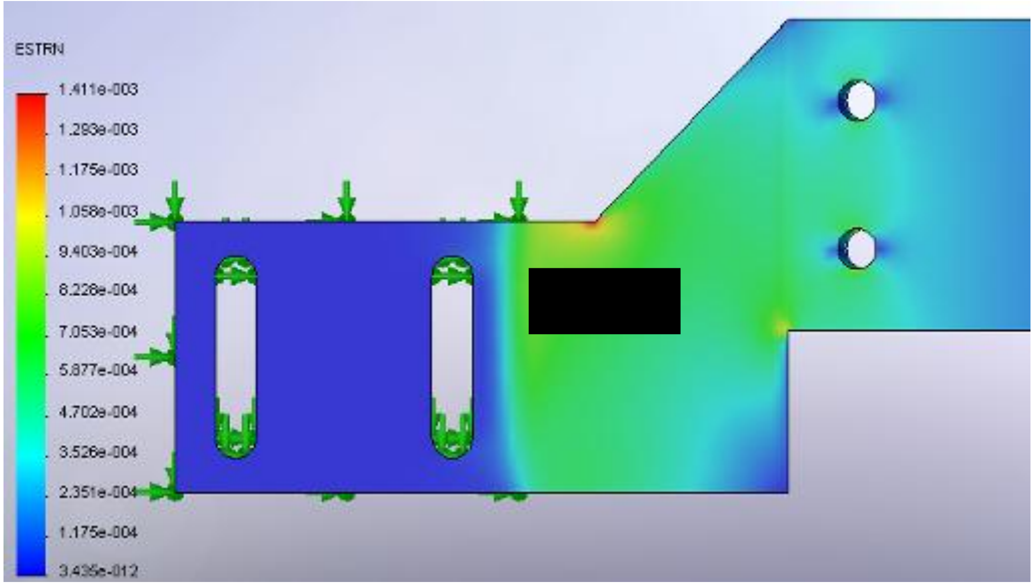
Figure 3: Gripper Finger is Fixed at One End and Loaded at the Point of Contact



The results from the FE analysis (Figure 4) show that the highest strain occurs at the location nearest to the fixed end. This matches the theoretical prediction that the highest stress/strain of a cantilevered beam experiencing bending will be at its base.

We completed hand calculations in parallel with our FEA, to ensure the accuracy of our results. The results from our hand calculations, using the same loads and setup, agree with our FEA results to within 5%.

Figure 4: Stresses on the Gripper Finger are Highest in the Region Close to the Fixed Point



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Skin-Stretch

For the skin-stretch feedback, a portion of skin on the forearm will be tugged in a given direction for the purpose of indicating when an object being manipulated is being deformed by the gripper. We considered two different designs for this. The first design is a rubber cuff strapped to the forearm, a portion of which is tugged linearly by a servomotor towards the elbow or transversely across the arm. The second design uses a servomotor to twist a portion of skin on the forearm. Literature on the effectiveness of haptic feedback systems describes using the second design [6], so we will use this for our design.

The skin-stretch system is dependent on the two-point discrimination threshold [6]. The servomotor wheel will have two inserts that contact the skin. The points must be close together so that both points remain in contact with the skin, yet far enough apart for the user to determine direction and magnitude of stretching. Research indicates that this distance is 12.7 mm [7].

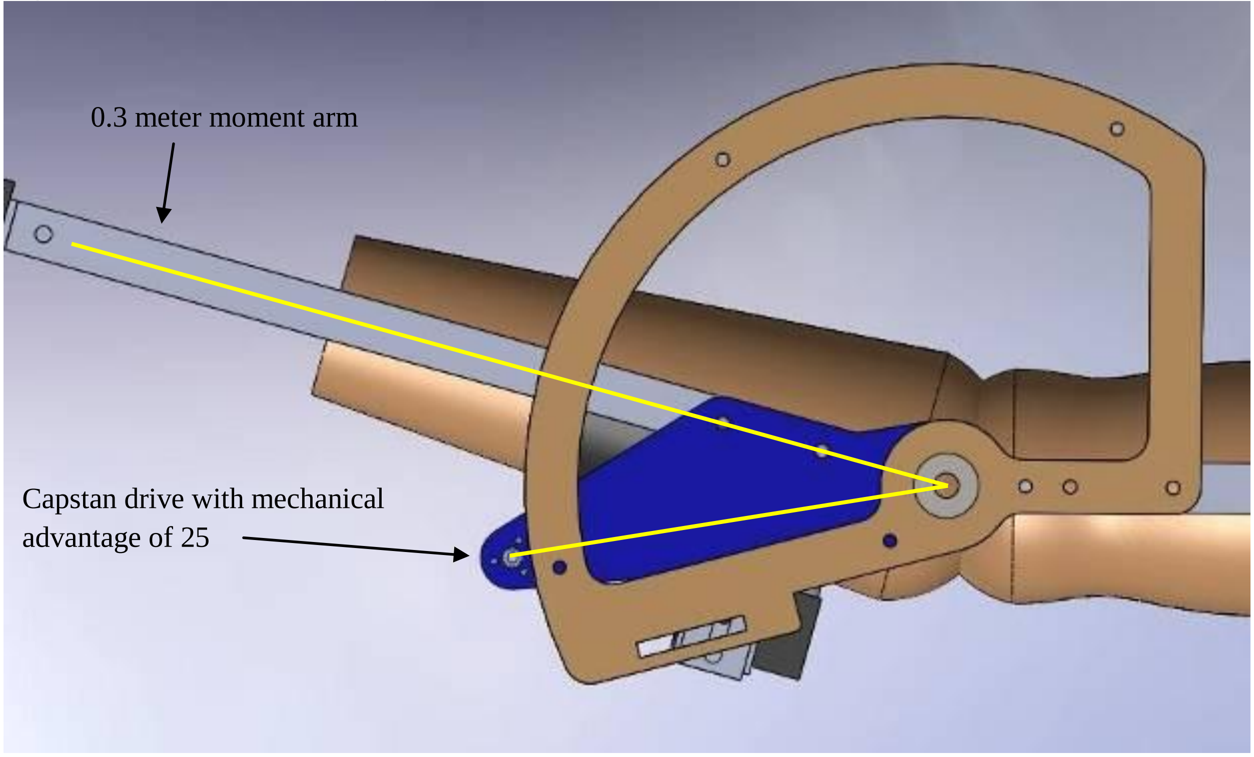
We will be using a skin-safe adhesive to interface the skin-stretch contact points with the skin to ensure proper function. There are two ways to use skin-stretch as feedback. The first way is to provide feedback via the angle of a rotational input; a certain angle will correspond to a certain force. The second way is to apply a certain amount of torque to the user's skin corresponding to the feedback signal. We need to be certain that the servomotor will be able to apply the adequate torque for optimal haptic feedback. The Dynamixel AX-12+ servomotor is capable of applying an operating torque of 10.7 kg-cm and holding torque of 16.5 kg-cm. Our literature search details an experiment comparing position using a reference angle of 20 degrees with an average difference threshold of about 1.5 degrees, and an average torque difference threshold of about 6 mN-m (0.06 kg-cm) [8]. We are confident that the servomotor will be able to operate within these ranges. We will be testing the usability of this system with our prototype.

Elbow Drive Analysis

The existing prototype features a capstan drive system which uses a small form-factor DC motor to exert a torque about the user's elbow. Analysis was completed to determine the necessary torque in order to select a new motor that meets all of the requirements of this subsystem (see Figure 5, page 12).

The analysis starts with understanding the desired torque output of the capstan drive system. We chose to equate this torque to a torque felt about the elbow by a theoretical object in the user's hand. In this way, we could translate a certain object weight into an equivalent torque about the elbow, thus simulating how much force the user's bicep would be asked to output.

Figure 5: Capstan Drive Analysis



The threshold for this simulated object weight was determined by examining the amount of weight in the user's hand that is easily discernable, taking into account the bicep's reduced sensitivity compared to the forearm muscles. Since the bicep is essentially taking over for the non-functional muscles in the amputated limb, we felt that this comparison was appropriate.

We chose to perform our calculations assuming that the object in the user's hand weighs 70 N, which is essentially 15 lbs. The moment about the elbow of the user is simply this force multiplied by the distance between the user's palm and the elbow hinge axis. Taking an average of this distance among our four teammates, we determined this distance to be approximately 0.3 m, which is accurate enough for the purpose of our calculations. The resulting moment about the user's elbow is 21 N-m.

The next step was to calculate the desired output of the DC motor. The current capstan drive configuration has a mechanical advantage of 25, meaning that the output shaft of the motor must be capable of producing 0.84 N-m of torque.

Based on the necessary torque output, we considered the use of several 20 Watt RE 25 Maxon DC motors. An important design constraint outside of performance or torque output is packaging size; these motors are small enough to meet that requirement. These motors can provide continuous torque from 11.8-26.3 mN-m and maximum torque outputs of 210-283 mN-m. This series of motors can be purchased with planetary gearhead attachments to amplify the torque output of the motor itself. Given the ranges of torque output, for both the continuous and maximal outputs, we chose to implement a two stage planetary gearhead with a 14:1 reduction ratio.

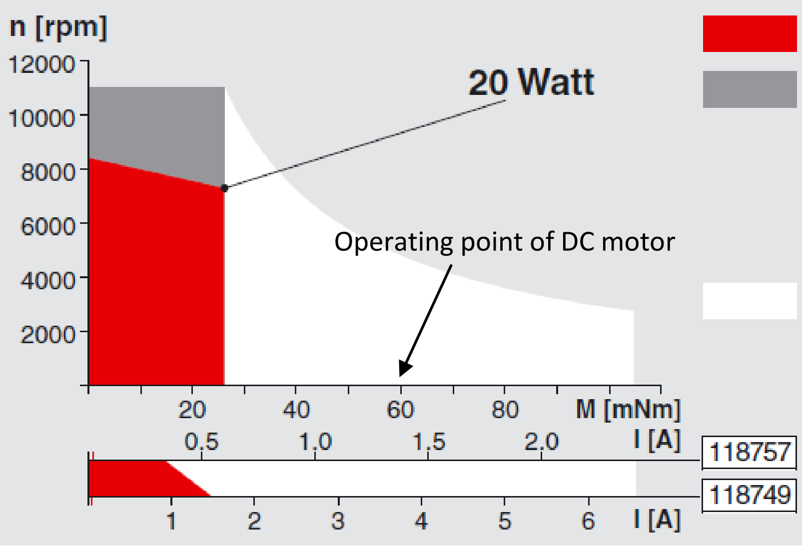
Table 6: DC Motor Specifications

Stall Torque	Max. Continuous Torque	Thermal Time Constant	Motor Weight	Gearhead Reduction
243 mN-m	26.1 mN-m	12	130 g	14:1

Table 6 contains several key motor specifications we considered when making our final selection. Coupling our motor with the 14:1 reduction gearhead means that our motor must output 60 mN-m to generate 21 N-m of torque through the capstan drive. The maximum continuous torque is limited to 26.1 mN-m.

The torque output of the motor is determined by the amount of current passing through the windings. The higher the current input, the higher the torque output. Figure 7 below shows three regions of operation. The grey area is the region in which continuous operation is acceptable. The red area is contained by the grey area and it shows the recommended operating range. Finally, the white area represents the operating conditions that should only be used for a short duration of time. Operating in the white region is limited by the temperature of the coils. When inputting larger currents, the winding temperature increases, but as long as the current stays below the critical value winding temperature of 125 C, the motor won't sustain damage. The thermal time constant for the windings represents how long in seconds it will take the windings to reach this critical temperature when it is given a maximum current input. Because the DC motor in this particular application will be operating in the white region of the graph for short periods of time and at currents less than the maximum current, we feel that it is an appropriate selection for this application.

Figure 7: Operating Ranges of Maxon DC Motor [9]



Brace Analysis

Our brace design consists primarily of two free-swinging knee joint hinges joined together by copolymer cuffs and Velcro^{TM} straps. Our skin-stretch mounting assembly and gripper assembly provide additional structural rigidity between the two separate hinges.

A problem with the design described above is that when a user with a smaller arm tries to wear the device, forcing the cuffs to conform to their arm could cause the axes of the hinges to become misaligned, significantly increasing the friction present in the system, if not completely limiting functionality.

A potential solution to this problem is to mount additional members between the two hinges, thus increasing the stiffness of the entire assembly. The location of these additional supports would be directly under the copolymer cuffs, thus minimizing the package size and adding material, and therefore stiffness, right at the locations of force input. These two considerations maximize their effectiveness.

In order to determine which design configuration is superior, we completed FEA of the main structure of the brace to determine the relationship between estimated force inputs and the resulting deflections of the structure. At each cuff location on both hinges, we applied a 23 N force inward and a 10 N force upward to simulate the forces involved in tightly strapping the device to a user with an undersized arm. The boundary conditions are setup to mimic the condition of the device being attached to the user's arm. The mounting holes for the capstan drive are fixed in relation to each other since the capstan drive can be considered a rigid body in a static analysis configuration. These loading conditions were used to study both configurations and the results follow.

Figure 8: Brace Structure without Additional Members

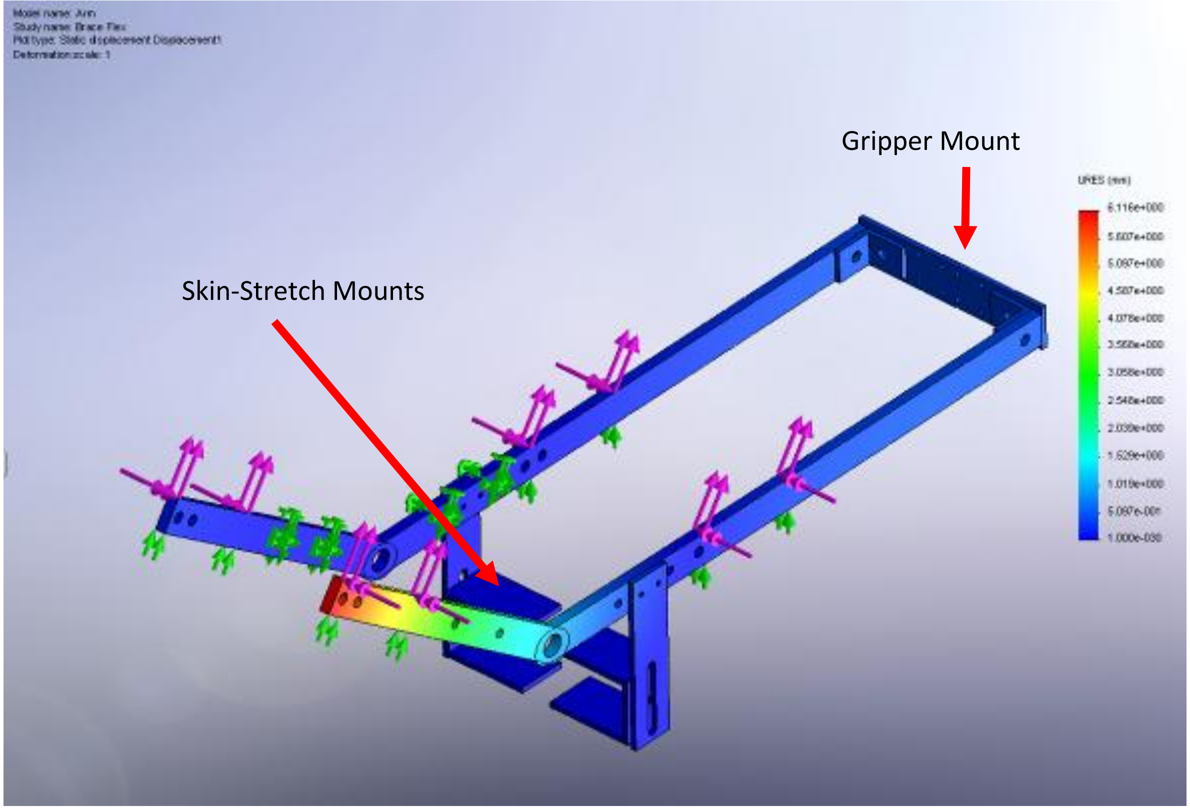
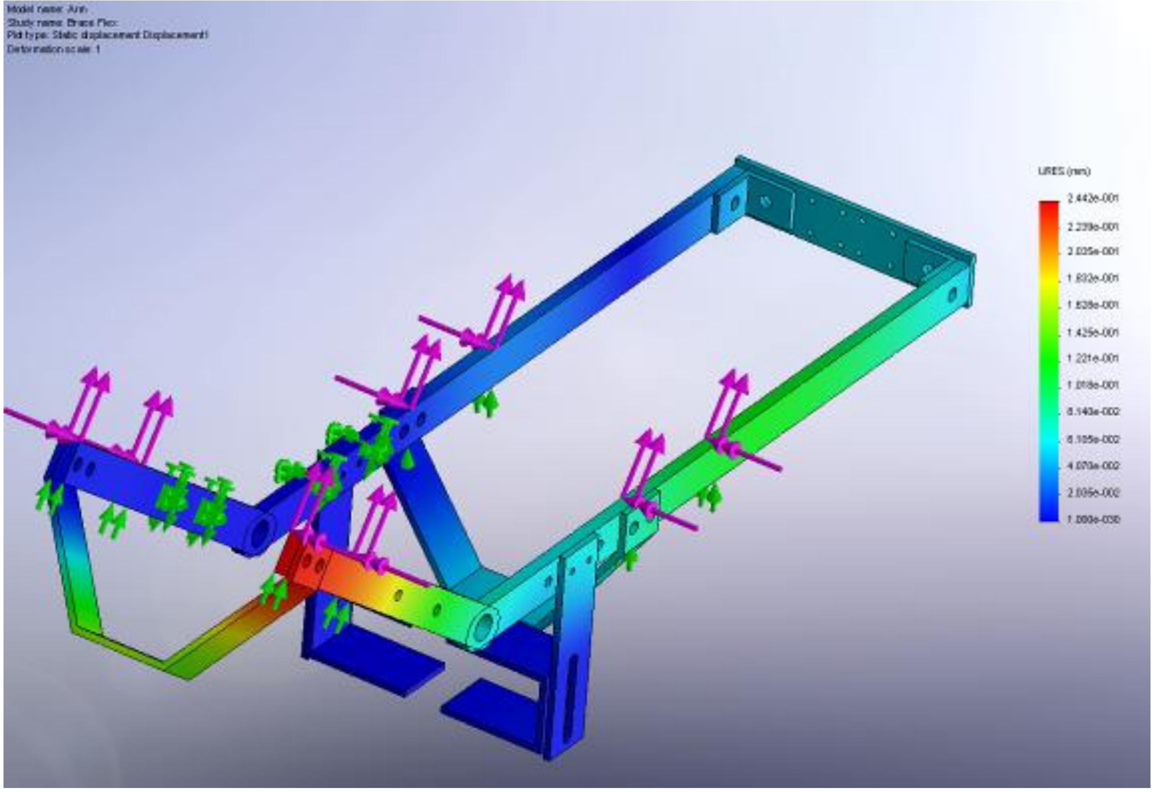


Figure 8 shows the design study without additional members between the hinges. This analysis shows a deflection of ~6 mm at the end of the right side hinge, with deflections at the hinge joint being approximately 1-2 mm. Figure 9, page 16, shows the same analysis setup in terms of loads and boundary conditions but features the additional structural members. The additional parts result in a significant improvement in the stiffness of the structure, reducing the previous deflection at the end of the hinge to ~0.25 mm, a factor of 25 better than without them, at minimal weight cost. However, manufacturing two additional parts adds monetary and time costs to the project, making a simpler solution more attractive on a tight timeline. Therefore, we have decided to go with the configuration in Figure 8 without the additional members. In order to safeguard against the deflection of the brace structure, we will use thin, stiff, foam shims to properly interface the user's arm to the inside of the brace. If a user with an undersized arm intends to use the device, a certain number of these shims will be stacked on top of each other in the cuff and then as the straps are cinched down in preparation for the use of the device, minimal deflections will occur.

Figure 9: Brace Structure with Additional Members



Design for Environmental Sustainability

SimaPro 7.1 was used to do an analysis of the impact the chosen materials would have on humans, the environment, and resources. The analysis compared two choices of aluminum alloys, 6060 aluminum and 6005 aluminum. Based on the prototype requirements and the impact each alloy would have on humans, the environment and resources, 6005 aluminum alloy is suitable for the purposes of the prototype. Results can be viewed in Appendix C2, page 70.

Design for Safety

In this section, we will discuss the various risks in the overall final design, manufacturing, assembly, and validation testing. FMEA and DesignSafe analysis were used to identify hazards and risks with high priority.

Design Elements

Safety risks for the design include burns and fire hazards from the motors. However, these failure modes are extremely unlikely to occur as the control algorithm will limit the torque and current inputs of the motor. All failure modes which have a substantial Risk Priority Number, determined by FMEA, cause loss of function -- not personal or property damage. Also, various electrical hazards exist due to the wiring of the prototype. To address this concern, wires will be properly soldered, organized, and secured.

Manufacturing Elements

Manufactured components will require CNC milling, drilling, cutting, sanding and filing. Manufacturing hazards include burning, air contaminants, severing, cutting, crushing, entanglement, pinching, and flying debris. To reduce these risks, safety glasses, machine shop training, and supervision will be helpful. Most of these components require simple machine operations (particularly drilling).

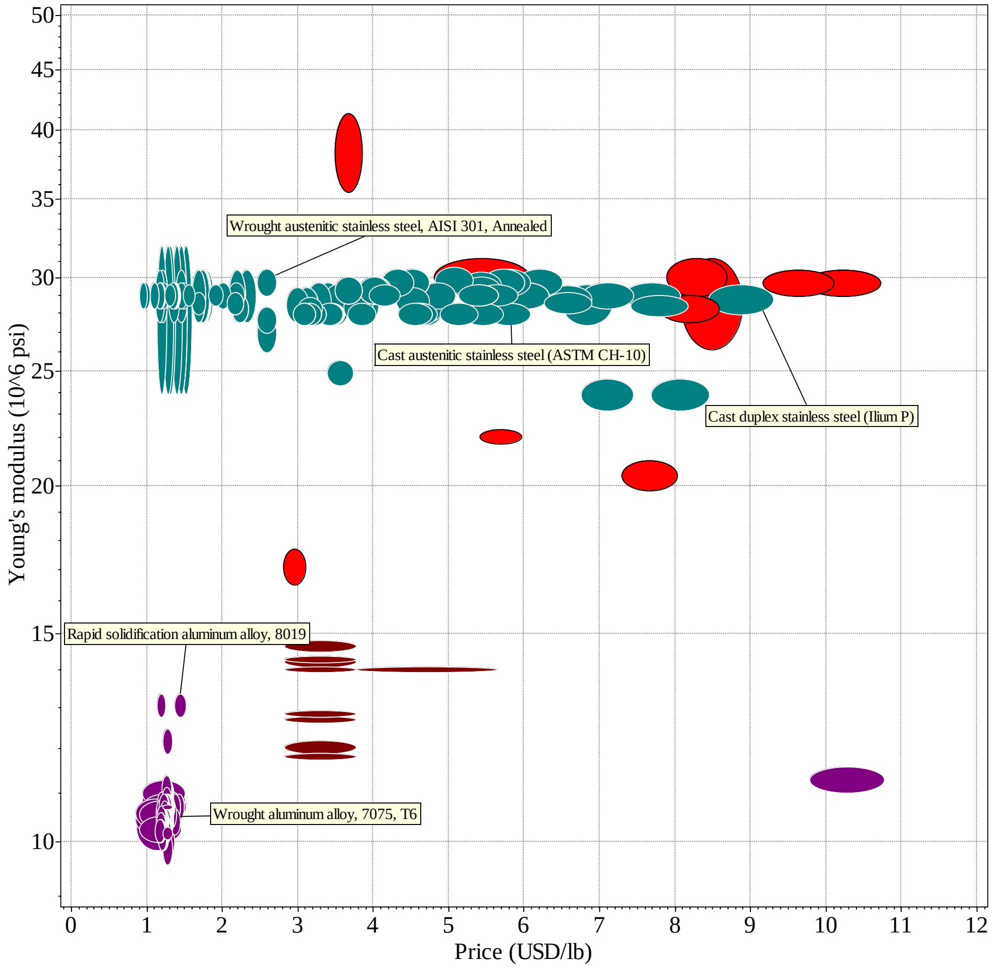
Assembly Elements

Assembly of our prototype involves mostly screwing and snapping parts together. Pinch points, minor cuts, and minor burns can all be prevented with careful work. Skin exposure to lead (from soldering) can be addressed with proper hand-washing.

Material Selection for Manufactured Components

In choosing materials, we considered weight, durability, price, and strength. We completed material selection with Cambridge Engineering Selector. The results for the brace are shown below in Figure 10, various aluminum alloys and stainless steels are marked for reference.

Figure 10: Cambridge Engineering Selector Results for Brace



We chose to use aluminum 6061 T651 based on its availability and advice from our collaborators at the University of Michigan Orthotics and Prosthetics Center.

Manufacturing Process Selection

Since our project is a prototype that will be used for testing purposes, we expect the real-world production volume to be low. Because our sponsor is working with other researchers on this prototype, we expect that at least four of our prototypes will be manufactured and given to each of them so that they can continue their research. We hope that our prototype will lead to other prototypes, which will lead to a final product that would be mass produced.

CES process selection software was used to analyze the feasibility of different manufacturing methods involved in manufacturing the prototype. Two topics to consider are the economic batch size for different processes and the ability to stay within the proper tolerances. Milling and drilling operations satisfy our requirements. Both processes are suitable for batch sizes ranging from a single unit. In addition, both processes are capable of tolerances significantly smaller than 0.01 inches, which is more accurate than what the prototype required. Further information can be found in Appendix C3, page 72.

Beta Design Description

Further development of the Alpha design led to our Beta prototype design as shown in Figures 11, 12, and 13. Each subsystem was developed independently; in this section we will discuss the design changes and additions to the Alpha design in all subsystems, except the vibrotactile mechanism (which remains the same).

Figure 11: Top View

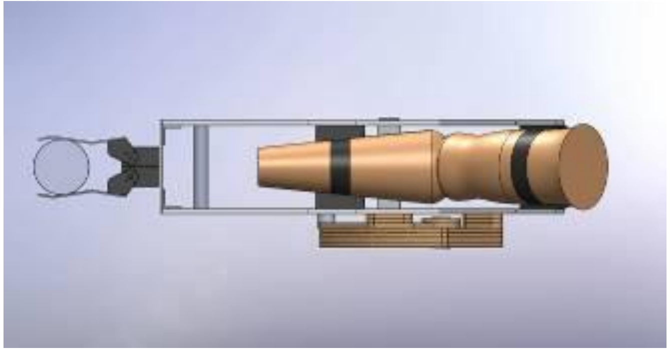


Figure 12: Left View

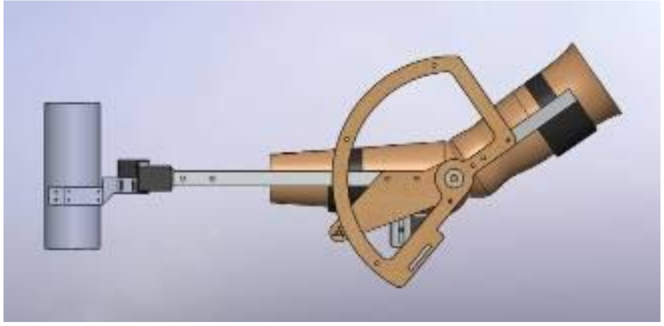
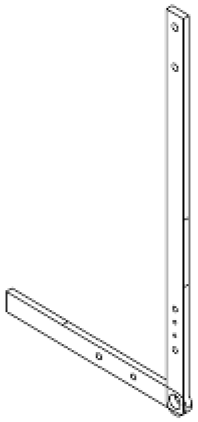


Figure 13: Isometric View

Exoskeleton

Further development of the custom exoskeleton focused on hinge choice and arm cuff design.

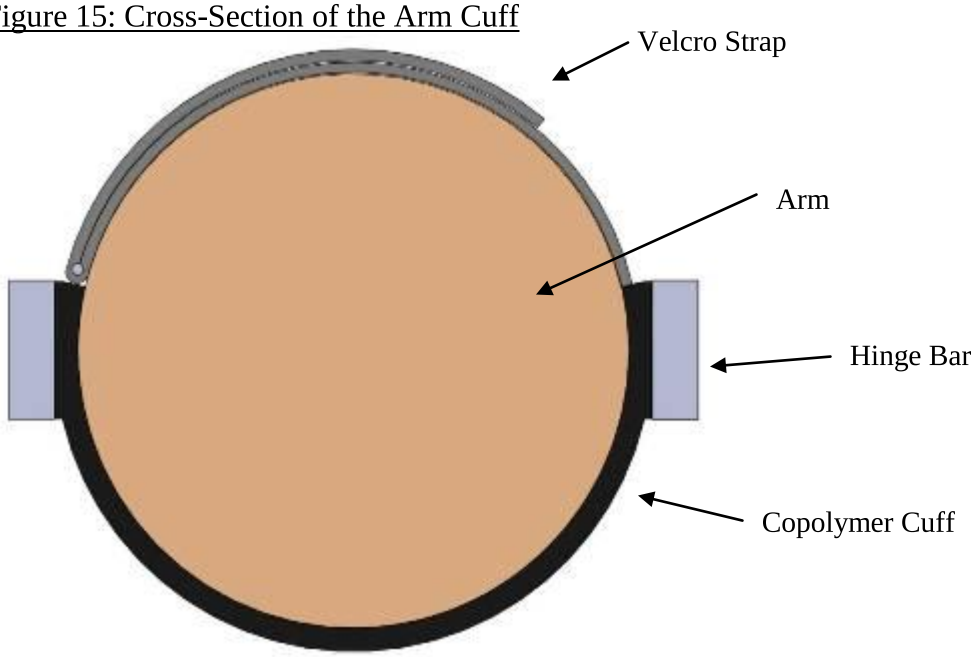
Figure 14 : KAFO Joint



With the use of an elbow hinge for our device, additional bars would have had to be added to each hinge to extend forward to the gripper mount interface. After speaking with a collaborator at the University of Michigan Prosthetics and Orthotics Center, we chose to use a Knee Ankle Foot Orthotic (KAFO) joint shown at right (Figure 14). It is essentially a knee joint, so because it is made for the size of a leg; the links extend well past the hand. The links are made of aluminum, which is lightweight and durable, while the hinge joint itself is made out of steel, for better resistance to wear over time.

To address concerns that the brace structure is easily deformable and that the hinges can easily become misaligned, we considered additional structural members between the hinge bars for added rigidity. After performing an analysis for both designs, we determined that the original concept was sufficient. In addition, we had to consider ease of use, a primary factor being the ease with which the device can be strapped to the user. With these considerations, we developed the exoskeleton design to be sufficiently rigid while maintaining adjustability, comfort, and durability. The cuffs will be made of a formed copolymer, which is a mixture of >90% polypropylene and <10% polyethylene, while the manufactured metal components will be made out of aluminum 6061 T651. A cross-sectional drawing is shown in Figure 15, below.

Figure 15: Cross-Section of the Arm Cuff



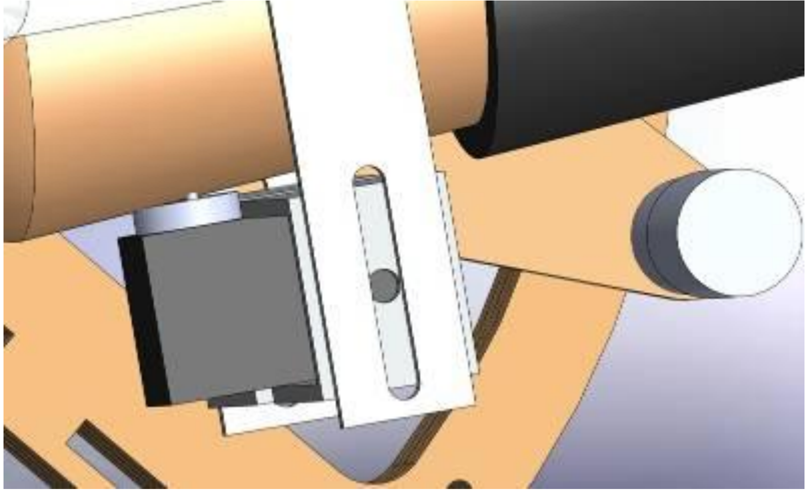
Force Feedback Subsystem

As described in the Analysis section, we determined the necessary minimum specifications of the DC motor and gearhead for the force feedback system. From this analysis, we chose the Maxon RE 25 DC motor.

Skin-Stretch Mechanism

After further research, we chose to use a twisting skin-stretch. The skin-stretch assembly can be seen below in Figure 16. As shown, the skin-stretch mechanism will utilize an AX-12+ servomotor with two inserts spaced 1.6 cm apart. These inserts will be placed snugly against the skin with the shown adjustable mounting assembly. This entire system will be attached to the KAFO joint and mounted below the arm.

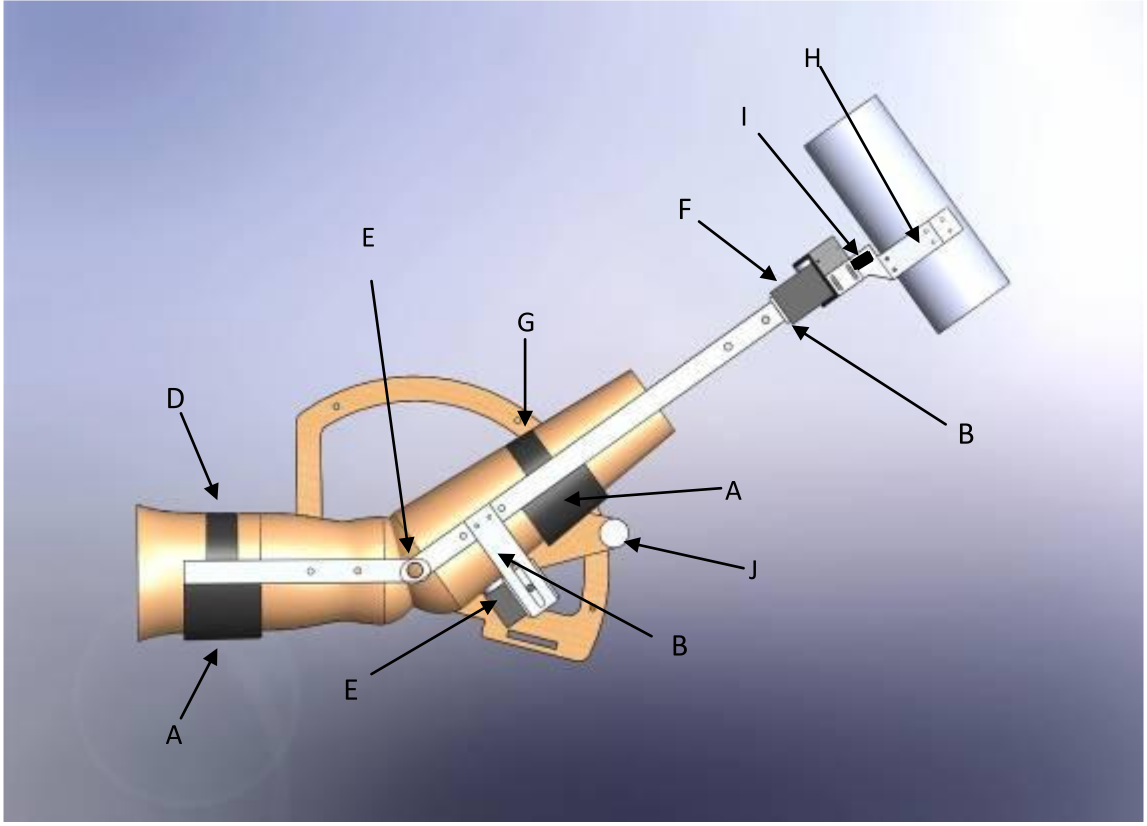
Figure 16: Skin-Stretch Mechanism



Prototype Material & Purchased Component Inventory

Figure 17 below of the Beta prototype design is used to visualize the components in the inventory.

Figure 17: Component Placement



Raw Material Inventory for Manufactured Components

A. Arm Brace Cuffs

Material:	> 90% Polypropylene, <10%Polyethylene copolymer
Source:	University of Michigan Prosthetics and Orthotics Center

Description:

The arm brace cuffs will hold the bottom of the users arm in the device while Velcro straps will be used to keep the device attached to the user.

B. Servo Mounting Plate/Skin-Stretch Motor Mount/Skin-Stretch Slider (not shown)

Material:	Aluminum 6061 T651
Source:	ASAP Source

Description:

These components attach to the hinge (KAFO joint) and hold the skin-stretch mechanism and the gripper. All custom fabricated components related to mounting subsystems to the hinge bars will be manufactured out of alumininum 6061.

C. Handle (not shown)

Material:	PVC
Source:	ASAP Source

Description:
The handle acts as a hand rest for the user's hand.

<u>Purchased Component Inventory</u>
Many of the components used in the prototype will be purchased from outside vendors. While we could have designed and manufactured our own gripper digits and exoskeleton joints, we believe that the overall prototype will benefit from the time saved on production. Also, usability, device performance, and durability will benefit from purchasing these components instead of manufacturing them.

D. Velcro Strap

Quantity:	2
Vendor:	JoAnn Fabrics

Description:
The Velcro straps are tightened to secure the user's arm into the device.

E. KAFO Joint

Quantity:	1 set (contains two joints)
Vendor:	Becker Orthopedic
Catalog Listing	S2005-A4

Description:
The KAFO joint allows for rotation about a single axis at the elbow, provides structure to the prototype, and acts as a mounting point for most of our subsystems. It is made of primarily of Aluminum 2024T, although steel is used at the actual hinge point.

F. Servomotor

Quantity:	3
Vendor:	CrustCrawler Robotics
Catalog Listing	AX-12+

Description:
The AX-12+ servomotors actuate the gripper digits and provide the twisting motion for our skin-stretch mechanism.

G. Vibromotor

Quantity:	1-3
Vendor:	SparkFun Electronics
Catalog Listing:	ROB-08449

Description:
The vibromotor provides the vibrotactile feedback to the user. It is 10 mm in diameter and 3 mm tall and operates at a voltage range of 2.5-3.8 V.

H. Gripper Digit

Quantity:	2
Vendor:	CrustCrawler Robotics
Catalog Listing:	bgh

Description:
The gripper digits are used to manipulate objects and are made of aluminum. They will also serve as a mounting platform for our strain gauges.

I. Strain Gauge

Quantity:	2
Vendor:	Omega
Catalog Listing:	SGD-3/350-LY13

Description:
The strain gauges detect strain in the gripper digits and this information is an input to the control algorithms that govern our force feedback and skin-stretch systems.

J. DC Motor with Gearhead and Encoder

Quantity:	1
Vendor:	Maxon
Catalog Listing:	118752, 166158, 110511

Description:
The DC motor provides the movement of the force feedback system. The attached gearhead for the motor increases the effective torque output of the motor. All internal gears are metal for durability. Additionally, an optical encoder is mounted to the DC motor for accurate readings of position.

K. L-Bracket (not shown)

Quantity:	2
Vendor:	Home Depot
Catalog Listing:	Miscellaneous

Description:
Aluminum L-brackets will be used to attach the servo mounting plate to the hinge.

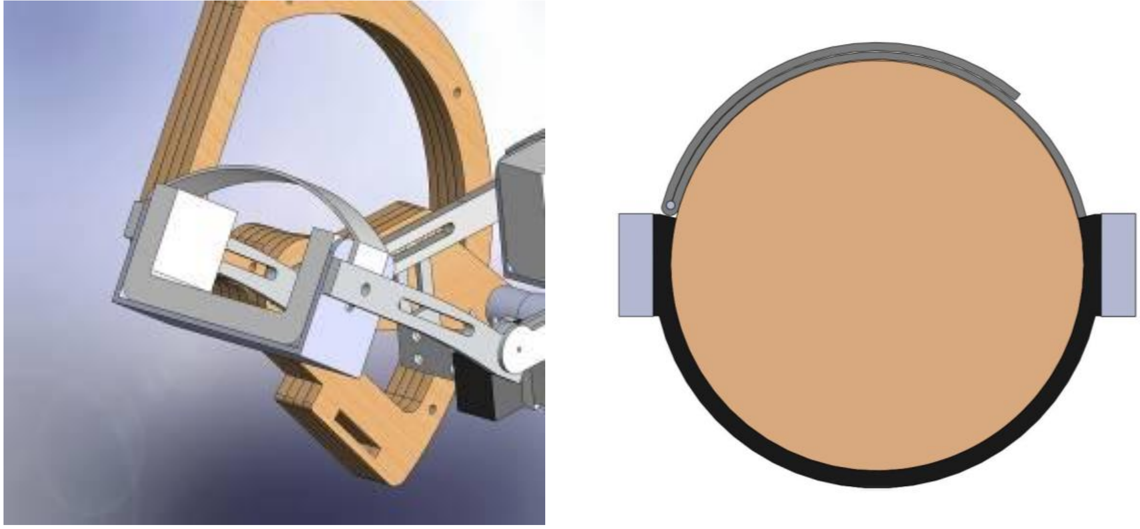
Engineering Changes

As described thus far, the design of our prototype has evolved from concepts, to the Alpha design, to the Beta design. However, the final design was further developed with concerns over structural rigidity, manufacturability, and assembly. These changes are discussed below.

Cuff Design

The most dramatic component design change between the Beta design and the prototype of our device was the cuff design. Our Beta design featured custom formed copolymer cuffs, but after meeting with our sponsor and re-evaluating the analysis that was performed on the brace structure we decided to go with bent aluminum cuffs with foam padding to cushion the user's arm. Using bent aluminum cuffs ensured that the brace would be structurally sound. Figure 18 shows the difference between the new bent metal cuff and the custom copolymer cuff.

Figure: 18



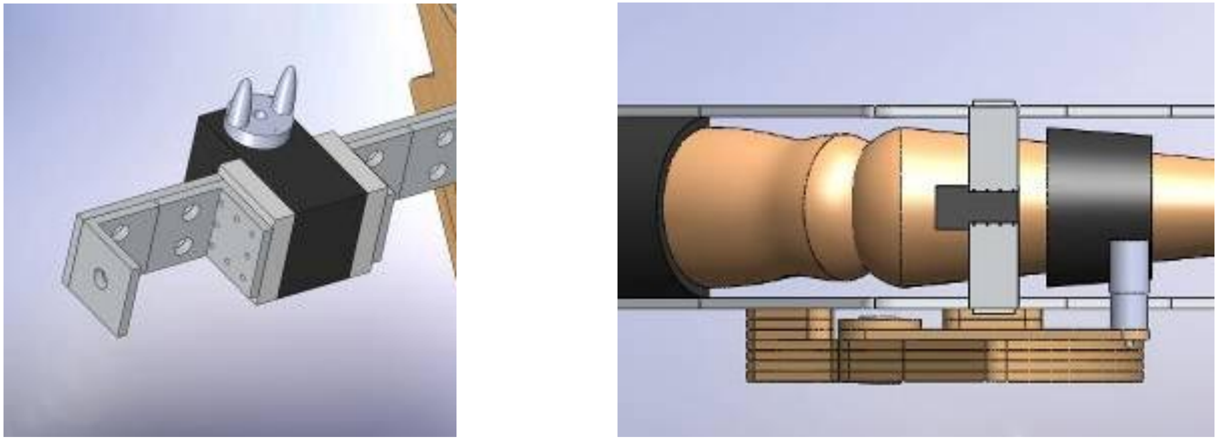
a) New Bent Aluminum Cuff Design

b) Cross Section Formed Copolymer Cuff Design

Skin-stretch Motor Mount

The second significant change was made to the skin-stretch motor mount assembly. The design implemented for the prototype takes advantage of standard material stock sizes and simple drill press operations, which significantly sped up the production of the component and reduced material costs. Figure 19, page 25, shows the difference between the Beta and prototype design. The component is essentially a C-bracket which has been turned 90 degrees for the prototype and made into three separate components which were then fastened together into one part. The motor mount interfaces to a mount piece on the side of the motor now, rather than holes on the top and bottom of the motor like it did originally. This change takes advantage of a mount interface part that came with the motor and results in a more rigid assembly.

Figure: 19



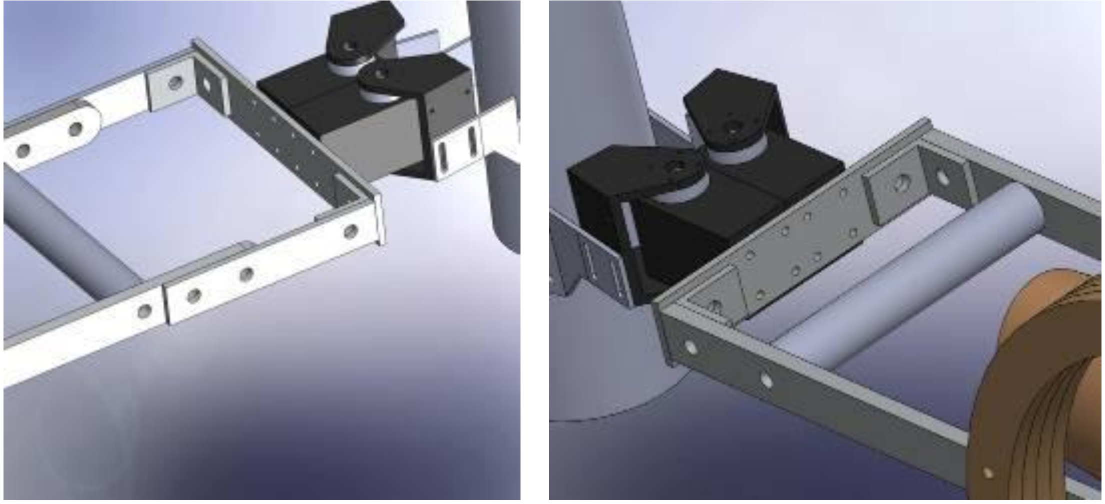
a) New Three Piece Skin-Stretch Motor Mount

b) Old Single Piece Skin-Stretch Motor Mount

Hinge Link Extension

An additional part was designed and implemented for the prototype to extend the forearm hinge links forward to account for users with longer arms. The original configuration of the knee joint that was used for the hinge was changed in order to simplify manufacturing. Originally, the capstan drive that we implemented from a previous prototype would have had to be remade to account for a hinge geometry which differed from the original prototype. Figure 20 highlights the difference between the final design and the prototype design.

Figure: 20



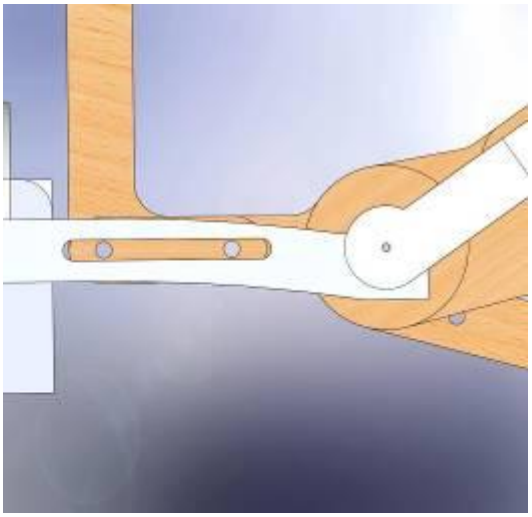
a) New Hinge Extension Part

b) Old Hinge Assembly without Extension

Capstan Mounting Method

Initially the capstan force feedback system was going to be mounted to the hinge bars through post-machined holes. When working with the hinges it was determined that referencing the part properly would be very difficult, which would be necessary for accurate placement of the hole patterns, so the decision was made to machine slots in the hinge bars as shown in Figure 21. The main disadvantage of this approach is that the capstan drive can be installed in such a way that its axis of rotation does not line up perfectly with the hinge axes, but as long as proper care is taken the final installation will lead to a satisfactory result (as was demonstrated with the prototype).

Figure 21: Capstan Mounting Slot



Dimension Changes

Additionally, three other components had dimensions altered between the final design and the prototype due to improved fitting measurements that were made during initial fabrication. These changes were expected and the Beta part designs were modeled to show the intent of the design, not the exact dimensions of the prototype. The distance between the hinges increased, which necessitated increasing the length of the handle, the servo mount plate, and widening the skin-stretch assembly. The changes to each part are specified in our engineering drawings in Appendix B, page 55, which can be used as a reference to see the dimensions of our prototype device.

Fabrication Plan

Many different components for our design required fabrication including the hinges, hand rest, arm cuffs, back plates, motor L-brackets, slider L-brackets, skin-stretch motor sliders, contact points, servo mounting plate, hinge extensions, the hinge assembly brackets, vibromotors, Velcro strips and cuff, coding, strain gauges, adhesive gripper padding, wiring, and two Wheatstone bridges. All of the metal components are made of aluminum. The skin-stretch contact points which are made of nylon. Fabrication methods that were used include milling, drilling, turning, cutting, bending, and buffing. Machines that were required included a 3-axis mill, drill press, lathe, band saw, metal press, and a buffer. Fabrication was done at the University of Michigan Orthotics & Prosthetics Center, the University of Michigan Undergraduate Machine Shop, and at the Wilson Center.

Hinges

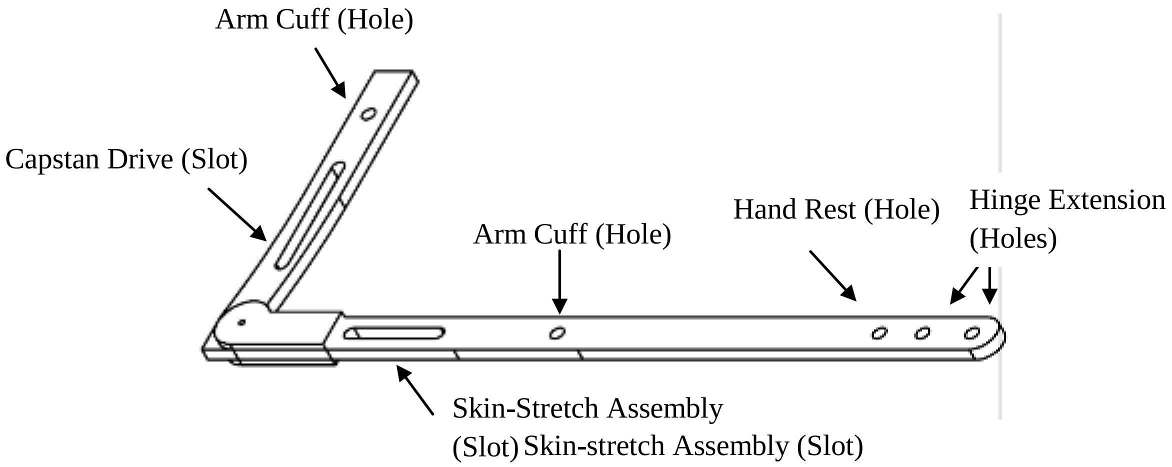
Two hinges were bought from Becker Orthopedic and milling, cutting, and buffing were used in their fabrication (Figure 22, pg 27).

Milling

Milling was done to fabricate holes and slots in the hinges. The holes were made to so that the two arm cuffs, skin-stretch assembly, gripper, and hinge extension could be attached, and the slots that were milled were made so that the skin-stretch assembly could be adjustable and to attach the capstan drive to the hinges. All of the milling was done at a spindle speed of 2500-3000 rpm and was done using a 1/4” mill bit. In each hinge, two holes were milled in order to attach the arm cuffs, one hole was milled to attach the hand rest, and two holes were milled to attach the hinge extension. Slots were milled so that the capstan drive could be attached to the hinge and so that the skin-stretch assembly could be adjustable.

Cutting and Buffing
A band saw was used at a speed of 1000 fpm to cut the length of the hinge to a desired length. Buffing was then done to smooth the edges for safety and aesthetic purposes

Figure 22: Holes and Slots that were Milled for the Hinges



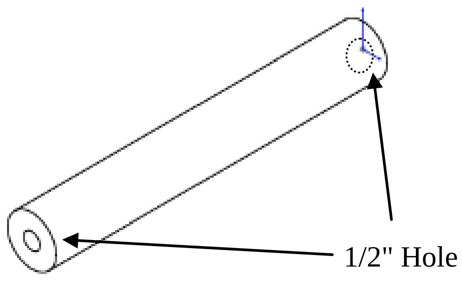
Hand Rest

Round stock 3/4” PVC was bought and fabricated by cutting and turning as shown in Figure 23.

Cutting
A band saw was used at a speed of 1000 fpm to cut the hand rest to a length of 5.118”.

Turning
Two holes were drilled on the lathe at each end of the hand rest so that it could be attached to the hinges. A lathe was used at a speed of 1500 fpm and a 1/2” drill bit

Figure 23: Holes that were Drilled on the Hand Rest



Arm Cuffs

Two arm cuffs were made from 2” x 1/8” aluminum stock. Fabrication required cutting, buffing, milling and bending (Figure 24).

Cutting and Buffing

A band saw was used at a speed of 1000 fpm to cut the aluminum stock to a length of 10.24”. Subsequent buffing was then used to round each of the corners.

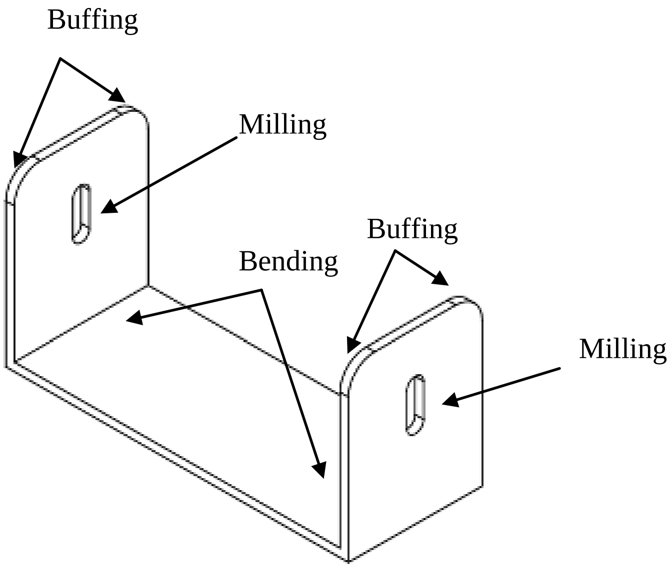
Milling

Milling was done using a 1/4” mill bit and at a speed of 2500-3000 rpm for the slots which were used to attach the cuffs to the hinges and allowed them to be adjustable.

Bending

Both ends of the aluminum stock were bent approximately 90° using a metal press. Both bends were done approximately 2.56” from both ends of the plate.

Figure 24: Location of Bending and Milling Operations for the Arm Cuff



Skin-Stretch Assembly

The skin-stretch assembly (in Figure 25 and 26) consists of ten parts: two Skin-Stretch Motor Back Plates, two Motor L-Brackets, two Slider L-Brackets, two Skin-stretch Motor Sliders, and two Contact Points.

Figure 25: Components of the Skin-Stretch Assembly

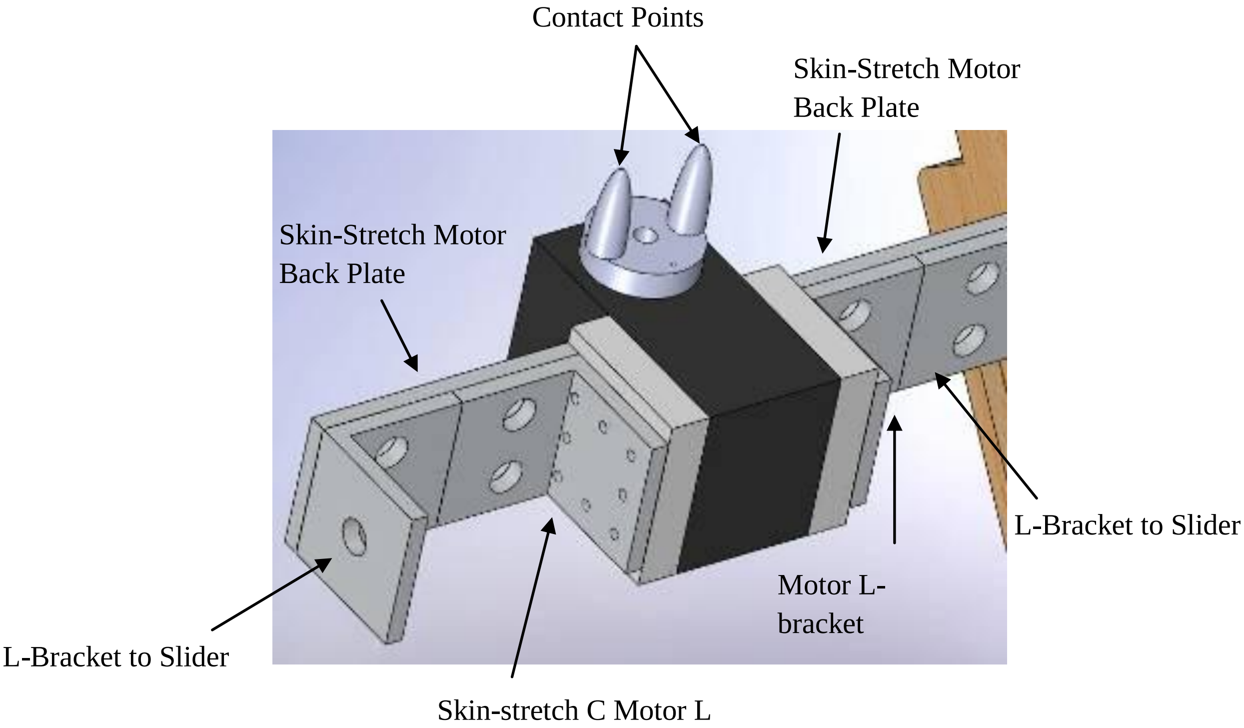
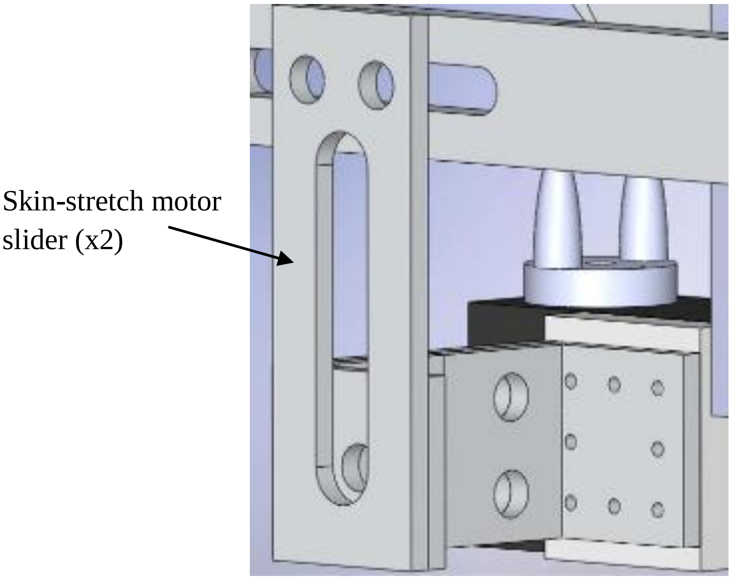


Figure 26: Skin-stretch motor slider used for the Skin-Stretch Assembly



Skin-Stretch Motor Back Plate

Two back plates were fabricated from 1” x 1/8” aluminum stock. Fabrication processes included cutting and drilling as shown in Figure 27.

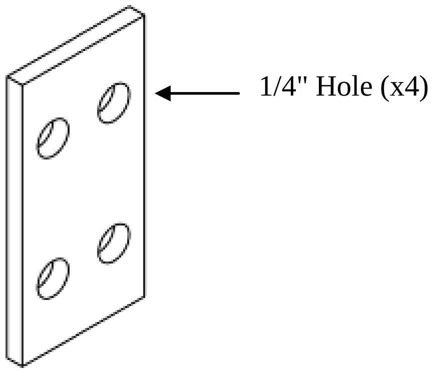
Cutting

A band saw was used to cut the aluminum stock to a length of 2” at a speed of 1000 fpm.

Drilling

A drill press was used to drill four holes at a speed of 2500-3000 rpm and with a 1/4” drill bit.

Figure 27: Holes for the Skin-Stretch Motor Back Plate



Motor L-Brackets

Two motor L-brackets shown in Figure 28, page 31, were fabricated to attach the servo motor to the rest of the assembly. Two 1” pieces were fabricated from L-bracket aluminum stock via cutting and milling.

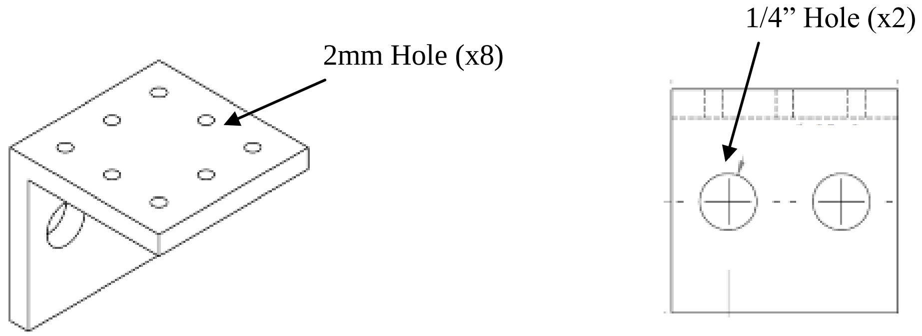
Cutting

A band saw at a speed of 1000 fpm was used to cut two 1” L-brackets.

Milling

A manual mill was used to drill ten holes into the motor L-brackets. At a spindle speed of 2500-3000 rpm, two 1/4” holes were drilled on one face of the L-bracket to connect it to the motor back plate. At a spindle speed of 2500-3000 rpm, eight holes were drilled on the other face to connect it to the skin-stretch servo motor.

Figure 28: Holes that were Drilled on for the Motor L-Bracket



Slider L-brackets

Two L-brackets were fabricated as shown in Figure 29 to attach the skin-stretch assembly to the hinges. Two 1” pieces were fabricated from L-bracket aluminum stock using drilling and cutting operations.

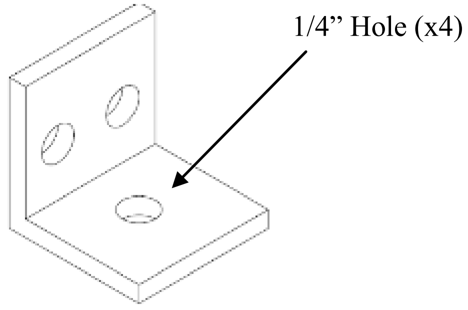
Cutting

A band saw was used at a speed of 1000 fpm to cut two 1” L-brackets.

Drilling

Three 1/4” holes were drilled into the L-brackets using a drill press at a speed of 2500-3000 rpm. One hole was drilled on one face so that it can be attached to the slider and two holes were drilled on the other face so that it can be connected to the back plate.

Figure 29: Holes that were Drilled on for the Slider L-brackets



Skin-stretch motor sliders

Two sliders were fabricated from 1” x 1/8” aluminum stock using milling and cutting operations (Figure 30, page 32).

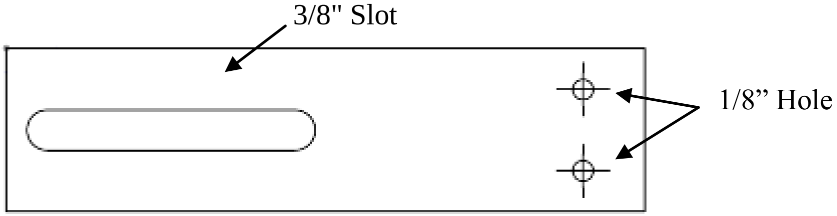
Cutting

A band saw was used at a speed of 1000 fpm to cut two plates that were 3.88” long.

Milling

Milling was used to make two holes and a slot in each plate. Two 1/8” holes were drilled at one end of the plate at a spindle speed of 2500-3000 rpm. A 1.5” slot was milled using a 3/8” mill bit which allows for the skin-stretch to be adjustable.

Figure 30: Holes and Slots that were Milled for the Skin-stretch motor sliders



Skin-Stretch Contact Points

Skin-stretch contact points consist of two parts: a conical peg and a threaded rod as shown in Figure 31. The conical pegs were fabricated from round stock nylon and the threaded rod was fabricated from a 2mm screw. Fabrication was done using cutting, drilling, and buffing.

Cutting

Cutting was used to make 1/2" long nylon contact points on a band saw at a speed of 1000 fpm. The band saw was also used to cut the threaded rod to a length of 1/4" at a speed of 1000 fpm.

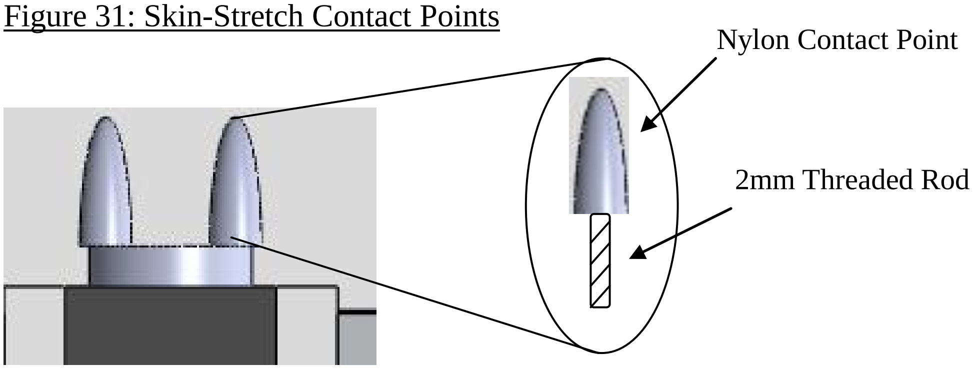
Drilling

One hole was drilled into the base of each nylon contact points at their base using a lathe at a speed of 1500 rpm. The threaded rod was then put into the hole so that they could be connected to the servo motor.

Buffing

Buffing was done to shape one of the ends of the 1/4" nylon rods into a conical shape.

Figure 31: Skin-Stretch Contact Points



Servo Mounting Plate

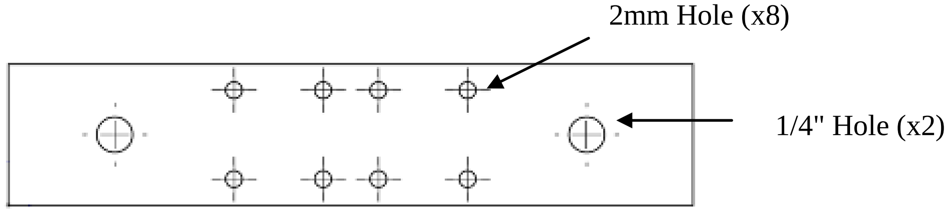
A servo mounting plate was fabricated from 1" aluminum stock using cutting and milling operations (Figure 32, page 33).

Cutting

A band saw was used at a speed of 1000 fpm to cut a plate that is 5.875" long.

Milling
A total of ten holes were drilled in the servo mounting plate. Two holes used to connect the servo mounting plate to the hinge extensions were milled using a 1/4" mill bit at a speed of 2500-3000 rpm. Eight other holes used to connect the two gripper servo motors to the mounting plate were milled using a 2mm drill bit at a speed of 2500-3000 rpm.

Figure 32: Holes that were Milled for the Servo Mounting Plate

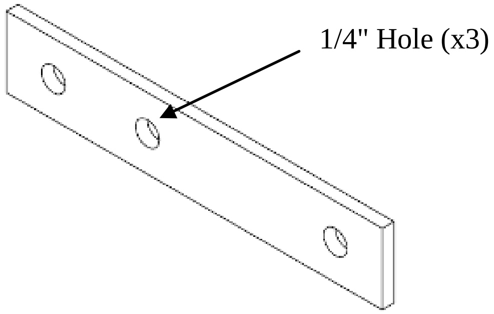


Hinge Extensions
Two hinge extensions were fabricated from 1" x 1/8" aluminum stock using cutting and drilling operations as shown in Figure 33.

Cutting
A band saw was used to cut two plates that were 4" long at a speed of 1000 fpm.

Drilling
Three holes were drilled in the plates; two to connect the plate to the hinge, and one to connect the servo mounting plate L-bracket to the extension. All three of the holes were drilled on a drill press with a 1/4" drill bit and at a speed of 2500-3000 rpm.

Figure 33: Holes that were Drilled for the Hinge Extensions



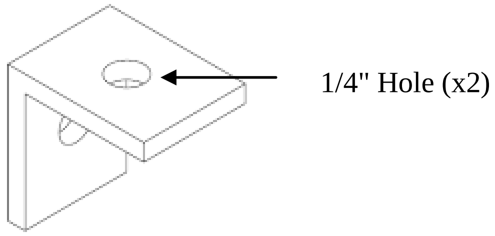
Hinge Assembly Bracket
Two L-brackets shown in Figure 34, page 34, were fabricated to attach the servo mounting plate to the hinges. Two 1" pieces were fabricated from aluminum stock L-brackets using drilling and cutting operations.

Cutting
A band saw was used at a speed of 1000 fpm to cut two 3/4" L-brackets.

Drilling

Two 1/4” holes were drilled into the L-brackets using a drill press at a speed of 2500-3000 rpm. One hole was drilled on one face so that it can be attached to the hinge and the other hole was drilled on the other face of the L-bracket to attach it to the servo mounting plate.

Figure 34: Holes that were Drilled on for Hinge Assembly Bracket



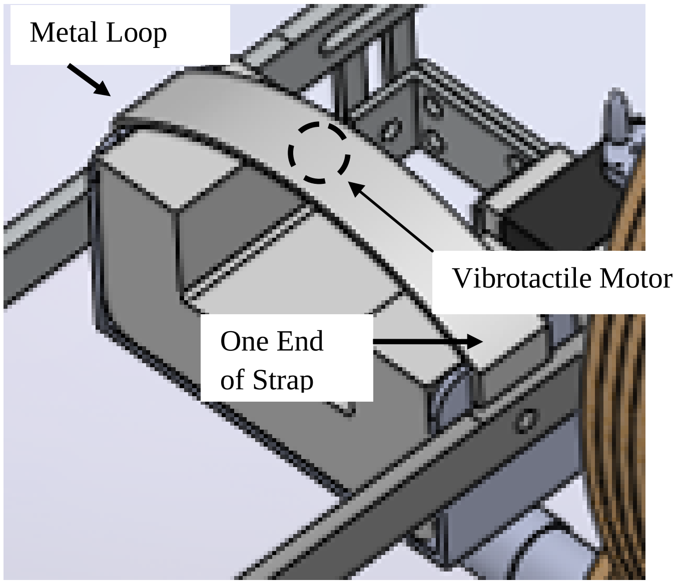
Arm Cuff Straps

Straps with Velcro® were used on both of the arm cuffs in order to attach the assembly to the user. A 12” x 1.5” long piece of material was cut and then two 4” x 3/4” long pieces of Velcro® were sewn into it. On the side of the prototype that did not have the capstan drive, one end of the strap was riveted to the cuff. On the other side of the cuff, a metal loop was riveted allowing for the strap to be tightened.

Vibrotactile Motor on Forearm Cuff Strap

Under the forearm cuff strap on the piece that was closest to the skin of the user, a vibrotactile motor was sewn onto it as shown in Figure 35.

Figure 35: Straps and Implementation of Vibrotactile Motors into the Strap

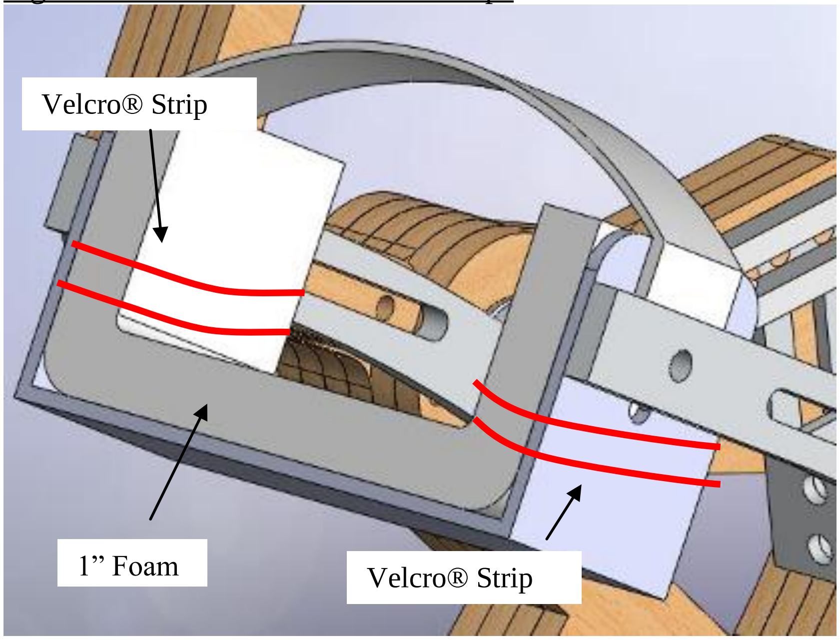


Arm Cuff Padding and Velcro Strips

The padding for the upper arm cuff was 1” thick foam that was measured to fit the length of the arm cuff. Two, 1” thick foam pieces were used for the forearm. The foam was put into a sewn fabric pocket which allows for more foam to be added or taken out.

Two strips made from Velcro® that were 5 inches long were used on each cuff to keep the padding in the cuff. Their placement is shown in Figure 36.

Figure 36: Placement of Velcro® Strips



Control Algorithms

We added code to the existing C++ code (Appendix E, page 77) so that our feedback systems could be integrated into the assembly. Our code allowed for the additional feedback methods to be controlled via the strain gauges. Once the amplified average strain gauge value is greater than 0.15 volts, the vibrotactile motors are actuated and the skin-stretch initiated if the object is being deformed. The logic behind coding our feedback systems in this manner is that upon contact users will feel a vibration and then as an object begins to be deformed the skin-stretch actuates.

Strain Gauge

A strain gauge was place on the outside of each gripper using an epoxy (Figure 37, page 36). Hot glue was also applied at the connection between the strain gauge leads and the signal wires that connected them to the Wheatstone bridge.

Figure 37: Strain Gauge on Outside of the Gripper

Gripper Padding

Adhesive padding was placed on the inside of each gripper digit to add friction between the gripper and objects (Figure 38).

Figure 38: Padding Placed on Inside of Gripper

Electrical Wiring

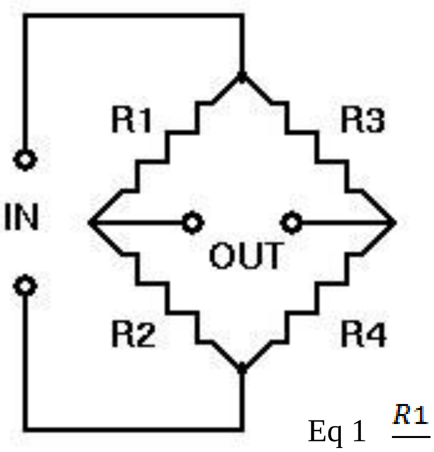
We used soldering to connect wires together in order to make the connections longer and to implement different types of feedback. We used heat shrink to organize and strain relieve the electrical wires near connectors.

Wheatstone Bridge

To measure the signal generated by the strain gauges we designed and implemented Wheatstone bridges to isolate the signal for amplification. Each strain gauge fed into its own Wheatstone bridge, which were each connected to a signal amplifier, raising the bridge outputs from the 0-5 mV to 0-4 V.

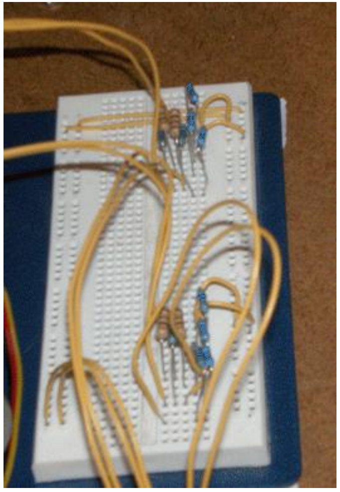
In Figure 39 page 37, a classic Wheatstone bridge diagram is shown. In our design (Figure 40, page 37), the strain gauge, with a nominal resistance of 350 Ohms, was wired to be R3, and that portion of the right leg was matched by making sure R1 also measured 350 Ohms, by wiring 2 100 Ohm and 1 150 Ohm resistor in series, which adds the values of the three resistors. The bottom portions of each leg were also balanced with each other, using 1 300 Ohm and 1 47 Ohm resistor in series for both R2 and R4. As long as the ratios in Equation 1 hold, the Wheatstone bridge will match theoretical predictions. An ideal Wheatstone bridge will have a voltage output of zero at its designed zero point, but due to the tolerances of our precision resistors this was not the case for our Wheatstone bridges. This was taken care of in our computer code by introducing an offset to the signal values when the device is initialized.

Figure 39: Wheatstone Bridge Design



Eq 1 $$\frac{R1}{R2} = \frac{R3}{R4}$$

Figure 40: Fabricated Wheatstone Bridge



Mechanical Assembly

The following figures (Figure 41, Figure 42 page 38, and Figure 43 page 39) show a blowup of all of the components that were assembled for our prototype. The connection between each component is labeled with a number and the key is listed afterward. The description and photos of the fasteners are provided after the connection key.

Figure 41: Prototype Assembly

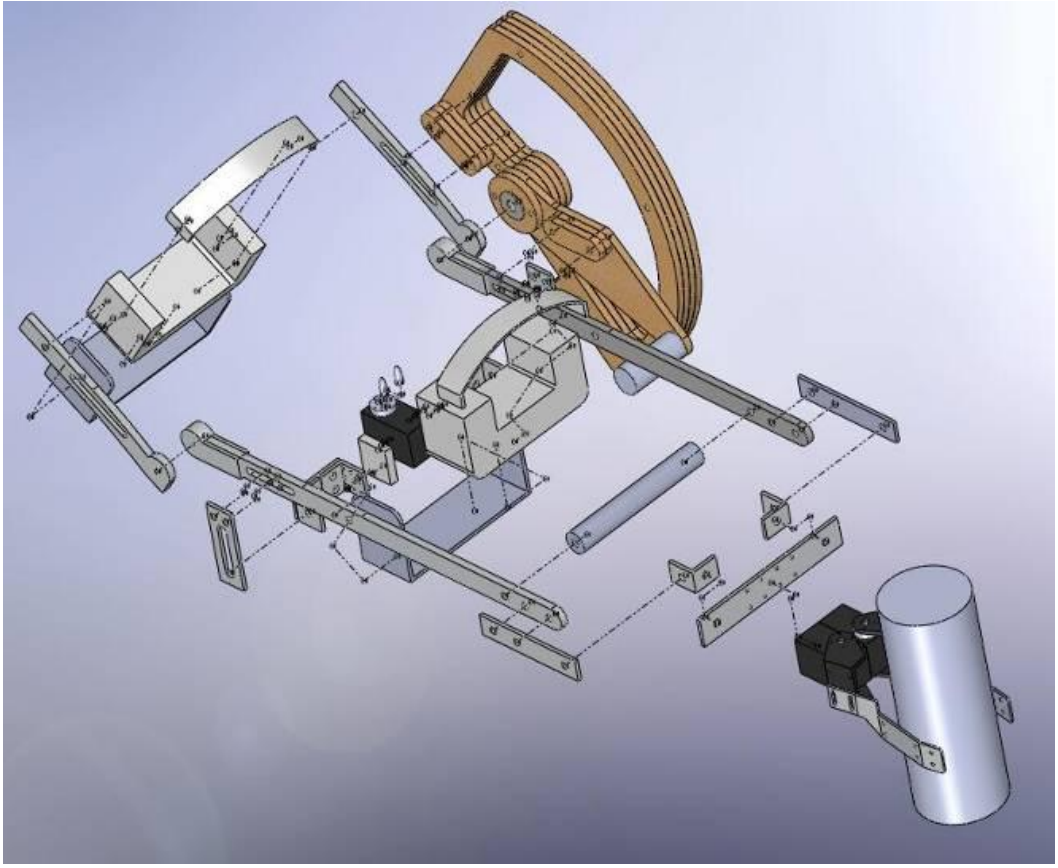


Figure 42: Assembly for the Lower Portion of the Prototype

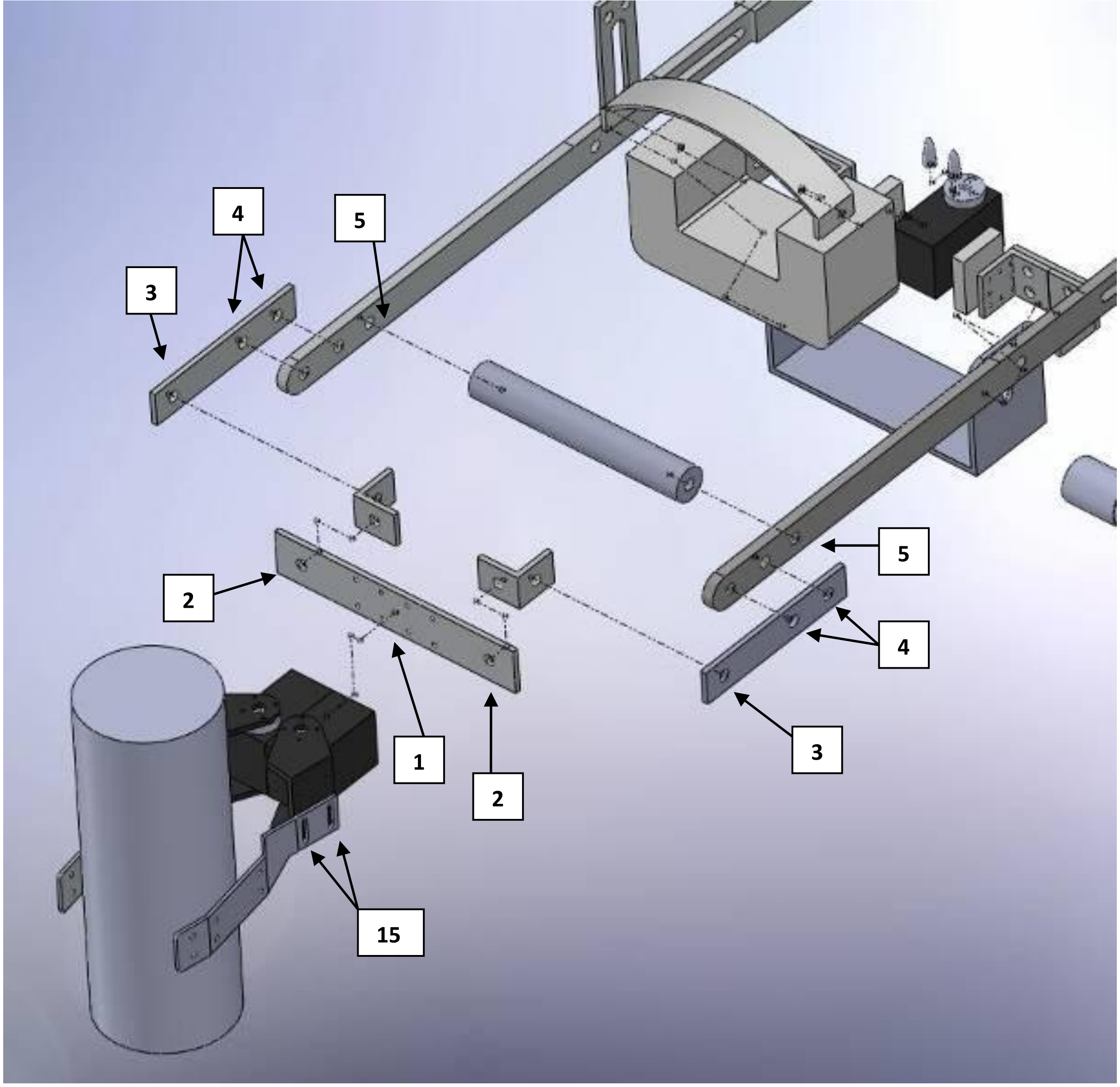
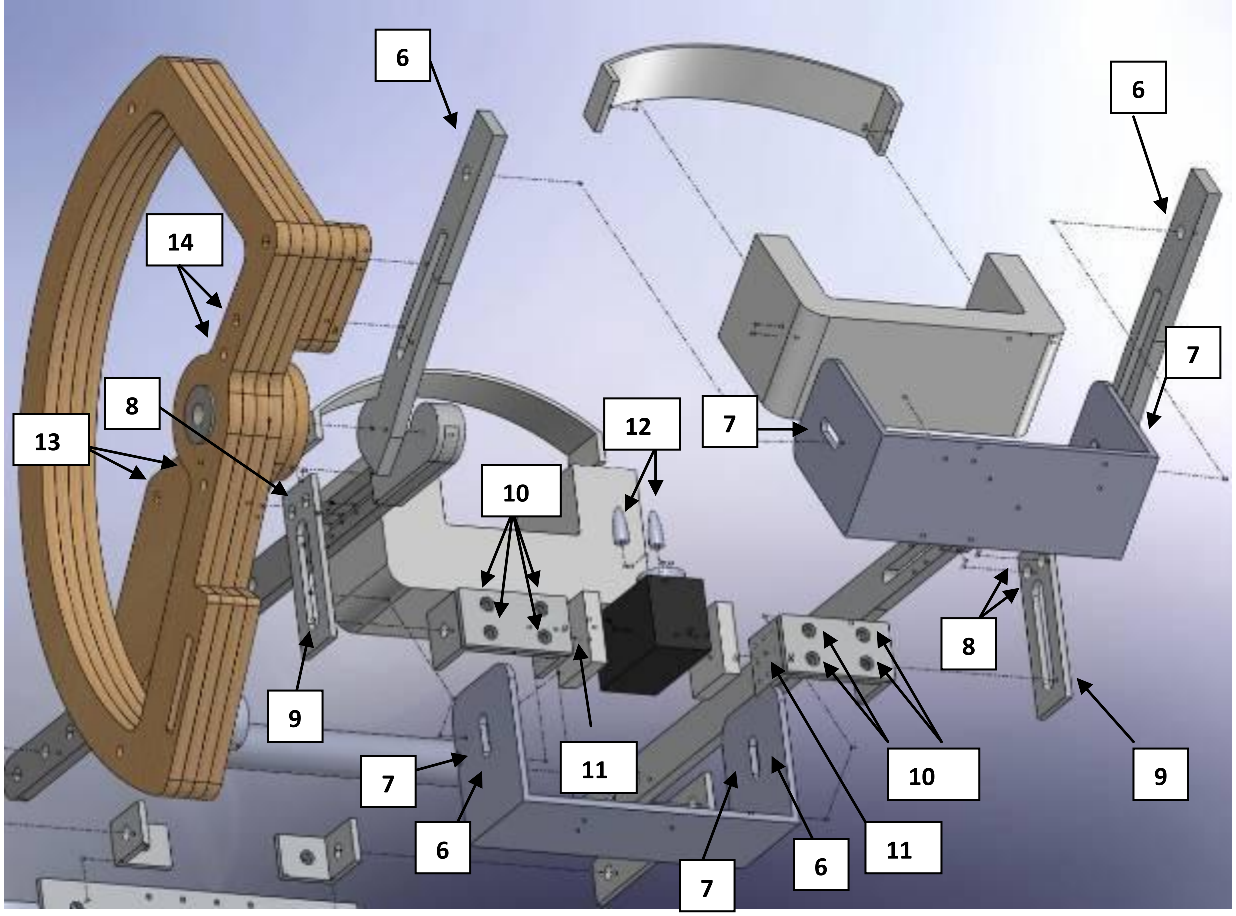


Figure 43: Assembly Skin-Stretch, Arm Cuffs, and Capstan Drive



Key to the Mechanical Assembly

1. Gripper Servo Motors to Servo Mounting Plate
    - Eight 4-40 x 1/8” Phillips-head machine screws

2. Hinge Assembly Bracket to Servo Mounting Plate
    - One 1/4" x 1/4" screw post

3. Hinge Assembly Bracket to Hinge Extension Plate
    - One 1/4"x 1/4” screw post

4. Hinge Extension Plate to Hinge
    - One 1/4" x 3/8” screw posts

5. Hand Rest to Hinge
    - One 1/4" x 1/2" Phillips-head screws

6. Arm Cuff to Hinge
    - One 1/4-20 x 3/4” hexagonal bolt
    - Spacer
    - 1/4-20 lock nut

7. Velcro Strap to Arm Cuff
    - One 1/4” Rivet

8. Skin-Stretch Motor Slider to Hinge
    - One 1/4" x 3/8” screw posts

9. Skin-Stretch C Motor Slider L to Skin-Stretch Motor Slider
    - One 1/4" x 1/2" hexagonal bolt
    - One washer between skin-stretch motor slider and bolt
    - Wing nut

10. Skin-Stretch C Motor Back Plate to Skin-Stretch C Motor L and Skin-Stretch C Motor Slider L
    - One 1/4" x 1/4" screw post

11. Skin-Stretch C Motor L to Skin-Stretch Servo Motor
    - M2-0.4 Phillips head screw (x8)

12. Skin-Stretch Contact Pegs to Skin-Stretch Servo Motor
    - M2-0.4 threaded rod

13. Capstan Drive to Hinge (Forearm)
    - 10-40 x 2” Phillips-head screw
    - Lock bolt

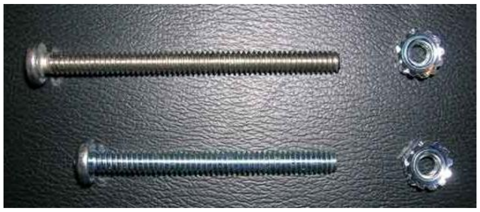
14. Capstan Drive to Hinge (Bicep)
    - 10-40 x 2.5” Phillips-head screw
    - Lock bolt

15. Gripper Digit to Servo Motors (x2)
    - M4-0.4 Phillips head screw
    - Lock Nut

Fasteners

- 4-40 x 1/4” Phillips-head machine screw

- 10-40 x 2” Phillips-head screw
  10-40 x 2.5” Phillips-head screw
  Lock Nut



- 4-40 x 1/4" Phillips-head screw
  Lock nut

- 1/4" x 3/8” screw post
  1/4" x 1/4” screw post

- M2-0.4 Phillips-head screw

- One 1/4-20 x 3/4” hexagonal bolt
  Spacer
  1/4-20 lock nut

- One 1/4" x 1/2" hexagonal bolt
  One washer between skin-stretch motor slider and bolt
  Wing nut

Electrical Assembly

The assembly for the electrical wires is shown below (Figure 44). The wires were heat-shrunk near all connectors to provide strain relief and zip-tied to the brace. Besides the wire from the gripper servo to the skin-stretch servos, one end of each wire was zip tied and grouped with the other wires under the forearm cuff (Figure 45). The connectors between the wire harness and the brace were fastened to the cuff.

Figure 44: Electrical Wiring

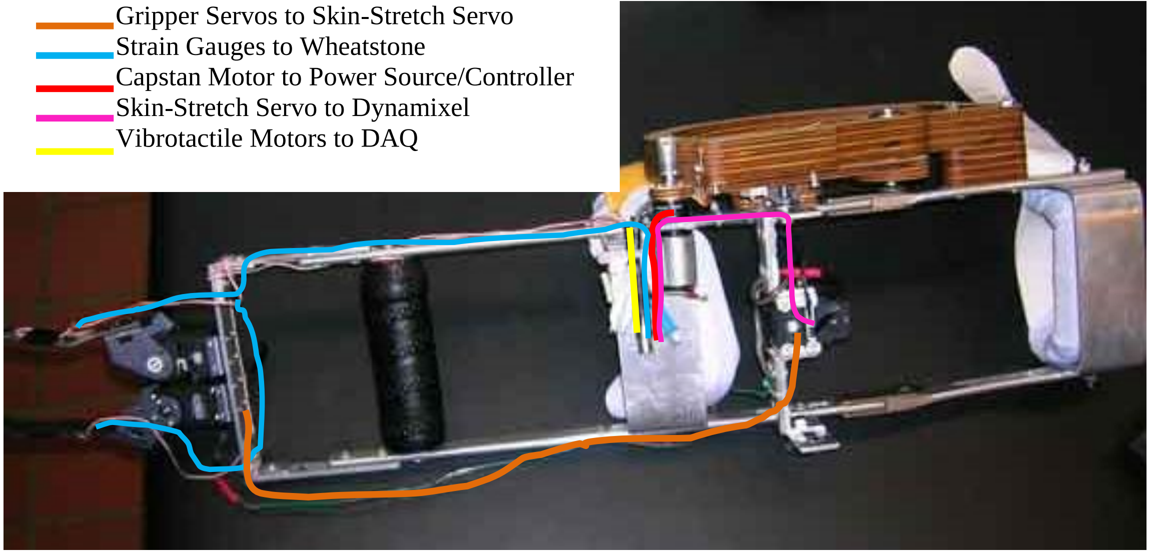
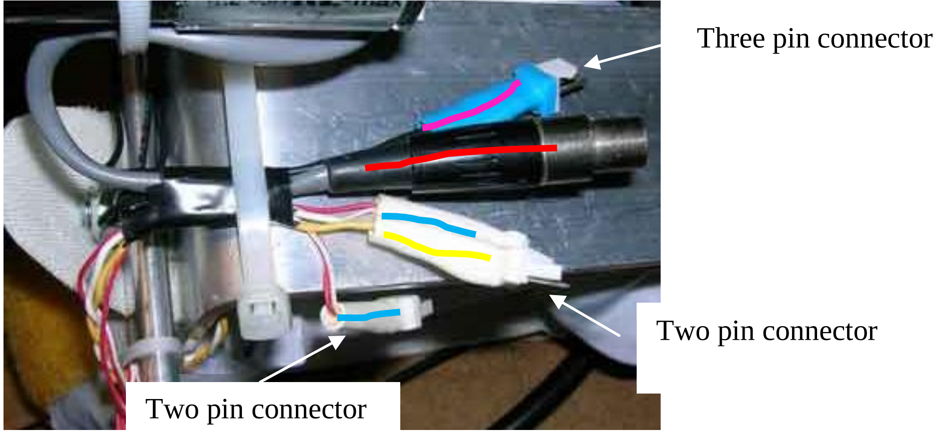


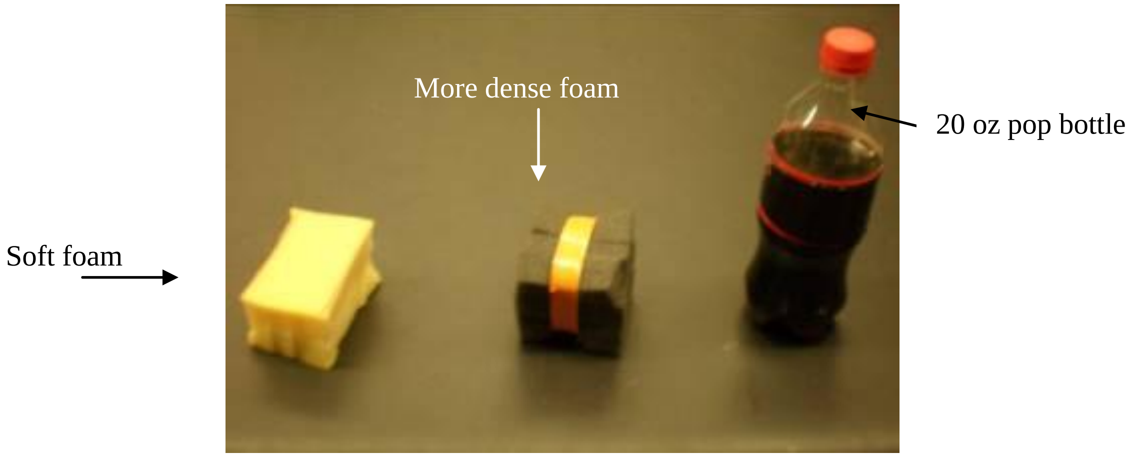
Figure 45: Wires Collected under Arm Cuff



Prototype Validation

Upon completion of our prototype, we tested each individual feedback (skin-stretch, vibrotactile, and force). We found that each type of feedback worked. We were able to correctly integrate the previously developed force feedback. The skin-stretch feedback allowed the user to differentiate between a stiff and a less stiff object (particularly, the test subject could tell the difference between each object pictured in Figure 46, page 43). The vibrotactile motors actuate within a small strain range associated with just touching an object.

Figure 46: Test objects



At the Design Expo, we performed a demonstration on 25 random subjects. Each person was asked to fill out the following survey (shown here in condensed form) after using the device. Results are shown in **bold**.

1. Which type of feedback did you find conveyed the most information?

24% *Force feedback*
36% *Skin-stretch feedback*
40% *Vibrotactile feedback*

2. Which type of feedback conveyed the least information?

33% *Force feedback*
44% *Skin-stretch feedback*
28% *Vibrotactile feedback*

3. How would you rate the amount of torque created at the elbow for the force feedback? Circle One:

33% *Not Enough*
48% *Just Right*
10% *Too Much*

*4. Without looking, could you tell the difference between the two objects (*it was explained that this meant the hard and soft foam*)?*

82% *Yes*
6% *No*

5. How would you rate the amount of vibration from the vibrotactile motors?
Circle One:

29% *Not Enough*
67% *Just Right*
0% *Too Much*

6. With all three feedback systems in use, was there too much "going on"?

_17%_ *Yes*
_83%_*No*

Additional Comments:

First, it is important to note that this survey was given to men and women of all sizes and sometimes the prototype did not fit correctly. In those cases, the user was usually unable to feel the skin-stretch feedback. Also, the code which controls the vibrotactile feedback needs further development and was not always working as intended. We asked these users to mark N/A for the feedback which they were unable to feel.

As shown, 76% of the users thought the skin-stretch or vibrotactile feedback conveyed the most information. This is promising, as it suggests that our design additions of these two types of feedback were worthwhile. In addition, 83% said there were not too many types of feedback; we were concerned that users may be confused with three feedback systems working at once.

Finally, 82% of the users who answered question number four could tell the difference between the stiff and soft foam. This is one of the biggest improvements from the previously developed prototype which, with testing, did not convey stiffness well.

Plotting a comparison of the commanded gripper position (red) against the EMG signal (green) over a time step shows the gripper servomotors responding directly to the strength of the EMG signal (see Figure 47 page 45).

Figure 47: EMG Signal vs. Gripper Servomotor Command Position

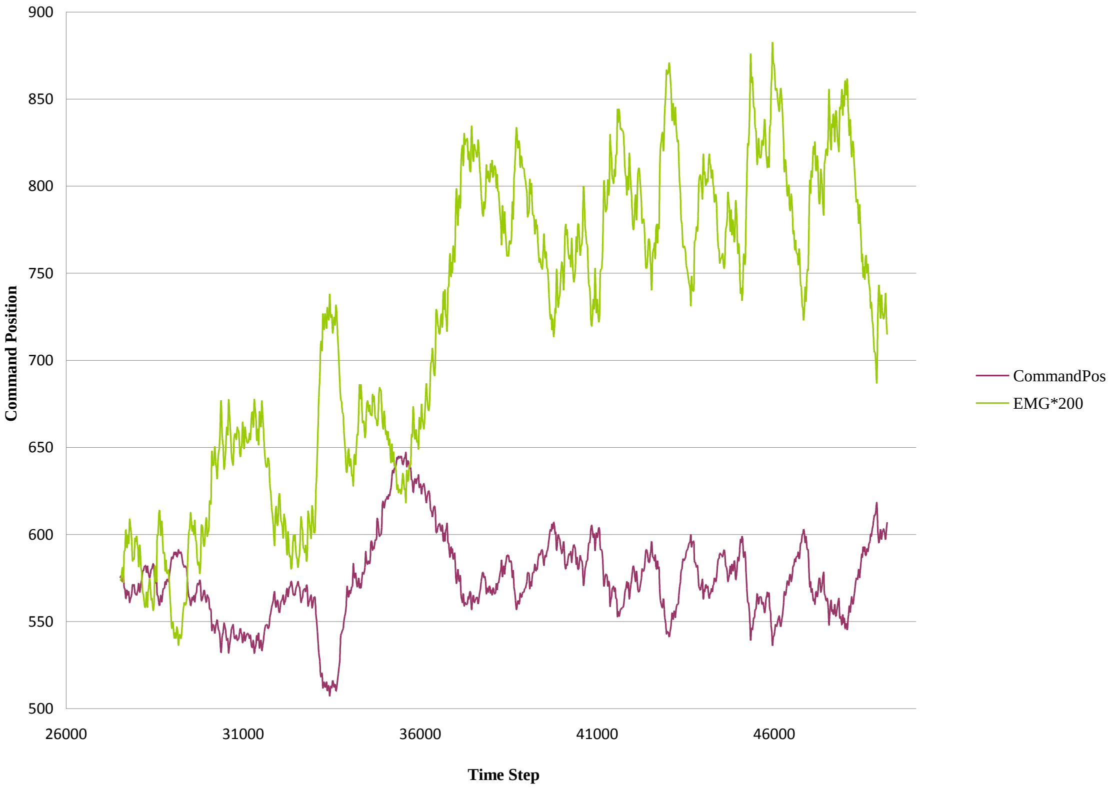
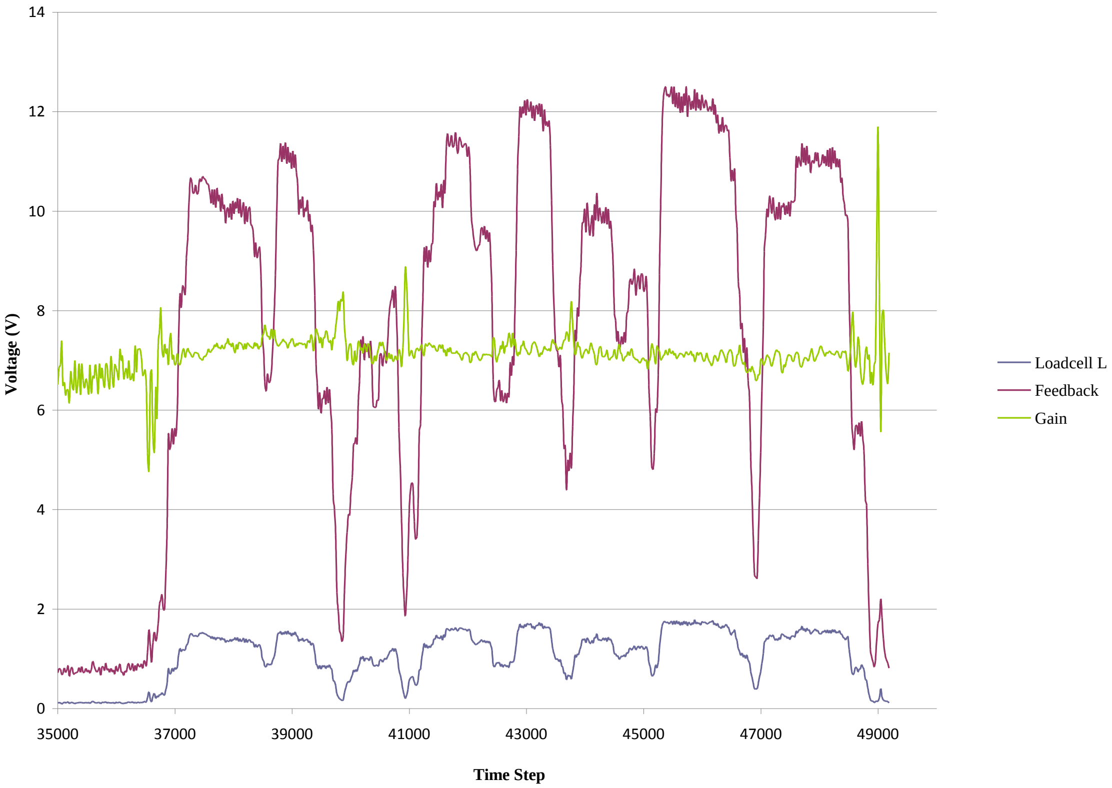


Figure 48, page 46 shows the voltage strength of the feedback signal (red) to the voltage strength of the loadcell L (left strain gauge) signal (blue) over a time step. The green line displays the gain (feedback/loadcell) which is consistently between six to eight volts for the operational period. This shows that our design's usage of strain gauges as a signaling method is suitable for testing purposes.

Figure 48: Feedback Signal vs. Loadcell L Signal and Gain



With more time and after further development of the computer code which controls the feedback, we would carry out the following experiment with the object shown previously in Figure 46, page 43.

1. A subject who has never used myoelectrically-controlled devices will be blindfolded and strapped into the prototype and normal operations are carried out for calibration.
2. The subject will be asked to lightly touch a piece of dense foam with each gripper digit individually to test the vibromotors.
3. The force feedback system will be turned off in order to test only the feedback systems that we developed.
4. The subject will then be asked to pick up a piece of soft foam on the table and put it down again. The subject is asked which object he thought he picked up (given three options) with only the skin-stretch feedback.
5. The subject will then be asked to pick up a piece of more dense foam on the table and put it down again. The subject is asked which object he thought he picked up (given three options) with only the skin-stretch feedback.
6. The subject will then be asked to pick up a full 20oz bottle of pop on the table and put it down again. The subject is asked which object he thought he picked up (given three options) with only the skin-stretch feedback.
7. 10 trials should be done to repeat steps 4-6 (however, the order of the objects should be changed).

Critique

Several issues with the design were not apparent until manufacturing had been completed and we had begun the validation process. The primary categories that can be improved upon are the brace fit and the control system.

The brace was designed with some variation possible; the cuffs could be slid in the direction normal to the brace to better fit different users. Velcro straps to hold the brace in place gave some variation for different arm sizes. However, we found that the brace worked best for a certain size user. Individuals with thinner arms had some difficulty keeping the brace in the proper position. Individuals with comparatively longer arms had to adjust their hand position to make use of the hand rest.

Additional straps would assist in ensuring a better fit. This is of particular concern for the forearm where haptic feedback systems are placed. One of the difficulties encountered was the proper fitting of the skin-stretch system. An additional strap in this region close to the elbow would assist with the issue of maintaining contact.

Steps should also be taken to reduce the weight of the device. For example, some aluminum, structural components could be replaced with carbon fiber or cuffs could be replaced polyethylene/polypropylene copolymer.

Further development of the code which controls each feedback system is needed. The control algorithm for the skin-stretch feedback did not work well when releasing an object. The strain range for the vibromotor should be changed to prevent the vibromotor from actuating continuously while manipulating a soft object.

The skin-stretch unit could be forced to maintain contact by fitting a spring to the underside of the mechanism. The current design requires that the unit be slid into position then tightened to affix in that position. This does not permit constant consistent contact with the user in different arm positions once in place, and is painful when not positioned at a suitable height.

The design requires that the hand-rest be held in a reverse grip, i.e. palm down. A more ergonomic grip would permit individuals to use a vertical grip or a bicep-isolation (palm up) grip. Either hand position would have the additional possible benefit of improving the source signal for the EMG pads. A problem with the palm-down grip is that it bends the elbow outwards, thus shifting the user’s arm to the outer side of the prototype brace. Due to the width of our prototype, individuals with thinner arms had more difficulty keeping their arms in the optimal position to experience the feedback systems. However, attempts to use the palm-up grip cause the brace to slip out of place; the poor hand position braced the arm within the frame despite the poorly fitted cuffs. Changing the grip will require that the cuff design be greatly improved.

The force-feedback system features a capstan drive system which uses a small form-factor DC motor to exert a torque about the user’s elbow. The first issue with this feature is the size and weight. Even on the initial prototype with no other feedback systems, the sheer bulk of the capstan drive was difficult to handle. A second issue with the capstan drive is that the feedback is difficult to notice when dealing with soft objects.

Strain gauges affixed to the gripper fingers provide the signal for the feedback systems. Given the accuracy of this signal, the vibrotactile actuators could receive a signal within the range of “initial contact” and vibrate continuously rather than momentarily.

Strengths

One of the features that became important for testing in the prototype is that the haptic feedback systems can be experienced even in situations where user-controlled EMG signaling is impossible. The user can wear the prototype while manually controlling the gripper through the computer, and the feedback systems will respond in the normal manner.

A second strength of the design, and one important for testing, is the ability to isolate the different feedback systems for testing. The effectiveness of different combinations of feedback can be tested.

A final strength of the current prototype is the amount of free space on the frame and about the user’s arm, which is conducive to incorporating different feedback systems in future designs.

Recommendations

Future designs should be able to better fit users. Copolymer cuffs could be affixed to the aluminum frames of the existing cuffs to accommodate users’ arms. The hand rest can be altered to a more ergonomic position. This would improve alignment between the arm and the brace, thereby improving fit, comfort, and the feedback systems’ effectiveness.

Several different feedback systems had been considered. The final design incorporated vibrotactile actuators, a skin-stretch system, and a force-feedback system; however, additional feedback systems should be investigated. For example, the skin-stretch system uses a servomotor to twist a portion of skin on the forearm. A different skin-stretch idea had been to wrap a rubber cuff around the forearm and have a servomotor tug on the strap linearly along the forearm. The current design does not incorporate this method due to space issues and weight considerations, but future tests could compare similar/dissimilar systems for specific gripper information feedback systems.

A final consideration for future designs is that the current setup, meaning the brace and feedback systems, signal filtering systems, and signal amplification systems, is bulky. Future designs could focus on developing a compact setup.

Conclusion

The purpose of this project was to design a myoelectric prosthetic prototype that incorporates different types of haptic feedback for the gripper manipulating an object. The prototype is for testing purposes and must also be wearable by an able-bodied person for the tests.

Literature searches provided information about controls, feedback, and signal processing which set benchmarks for the project. Engineering specifications and requirements were determined and developed into concepts for the Alpha prototype. Analysis of the subsystems was done to ensure that the specifications were met and to improve the alpha prototype. The final design was selected and the fabrication plan was made. Upon final assembly, the prototype was tested to validate its design.

The validation test shows that the prototype fulfills the project requirements and provides haptic feedback to give information about how the gripper is manipulating an object in response to myoelectric signals from the user. The device is controlled by picking up myoelectric signals from the bicep. The grippers respond to this signal, and the force exerted on the grippers is picked up by strain gauges. The signal from the strain gauges activates the vibrotactile actuators, the skin-stretch system, and the force-feedback system.

Some issues with the design still remain. The brace for the prototype does not fit all potential users, limiting the number of people available for testing. The signal from the strain gauges is suitable for the design, but the vibrotactile actuators will sometimes activate continuously rather than momentarily as they should. The skin-stretch assembly works as designed but is difficult to position perfectly. These issues could be dealt with in future designs.

Acknowledgments

We thank Professor Brent Gillespie, our project sponsor, for giving us the opportunity to work on this project and for his guidance over the course of the semester. Thank you to John Baker for your assistance in the project and overall patience while working with us. Thank you to Alicia Davis and Tom Sorensen at University of Michigan Prosthetics and Orthotics Center for answering our questions, assisting in fabrication, and allowing us to use their facilities for fabrication. Thank you to Rob Wagner at Wright & Fillipis and John Carpenter at Touch Bionics for teaching us more about current design concepts in the prosthetics field. Thank you to Todd Wilbur for helping us with the strain gauges.

Information Sources

Current myoelectric-controlled prostheses that provide feedback depend on force sensors on the grippers sending a signal to force inducers on the user's body. Other feedback methods, such as vibration and force feedback, are still being developed. Each function used in the prosthetic arm has been independently developed, including the EMG pads for control, EMG pad placement options, signal processing methods for both control and feedback systems, and various feedback methods.

The remote manipulators of the 1940s and 1950s first relied on wire control; an action performed by the operator was simultaneously performed by the manipulators. An important feature of the 'control-by-wire' systems such as for the M-1 was that the operator would feel the one-to-one effect of interacting with objects being manipulated. With the advent of powered telerobotics, feedback became an issue. Relying solely on visual feedback creates problems involving system latency and a lag in the response. One solution, developed in the 1950's, was the E-1 for which the slave end was motorized to respond to the user's input and the master side was motorized to respond to impedance on the slave side. A further improvement was to create a signaling system sensitive to acceleration so that the operator could feel sensations such as tapping the object.

Prostheses are limited in that the user does not have the corresponding body part with which to operate the device; rather, the device is to replace a lost part. However, there are similarities between the two types of systems. Body-powered prostheses are similar to the early remote manipulators in that they also provide force feedback through the action/reaction coupling of the push-pull cables. The movement to manipulate the gripper enables the user to feel the tension or lack thereof in the wire, indicating the gripper’s status. Myoelectric-controlled prostheses are controlled by tensing a muscle set, but the muscle is not working against anything. Not only is there a lack of effort to operate the gripper, but there also isn’t any feedback other than visual feedback. A second problem with feedback is that the controlling muscle has no point at which a feedback force can interface with. A haptic feedback system for the myoelectric-controlled hand must overcome this limitation to be intuitive for the user.

Feedback can come in a variety of forms. Visual feedback is possible (for those amputees without visual impairments) in most cases. Body-powered prostheses provide force feedback [1]. For myoelectric control, feedback can be visual, cutaneous, tactile or force driven.

Feedback signals from the manipulators come from several different types of signals: “motion, impedance, and physiological paradigms” [2]. For example, force can be determined from the comparison of intended gripper position to actual position or torque measurement from the servomotor. The signal is converted to haptic feedback by pressure, vibration, skin-rubbing, skin-stretching, or force.

Patents exist for including both prostheses with feedback systems as well as individual components which can be implemented to provide haptic feedback. For example, vibrotactile actuators are used in cell phones and buzzers. Patent 5888213: **Method and Apparatus for Controlling an Externally Powered Prosthetic** includes sensors on the gripper which activate force inducers on the operator’s forearm indicating the amount of force being applied to an object. The force-feedback system, such as Patent 4908187: **Tactile Stimulus Receptor for a Hand Prosthetic,** is a force transducer designed for positioning on a prosthesis’ gripper digits to detect the amount of force experienced by the grippers and send a signal to a feedback system.

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[10] Garcia, Gerardo. "The Cutting Edge of Haptics Research." Project Mechatronics. 2008. National Instruments. October 17, 2008, from

Appendix A: Bill of Materials

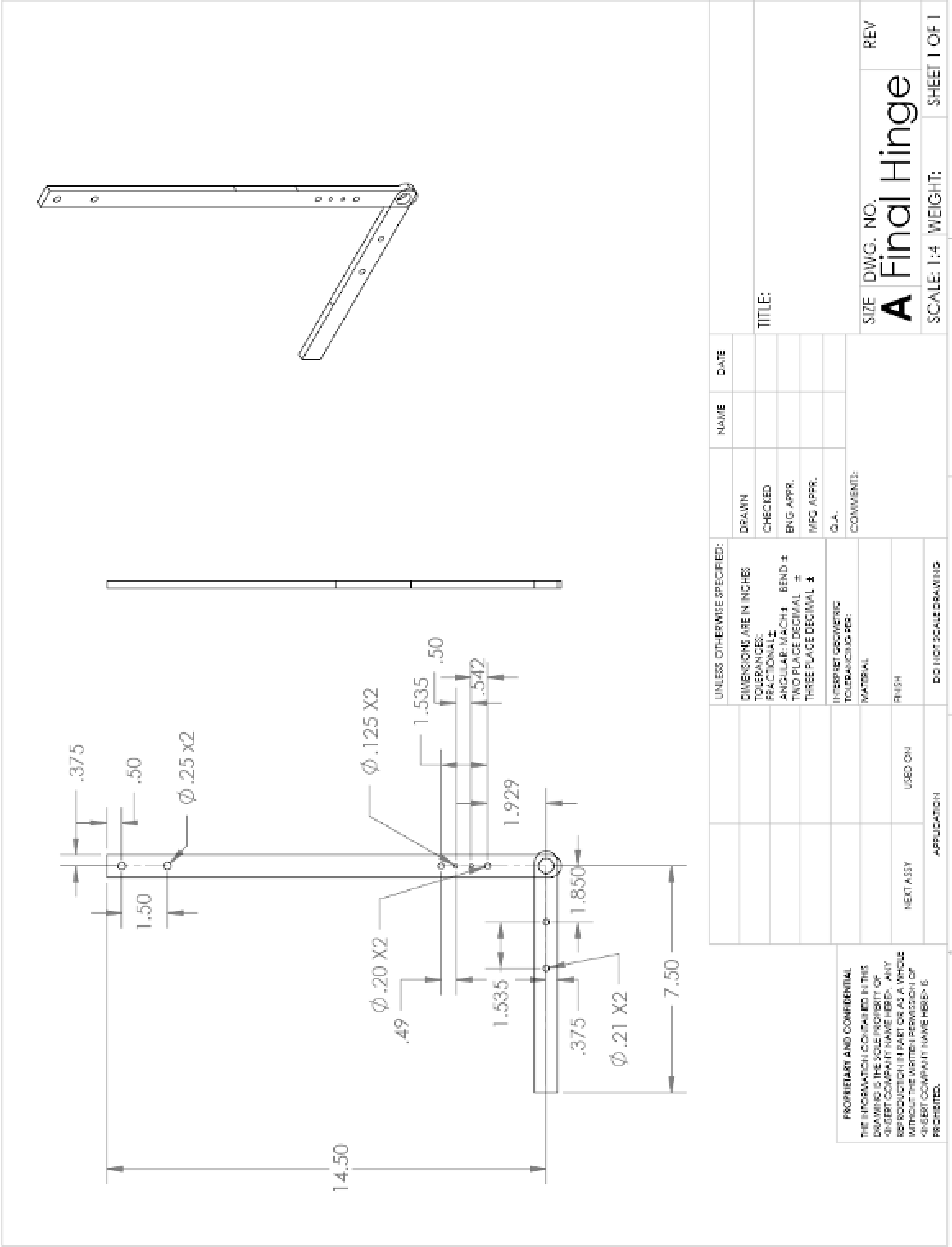
Part Number	Part Name	Qty	Material	Size (in)	Vendor / Mfg. Process	Cost (USD)	Function	Notes
	Metal Cuff	2	aluminum 6061	1/8 x 2 x 20	ASAP Source / cutting, bending	5.83	maintains hinge axis	
	Servo mounting plate assembly	1 set	aluminum 6061	1/8 x 1 x 16	ASAP Source / cutting, bending	3.65	mounting systems	
21435950	1/8x3/4 6061-T6511 Ext 36in precut	1	Aluminum	1/8 x 3/4 x 9	ASAP Source / cutting, bending	2.55	mounting systems	
	Handle	1	PVC	3/4in round x 6in	ASAP Source / cutting	1.96	hand rest	
	1/4 x 1/4 screw posts	12	aluminum		Stadium Hardware	8.40	overall assembly	
	1/4 x 3/8 screw posts	8	aluminum		Stadium Hardware	5.60	overall assembly	
	1/4-20 x 3/4 hex-head bolts & nuts	4	steel		Carpenter Bros. Hardware	2.80		
	10-40 x 2"	2	Steel		Carpenter Bros. Hardware	1.50		
	10-40 x 2 1/2"	2	Steel		Carpenter Bros. Hardware	2.50		
S2005-A4	KAFO Joint	1 set	aluminum		Becker Orthopedic	78.84	hinge joint for brace	
ax-12	Servomotor	3			CrustCrawler Robotics	134.70	provide movement of gripper digits and skin-stretch mechanism	AX-12+ servo
ax-12c	12 in AX-12 Cable	2			CrustCrawler Robotics	12.98	electrical cable	

Part Number	Part Name	Qty	Material	Size (in)	Vendor / Mfg. Process	Cost (USD)	Function	Notes
USB2Dynamixel	USB2Dynamixel	1			CrustCrawler Robotics	59.90	USB connection	
bgax	Big Grip w/ AX-12	1			CrustCrawler Robotics	174.00	Additional servo & gripper finger	
SSB-45	SSB-45 Bracket	1			CrustCrawler Robotics	13.95	Connecting bracket	
ROB-08449	Vibration Motor	1			Sparkfun Robotics	7.95	provide vibrotactile feedback	
bgh	Gripper Digit	2	aluminum		CrustCrawler Robotics	129.00	to manipulate objects and act as a mounting for sensors	Big Grip 2 in 1
SGD-3/350-LY13	Strain Gauge	2			Omega	11.00	detect strain in gripper digits and their data is used in force feedback and skin-stretch actuation	
P1502310	3/4 RD PVC Type I Gray 12ft precut	1	PVC		Alro Mteals Plus - Ann Arbor	3.91	Skin-stretch contact points	
	100 ohm Resistor	4			Radioshack	3.96	Part of strain gauge filtering system	
	47 ohm Resistor	2			Radioshack	2.98	Part of strain gauge filtering system	
	150 ohm Resistor	2			Radioshack	2.98	Part of strain gauge filtering system	
	300 ohm Resistor	2			Radioshack	3.96	Part of strain gauge filtering system	

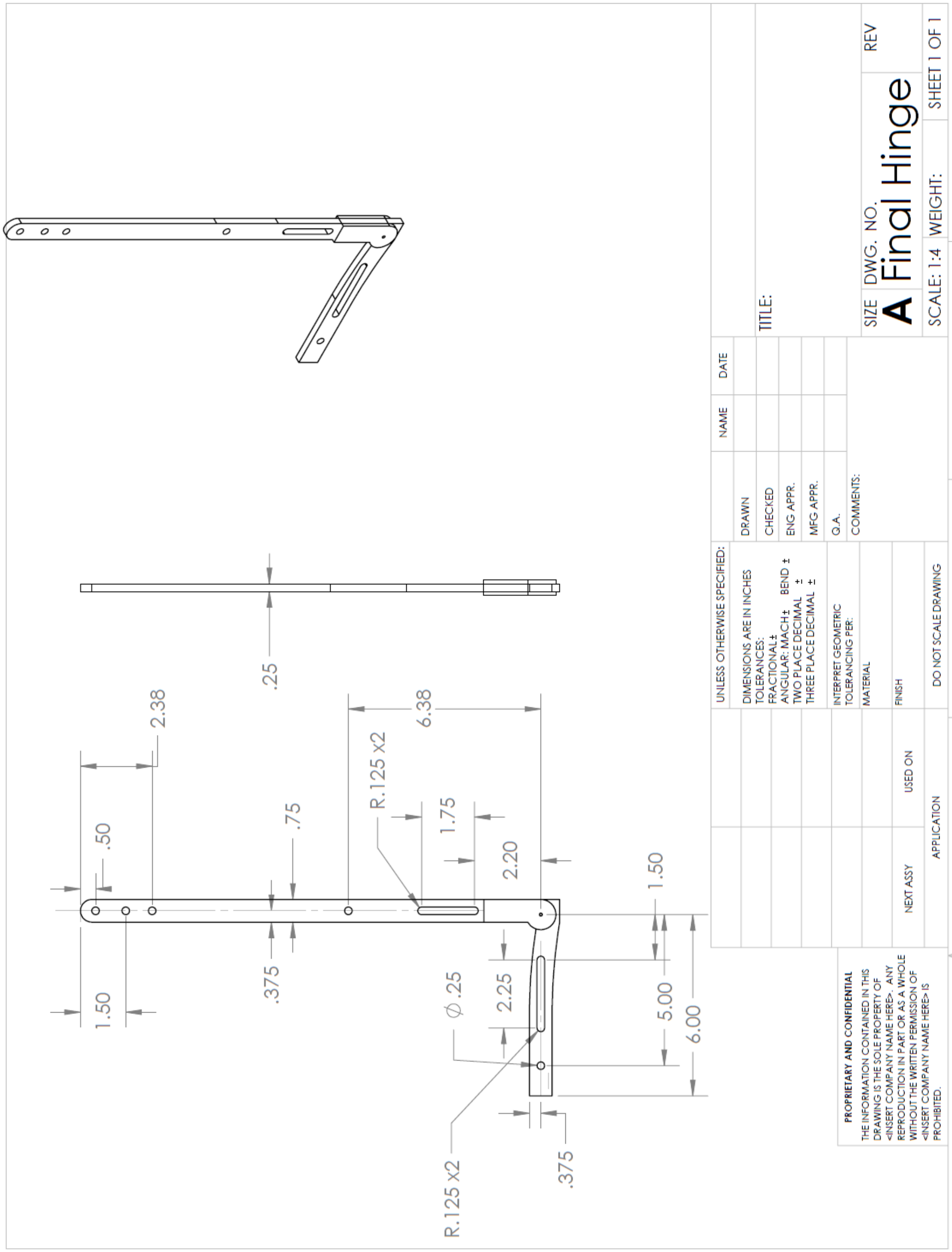
Part Number	Part Name	Qty	Material	Size (in)	Vendor / Mfg. Process	Cost (USD)	Function	Notes
6203194	Ultra Cushion Replacement	1	Rubber		Dunham's Sports	5.99	Part of hand rest, for comfortable grip	
29434010003	1 in HD Foam BTY	0.222 YD	Foam		Joann Fabrics	3.55	Padding	
29434000509	1/2 in HD Foam BTY	0.417 YD	Foam		Joann Fabrics	4.17	Padding	
75967906672		2	Velcro straps		Joann Fabrics	8.98	Holds padding in place	
		1	velcro strips			4.29		From O&P Center
					Total	**701.88**		

Appendix B: Engineering Changes and Engineering Drawings

Old Hinge



New Hinge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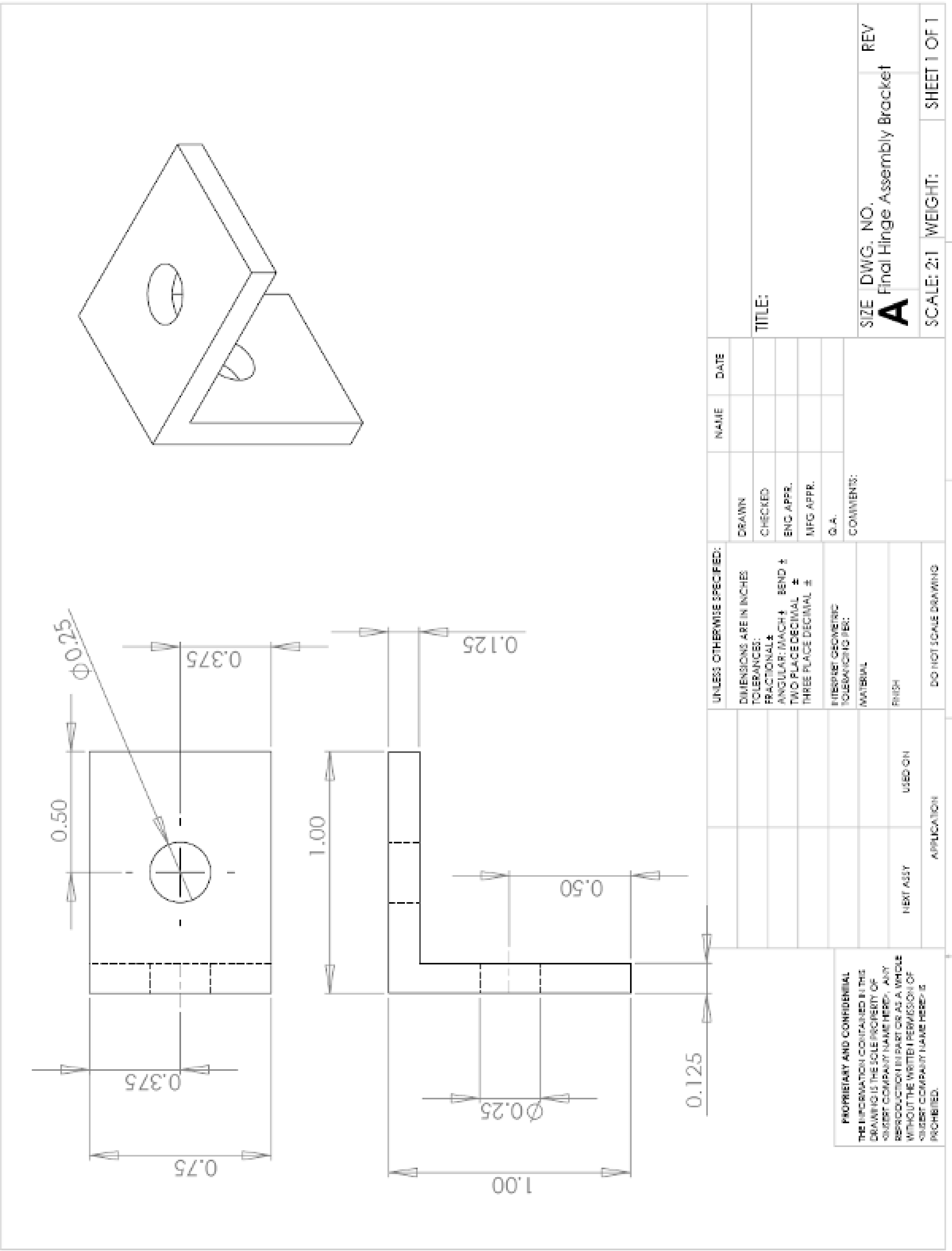
<u>Hinge Assembly Bracket</u>



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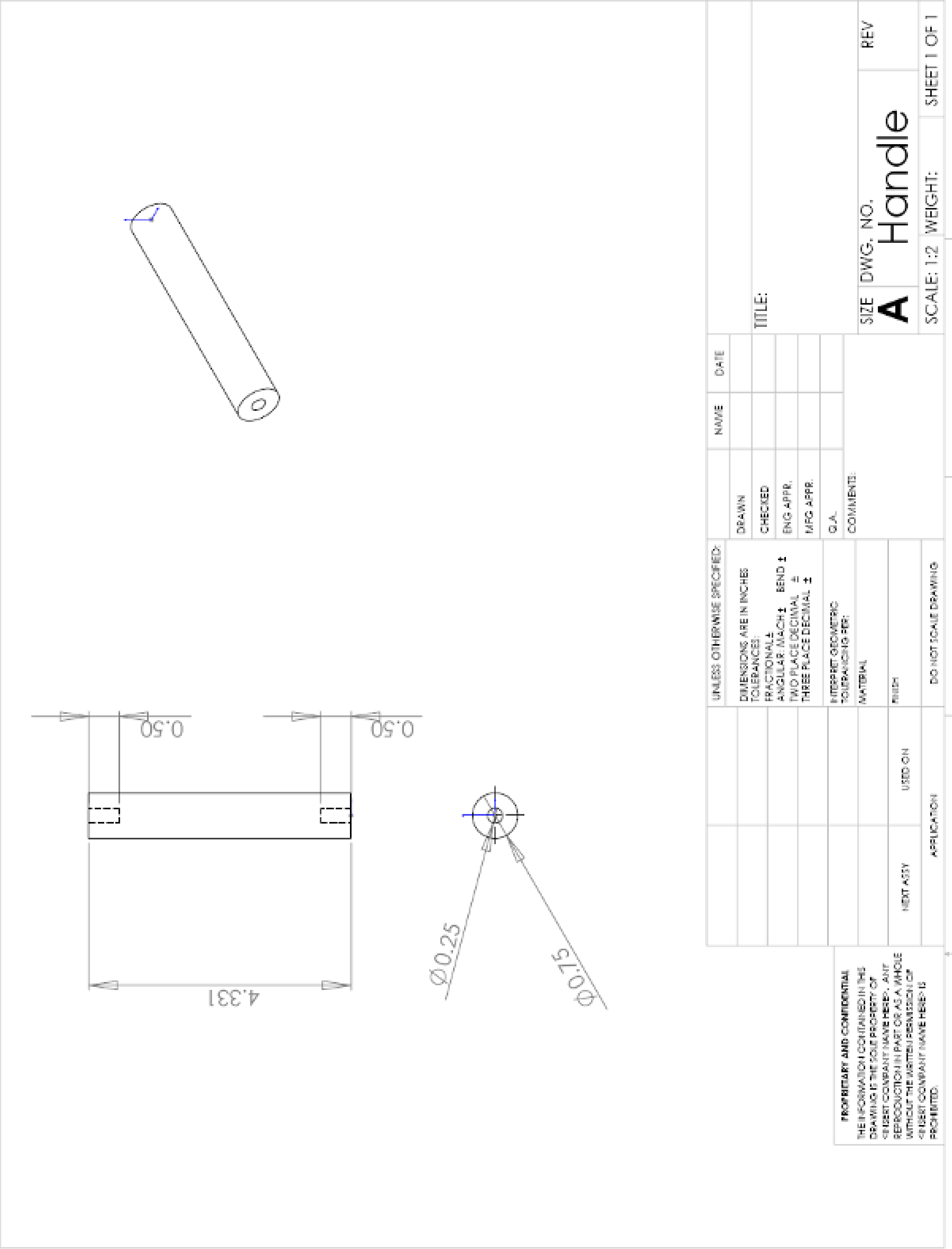
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DIMENSIONS ARE IN INCHES
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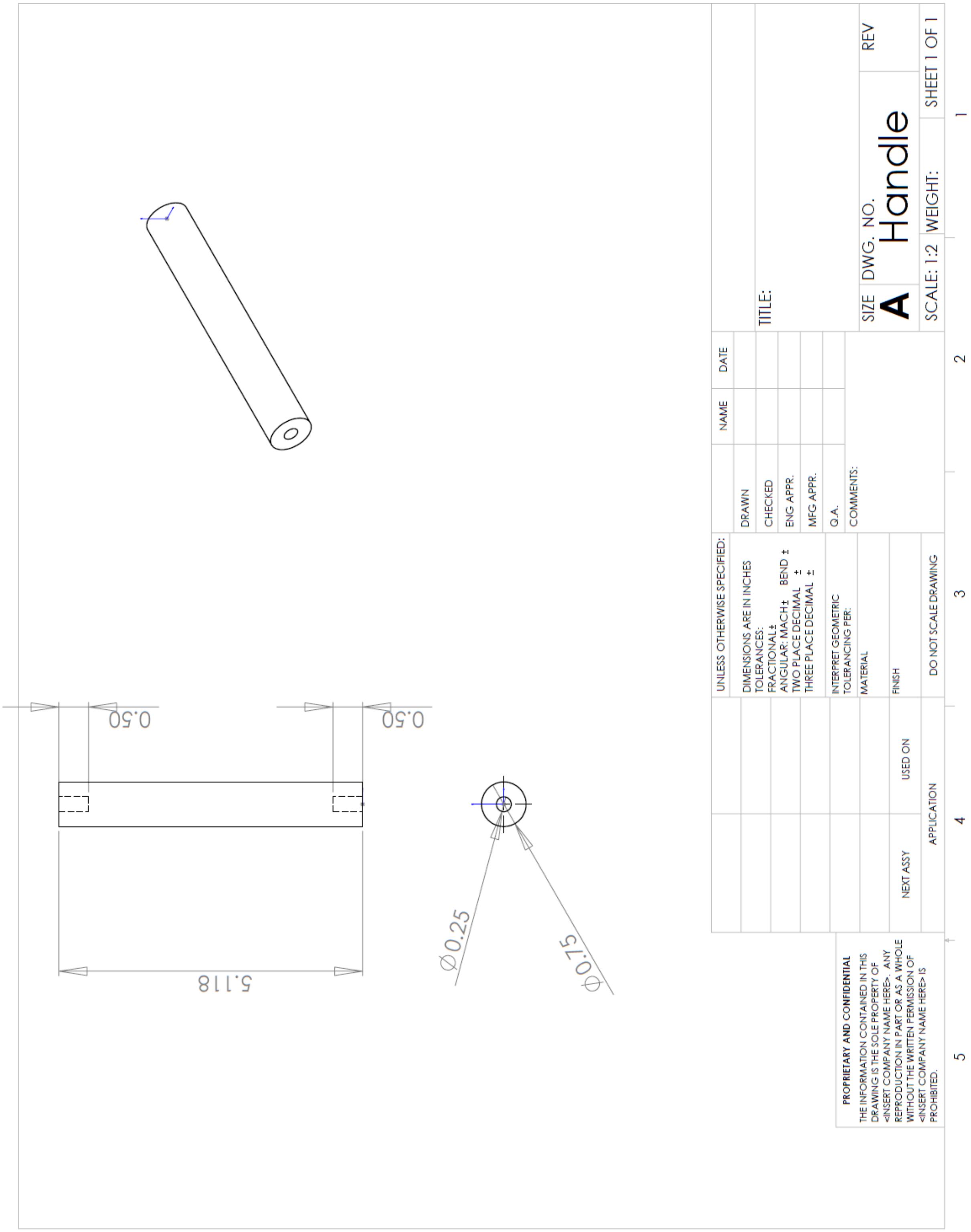
New Handle


0.50
0.50
5.118
Ø0.25
Ø0.75
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
SIZE
A
DWG. NO.
Handle
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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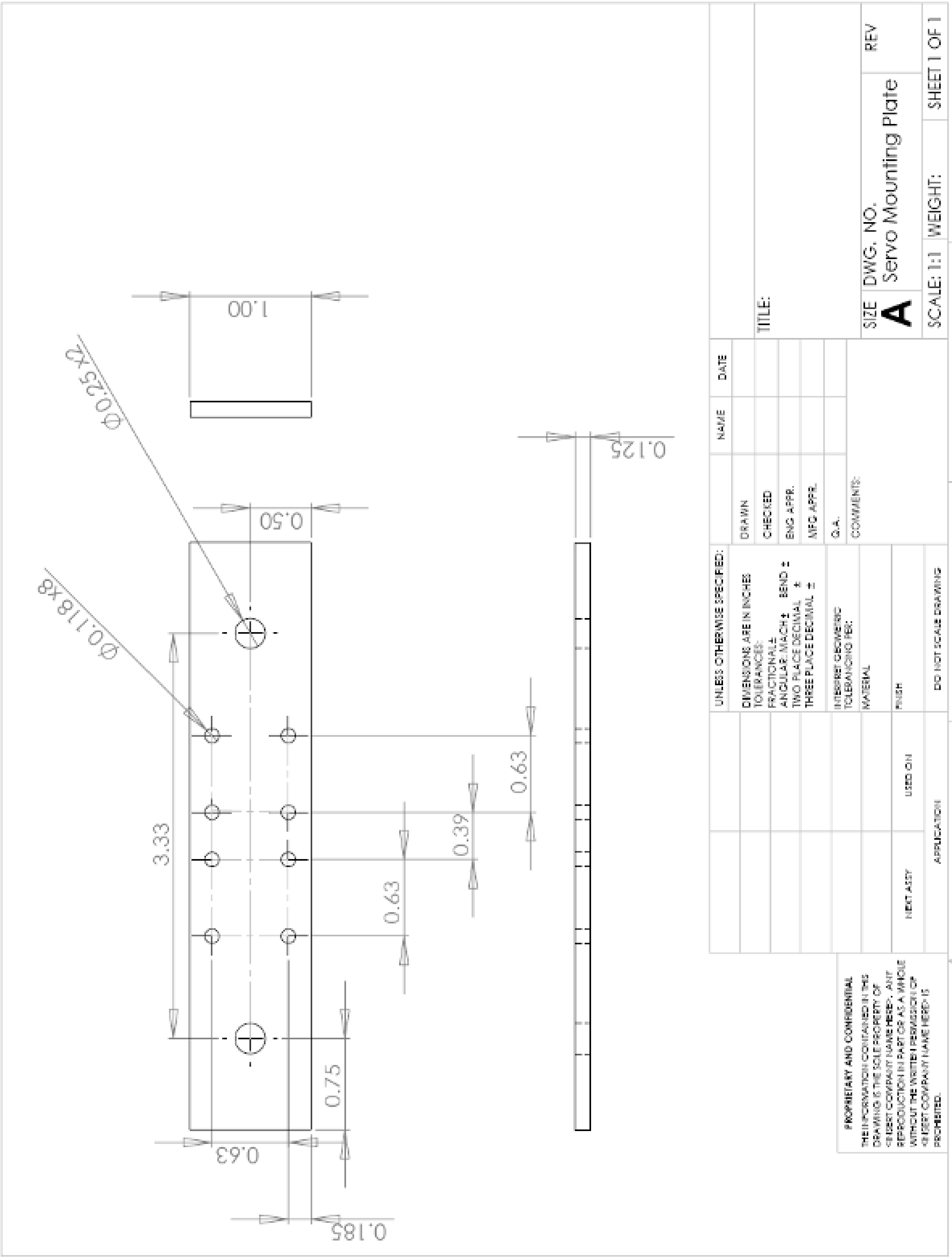
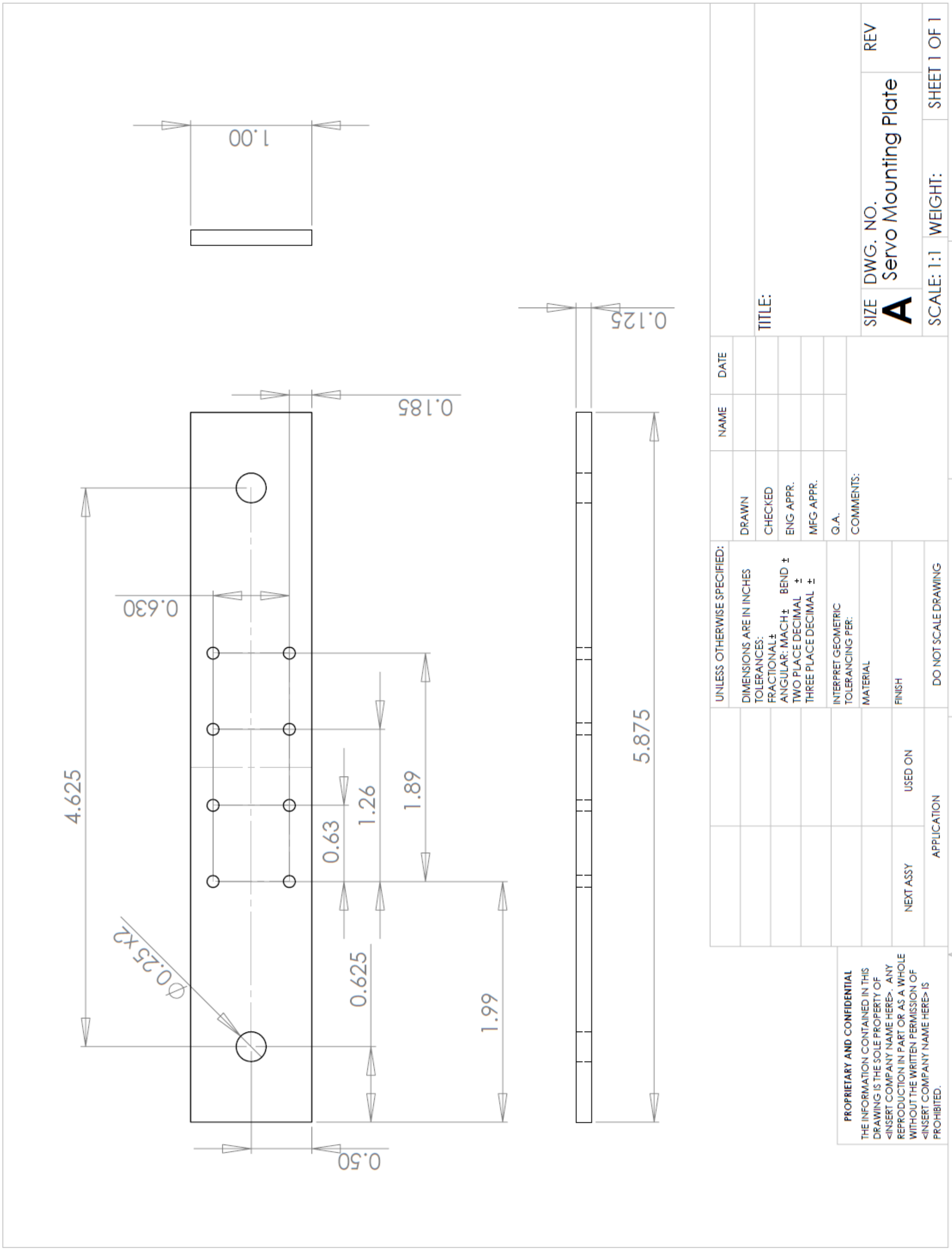
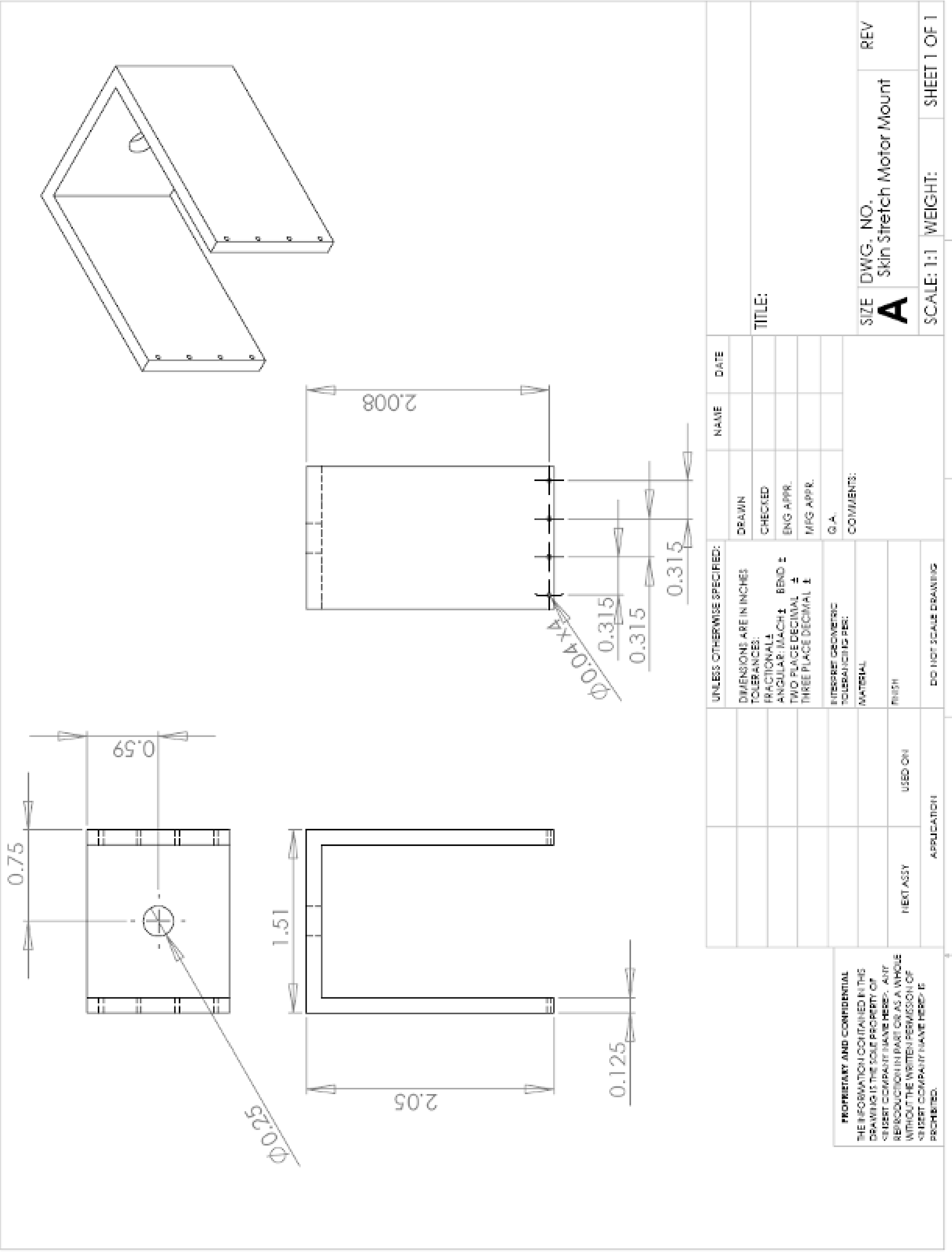
Old Servo Mounting Plate



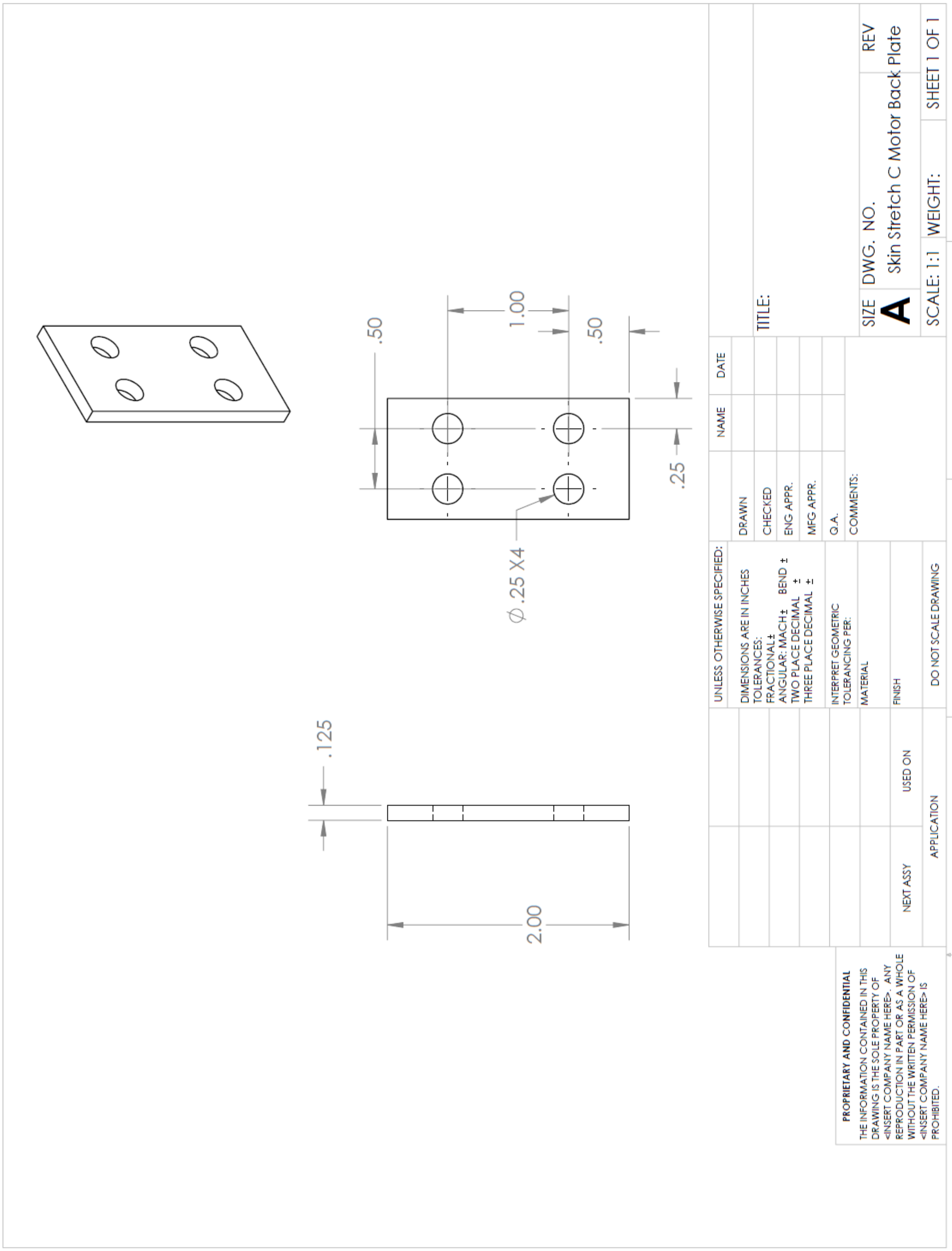
New Servo Mount Plate



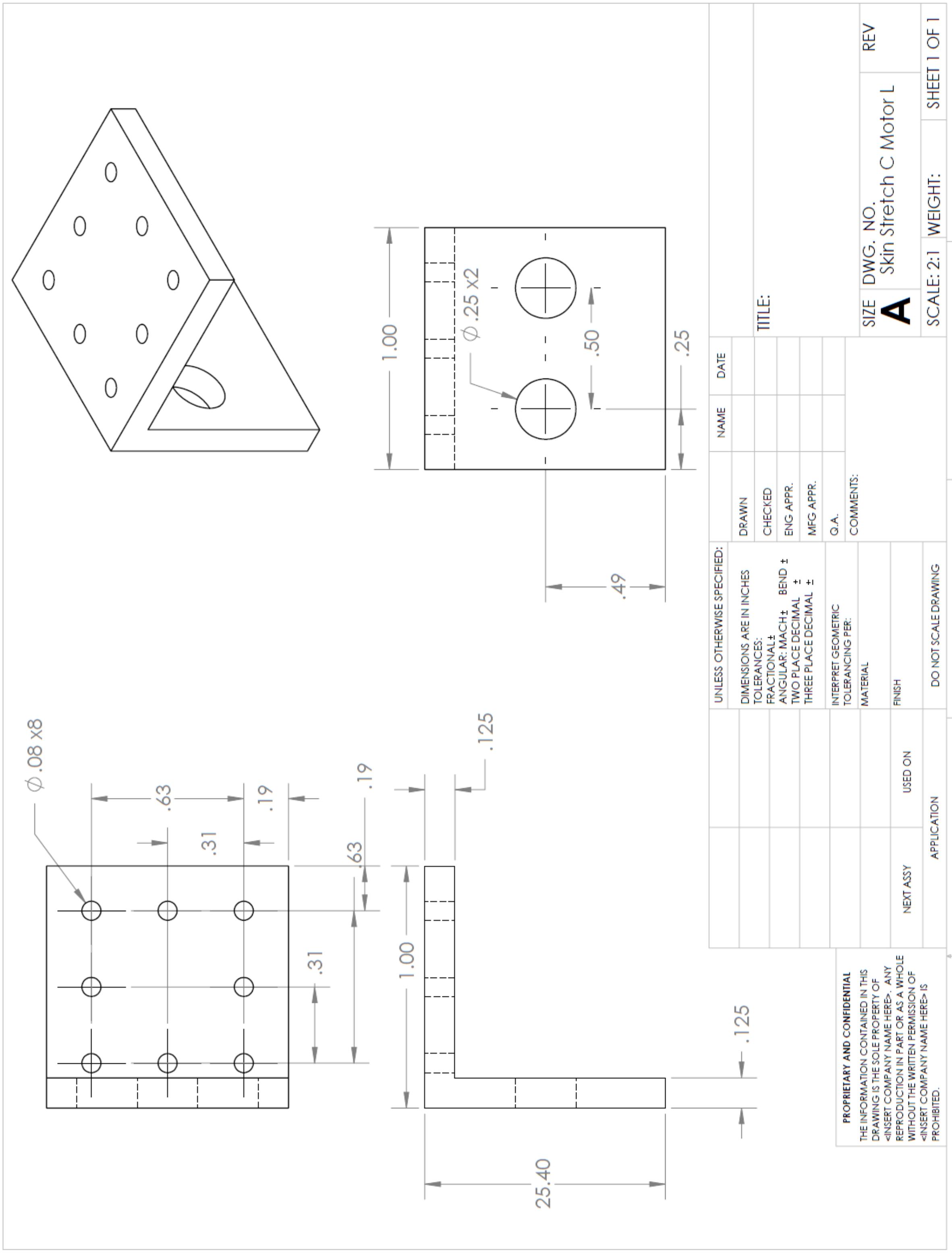
Old Skin-Stretch Motor Mount



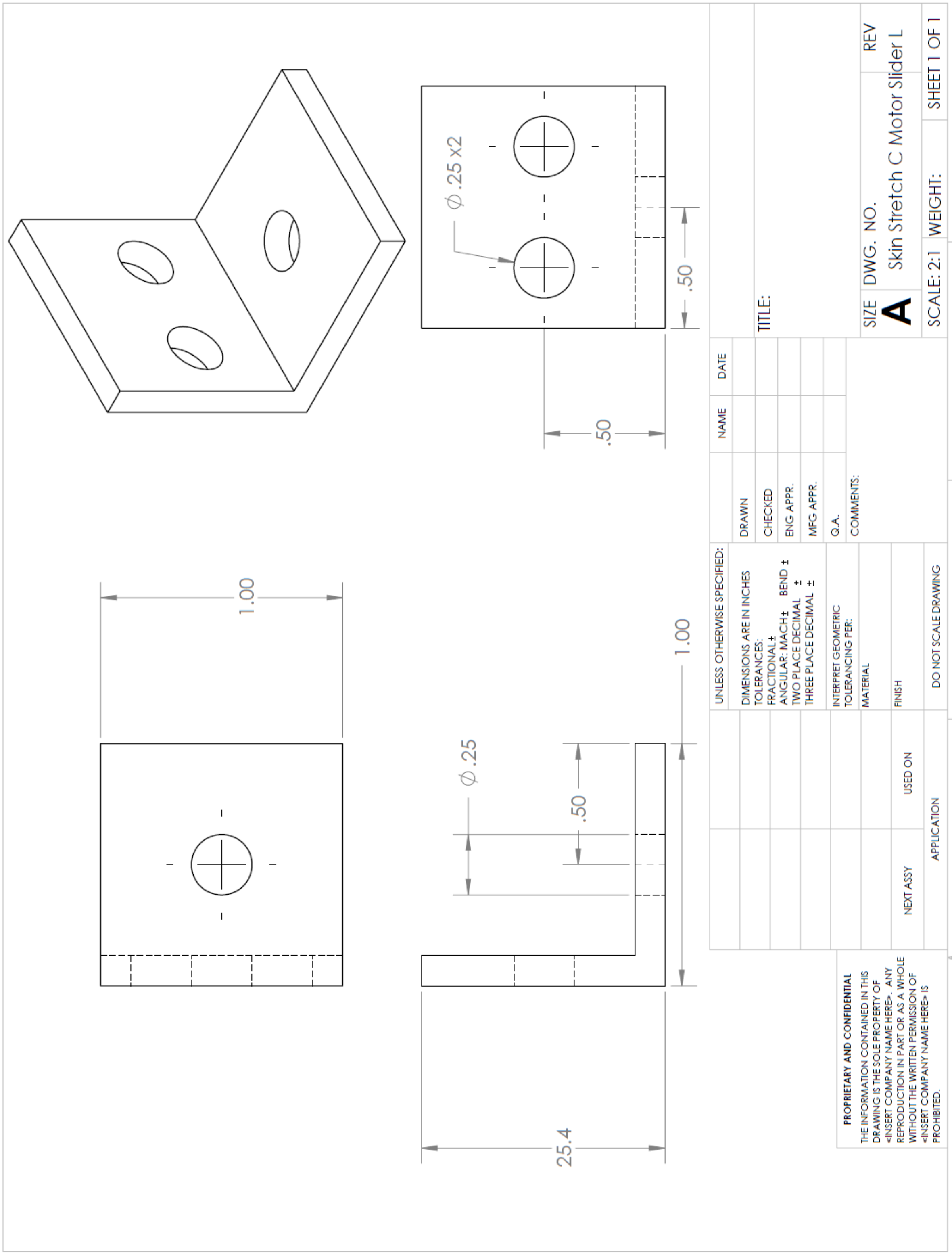
New Skin-stretch Motor Back Plate



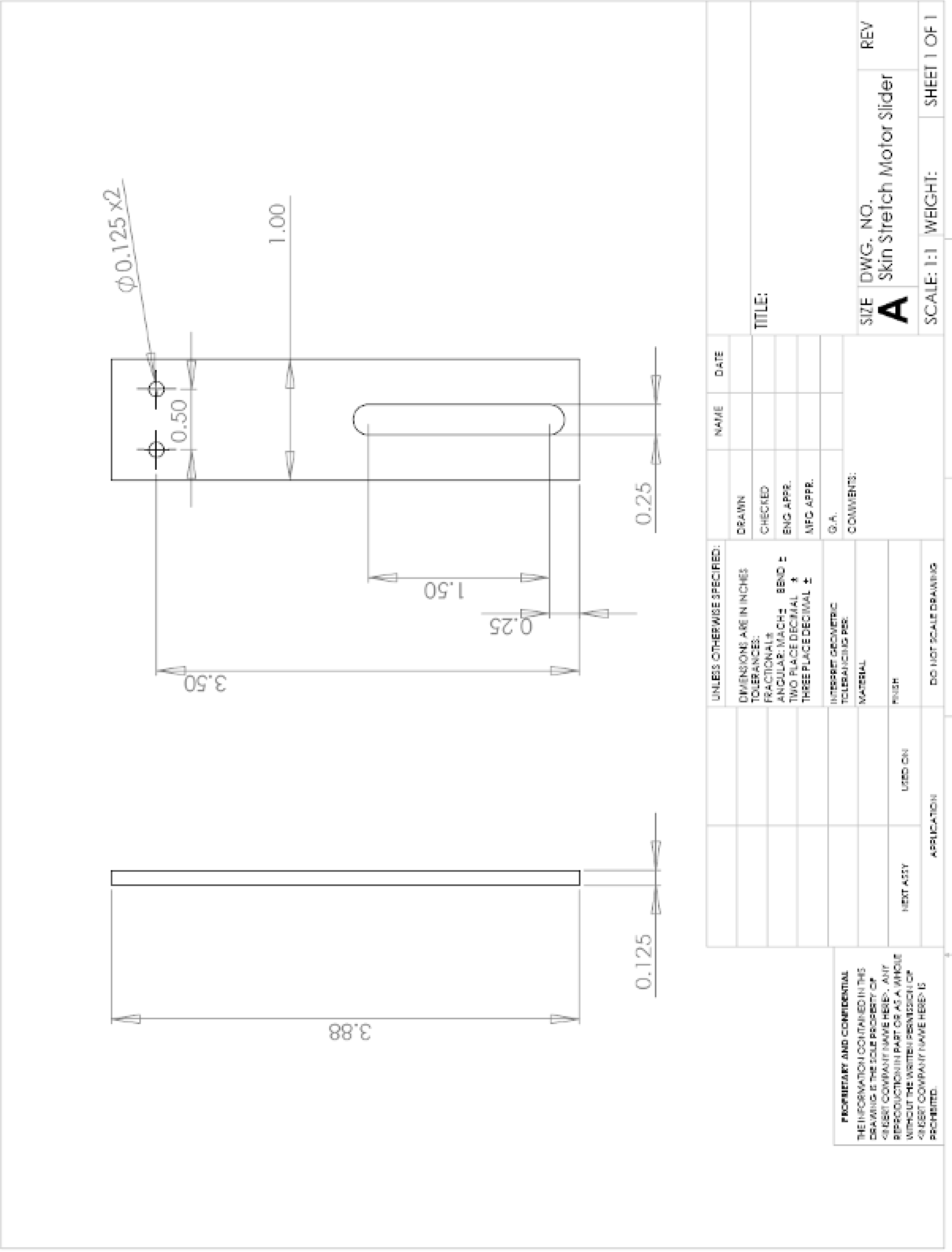
New Skin-stretch Motor L-bracket



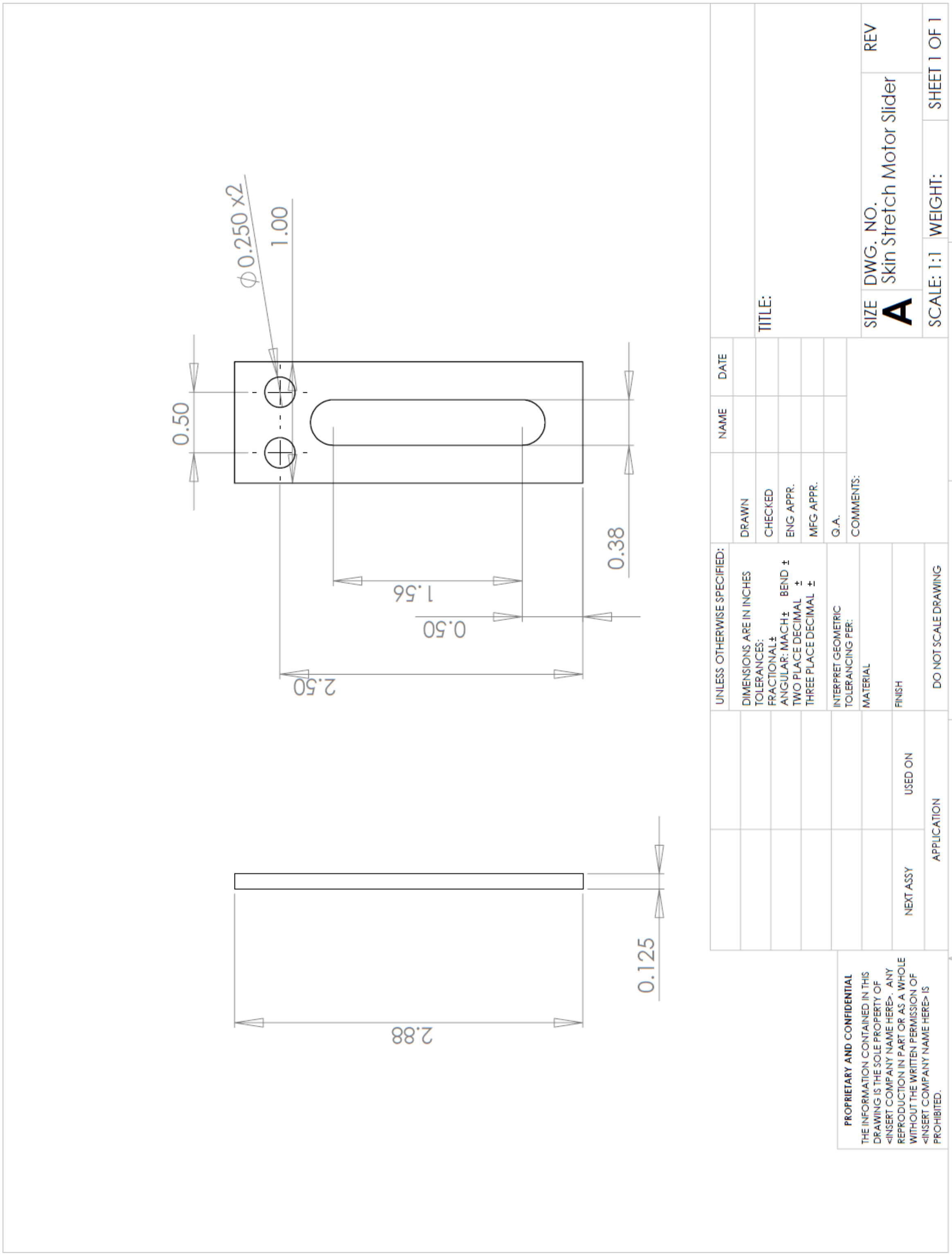
New Skin-stretch Motor Slider L-bracket



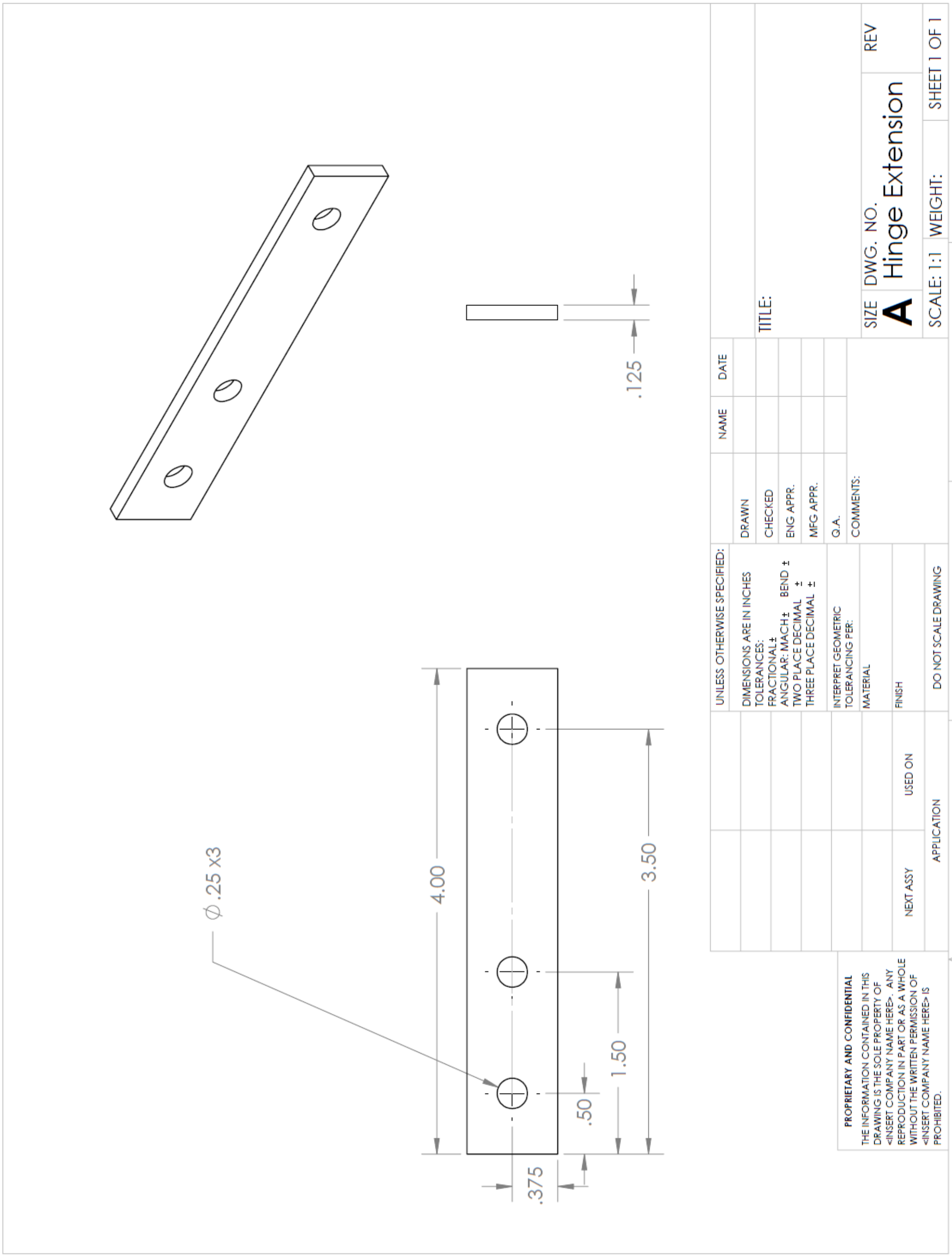
Old Skin-Stretch Motor Slider



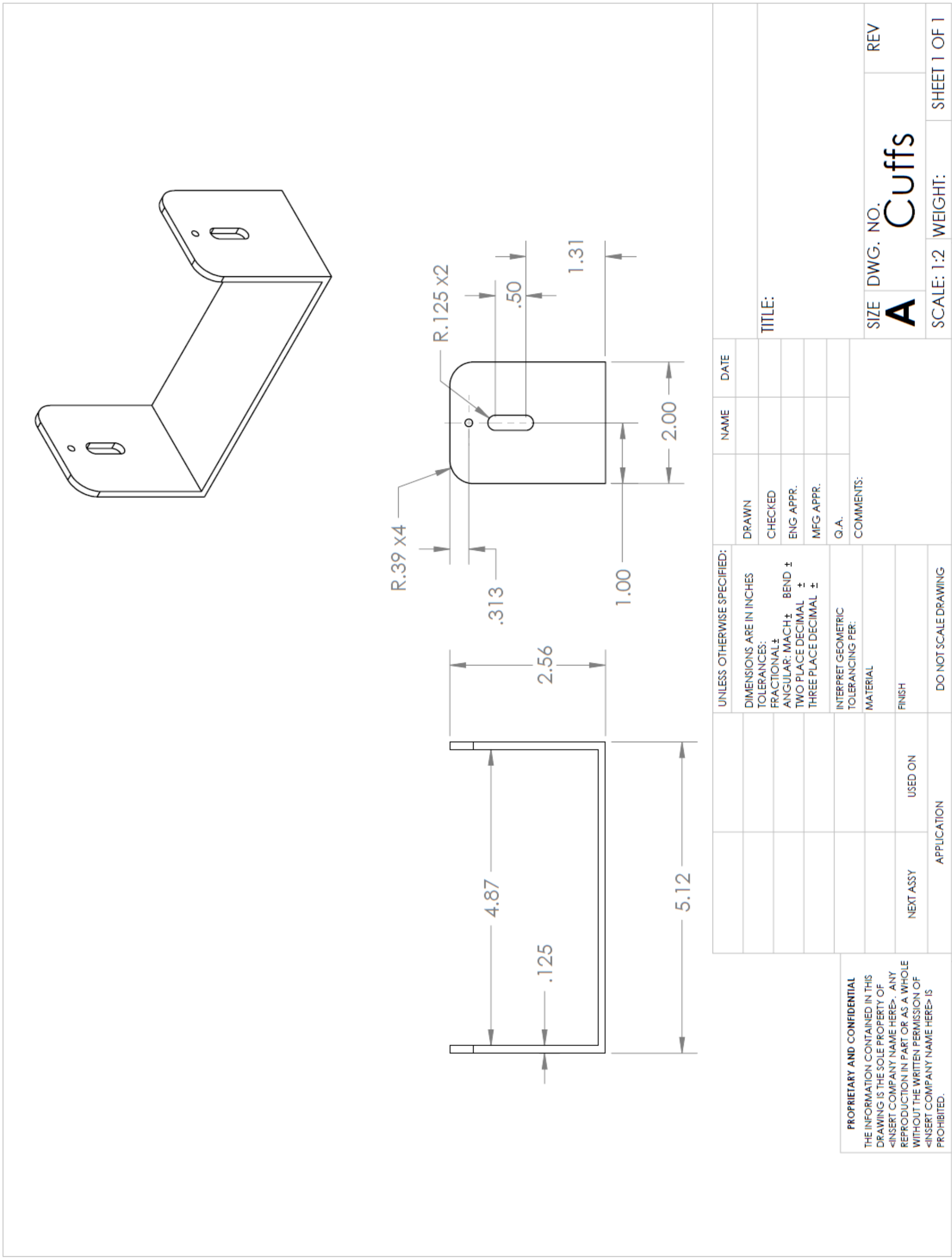
New Skin-Stretch Motor Slider



Hinge Extension



New Cuff


R.125 x2
.50
1.31
R.39 x4
.313
2.00
1.00
2.56
4.87
.125
5.12
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
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NAME
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MFG APPR.
Q.A.
COMMENTS:
TITLE:
SIZE
A
DWG. NO.
Cuffs
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
NEXT ASSY
USED ON
APPLICATION
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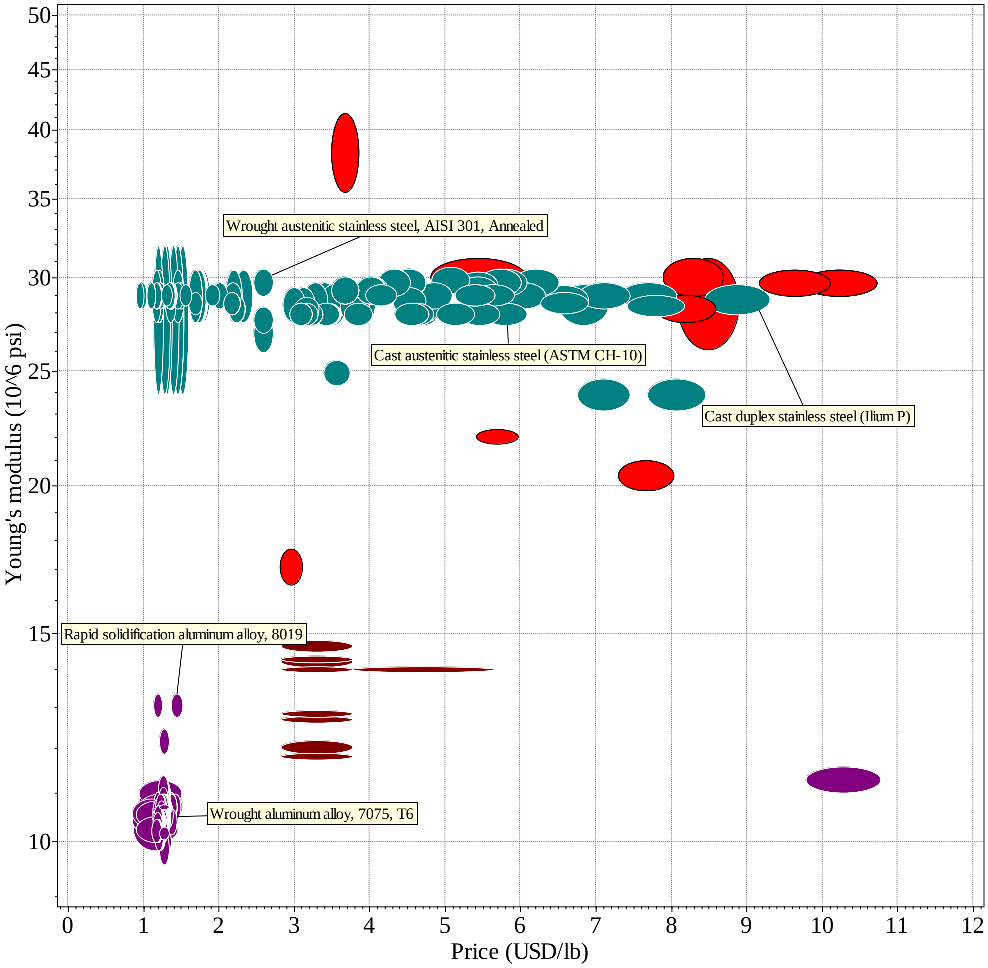
Appendix C: Design Analysis

1. Material Selection Assignment (Functional Performance)

In choosing materials, we considered weight, durability, price, and strength. We completed material selection with Cambridge Engineering Selector. The results for the brace are shown below in Figure i, various aluminum alloys and stainless steels are marked for reference.

Figure i: Cambridge Engineering Selector Results for Brace



We chose to use aluminum 6061-T651 based on its availability and advice from our collaborators at the University of Michigan Orthotics and Prosthetics Center.

2. Material Selection Assignment (Environmental Performance)

For the purpose of our design, our choice of material was limited to different types of aluminum, 6060-T6 Al and 6005 Al. It is difficult to ascertain the proportions of these two materials in the design. Therefore, this analysis is based in the assumption that a prototype could consist entirely of a single alloy. The mass of aluminum used in the prototype is 0.873 kg. This analysis was performed using SimaPro 7.1.

Table ii: Inventory of emissions in kilograms

	Raw	**Air**	**Water**	**Waste**
6060-T6	164892	40912.04	248.5156	1849.31
6005	163881.8	24363.23	193.5075	1602.254

Figure iii: Plot of material production emissions comparing 6060-T6 Al to 6005 Al confirming that 6060-T6 Al has higher emissions in each of the four categories, most noticeably in regard to air emissions.

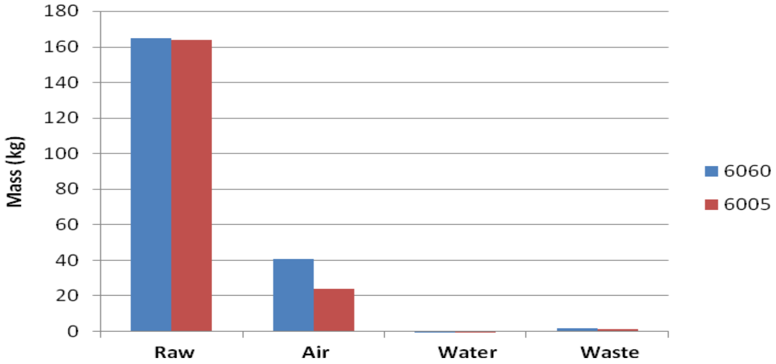


Figure iv: Comparison of the characterizations of 6060-T6 Al and 6005 Al. 6060-T6 has a bigger impact on the environment in every EcoIndicator 99 damage classifications. However, only in the acidification/butrophication category is the difference greater than ten percent.

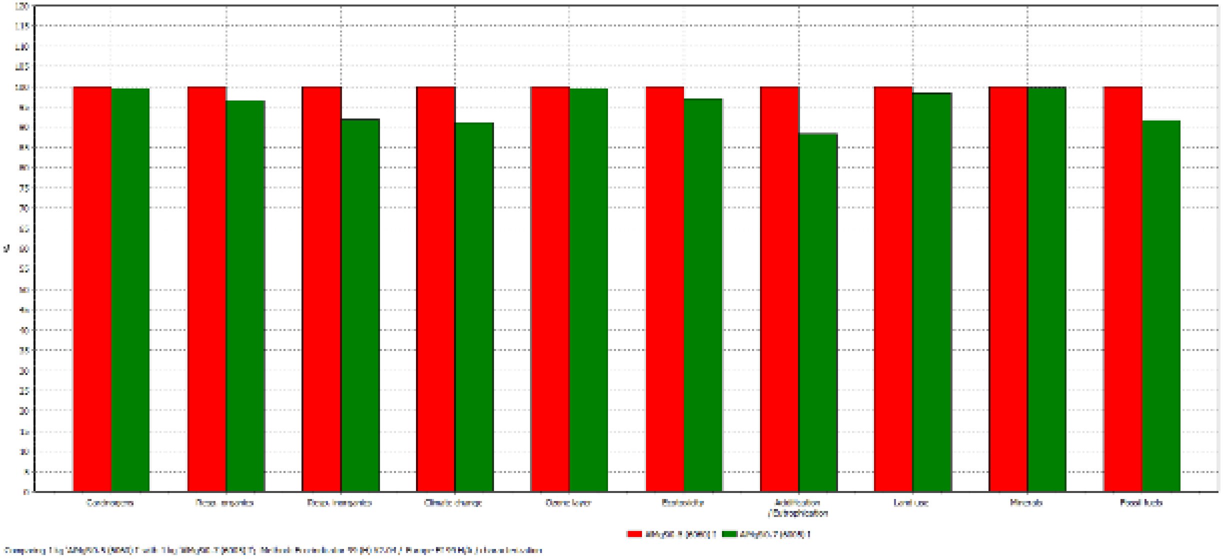


Figure v: The normalization scores show that 6060-T6 Al has a greater impact on humans, the environment, and resources than 6005 Al.

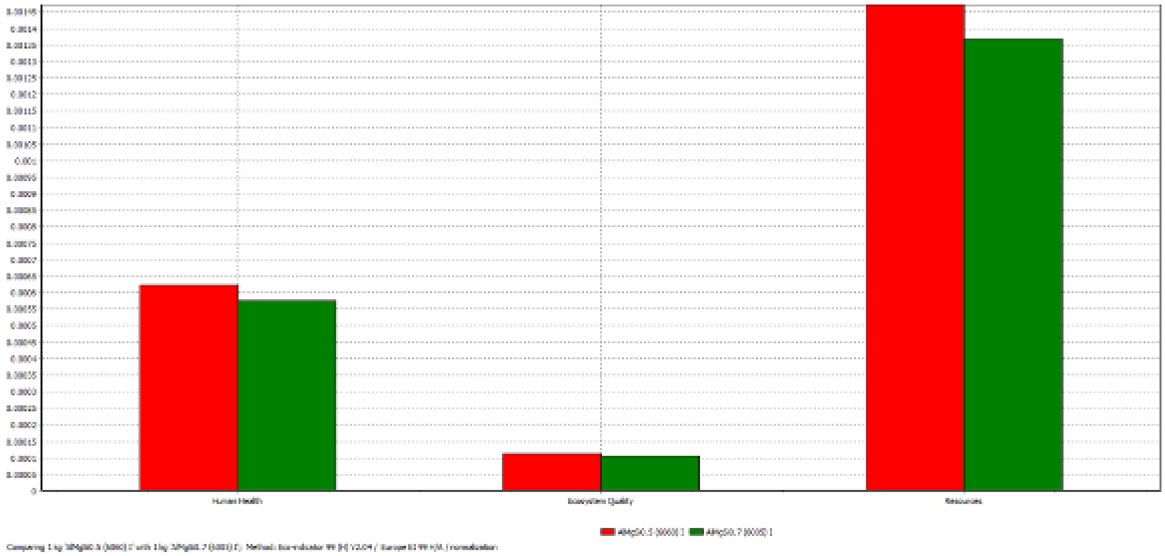
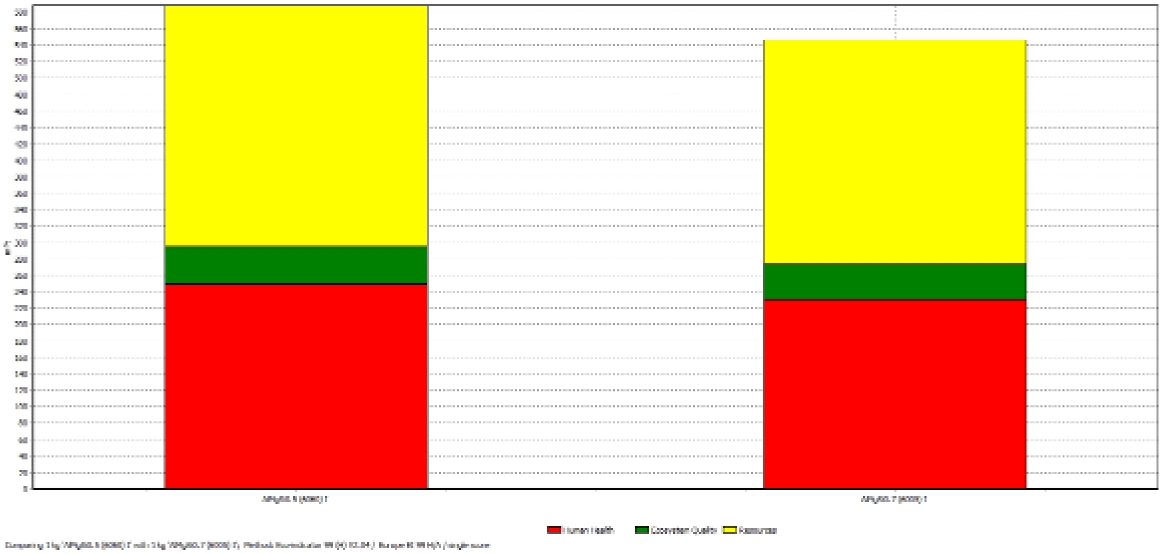


Figure vi: The single score assessment reaffirms that 6060-T6 Al has an overall higher impact on humans, the environment, and resources. Based on the EI99 point values, the resources factor is most likely to be important, and will have the biggest impact when the design's life cycle is taken into consideration.



The results of this analysis show that in 6060-T6 aluminum alloy has a higher EI99 point value and will have a larger impact than 6005 aluminum alloy.

3. Manufacturing Process Selection

Since our project is a prototype that will be used for testing purposes, we expect that the real-world production volume to be low. Because our sponsor is working with other researchers on this prototype, we expect that at least four of our prototypes would be manufactured and given to each of them so that they can continue their research. We hope that our prototype would lead to other prototypes, which would lead to a final product that would be mass produced.

CES process selection software was used to analyze the feasibility of different manufacturing methods involved in manufacturing the prototype. Two topics to consider are the economic batch (Figure viii) size for different processes and the ability to stay within the proper tolerances (Figure vii). Milling and drilling operations satisfy our requirements. Both processes are suitable for batch sizes ranging from a single unit. In addition, both processes are capable of tolerances smaller than 0.01 inches, which is more accurate than what the prototype required.

Figure vii: Milling and drilling have performance tolerances suitable for manufcturing the prototype.

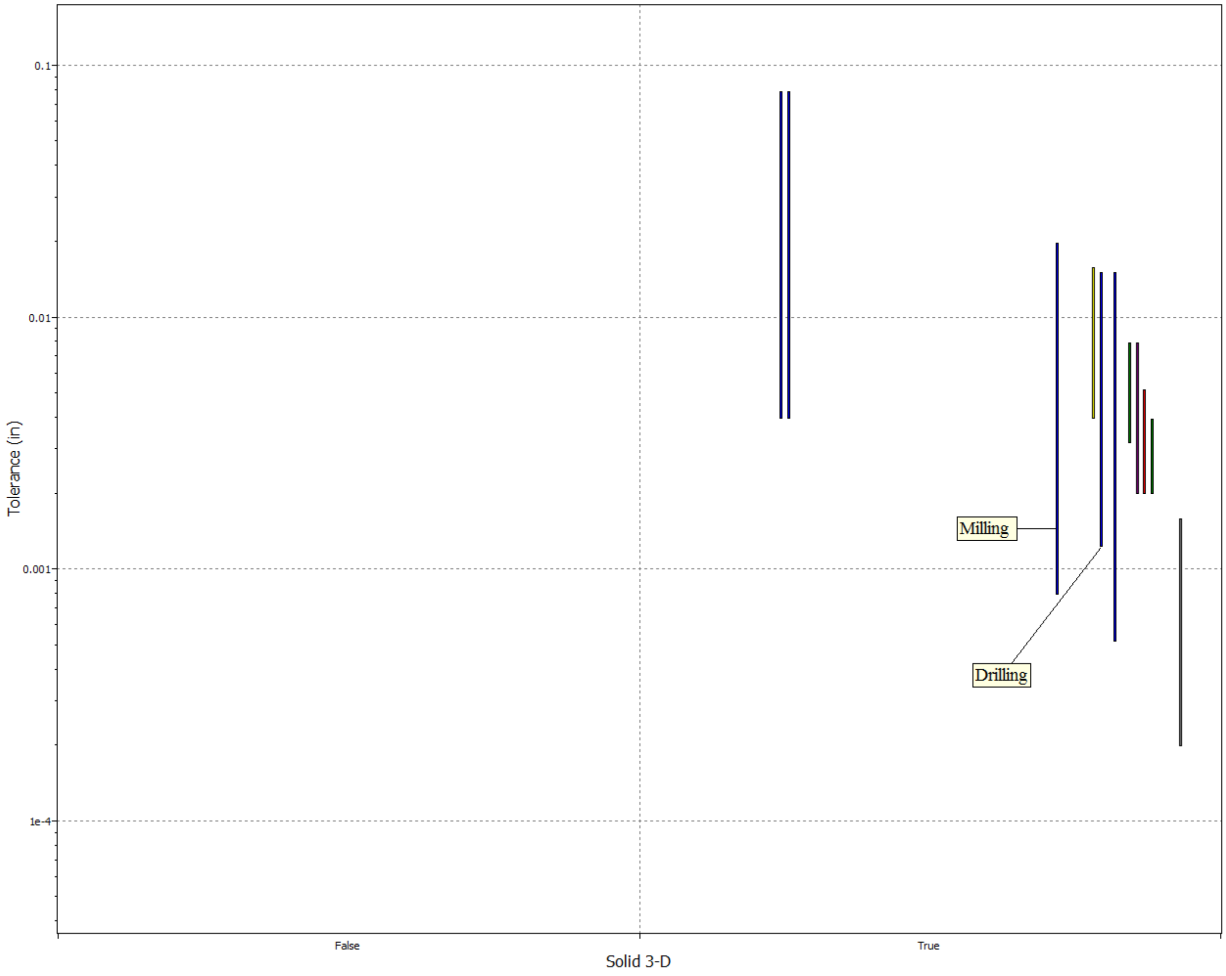
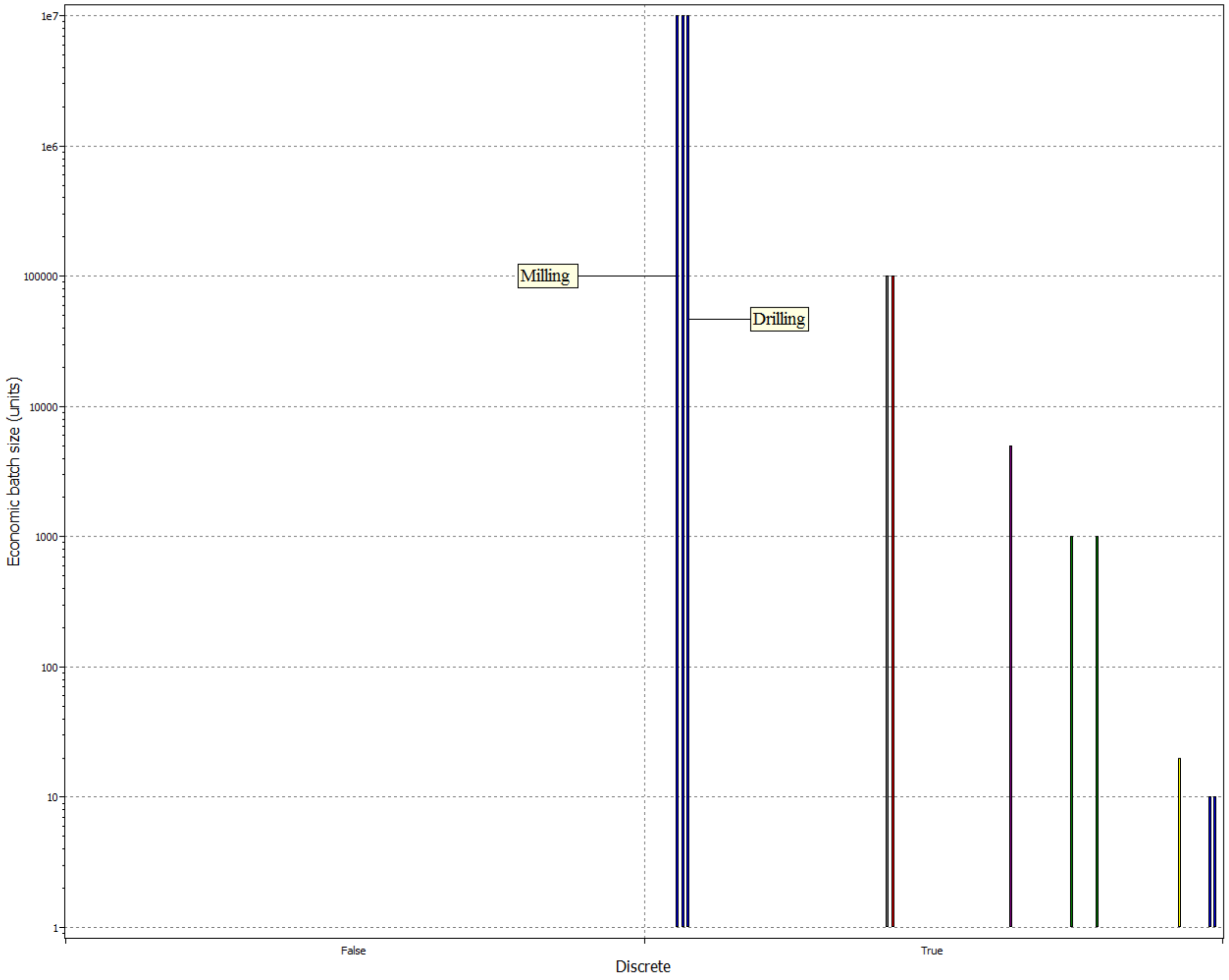


Figure viii: Milling and drilling are economical to use with any number of units to be manufactured



Appendix D: Concepts Generated

1. Feedback
    a. Vibration
        i. Vibration Motor
    b. Silicone skin-stretching
        i. Servomotor
        ii. Linear Actuator
        iii. DC motor
    c. Pressure sleeve
        i. Pneumatic sleeve
        ii. Motor with tightening band
            1. Servomotor
            2. DC motor
            3. Linear Actuator
    d. Elbow Torque
        i. Capstan drive
        ii. Electromagnets
    e. Perceived Senses
        i. Object Weight
        ii. Temperature
        iii. Surface Roughness
        iv. Object slippage
        v. Object Stiffness
2. Gripper
    a. Sensors
        i. Force/Pressure
            1. Force-sensing resistors
            2. Strain gauges
            3. Pressure transducers
        ii. Displacement
            1. Optical Encoder
            2. Potentiometer
            3. Servo displacement output
    b. Interface with human hand
        i. Handle
        ii. None
        iii. Commercial Wrist Brace
        iv. Formed, half bed
    c. Finger Design
        i. Two, opposing
        ii. Hook style
        iii. Three, alternating
    d. Pronation/Suponation
        i. Friction joint
        ii. Rotary motor

        iii. None
3. Exoskeleton
    a. Off-the-shelf elbow brace
    b. Custom-made
        i. Materials
            1. Polypropylene
            2. Medical plastic
            3. Stainless steel
            4. Velcro closure
            5. Elastic sleeve
        ii. Hinge
            1. Purchased
            2. Manufactured
4. EMG Signal Acquisition
    a. Electrodes
        i. Placement
            1. Bicep only
            2. Tricep only
            3. Bicep and tricep
            4. Forearm
    b. Signal Filtering
        i. Band-pass
        ii. Computational methods pre-processing
    c. Calibration
        i. LabVIEW GUI
        ii. Weights
        iii. Pattern recognition software
5. Unit Control Methods
    a. Dual flex of bicep and tricep
        i. Locking elbow
        ii. Locking gripper
    b. Closed gripper is default (like body-powered hooks)
6. Computer controls and data acquisition
    a. LabVIEW
    b. C++

Appendix E: Visual Studio 2005 C++ Code

```
////////// INCLUDES //////////

#include <windows.h>
#include <conio.h>
#include <time.h>
#include <math.h>
#include <iostream>
#include <fstream>
#include <stdlib.h>
#include "NIDAQmx.h"
#include "dynamixel.h"
using namespace std;

////////// DEFINITIONS //////////

#define P_GOAL_POSITION_L     30
#define P_GOAL_POSITION_H     31
#define P_PRESENT_POSITION_L          36
#define P_PRESENT_POSITION_H          37
#define P_MOVING                  46
#define P_LOAD_L                  40
#define P_LOAD_H                  41
#define MOVING_SPEED_L                32
#define MOVING_SPEED_H                33
#define P_SPEED_L                 38
#define P_SPEED_H                 39
#define SPEED_MIN                 1
#define SPEED_MAX                 1023
#define CW_LIMIT_L                6
#define CCW_LIMIT_L               8
#define SERVO_CCW                 816               // FULLY OPEN
#define SERVO_CW                  552               // FULLY CLOSED
#define NUM_ACTUATOR                  3                 // # of Servos
#define PI                        3.141592f
#define FEEDBACK_MAX                  5.0f
#define FEEDBACK_MIN                  0.0f
#define  GRASP_MIN                0.3f
#define TOUCH_MIN                 0.15f
#define GRASP_START               0.2f

////////// FUNCTION PROTOTYPES /////////

float64* ReadFromAnalogIn(void);
void WriteToDigitalLine(void);
void WriteToAnalogLine(float64[2]);
void ReadFromCounter(void);
int dxl_write_all_pos(int[NUM_ACTUATOR]);
int dxl_open(void);
int dxl_load(int);

////////// MAIN //////////

int main(){
```

```
////////// INIT COUNTERS & FLAGS //////////

char kb = 0;
int i = 0;
int row = 0;
int count = 0;
int countPrint=0;
long loopTimer=0;
int Pulsed=0;
char Grasp = 0;


////////// INIT TIME KEEPING //////////

time_t TimeStamp=0;

////////// INIT SERVOS VALUES //////////

int baudnum = 1;
int ServoErr = 0;
int PresentPos[NUM_ACTUATOR];
int PresentLoad[NUM_ACTUATOR];
int PresentSpeed[NUM_ACTUATOR];
int CommandPos[NUM_ACTUATOR];
int CommandSpeed[NUM_ACTUATOR];
int InitGraspPos = 0;

//          PresentPos[i] = dxl_read_word(i, P_PRESENT_POSITION_L);

CommandPos[0] = SERVO_CCW;
CommandPos[1] = SERVO_CCW;
CommandPos[2] = 0;
CommandSpeed[0] = 0;
CommandSpeed[1] = 0;
CommandSpeed[2] = 0;

int presentPos = 0;  //New Position of Grippers
int oldPos = 0;  //Old Position of Grippers

////////// INIT CONTROL VALUES //////////

float64 Feedback[2] = {FEEDBACK_MIN,FEEDBACK_MIN};
float64 FeedbackWidth = FEEDBACK_MAX-FEEDBACK_MIN;
float64 CurrRefOut = 0.0; //ReadFromAnalogIn(2);
float64 CurrMonOut = 0.0; //ReadFromAnalogIn(3);

////////// INIT EMG VALUES //////////

float64 Emg=0.0;
float64 EmgMin = 5.0;//ReadFromAnalogIn();
float64 EmgMax = 0.0;//ReadFromAnalogIn();
float64 EmgWidth = 0.0;
float64 EmgSum = 0.0;
float64 EmgAvg = 0.0;
```

```
    int EmgGain = 0;
    float64 ExoGain=7.0;
    float64 *AnalogIn = 0;      // Pointer for array returned by Analog aquisition function (Oh-hoh Mr Fancy Pants!)

    ////////// INIT EMG SENSOR //////////

    int done=0;
    printf("Move the EMG Sensor from Max to Min and then press ESC\n");
    while(!done){
        AnalogIn = ReadFromAnalogIn();
        Emg = AnalogIn[0];
        if(Emg<0.0) EmgMin=0.0;
        else if(Emg<EmgMin) EmgMin=Emg;
        if(Emg>5.0) EmgMax=5.0;
        else if(Emg>EmgMax) EmgMax=Emg;
        printf("EMG[% 2.1f] LOW[E% 2.1f] HIGH[E% 2.1f]\r",Emg,EmgMin,EmgMax);
        if(_kbhit()) if(_getch()==0x1b) done=1;
    }
    EmgWidth=fabs(EmgMax-EmgMin);

    printf("\nDetermining load cell offset: ");

    float64 LoadCell_L=0.0;
    float64 LoadCell_R=0.0;
    float64 LoadCell_L_AVG=0.0;
    float64 LoadCell_R_AVG=0.0;
    float64 LoadCell_AVG=0.0;
    for(int i=0;i<100;i++){
        AnalogIn=ReadFromAnalogIn();
        LoadCell_L+=AnalogIn[1];
        LoadCell_R+=AnalogIn[2];
    }
    LoadCell_L_AVG=LoadCell_L/100;
    LoadCell_R_AVG=LoadCell_R/100;

    printf("Left[%5.2f] Right[%5.2f]\n",LoadCell_L_AVG,LoadCell_R_AVG);


    ////////// OPEN FILE STREAM /////////

    time_t seconds = time(NULL);
    char filename[32];
    sprintf_s(filename,"gripLog-%d.txt",seconds);
    ofstream DataLog;
    DataLog.open(filename);
    printf("--> Opening File Stream:");
    if(!DataLog.is_open()){
        printf(" Failed!\n");
        system("PAUSE");
        goto END_MAIN;
    }else{
        printf(" Succeeded!\n");
    }
    DataLog << "EmgMin" << '\t'
```

```
                    << "EmgMax" << '\t'
                    << "LoadCell_L_AVG" << '\t'
                    << "LoadCell_R_AVG" << '\n'
                    << EmgMin << '\t'
                    << EmgMax << '\t'
                    << LoadCell_L_AVG << '\t'
                    << LoadCell_R_AVG << "\n\n\n"
                    << "TimeStamp" << '\t'
                    << "CommandPos" << '\t'
                    << "Feedback" << '\t'
                    << "Emg" << '\t'
                    << "LoadCell_L" << '\t'
                    << "LoadCell_R" << '\t'
                    << "EmgGain" << '\t'
                    << "ExoGain" << '\n';

////////// INIT DYNAMIXEL SERVOS //////////

printf("--> Opening USB2Dynamixel: ");
if( dxl_initialize() == 0 ){
          printf( "Failed to Initialize.\n" );
          goto END_MAIN;
}else{
          printf(" Succeeded!\n");
}
printf("--> Starting Servos: ");
dxl_set_baud( baudnum );
dxl_write_word( BROADCAST_ID, P_SPEED_L, 0 );
if(!dxl_open()){
          printf( "Failed to Open.\n" );
          goto END_MAIN;
}else{
          printf(" Succeeded!\n");
}
printf("--> Starting Control Loop.\n\n");

printf("\n\nCommmands:\n");
printf("A - Increase EMG Gain\n");
printf("S - Decrease EMG Gain\n");
printf("e - Increase Feedback Gain\n");
printf("r - Decrease Feedback Gain\n");
printf("ESC to Exit\n\n");

while(1){

          ////////// MODIFY GAINS OR EXIT //////////

          if(_kbhit()){
                    switch(_getch()){
                              case 0x1b: //esc
                                        goto END_MAIN;
                                        break;
                              case'h':
                              case'H':
                                        Feedback[1] += 0.25;
```

```
                    break;
                case'j':
                case'J':
                    Feedback[1] -= 0.25;
                    break;
                case'a':
                case'A':
                    EmgGain += 10;
                    break;
                case's':
                case'S':
                    EmgGain -= 10;
                    break;
                case'e':
                case'E':
                    ExoGain += 0.1;
                    break;
                case'r':
                case'R':
                    ExoGain -= 0.1;
                    break;
                default:
                    break;
            }
        }

        //////////// CONTROL //////////

        //Feedback[1]=0.0;                          // This stays at 0.
        time_t wait = time(NULL);
        AnalogIn = ReadFromAnalogIn();
        Emg=AnalogIn[0];
        LoadCell_L=AnalogIn[1]-LoadCell_L_AVG;
        LoadCell_R=AnalogIn[2]-LoadCell_R_AVG;
        LoadCell_AVG = (LoadCell_L+LoadCell_R)/2;

        presentPos = dxl_read_word(0, P_PRESENT_POSITION_L); //Read the present position of the of
the left servo
        //PresentPos[2]=dxl_read_word(2, P_PRESENT_POSITION_L); //Read the present position of
the of the left servo


        for(i=0;i<NUM_ACTUATOR-1;i++){
            CommandPos[i] = (int)(SERVO_CCW-(SERVO_CCW-SERVO_CW)*Emg/EmgWidth-
EmgGain);
            //if(CommandPos[i]>SERVO_CCW){
            //      CommandPos[i]=SERVO_CCW;
            //}else if(CommandPos[i]<SERVO_CW){
            //      CommandPos[i]=SERVO_CW;
            //}
        }

        Feedback[0] = ExoGain*(LoadCell_L+LoadCell_R)/2.0;

        /////////Vibrotactile Motor///////////
```

```
        if (((TOUCH_MIN <= LoadCell_L)||(TOUCH_MIN <= LoadCell_R)) && (GRASP_MIN >=
LoadCell_AVG)){
            Feedback[1] = 3.0;          // 3 Volts
        }else{
            Feedback[1] = 0;
        }

        /////Skin-stretch//////

        if (GRASP_START <= LoadCell_AVG){
            if (Grasp){ // If I'm grasping an object
                CommandPos[2] = (10*(InitGraspPos-presentPos));//+PresentPos[2];    //
Command skin-stretch to occur
            }else{
                InitGraspPos = presentPos;
                Grasp = 1;
            }
        }else{
            if(CommandPos[2]>0){
                CommandPos[2]-=4;
            }else if(CommandPos[2]<0){
                CommandPos[2]+=4;
            }else{
                CommandPos[2]=0;
            }
                Grasp = 0;
        }

        WriteToAnalogLine(Feedback);                    // Command elbow motor feedback
        ServoErr=dxl_write_all_pos(CommandPos);  // Command servo position and return status

        ////////// DISPLAY //////////

        if(countPrint=100){
            printf("S[%*d:%*d:%*d] E[%*d] LC[%5.2f][%5.2f] M[%5.2f:%5.2f]x[%5.2f]
G[%*d]\r",
                    5,CommandPos[0],
                    5,CommandPos[1],
                    5,CommandPos[2],
                    5,EmgGain,
                    LoadCell_L,
                    LoadCell_R,
                    Feedback[0],
                    Feedback[1],
                    ExoGain,
                    1,Grasp);
            //printf("Vib:%5.2f\r",Feedback[1]);
            //printf("[%5.2f][%5.2f][%5.2f]\r",Emg,LoadCell_L,LoadCell_R);

            countPrint=0;
        }else{
            countPrint++;
        }
        TimeStamp = clock();
```

```
			DataLog << TimeStamp << '\t'		// Or something like that.. *glares at time.h*
					<< CommandPos[0] << '\t' // Servos are commanded the same position
					<< Feedback[0] << '\t'		// Feedback[1] is not wired, not using differential
control
					<< Emg<< '\t'
					<< LoadCell_L << '\t'
					<< LoadCell_R << '\t'
					<< EmgGain << '\t'
					<< ExoGain << '\n';
			row++;
		}

		////////// SHUTDOWN //////////

		END_MAIN:

		////////// HALT MOTORS & SERVOS //////////

		Feedback[0]=0.0;
		Feedback[1]=0.0;
		WriteToAnalogLine(Feedback);
		//WriteToAnalogLine(VibroMotor);
		printf("\n\n[*] Motor halted.\n");
		dxl_terminate();
		printf("[*] Servos reset and halted.\n");
		DataLog.close();
		printf("[*] File Saved.			\n\n");

		////////// EXIT //////////

		printf("System shutdown.\n");
		system("PAUSE");
		return 0;
}

////////// FUNCTIONS //////////

int dxl_load(int id){
		int raw_load = dxl_read_word(id, P_LOAD_L);
		int load = raw_load&0x3FF;
		if(!(raw_load&0x400)) load=load*-1;
		return(load);
}

int dxl_open(void){
		for(int i=0; i<NUM_ACTUATOR-1; i++){
			dxl_write_word(i, P_GOAL_POSITION_L,SERVO_CCW );
			//if(_kbhit()){
			//		if(_getch()==0x1b){
			//				dxl_terminate();
			//				dxl_initialize();
			//				dxl_set_baud(1);
			//				return(0);
			//		}
			//}
```

```
		}
		dxl_write_word(2, P_GOAL_POSITION_L,0);
		return(1);
}
int dxl_write_all_pos(int GoalPos[NUM_ACTUATOR]){
		int flag=1;
		while(flag){
			if(dxl_get_result()==COMM_RXSUCCESS){
				gbInstructionPacket[ID] = BROADCAST_ID;
				gbInstructionPacket[INSTRUCTION] = INST_SYNC_WRITE;
				gbInstructionPacket[PARAMETER] = P_GOAL_POSITION_L;
				gbInstructionPacket[PARAMETER+1] = 2;
				for(int i=0; i<NUM_ACTUATOR; i++ ){
					gbInstructionPacket[PARAMETER+2+3*i] = i;
					gbInstructionPacket[PARAMETER+2+3*i+1] = dxl_get_lowbyte(GoalPos[i]);
					gbInstructionPacket[PARAMETER+2+3*i+2] = dxl_get_highbyte(GoalPos[i]);
				}
				printf( "\r" );
				gbInstructionPacket[LENGTH] = (2+1)*NUM_ACTUATOR+4;
				dxl_txrx_packet();
				flag=0;
			}else{
				if(_kbhit()) if(_getch()==0x1b)	return(0);
				dxl_terminate();
				dxl_initialize();
				dxl_set_baud(1);
				//dxl_open();
			}
		}
		return(1);
}

void WriteToAnalogLine(float64 feedback[2]){
		//initialization
		TaskHandle taskHandleAO;
		DAQmxCreateTask("",&taskHandleAO);
		DAQmxCreateAOVoltageChan(taskHandleAO,"Dev2/ao0:1","",0.0,5.0,DAQmx_Val_Volts,"");
		DAQmxStartTask(taskHandleAO);

		//prepare signal data
		float64* dataAO = new float64[3];
		dataAO[0] = feedback[0];
		dataAO[1] = feedback[1];
		//write signal
		DAQmxWriteAnalogF64(taskHandleAO,1,1,10.0,DAQmx_Val_GroupByChannel,dataAO,NULL,NULL);

		//termination
		DAQmxStopTask(taskHandleAO);
		DAQmxClearTask(taskHandleAO);
}

//float64 ReadFromAnalogIn(int ChanInt){
//
//		char ChanID[9] = {'D','e','v','2','/','a','i','0',0};
//		char Chan = ChanInt+48;
```

```
//		ChanID[7]=Chan;
//		float64 dataAI[1];
//		int32 read;
//		//initialization
//				TaskHandle taskHandleAI;
//				DAQmxCreateTask("",&taskHandleAI);
//
		DAQmxCreateAIVoltageChan(taskHandleAI,ChanID,"",DAQmx_Val_Cfg_Default,0.0,5.0,DAQmx_Val_
Volts,NULL);
//				DAQmxStartTask(taskHandleAI);
//				//prepare signal data
//
		DAQmxReadAnalogF64(taskHandleAI,1,10.0,DAQmx_Val_GroupByChannel,dataAI,1,&read,NULL);
//				//termination
//				DAQmxStopTask(taskHandleAI);
//				DAQmxClearTask(taskHandleAI);
//		return dataAI[0];
//}

float64* ReadFromAnalogIn(){

		char ChanID[] = "Dev2/ai0:2";
		float64 *dataAI=new float64[3];
		int32 read;
		//initialization
				TaskHandle taskHandleAI;
				DAQmxCreateTask("",&taskHandleAI);

		DAQmxCreateAIVoltageChan(taskHandleAI,ChanID,"",DAQmx_Val_RSE,0.0,5.0,DAQmx_Val_Volts,N
ULL);
				DAQmxStartTask(taskHandleAI);
				//prepare signal data

		DAQmxReadAnalogF64(taskHandleAI,1,10.0,DAQmx_Val_GroupByChannel,dataAI,3,&read,NULL);
				//termination
				DAQmxStopTask(taskHandleAI);
				DAQmxClearTask(taskHandleAI);
		return dataAI;
}
```