ME 450 DESIGN AND MANUFACTURING III
Fall 2020

# DESIGN OF NOVEL WRIST AND GRIPPER: FINAL DESIGN REPORT

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# EXECUTIVE SUMMARY

Prosthetic devices have long been used to replace missing body parts and to restore some degree of their functionality. Upper limb prostheses have risen in popularity over the past century thanks to advances in technology allowing for powered actuation and enhanced functionality and performance. Powered grippers and wrists are a common choice for amputees who wish to regain the lost functionality resulting from an amputation of an upper limb. The loss of a hand places an amputee at a disadvantage when performing a variety of everyday tasks, including driving, cleaning, and cooking. The use of a prosthesis can allow an amputee to perform tasks they were previously unable to, or to do so with greatly increased speed. Our sponsors, Professor Awtar and his PhD candidate Revanth Damerla, were interested in designing a powered wrist-gripper prosthesis that builds upon some of the popular, but dated models that are currently available on the market,  and that also improves user satisfaction. Our end goal was to assess the context of the problem, generate design concepts, create a detailed design, and fabricate a prototype design.

The user requirements were developed using observations from existing designs and recommendations from resident prosthetist Megan Diemer. The requirements developed were that prosthesis should be: similar in size to the median adult male hand, lightweight, have similar wrist capabilities to those of the average adult male wrist, and have a gripper strong enough to securely grasp objects. Quantitative engineering specifications were defined to enable us to measure our success in meeting the user requirements.

The selected wrist concept consists of two baseplate connected in parallel by two ball screws to allow for 2 DOF movement. A universal joint is also placed in parallel with the ball screws to restrict 3 DOF movement, preventing an unactuated 3rd DOF. The selected gripper concept consists of two scissor-like tongs that are actuated by a bidirectional ball screw. The nuts of the ball screw are each attached to a roller that slides along a slot on the tongs. Ball screws were selected for their ability to apply high thrust loads in linear motion.

Our design verification section discusses the successes, failures, and items still needing to be tested in regards to how well the design measured up to the engineering specifications. To briefly summarize, the design was successful in achieving the desired wrist torque, wrist speed, and grip force.
The design failed to meet the mass requirement, exceeded the dimension requirements, and the flexion-extension ROM. Without a physical prototype, we were unable to demonstrate the design's capability to grip different objects.

We were successful in completing a majority of the detailed design, but were unable to fabricate a prototype design due to time constraint related to length of the ME 450 course and special conditions imposed by COVID-19 that limited our access to fabrication resources. Our sponsor plans to build upon the progress made by this project and fabricate a physical prototype next semester.

## PROBLEM DESCRIPTION

**Scientific Context**

The field of upper limb prosthetics has become increasingly sophisticated since the dawn of myoelectric signaling in the 1940's which allows a user to control a prosthesis without needing to utilize a working hand, foot, or other body part [1]. The overwhelming majority of these prosthetic hands focus on gripping capability as opposed to wrist movement. Further, the majority of powered wrists favor pronation and supination (as seen in Figure 1.a.) as opposed to flexion/extension or radial/ulnar deviation (Figure 1.b and Figure 1.c) [2]. This leaves a large gap in scientific research regarding flexion/extension and radial/ulnar deviation, resulting in very little data to support or refute the utility of these movements. Without further study into the use of flexion/extension and ulnar/radial deviation, it will be impossible to fully characterize prosthetic wrist movement with regard to the three axes of rotation that a human wrist is capable of.

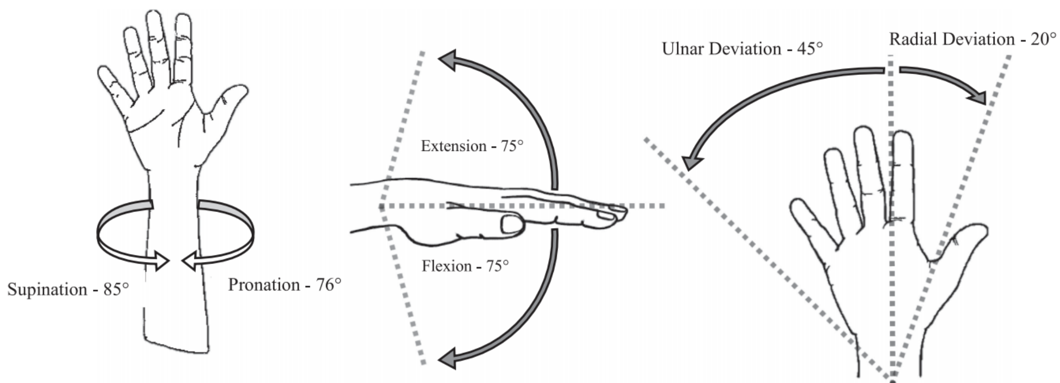


**Figure 1a.**
Pronation/supination is analogous to roll in an aircraft.

**Figure 1b.**
Flexion/extension is analogous to aircraft pitch.

**Figure 1c.**
Wrist ulnar/radial deviation is analogous to aircraft yaw

**User Experience**

The goal of any prosthetic study is ultimately to find methods of best enhancing user experience and capability. As such, it would be remiss to neglect user experience when designing any prosthesis, no matter how scientifically motivated the ultimate goal of the prosthesis design. Speaking with a resident prosthetist at the University of Michigan Hospital, Megan Diemer, who is also a stakeholder in this project, we obtained valuable insight into prosthetic user experience. Two factors that greatly add to the comfort or discomfort of a prosthetic user are weight and degrees of freedom (DOF). According to Diemer, even a prosthesis with an identical weight to the body part it is replacing is perceived as heavy and tiring to a user. In some cases, a user will even entirely reject a prosthesis on the grounds that it is too heavy to wear for long periods of time. Similarly, prosthetic wrists with 1 DOF are unfavorable to those with 2 or more DOF. A single DOF prosthesis limits wrist movement and causes the user to compensate for the lack of freedom by moving their shoulder or elbow in uncomfortable configurations as seen in Figure 2 [3]. These uncomfortable shoulder and elbow configurations can result in chronic pain over time and thus should be avoided as much as possible.

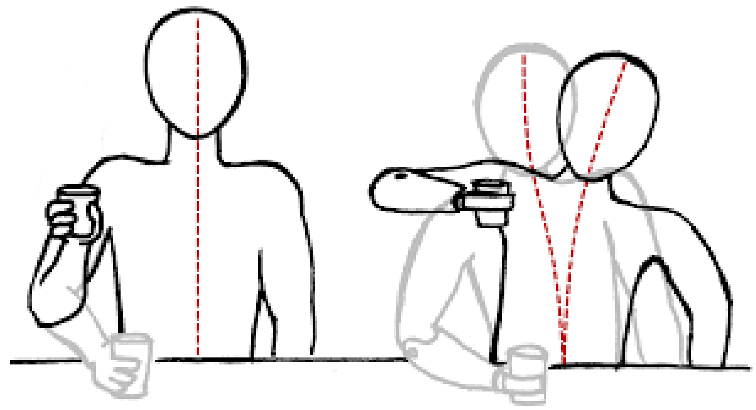

**Figure 2.** A single DOF wrist results in awkward shoulder movements to accomplish simple tasks [3]

# INFORMATION SOURCES

**Literature Review**

Our process began with a rigorous review of existing literature to help shape our understanding of potential functional requirements and technical specifications of the prosthesis, while also informing us of potential concepts to consider when beginning concept generation. The literature review focused on reviewing a paper on existing wrist designs in prosthetics and in the manufacturing industry to help inform us of actuated wrist concepts (specifically those with 2 degrees of freedom) [2], as well as a number of papers that focused on hand and wrist dimensions and dynamics. The purpose of reviewing these papers was to compile a data set of hand and wrist dimensions large enough to get an average that we would be confident in, which would then be used as the basis for our prosthesis.

*Hand and Wrist Dimensions and Weight:* To build a proper prosthetic hand and wrist, we reviewed different sources that measured the hands of different male and female subjects. Using these sources, we were able to compile values and develop a baseline for our prosthesis to be built to. Table 1 below shows hand length, width and thickness of an average hand across male and female subjects.

**Table 1:** Hand Length, Width, and Thickness measurements of male and female subjects from different studies.

| Citation | Hand Length (cm) | | Hand Width (cm) | | Hand Thickness (cm) | |
|---|---|---|---|---|---|---|
| | M | F | M | F | M | F |
| [4] | 19.3 | 17.2 | 8.90 | 7.80 | - | - |
| [5] | 19.33 | 18.11 | 8.83 | 7.82 | - | - |
| [6] | 19.71 | 17.93 | 8.97 | 7.70 | 3.28 | 2.77 |

*Wrist Dynamics:* Values such as range of motion (RoM), angular velocity, and joint torque exhibited by a healthy adult hand and wrist were compiled to generate a baseline our prosthesis would aim to replicate. These values were sorted in the flexion/extension, radial/ulnar deviation, and pronation/supination directions. Tables 2, 3 and 4 below show an excerpt from our data set displaying RoM, angular velocity, and joint torque values.

**Table 2:** Ranges of Motion averages (in degrees) from sources measuring wrist movements along the different axes.

| Citation | Sample Size | Flexion | Extension | Radial | Ulnar | Pronation | Supination |
|---|---|---|---|---|---|---|---|
| [7] | 24 M, 14 F | 63.5 | 63.5 | 32.5 | 32.5 | - | - |
| [8] | 60 M, 60 F | 68.3 | 68.2 | 19.6 | 26.1 | N/A | N/A |
| [9] | 22 M, 17 F | 62 | 57 | 21 | 28 | 81 | 101 |
| [10] | 39 M | 90 | 99 | 27 | 47 | 77 | 113 |
| [11] | 6 M, 7 F | 86.2 | 61.8 | 33.9 | 68.4 | 104.5 | 120.8 |

**Table 3:** Angular velocity averages (all in degrees/second) obtained from sources measuring wrist motions.

| Citation | Sample Size | Flexion | Extension | Radial | Ulnar |
|---|---|---|---|---|---|
| [12] | 3 M, 3 F | 120 | - | - | 100 |
| [13] | 3 M, 3 F | 140 | - | - | 140 |

*Values obtained for extension and radial deviation were assumed to be equal to flexion and ulnar deviation, respectively.

To determine joint torque values, our main source was from a paper that conducted a comprehensive study of wrist flexion and extension torques in healthy subjects from 5 to 80 years of both male and female subjects [14]. Table 4 below reproduces the results of flexion and extension torques in subjects between 20-59 below.

**Table 4:** Average torque values obtained in subjects from various age groups in flexion and extension [14].

| Age (year) | Sex | # of Subjects | Wrist Flexion (N-m) | | Wrist Extension (N-m) | |
|---|---|---|---|---|---|---|
| | | | Left | Right | Left | Right |
| 20-29 | F | 32 | 8.2 | 8.2 | 6.0 | 6.5 |
| | M | 27 | 14.2 | 14.5 | 10.7 | 11.4 |
| 30-39 | F | 31 | 8.0 | 8.4 | 6.0 | 6.5 |
| | M | 32 | 13.3 | 13.4 | 9.1 | 10.2 |
| 40-49 | F | 32 | 8.3 | 8.0 | 5.4 | 6.4 |
| | M | 26 | 14.1 | 13.8 | 10.6 | 11.5 |
| 50-59 | F | 29 | 8.1 | 7.5 | 5.4 | 5.8 |
| | M | 11 | 13.6 | 13.9 | 9.7 | 10.6 |

From the table above, we were able to determine that a target value of 10 N-m would be suitable for our prosthesis, which comes from averaging the values in the table (~9.6 N-m). We determined that an age range between 20-59 was suitable to use as a reference because there was not a large difference in wrist joint torques for adults in these ages.

**User Likes and Dislikes**

Amputees are the end users of prosthetic wrists, therefore it is crucial to understand what they like and dislike about commercial designs. We reviewed a study that examined functionality scores and user satisfaction of prosthesis users across standardized prosthesis models [15]. The authors highlighted what they perceived as important and remarkable quotes in their interviews with the prosthesis users after using each prosthesis for a duration of time. We took particular interest in the advantages and disadvantages that the users identified. We were able to identify key functionalities based on how often frequently a user categorized something as an advantage or disadvantage of the prosthesis in question. The key functionalities we identified were reliability, durability, movement restrictions, performance in everyday tasks, and appearance.

**Benchmarking**

During our literature review, we examined the technical specifications of different commercial grippers currently on the market. We found data sheets for the following grippers: System Electric Greifer [16], MC ProPlus Hand [17], AxonHook [18], and MC ETD2 [19]. Table 5 provides a comparison of the weight and grip forces for these four grippers.

**Table 5:** Benchmarking of commercial gripper weights and grip forces.

| Commercial Gripper | Weight (g) | Grip Force (N) |
|---|---|---|
| System Electric Greifer | 520 | 160 |
| MC ProPlus Hand | 479 | 100 |
| AxonHook | 400 | 110 |
| MC ETD2 | 454 | 107 |

The weights appear to be quite similar seeing as they all lie within a range of 120g. The grip forces of the MC ProPlus Hand, the AxonHook, and the MC ETD2 all lie within a range 10 N. The Griefer is an outlier with a grip force of 160 N. The Greifer is the heaviest out of the four, but also has the strongest grip force.

## USER REQUIREMENTS

After consulting the stakeholders: Professor Shorya Awtar of the Precision Systems Design Laboratory, Revanth Damerla, a PhD candidate at the Precision Systems Design Laboratory, and Meagen Diemer, a Resident Prosthetist at Michigan Medicine, we were able to develop four main user requirements. With guidance from the user requirements and significant literature research, we also determined a full set of engineering specifications that we aim to meet. The user requirements are as follows: (1) Lightweight, (2) Compact Dimensions, (3) Wrist Capabilities, and (4) Gripper Strength.

**Lightweight**

The most important requirement that we were advised by Diemer to have is that the device should be as light as possible. Based on the information provided by her, the user will feel that the prosthesis is heavy even if it was the same weight of their biological hand. This is due to the fact that no matter how the prosthesis is connected to the remainder of the arm, the sinew, bone and muscle tissues present in a healthy human represent the optimal way to attach an extremity to a limb. Because of this, we must construct a device that weighs less than the average human's hand and wrist.

**Compact Dimensions**

The dimensions of the prosthesis should be similar in size to that of the median adult male hand. The design should be compact and should not have extrusions that might get in the way of performing everyday activities or significantly obstruct the user's line of sight when gripping objects.

**Wrist Capabilities**

The wrist part of the prosthesis must have range of motion, joint torques and speeds similar to an adult human wrist. This prosthesis must be able to perform tasks that a human wrist is capable of doing, such as moving through an angle range of a human wrist with a speed of a human wrist and applying torque similar to a human wrist's torque. This requirement was advised by our prosthetist stakeholder Diemer and was agreed upon by the team due the fact that our design is aiming for a human's hand performance.

**Gripper Strength**
The gripper part of the prosthesis must be able to provide a reliable and strong grip on objects. The gripper must securely grip on objects with sufficient force so the user will feel comfortable enough that the object will not slip away.

## ENGINEERING SPECIFICATIONS

As a team and following the guidance of generating engineering specifications provided to us by the 450 learning blocks, we were able to translate every user requirement very carefully while making sure the specifications completely carry out the aspects of the requirements. The engineering specifications each has a target value that can be implemented in the design phase and validated when testing the prototype. The engineering specifications and the manner in which they were derived from are explained in detail below.

**Prosthesis Weight**
After using multiple sources of information such as researching what a human hand weighs, checking already existing grippers in the market and making a decision on targeting the average adult male amputee catagory which included the largest amout of amputees between all age and sex catagories. We decided to have a prosthesis with a weight of $\leq$ 500g which is similar to the Greifer Hand [16], one of the most commonly used grippers on the market. This weight is slightly less than the average adult male's hand weight.

**Flexion-Extension and Radial-Ulnar RoM**
Our wrist must rotate in the Flexion-Extension plane with an angle of 74-70 deg, and it must rotate in the Radial-Ulnar plane with an angle of 27-40 deg. We determined these values based on the research paper that we used [7], [8], [9], [10], [11] and after checking with Diemer for the validity of our choices.

**Flexion-Extension and Radial-Ulnar Torque**
Our wrist must rotate in the Flexion-Extension plane with torque up to 10 Nm and it must rotate in the Radial-Ulnar plane with torque up to 10 Nm [14], [20], [21], [22], [23], [24]. We decided to go with these values based on the aforementioned research papers and after checking with Diemer for the validity of our choices.

**Flexion-Extension and Radial-Ulnar Speed**
Our wrist must rotate in the Flexion-Extension plane with a speed of 120 deg/s and it must rotate in the Radial-Ulnar plane with a speed of 120 deg/s [12], [13]. We decided to go with these values based on the aforementioned research papers and after checking with Diemer for the validity of our choices.

**Gripping Force**

Our gripper must provide gripping force up to 160 N applied directly on objects. It is important to ensure that the objects are being gripped securely and reliably so they will not slip and fall. We reached a decision on this force value after comparing it with the Greifer Hand [16], one of the most commonly used grippers on the market. Diemer asked to refer to its gripping force value as users are satisfied with the strength provided by that gripper.

**Capability to Grip Various Objects**

Our gripper must be designed to grip objects of multiple shapes, sizes and stiffnesses. Main objects that our gripper must grip are: Hammer, Coke Can, Solo Cup, Pencil, M&M, Phone, Grocery Bag.These objects were chosen because they present a variety of form factors and methods of interaction that demand a highly versatile gripper and wrist combination. To demonstrate the strength of our gripper, we expect it to hold a hammer, and pick up a full grocery bag. For more refined maneuvers, holding thin, pliable containers of liquids such as Coke cans or solo cups present a different challenge: strength regulation. These items require vastly different amounts of force to be applied to their walls when compared to the secure grip that one uses to hold a hammer. Lastly, fine dexterity will be put to the test when the gripper is used to pick up a phone, a pencil, and an M&M. What all of these tasks share in common is the need for frictional points of contact. Each item listed would be impossible to pick up without a surface with adequate grip on the hooks of the gripper. To that end, we plan on fastening ~2mm thick rubber pads to the interiors of both hooks, regardless of the material the hooks themselves are made of. This will be completed by the use of rubber adhesives to provide a secure grip on objects that the gripper grasps.

**Table 6:** User requirements and engineering specifications synthesized from literature and stakeholder needs

| **User Requirements** | **Engineering Specifications** |
|---|---|
| Size of the median adult male hand | • Hand Length: 19.5 cm<br>• Hand Width: 9 cm<br>• Hand Thickness: 3.5 cm |
| Lightweight | • Prosthesis weight ≤ 500 g |
| Wrist range of movement, torques and speeds are similar to those of an average adult human wrist | • Flexion-Extension ROM: 74-70 deg<br>• Radial-Ulnar ROM: 27-40 deg<br>• Flexion-Extension torque: up to 10 N-m<br>• Radial-Ulnar torque: up to 10 N-m<br>• Flexion-Extension speed: 120 deg/s<br>• Radial-Ulnar speed: 120 deg/s |
| Gripper strong enough to securely grasp objects | • Force capacity: 160 N measured at the gripper base<br>• Capability to grip the following: Hammer, Coke Can, Solo Cup, Pencil, M&M, Phone, Grocery Bag |

# CONCEPT GENERATION AND DEVELOPMENT

As the design process moved into the concept generation phase, it was decided that the team should split into a wrist subteam and a gripper subteam. Each team held dedicated subteam meetings independently. The subteams then mutually relayed their findings at cross-team meetings. To ensure that neither group created a design that was incompatible with the other, we maintained open channels of communication so that subsystem updates were available for all group members to see. It was decided that the wrist subsystem should be contained in an area slightly under the palm of an average male hand, while the gripper subsystem should occupy the fingers and the distal portion of the palm. The approximate boundaries agreed upon by both subteams are shown in Figure 3.

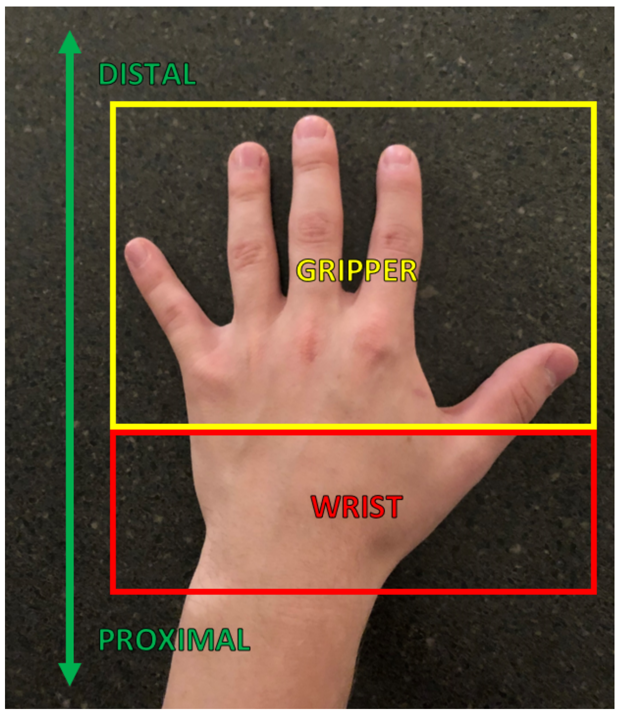


**Figure 3:** Approximate subsystem boundaries to consider during concept generation and evaluation.

### Wrist

The wrist team's focus was to design and actuate a wrist joint that is capable of satisfying the engineering specifications. Wrist concept generation examined parallel vs. series mechanisms, linear vs rotary actuators, type of transmission, and backdrivable vs non-backdrivable transmission. In order for the wrist to satisfy the high torque requirements in the specified 2-DOF, the wrist subteam must determine two motors and two transmissions that provide a large gear reduction or design wrist configurations that have large mechanical advantages. Ideally, the transmission and configuration of the wrist will allow us to select a motor that is lightweight as the motor will contribute significantly to overall weight. Concepts were generated and discussed at wrist subteam meetings. These brainstorming sessions allowed us to build off of each other's ideas, further increasing the rate that we generated new ideas.

**Serial vs. Parallel**

Based on the kinematic arrangements of joints and linkages, a mechanism can be defined as either being a serial or parallel mechanism. A serial mechanism is one that has a sequence of joints and links that move relative to a static base. A parallel mechanism contains several serial joints fixed to a common base, and attached on the other end to another platform or end effector [2]. While the human wrist is generally viewed as an RU serial chain (a revolute joint at the forearm plus a universal joint at the carpal bones), a parallel joint design allows for more freedom in creating a mechanism with multiple degrees of freedom while remaining within a smaller profile.

**Gripper**

The gripper team's focus was to design and actuate a gripper that is capable of satisfying the engineering specifications. Gripper concept generation examined gripper shapes, linear vs rotary actuators, coupled fingers vs separate actuation, type of transmission, and backdrivable vs non-backdrivable. The ideal transmission options are those that have large gear reduction ratios or that have large mechanical advantages. Gear reductions and other forms of mechanical advantage will enable us to select a lighter motor that can rotate at higher speeds, but produces a lesser torque. Concepts were generated and discussed at gripper subteam meetings. These brainstorming sessions allowed us to build off of each other's ideas, further increasing the rate that we generated new ideas.

The shape of a gripper can be best characterized by the way that it holds an object. Grip styles include encompassing, friction, and retention grips. Encompassing grips are shaped so that they encompass the object as opposed to a flat grip that would not be able to wrap around any object. Friction grips rely on a frictional force to hold an object between the grippers. Retention grips support an object from the bottom so that low friction does not cause them to slip out of the grippers. Grippers can also be characterized by whether they use an internal grip or an external grip. Internal grips secure an object from inside surfaces, while external grip secure an object from outside surfaces. Examples of these five grip styles are shown in Figure 4.

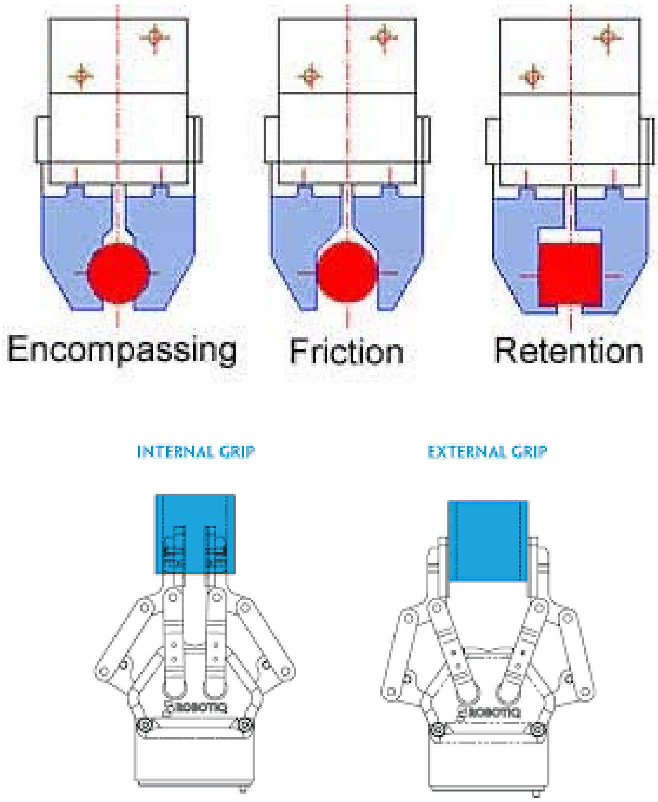


**Figure 4:** Grip styles include encompassing, friction, retention, internal, and external [27][28].

Gripper designs can also vary in the way that they open and close. Angular grippers move by rotating about a fixed pivot, while linear/parallel grippers move through translational motion. Each of these designs can be further broken down into unidirectional and bidirectional categories. In unidirectional grippers only one jaw rotates or translates to secure an object, whereas both jaws are able to move in bidirectional grippers.

From these gripper shapes and styles, we began the concept generation for the actuation style and corresponding transmission. Given our constraints on weight, torque, speed, longevity and volume, a number of actuation methods were up for consideration. Linkage, lead/ball screw, spur gears, worm gear, rack and pinion, and cable and pulley were our options. These methods all presented qualities that align with our idea of what an ideal transmission consists of. The linkage would provide consistent translational motion and can feature a wide variety of arrangements that highlight different types of motion. Lead screws and ball screws incorporate identical screws, the difference actually lies within the nut that surrounds the screw. In lead screws, threading within the nut allows for movement along the screw based on rotation, with an efficiency between 0.2 and 0.4, considering the forces required in our project. At these lower efficiencies, the nut becomes non-backdrivable. A ball screw incorporates a nut with a number of ball bearings located within to reduce the friction as it moves along the screw. This results in backdrivability, as efficiency is closer to 0.9. Spur gears and worm gears are similar in that neither of them are backdrivable due to their low efficiencies. These two options can also impart a mechanical advantage with the correct arrangement. Next, we looked at the rack and pinion, converting rotational motion into linear. Finally, the cable and pulley provided a lightweight option, capable of pulling, but not pushing.

To further develop our initial gripper concepts, we asked ourselves how we can add to or improve the functionality of the gripper. We used design heuristics to ideate a variety of design features. The first idea we came up with was the ability to hook onto an object. A detachable or retractable hook attached to the end of the gripper would aid the user in pulling an object closer towards them, or to more easily carry bags. Replaceable rubber grips were another idea we had. Rubber grips would improve the friction between the gripper and objects being held. To build on this idea, a padded rubber grip would assist the user in gripping delicate objects that they do not want to crush, such as a soda can.

## CONCEPT EVALUATION AND SELECTION

Once each subteam had sufficient time to develop multiple designs, the concepts were evaluated by the team as a whole to maximize feedback and ensure sound design decisions. The concepts were also reviewed with our stakeholders. Damerla provided us with his engineering expertise to ensure that the final design was able to meet our engineering specifications. Diemer provided us with her expertise as a prosthetist to ensure that the final design incorporated features that are appealing to users. Their suggestions and feedback will allow us to adjust our concepts and to narrow down until we reach our final selection.

**Wrist**

Our prosthetic wrist is a substitute for a human wrist, therefore it should function in a way that closely resembles a human wrist. Since our focus will be on the two DoF (Flexion-Extension and Radial-Ulnar) we started to think along the lines of matching the torques, speeds and RoM that a human hand has. Our two main concepts were actuating the wrist in series or parallel transmission.

**Serial vs. Parallel Mechanisms:** As we looked through both ways of actuation for the wrist, we were able to choose between the two methods based on their pros and cons:

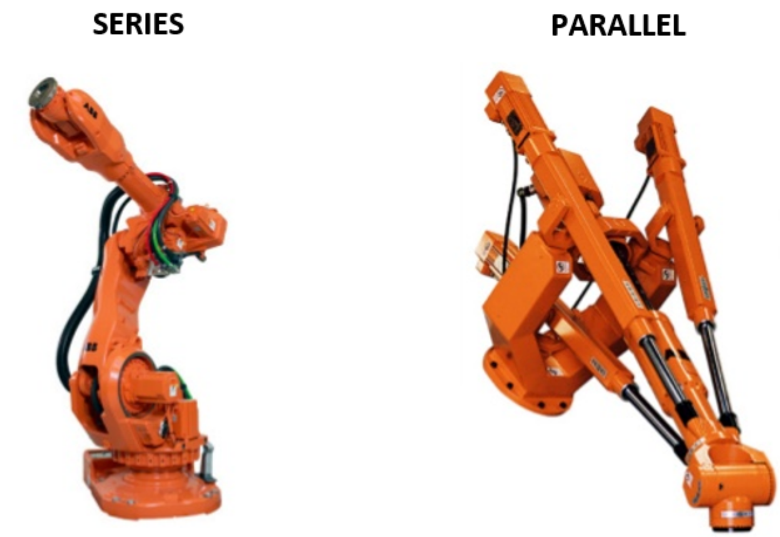


**Figure 5:** An example of a serial versus a parallel mechanism in practice.

**Table 7:** Evaluation table for wrist parallel vs series mechanism

| | Low Complexity (2) | Mass (3) | Output Forces and Torques (5) | Easy to move (minimized moving inertia) (2) | Total |
|---|---|---|---|---|---|
| **Parallel Mechanism** | **-1** | **-1** | **+2** | **+2** | **9** |
| **Series Mechanism** | **2** | **0** | **0** | **0** | **4** |

It was very clear that parallel actuation mechanism is the optimum way to operate the wrist. After choosing the parallel mechanism, we started looking for different ways a parallel mechanism could be operated to minimize the complexity and weight of the system and maximize the output torques, speeds and RoM of the wrist.

The following parallel mechanisms were considered for selection after they showed promising results based on their characteristics:

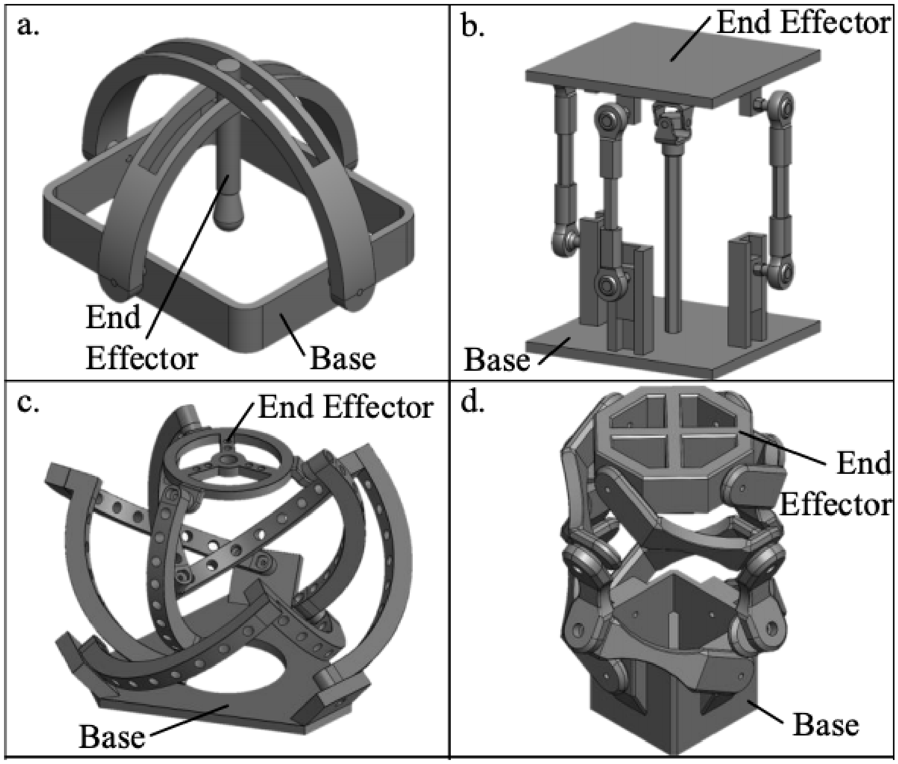


**Figure 6:** The 4 different parallel mechanism we considered for further investigation in our screening process

Design A was evaluated and was within the motion and space constraints but the way it rotates doesn't mimic the exact rotation of 2 DoF of interest, and that was the main reason it was avoided. It is also only actuated in a rotational way which exclude the options for any linear transmission options such as lead / ball screws, rack and pinion, twine and linear actuators.

Design D fits within motion constraints but would be difficult to manufacture and is too complex of a mechanism (contains many parts, therefore will potentially have high backlash). It also has a nice compact size in the diameter direction, but it is very long and will make our wrist-gripper prosthesis longer which is a downside, as users prefer shorter grippers. This is based on direct feedback from our stakeholder Megan Diemer, a resident prosthetist at the University of Michigan Hospital.

Design C does not fit within space constraints. It also has relatively low stiffness due to the 3 level arc connections that connect the base to the end effector. Controlling this mechanism is much harder than other mechanisms because of the 3-stage rotational connection that it has between the base and the 'End Effector.' From a machining point of view, it would be hard to machine the arcs involved in this mechanism with the capabilities that our ME machine shop has (based on previous experience from ME 250 / 350).

Design B was the most ideal design for our application and was the one we decided to move forward with as our specific parallel mechanism. Design A is described in details below:

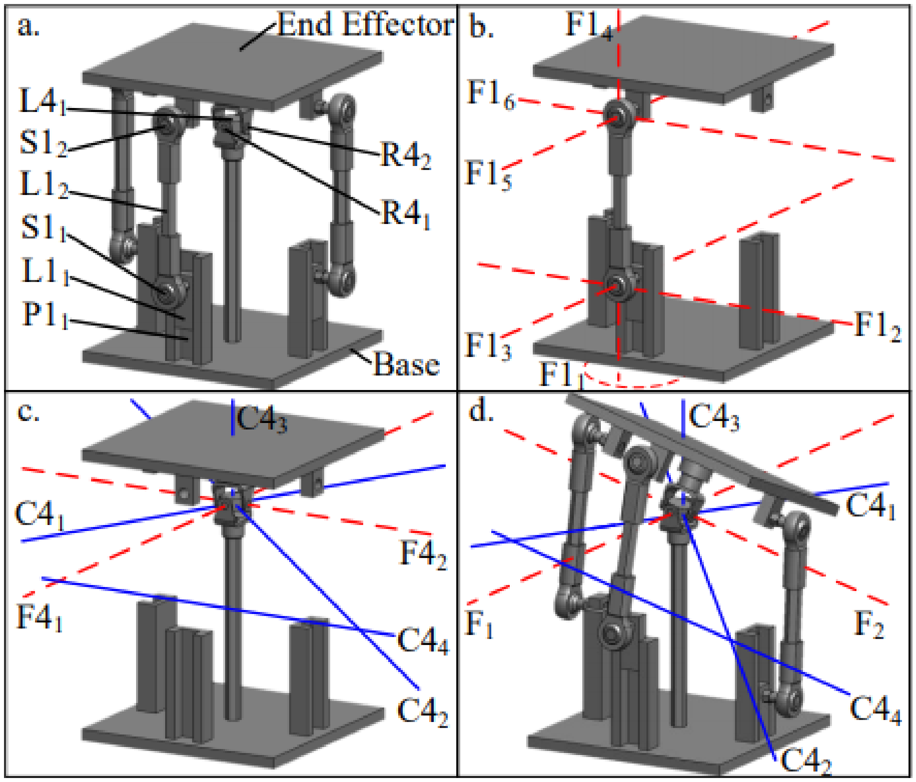


**Figure 7:** The best solution design concept for the wrist. The blues lines and F's show the axes where the 'End Effector' has freedom to rotate about or the directions it is free to translate in. The red dashed lines show the axes where the 'End Effector' is constrained from rotating about or the directions it is constrained to translate in.

Figure 7 shows in detail our selected design. We decided to go with this design concept because of the low complexity relative to the task that it is doing. The design fits well within our mass and space constraints, relatively easy to manufacture, simply operated in two linear motions, and is adjustable for future consideration of a 3rd DoF. The design concept above shows how the 'End Effector' or the (base plate) of the wrist is constrained in the 3rd DoF with a universal joint, while is free to rotate in the other 2 DoFs.The wrist base plate can rotate in the 2 DoFs when actuated in a linear manner by the tie-rod / ball joint assemblies shown in the above figure. Our methods of actuation / transmission for this specific design concept was another motivation to why we chose this specific design concept. This design is flexible in the types of transmissions used to actuate it. Any transmission that could provide a linear motion is a very good candidate for this wrist.

**Transmission Analysis:**

Once we had determined our overall wrist design, we then had to determine the transmission method that was necessary to actuate this design. We considered a number of different transmission methods including
normal gearing, rack and pinions, lead screws, ball screws, twine, planetary gearing, harmonic gears, worm gears, and belts. First, we scoped the market for components that would fit within baseline space

and weight constraints of fitting within the wrist dimensions and being under 150g per assembly (motor and transmission hardware). By doing this, we were able to quickly discount traditional gearing, planetary gearing, harmonic gears, and worm gears on the basis that these would not be able to transmit the necessary force while remaining under the required weight limit. We were also able to discount belt transmission as the components required for tensioning would take up too much space. We then evaluated rack and pinions, lead and ball screws, and twine actuation by roughly sketching an assembly for each transmission method as seen in the images below.

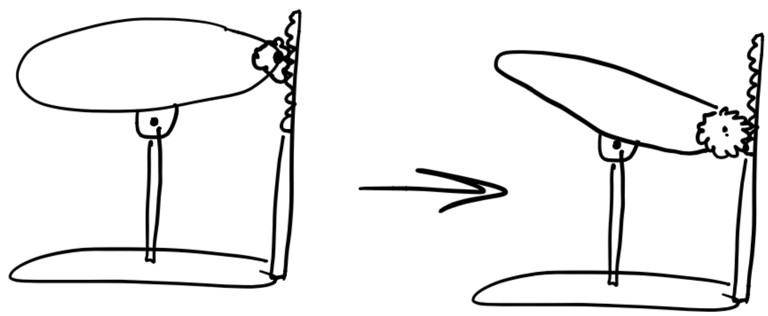

**Figure 8.** The rack and pinion method shows rotation about a single DOF (another duplicate mechanism would be implemented in the appropriate position to allow for 2 DOF, this is a simplified version for better visibility). A pinion would connect to the plate via a pin and the pinion would roll down a rack located on the outside of the plate to allow for a tilting of the plate.

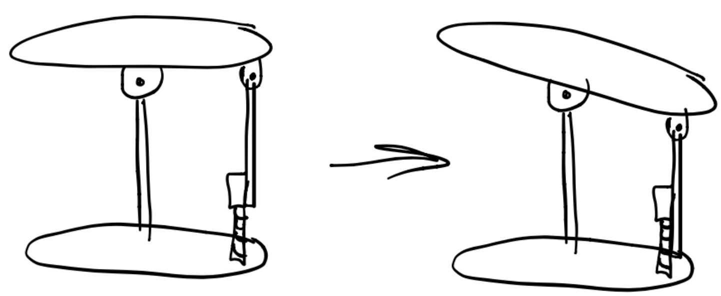

**Figure 9.** The lead/ball screw method shown rotating about a single DOF (a duplicate mechanism would be implemented in the appropriate position to allow for 2 DOF, this is a simplified version for better visibility). A lead/ball screw would be connected to a linkage via a nut. The linkage would connect to the plate via a pin or joint. The nut would then move along the lead/ball screw and induce a tilt in the plate via the linkage arm.

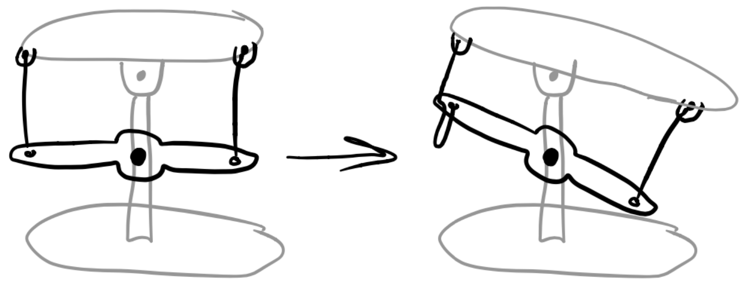

**Figure 10.** The twine method shown rotating about a single DOF (a duplicate mechanism would be implemented in the appropriate position to allow for 2 DOF, this is a simplified version for better visibility). Because twine can only operate in tension, two twines would need to be secured to the plate on opposite ends of the plate. These twines would be secured to a single rotary arm that when rotated would induce tension in one of the twines such that the plate tilted in the direction of the tensioned twine.

After generating these three, finalist transmission concepts we were able to perform an analysis to determine the winning transmission method. The best transmission was determined by evaluating each design for volume: the estimated amount of space the entire mechanism would take up, mass: the mass of the mechanism, load: the max load capabilities of the mechanism, efficiency: the ability of the mechanism to convert motor torque to applied force, and speed: the max angular speed of the base plate when rotating. Mass was weighted as the most valuable of these parameters closely followed by load as these aspects of our design are the most challenging and will result in the most revolutionary product. Speed and volume were the next most important parameters as we had to ensure that our design fulfilled our specifications for speed and volume. Efficiency contributes to mass as the more efficient the system, the less powerful and more lightweight the motor required.

**Table 8:** Evaluation table for wrist actuation method

| | **Volume (2)** | **Mass (4)** | **Load (3)** | **Efficiency (1)** | **Speed (2)** | **Total** |
|---|---|---|---|---|---|---|
| **Rack and Pinion** | **-1** | **-1** | **+1** | **0** | **+2** | **1** |
| **Lead Screw** | **+2** | **+1** | **+2** | **-1** | **0** | **13** |
| **Ball Screw** | **+2** | **+1** | **+2** | **+1** | **0** | **15** |
| **Twine** | **-1** | **+1** | **-1** | **0** | **+1** | **1** |

We concluded that lead screws and ball screws were the best options. Being almost identical in function aside from efficiency, their scores were very similar. As ball screws have a more efficient function, they pulled out as the ultimate victor in our transmission design.

**Gripper**

Our prosthetic gripper is a substitute for a human hand, therefore it should function in a way that closely resembles a human hand. Fingers mainly rely on an both an encompassing grip and frictional grip for picking up most objects. Our fingers have multiple joints that can produce a curvature that can adapt to a number of different object shapes.Once we have encompassed an object, we squeeze our fingers together to increase the friction between our fingers and the object so that gravity does not cause us to lose our grip. Occasionally we use our fingers and hand as a retention grip. An example of this is cupping your hand to hold loose change. Since most objects can be grasped using encompassing and frictional grips, we focused our efforts evaluating grippers that primarily rely on these two gripping methods.

We evaluated the most popular actuation methods for existing grippers. To recap, these included: linkage, lead/ball screw, spur gears, worm gear, rack and pinion, and cable and pulley. From these various styles of actuation for our application, we narrowed them down to the following three options: ball/lead screw, spur gears, and rack and pinion. The spur gear linkage we were considering was robust, easy to assemble, and could provide an inherent torque increase. It also had more pieces, quickly increasing weight and rate of deterioration, adding to the potential backlash. The rack and pinion allowed for smooth movement but would need to be carefully constrained to prevent excessive noise production. Beyond this, the rack and pinion would take up more volume than desired. Lastly, the ball/lead screw provides good torque, weight, and volume measurements, but may be lacking in opening/closing speed. These actuation methods are evaluated in Table 9.

**Table 9:** Evaluation table for gripper actuation method

| | **Volume (2)** | **Mass (5)** | **Load (4)** | **Speed (3)** | **Total** |
|---|---|---|---|---|---|
| **Gears+Linkage** | **-1** | **-2** | **+2** | **+2** | **4** |
| **Rack and Pinion** | **-1** | **-1** | **+1** | **+2** | **3** |
| **Lead/Ball Screw** | **+2** | **0** | **+2** | **-1** | **9** |

Following our analysis of available gripping mechanisms and transmissions, we developed 3 detailed gripper designs. Each design combines a gripper mechanism and transmission method in a manner that highlights the best implementation of each element.

The first design, located in Figure 11, features two pivoting links that are actuated by a fixed, bidirectionally-threaded ball screw. This design is very much comparable to a common pair of scissors. The ball screw exerts a force on the gripper links that causes them to open or close, much like the force exerted by the fingers when cutting with scissors. However, the gripper links are offset such that the flat surfaces of the links will be parallel when the gripper is completely closed. This prevents the gripper from cleaving a smaller object into two, much like a pair of scissors would. The ball screw is an excellent option to consider when a large linear force is needed. Additional mechanical advantage is gained when the force from the ball screw acts on the moment arm from the ballscrew to the pivot. The ball screw is positioned perpendicular to the length of the hand. This configuration conserves valuable space that can be used to make the gripper links longer, or to provide the wrist subsystem with extra space. The majority of the weight would come from the ball screw transmission. Otherwise, this design is relatively lightweight.

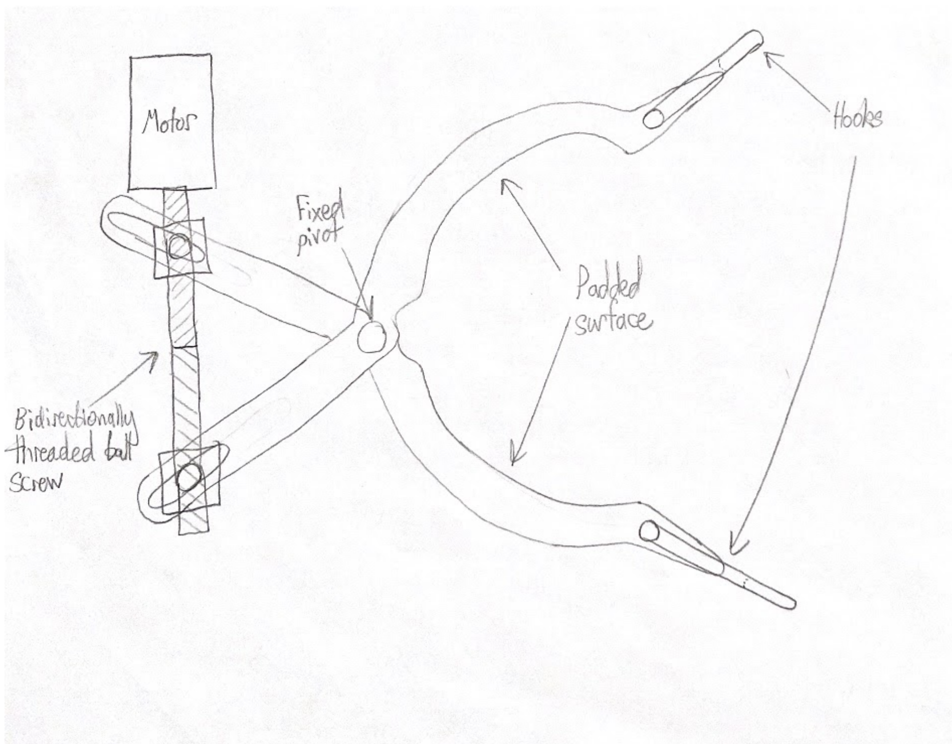


**Figure 11:** Gripper Design 1 utilizes a ball screw to achieve angular rotation.

The second design, located in Figure 12, features parallel four-bar linkages actuated by spur gears rigidly affixed to the driving links. The use of multiple gears in the transmission can allow for a greater gear reduction, but at the cost of adding weight to the system. The driving gear makes contact with one of the driven gears. This driven gear also makes contact with the other driven gear. The driven gears rotate in opposite directions, allowing both jaws to open and close in unison. The linkages are parallel to allow only for translational gripper movement. The jaws of the gripper extend forward as they close and retract as they open. This might take some getting used to for users that are used to prostheses that rotate about a fixed pivot. Each pivot will require a pin, bearing, and washers. These pins can significantly increase the weight depending on the materials used. Similarly, the presence of multiple links will also add to the system's weight.

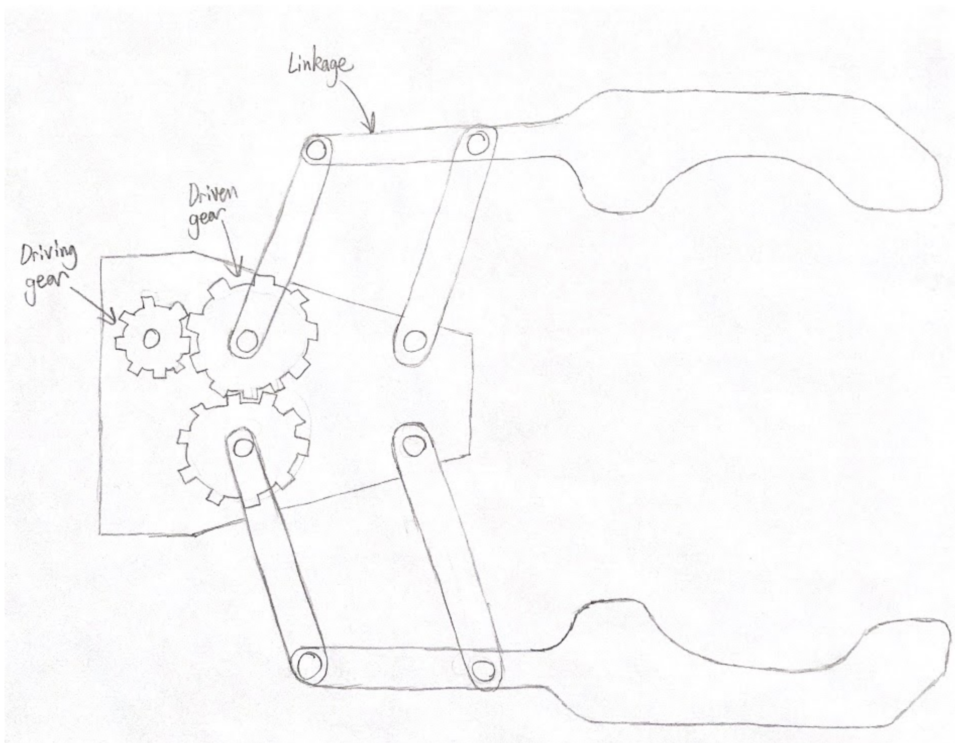


**Figure 12:** Gripper Design 2 utilizes spur gears to move a translational linkage.

The third design, located in Figure 13, features two links that each separately rotate about their own fixed pivots. These links are actuated by a rack and pinion connected by a pin to overlapping slots in each of the links. The linear movement of the pin causes the gripper jaws to open and close. The connection between the rack and the links in perpendicular or has a large perpendicular component throughout the rack's range of motion. The perpendicular component is beneficial because it creates a large mechanical advantage that in turn increases the grip force. The majority of the weight would likely come from the rack and pinion. The L-shape of the linkages may be of concern due to the force transmitted about the pivots. One solution is to add additional material to the design to strengthen weak points susceptible to bending or fracture. However, this will add weight to the system.

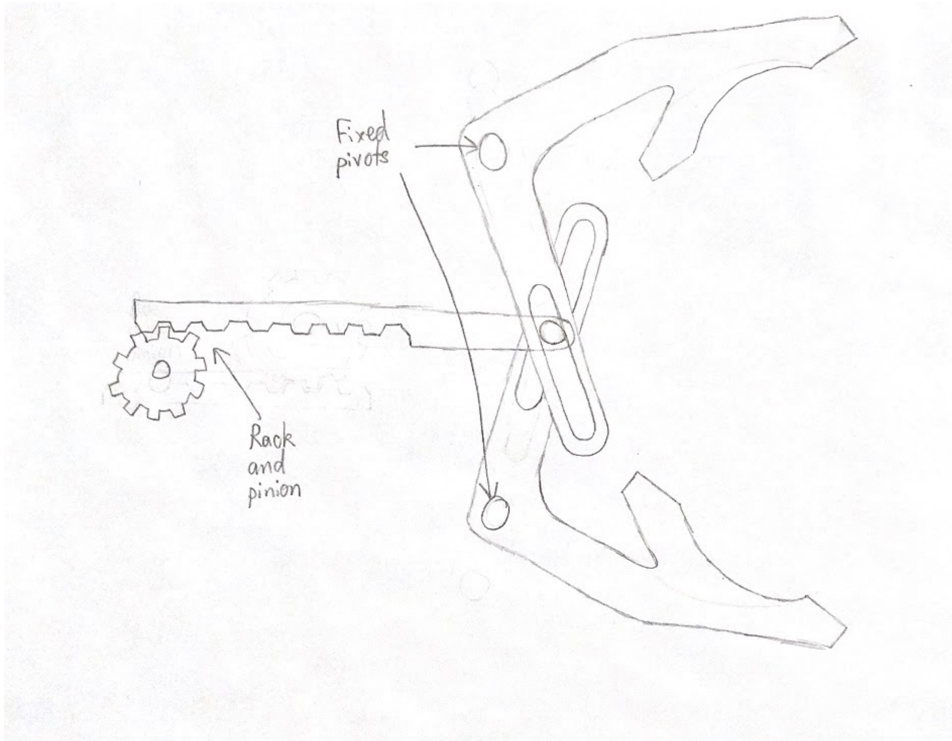


**Figure 13:** Gripper Design 3 utilizes a rack and pinion to achieve angular rotation.

The three gripper designs were evaluated using a Pugh chart, shown below in Table 10. The metrics we considered when scoring each design were compactness, motor torque, ease of use, mass, and aesthetics. Compactness describes how spaced out a design is, particularly in the length dimension. Motor torque is an estimate of how much motor torque will be required to achieve our desired grip force. Ease of use describes how easily a user can position the gripper to grab objects. Mass is an estimate of the total mass of a design. Aesthetics describes how pleasing to the eye a design looks. Each metric was assigned a weight on a scale of 1-3 relative to their importance. Designs were scored as either inferior (-1), equal (0), or superior (+1) to Design 1 which served as our base design.

**Table 10:** Pugh chart for evaluating the three detailed gripper designs

| Metric | Weight | Design 1 | Design 2 | Design 3 |
|---|---|---|---|---|
| **Compactness** | 2 | 0 | 0 | -1 |
| **Motor Torque** | 3 | 0 | -1 | 0 |
| **Ease of Use** | 2 | 0 | -1 | -1 |
| **Mass** | 3 | 0 | -1 | 0 |
| **Aesthetics** | 1 | 0 | 0 | -1 |
| **Total** | | **0** | **-8** | **-3** |

Design 1 scored the best out of the three designs, despite being our base design with a score of 0. According to the Pugh chart, Design 1 is superior or equal to the other two designs across all metrics. Design 2 score was hindered by the large input torque required, even if the driving gear was swapped out for a worm gear. This gripper might be difficult for users to position when precision movements are needed because the user's arm will need to move back slowly as the gripper jaws close in on the object. The additional mass of the gears and linkages in this design do not help its score either. Design 3 scored poorly in compactness because the rack and pinion occupy valuable space in the length dimension that could otherwise be used by the wrist mechanism. This design was rated as inferior in ease of use because there is a possibility that the slots connecting the link to the rack and pinion will dislodge the object being gripped. The aesthetics of this design suffer due to its clunky appearance.

Our team's general consensus agreed with the ranking of Design 1 as our top concept. Going forward, our detailed design will be based on Design 1. To recap, this design consists of two links that rotate about a shared fixed pivot. A bidirectionally threaded ball screw provides actuation so that only one motor is required to open and close both gripper jaws.

## SOLUTION DEVELOPMENT

Our solutions for the wrist and gripper subsystems were developed independently from each other for most of the detailed design process, until we were ready to integrate the two and attach the wrist's universal joint and ball screw rails to the baseplate of the gripper.

### Wrist - Design Overview

Our wrist is made up of a linkage system that is linearly actuated to create the flexion/extension and radial ulnar movement. An example of how this works is shown in the figure below (many components are hidden for simplicity). The basic schematic includes a motor connected to a 1:1 gear pair. The second of these gears is rigidly attached to a ball screw which will then translate rotational motion to linear motion by moving a nut along its threads. Connected to this nut (via an additional piece discussed later) is a tie rod which is attached to a base plate and will induce the tilting motion. This tilting motion will be oriented to create flexion/extension and radial/ulnar deviation as shown in Figure 14.

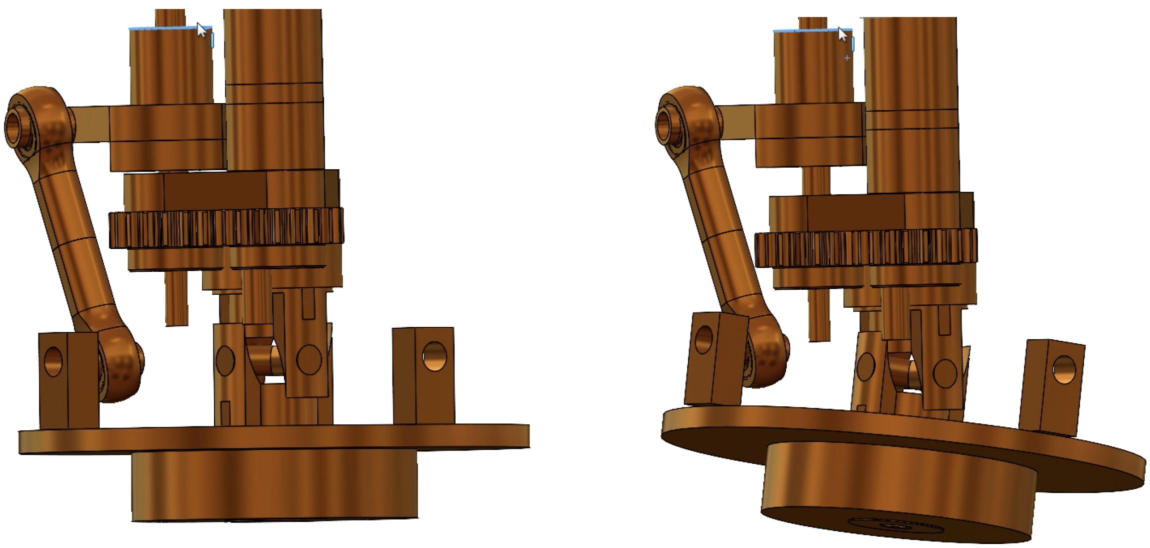

**Figure 14:** A ball screw moves a nut up and down as a result of being actuated by a motor and gears. This linear motion is translated along a tie rod which induces a tilting motion in the base of the mechanism. This can be implemented in two locations along the base and used to induce both flexion/extension and radial/ulnar deviation.

Other components include a support rod which will take all of the radial shear force from the system that would otherwise impact the ball screw and cause it to potentially fail. A connection between the ball screw and support rod is necessary to ensure that the support rod will absorb the radial motion while transmitting the axial motion to the nut to allow the mechanism to perform well. Thus, the tie rod inducing the tilting motion will actually be connected to this connection piece instead of directly to the nut as was alluded to earlier in this section. There is also a universal joint that will constrain the mechanism so that it may only move along the 2 DOF that we desire and can be more easily controlled and predicted. There will be a base plate that extends from the universal joint to support all the ball screws, motors, and support rods and hold them in place. Lastly, we include an encoder connected to the ball screw for control purposes in future renditions.

**Wrist - Component Selection**

Our novel wrist design solution relied heavily on the previous analysis conducted during the concept generation phase on the modified Stewart mechanism design we were pursuing. The most involved portion of the design was the decision to go with two Planetary SP 13mm motors from Maxon. The decision to go with this option was determined using a Matlab script that parsed through a motor catalog database compiled from our sponsor's lab. The script required initial inputs of desired motor speed and torque, as well as a maximum motor weight (see Engineering Analysis: Motor Selection Overview). This analysis helped to justify and simplify the design decision we made. A similar approach was done when selecting the ball screw option from KSS. An integral part of the design was the universal joint, which needed to be as low profile as possible while also bearing high loads. We were able to find a universal joint from Allied, an automotive supplier, that had a maximum torque of 600 Nm, much higher than the required torque of ~45 Nm. (The specification of 600 Nm seemed incredibly high so we double checked with the vendor that it was accurate and Allied assured us that rating was accurate. One possible course of action that could be taken should we remain suspicious of this incredible capability would be to perform our own tests on the joint to ensure its rating. In order to do this, we would need to order multiple sacrificial universal joints so for the sake of the cost and amount of time it would take to design a test, we forgoed this option). The universal joint was chosen because of its low profile (34mm/1.33 inches) and small diameter (16mm/0.63 inches), which was crucial to keeping the subsystem within our volume constraints. Shown below is a picture of the wrist subassembly.

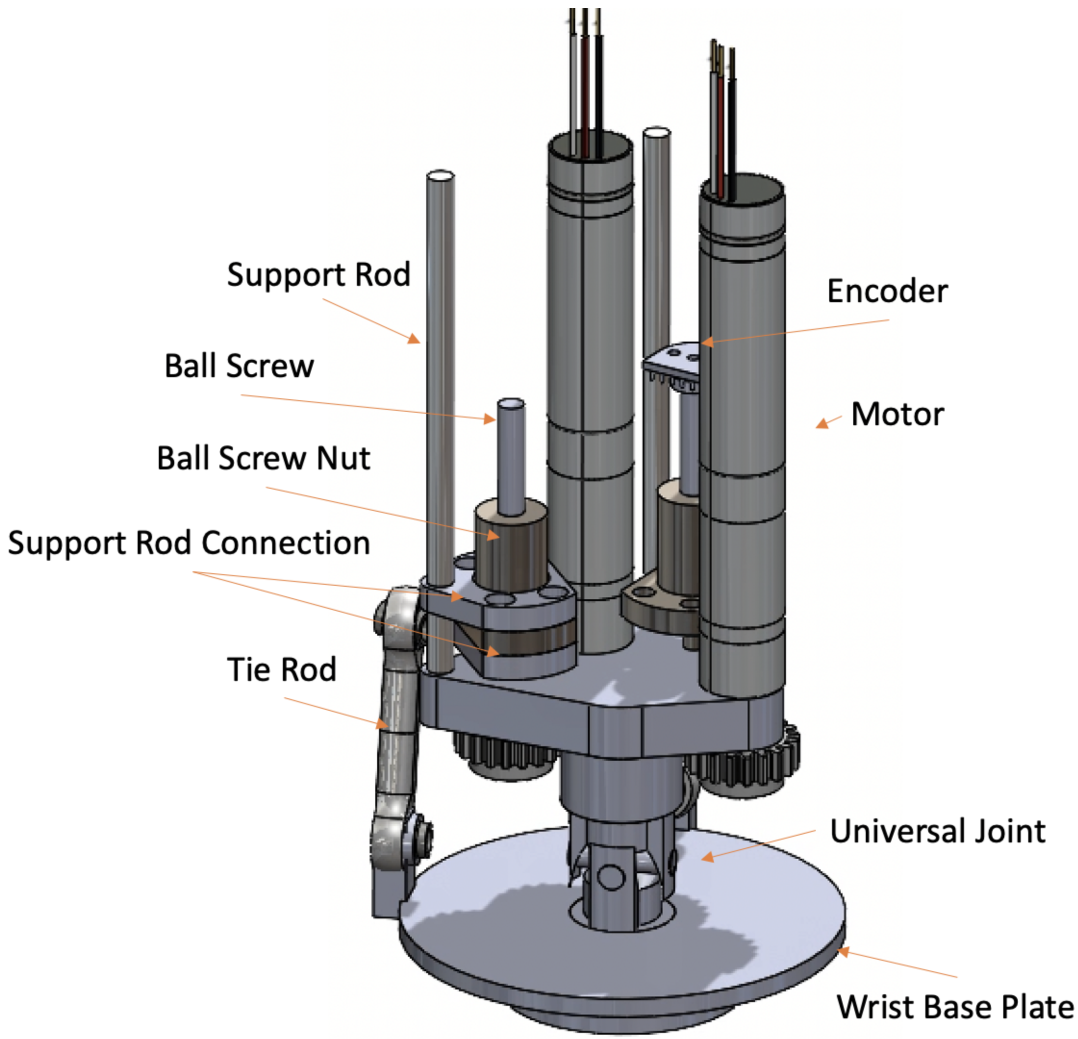


**Figure 15:** Current wrist subsystem CAD model

**Gripper - Design Overview**

Our final gripper solution consists of two scissor-like tongs that are actuated by a bi-directional ball screw. The motor transmits torque to the ball screw through gears that are attached to each shaft. A direct connection between the motor shaft and the ball screw would be preferable, however this would significantly add to the width of the design and the extruding motor would get in the way of hand movements. We could have also used a belt instead of gears, however the small distance and the low weight of the nylon gears negated the main benefits of using a belt. We found that gears with a 1:1 gear ratio would be an easy way to transmit torque between the shafts while keeping design as condensed as possible. The final gripper CAD is shown below in Figure 16.

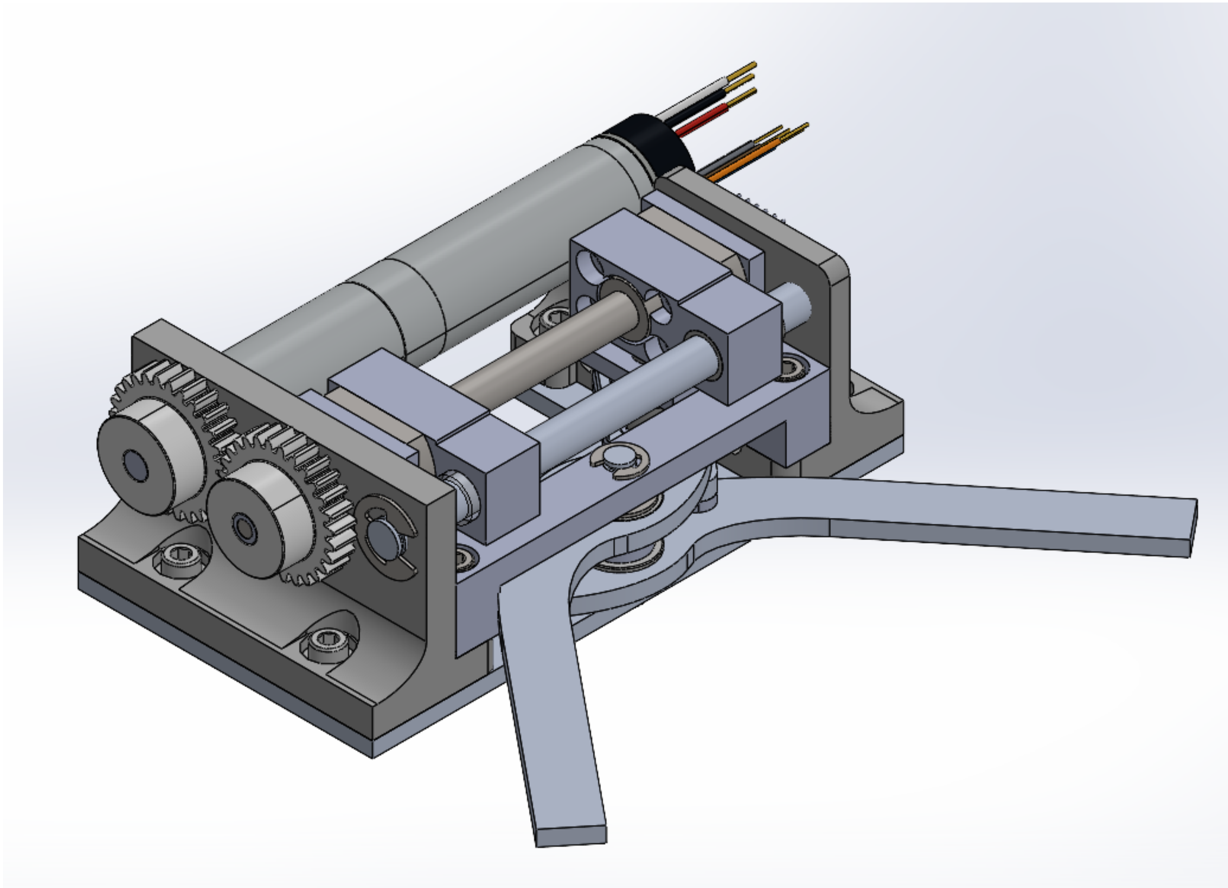

**Figure 16:** Final gripper CAD at maximum gripper opening angle of 80 degrees.

**Gripper - Component Selection**

The same methods for determining the motor and lead screw for the wrist were used on the gripper subsystem.

**Full Prosthetic - Integration Challenges**

Integrating the two subsystems was a challenge because of the geometry and locations of different parts, primarily the positioning of the motors powering the wrist as the motors powering the wrist could not interfere with the base plate of the gripper. The positing of the motors was also key as that position influences the location of the ball screws and support rods so much care was taken to ensure all components would fit well with the given space constraints.

**Full Prosthetic - Connections**

To connect the wrist and gripper subsystems together, there are two fixtures at play. First, there is a support rod shown in Figure 17 in blue which serves to provide structural support between the two subsystems and ensure that the forces transmitted between the subsystems will not cause other components to fail or misalign. This support rod was verified using a bending analysis at the worst case loading scenario of the prosthetic. The rod will be 3D printed using *Formlabs Rigid 4000* printing material which is highly rated in terms of strength and lightweightedness. The second connection point between the gripper and wrist subsystems will be the connections between the gripper base plate and the ends of the lead screws and their support rods. The purpose of this connection is mainly to provide a support for the end of the wrist lead screws and support rods, but will also serve to enhance the rigidity between the gripper and wrist. This connection will be similar to the connections found in the gripper subassembly and will be discussed further in a later section of  the report (see Discussion and Recommendations) The full prosthetic CAD can be seen in Figure 17.

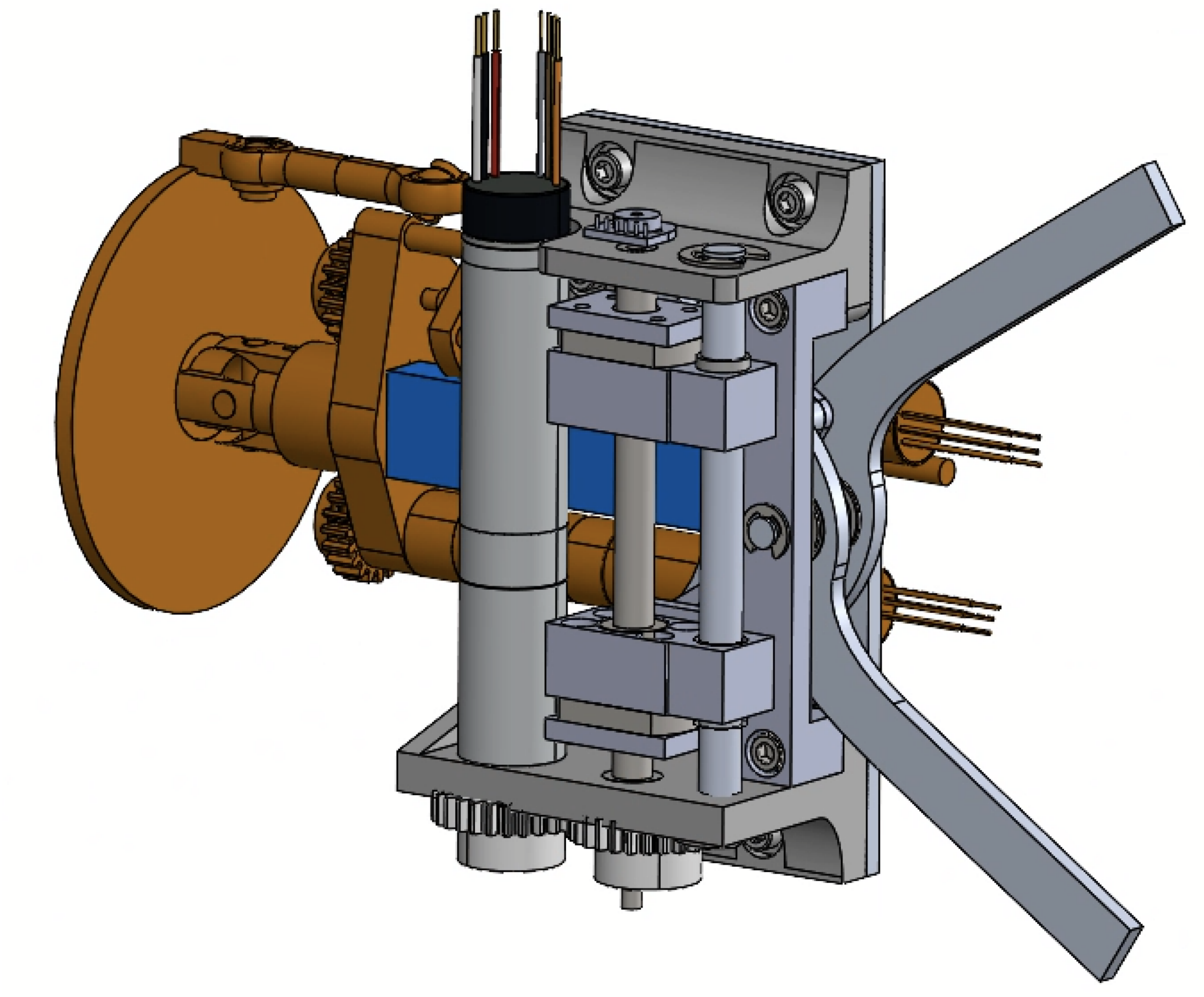

**Figure 17:** Wrist and gripper CAD integrated into a single prosthetic.

# ENGINEERING ANALYSIS

### Screw and Motor Selection Overview

As the weight of our design is one of our top priorities, we must take care to select the lightest possible motor that fulfills our design specifications. It is a good rule of thumb to assume there is a linear relationship between motor power and weight. This means that, generally, the more total power a motor must supply the heavier it will be. Power is made up of a combination of driving torque and driving speed, so we must work to find a balance between torque and speed that minimizes the power the motor must supply. This is why the selection of the ball screw must be done with great care as the pitch of the screw influences both the driving torque and driving speed.

### Wrist Force Calculations

First, we must determine the raw force to be applied by the lead screw at the base plate ( $F_{Link}$ ) to meet our design specification of a 10Nm moment on the base plate. These calculations and the FBD for which these are derived can be seen below in Equations (1), (2), (3), (4) and Figure 18.

$$d = sin(\gamma) * R \tag{1}$$

$$L_y * cos(\alpha) \; = \; d + L_y - y \tag{2}$$

$$R(1 - cos(\alpha)) = L_y * sin(\alpha) \tag{3}$$

$$F_{Screw} = T_{Req} * \frac{cos(\alpha)}{R * cos(\gamma - \alpha)} \tag{4}$$

Where $L\gamma$ [m], $R$ [m], $y$ [m], and $T_{Req}$ [Nm] are given values with $L\gamma$ , $R, y$ shown in Figure 18 and $T_{Req}$ is the required torque acting on the baseplate (10Nm by our specifications). $\gamma$ [rad], $\alpha$ [rad], $d$ [m], and $F_{Screw}$ [N] are unknowns shown in Figure 18. These 4 equations and 4 unknowns can be solved for $F_{Screw}$ .

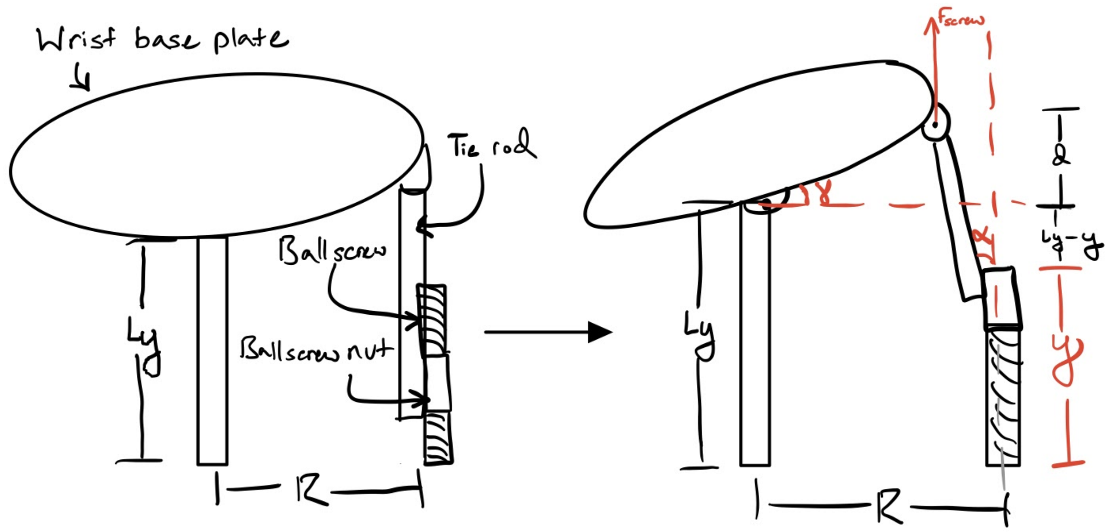


**Figure 18.** Shown is a diagram of the base plate and all relevant variables. The base plate is shown in the neutral position on the left and a tilted position on the right.

**Gripper Force Calculations**

To determine the raw force to be applied by the lead screw at the gripper to meet our design specification of a 160N grip force, we utilized Equation 5 shown below.

$$F_{Screw} = cos(\theta) * F_{Grip} * \frac{L_{Bottom}}{L_{Top}} \quad (5)$$

Where $F_{Screw}$ [N] is the required force from the ball screw, $\theta$ [rad] is the angle between the two gripper tongs, $L_{Bottom}$ [m] is the length of the bottom portion of the gripper tong (portion nearest the base), and $L_{Top}$ [m] is the top portion of the gripper tong.

**Motor Torque Requirement**

After determining the raw force needed at the base plate or gripper, one can solve for the necessary driving motor torque given the ball screw pitch as seen in Equation 6.

$$T_{Motor} = F_{Screw} * \frac{P}{2\pi*\eta} \quad (6)$$

Where $T_{Motor}$ [Nm] is the required motor torque, $F_{Screw}$ [N] is the calculated ball screw force, $P$ [m/rot] is the pitch of the ball screw, and $\eta$ is the efficiency of the ball screw.

**Motor Speed Requirement**

To solve for the angular speed required by the motor, we must solve for the linear velocity of the nut on the ball screw and combine this value with the pitch of the ball screw. This is shown in Equation (7).

$$\omega_{Motor} = v_{Nut} * \frac{2\pi}{P} \quad (7)$$

Where $\omega_{Motor}$ [rad/s] is the required motor speed, $P$ [m/rot] is the pitch of the ball screw, and $v_{Nut}$ [m/s] is the linear velocity of the nut that travels along the ball screw. $v_{Nut}$ was calculated by taking the time derivative of Equation (2) and Equation (5). The equations themselves are not shown for simplicity.

**Screw and Motor Selection**

We used the knowledge gleaned from the above analysis in conjunction with existing motors and ball screws found in the market to find the optimal pairing that minimized weight while meeting our requirements. Below are the results of our selection process shown in Table 11.

**Table 11:** Final Selections of Screws and Motor

| Subsystem | Motor Torque [Nm] | Motor Speed [rad/s] | Screw Radius [mm] | Motor gearbox ratio | Motor Weight [g] |
|---|---|---|---|---|---|
| Wrist | 0.149 | 205 | 2 | 25:1 | 59.7 |
| Gripper | 0.122 | 325 | 3 | 16:1 | 99 |

**Gear Selection**

In order to transmit rotational energy from the motor axle to the ball screw, we elected to use 1:1 gears connecting the motor axle to the ball screw axle. For the sake of weight, we wanted to use nylon gears instead of metal gears. In order to ensure failure would not occur in the nylon gears, we performed gear analysis to ensure the bending stress and contact stress would not exceed the yield stress of nylon. This analysis can be seen in Equation (8), Equation (9) and Equation (10) [29] below showing calculation for bending stress and contact stress, respectively.

$$F_{Gear} = \frac{T_{Motor}}{R_{Gear}} \tag{8}$$

$$\sigma_{Bending-Nominal} = \frac{6*F_{Gear}*H_{Tooth}}{t_{Gear}*W_{Tooth}} \tag{9}$$

$$\sigma_{Bending-Factor} = K_v * K_0 * K_s * K_m * K_B * SF * \sigma_{Bending-Nominal} \tag{10}$$

Where $F_{Gear}$ [N] is the tangential gear force, $T_{Motor}$ [Nm] is the required motor torque, $R_{Gear}$ [m] is the radius of the gear, $\sigma_{Bending-Nominal}$ [Pa] is the nominal bending stress, $H_{Tooth}$ [m] is the gear tooth height, $t_{gear}$ [m] is the gear thickness, and $W_{Tooth}$ is the tooth width. $\sigma_{Bending-Factor}$ [Pa] is the Factor-Adjusted Tooth Bending Stress which accounts for $K_v, K_0, K_s, K_m, K_B$ and $SF$ which are the dynamic factor, overload factor, surface condition factor, size factor, load distribution factor, and safety factor respectively [29].

**Ball Screw Support Rail**

Ball screws can handle large loads in the axial direction, but will fail if the radial load is too great. To prevent radial load on our ball screw, we added a rail that runs parallel to the ball screw. We created a connector that connects the ball screw nut to the rail. The connector has a thrust bearing that allows the connector to slide along the rail with low friction. The analysis to determine the bending stress that the rail will experience can be found in Appendix B. The total force acting on the rail as a result of the torque produced by the ball screw can be calculated using Equation (11). The moment of inertia I can be calculated using Equation (12). The bending stress can be calculated using Equation (13).

$$F = \frac{t*\tau}{r} \tag{11}$$

$$I = \frac{\pi}{4r^4} \tag{12}$$

$$�� = \frac{M*y}{I} \tag{13}$$

Where $t$ is the torque multiplier, $\tau$ [Nm] is the torque from the ball screw, and $r$ [m] is the center-to-center distance between the ball screw and the rail. The support rail has a total of four forces acting on it, consisting of the support forces on its two fixed ends and the two forces from the ball screw. The rail can be treated as a four-point bending problem. $I$ [$m^4$] is the moment of inertia and will be needed to find $\sigma$ [Pa], the bending stress, $r$ [m] is the radius of the support rail, $M$ [Nm] is the moment, and $y$ [m] is the distance from the neutral axis.

**Gripper Tong Design**

We began designing the gripper tongs by deciding how long we wanted them to be. The first decision we made was that the part of the gripper tong used by the user to grip object objects the same length as the average male index finger, 7.52 cm. The grip force is measured at half of this length, meaning that the 160 N grip force will act at a distance of 3.76 cm from the pivot. In our spreadsheet we calculated the distance of the ball screw from the pivot as a proportion of palm length. The farther away the ball screw was located, the farther the ball screw nuts would be required to travel.This had the effect of increasing the speed that the ball screw was required to rotate to open and close the gripper tongs. We also wanted to leave as much room in the palm as possible for the wrist components. Through iterations, we found that a ball screw at a distance of 0.16 times the palm length, or 1.776 cm, would result in the lightest motor options. By doing a simple moment and force balance, the required ball screw output force was determined to be 339 N. This force is transmitted by the ball screw to the tongs through two rollers that slide along a slot in each of the tongs. The cross-section of the tong material around the slot was determined through an analysis of the stress from the roller pushing against the slot. The calculations for this analysis are shown in Appendix E. With the assurance that the aluminum will prevent the roller from bending the tong, we created a plastic piece that will snap into the top of the tong so reduce the friction between the roller and the surface on which it glides.

**Wrist Joint Selection**

To select appropriate ball and universal joints for the gripper such that our ROM and force specifications would be accomplished, we utilized the diagram from Figure 19. and derived Equation (14) and Equation (15) for forces acting at the joints.

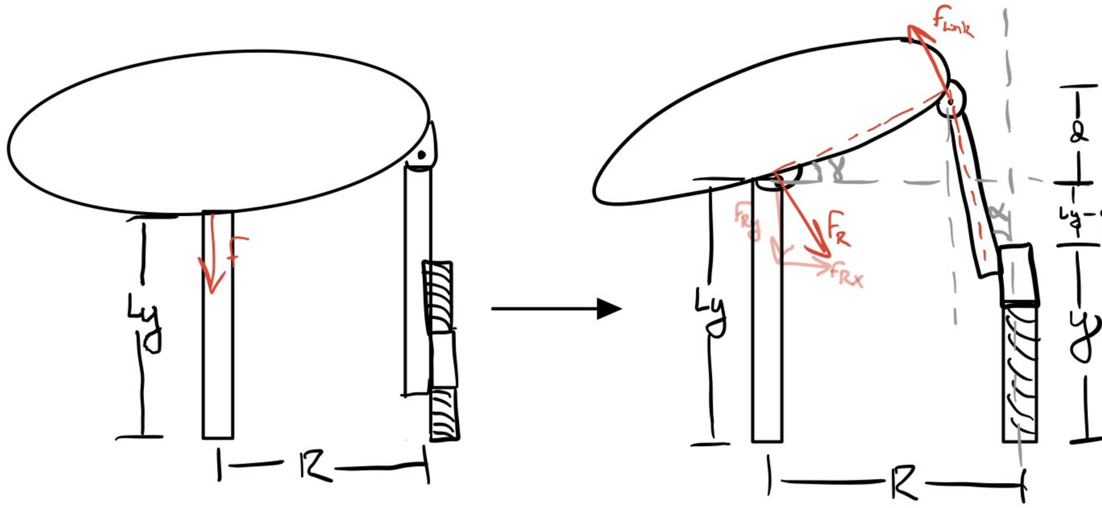


**Figure 19:** Diagram for the universal joint calculations, the left orientation shows neutral position while the right orientation shows a tilted position

$$F_{Ry} = F_{Link} * cos(\alpha) \tag{14}$$

$$F_{Rx} = F_{Link} * sin(\alpha) \tag{15}$$

Where $F_{Ry}$ [N], and $F_{Rx}$ [N] are the respective y and x forces at the universal joint, and $F_{Link}$ [N] is the force from the ball screw and $\alpha$ [rad] is shown in the diagram.

## RISK ASSESSMENT

To analyze the potential failure modes and their effects on the system's effectiveness, we developed a Failure Mode and Effects Analysis (FMEA). It includes the items where the failure could occur, the potential failure mode, the potential causes, and recommended actions to prevent failure. FMEA table also includes the probability that each of the failure mode would occur (OCC), the severity (SEV) of the failure mode when happening, probability of catching failure mode prior to customer delivery happening (DET) and the risk priority number (RPN) which equals to (OCC)*(SEV)*(DET). All numbers were set to be on a scale from 1 to 10. FMEA table could be found on page X.

According to our FMEA table, the aspect of our design with the highest risk is the disconnection of power lines of the motor which had the highest RPN score of 90. We gave the likelihood of failure at a 5 because users tend to use the prosthesis aggressively by either shaking it very rapidly or using it as a hammer to knock stuff with it. Since our design decision was to give up a non-back drivable system to gain more efficiency in our transmission, we decided to apply non-back drivability through controls strategies. Revanth, our sponsor and graduate student in charge of the project will use controls to make the wrist work a bit like a spring to absorb shocks and withstand more aggressive motion by the user.

We believe that with this control design strategy our prosthesis will become more shock resistant and will withstand higher impact from the user when used aggressively. We believe with the right control strategy the likelihood of failure will drop to 2 and therefore our RPN score for this specific failure mode will become 36 down from 90.

Other steps we have taken to reduce failure modes was implementing changes in the design such as using nylon gears and aluminum rails and plates instead of steel ones to reduce the oxidation of the parts which could cause the prosthesis to jam and therefore motors reach stall torque. This failure mode will be specifically dangerous because overheating occurs quickly if motors are not turned off.

Doing the above steps in efforts to reduce the risk of the device will enhance the safety of the design and will make the prosthesis operate with an acceptable level of risks. With that being said, there will still be more steps to take to reduce the chance of other failure mode to happen. Most important failure modes that still need improvement are implementing a water-resistant housing, so the prosthesis doesn't get contaminated with water easily, designing a stronger geometry with a higher moment of inertia in all axes to improve strength of the gripper tongs against bending and twisting.

**Table 12:** FMEA table

| Item / Function | Potential Failure Mode | Potential Effect on User Because of Defect | SEV | Potential Causes | OCC | Current Process Control | DET | RPN | Action Recommende d | Resp & Target Date | Action Taken | New SEV | NEW DET | NEW RPN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Motor electrical connection | Disconnected while operating | Object that user is holding will fall | 9 | Severe movement of prosthesis | 5 | None | 2 | 90 | User should avoid severe movement or wrecking of prosthesis | M Miro, 11-11-20 | Rold Revanth (Sponser) about creating a spring design through control | 6 | 2 | 12 |
| Wrist-socket interface | Fracture of interface part | User will lose balance/ object they are using will fall | 5 | Exceeding torque / force limit of prosthesis | 4 | Using stroger material to make the part | 2 | 40 | User should avoid overuse of prosthesis | | | | | |
| Wrist | Wrist won't move | Inconvenience for user | 1 | Debris in first stage gears | 2 | Indoor / Outdoor usage feature | 4 | 8 | Minimize usage in dusty environment | J Foote, 11-28-20 | Housing that minimizes debris entering the system | 1 | 2 | 2 |
| | Wrist won't move | Inconvenience for user | 4 | Water Contamination | 2 | Ensures water resistance | 3 | 24 | Avoid contamination by water or other liquids | | | | | |
| Gripper | Gripper tongs won't move | Inconvenience for user | 1 | Debris in first stage gears | 2 | Indoor / Outdoor usage feature | 4 | 8 | Minimize usage in dusty environment | | | | | |
| | Gripper tongs won't move | Inconvenience for user | 4 | Water Contamination | 2 | Ensures water resistance | 3 | 24 | Avoid contamination by water or other liquids | | | | | |
| Gripper tong | Gripper tongs breakoff | Arm / Sholder Injury might occure | 8 | Twisting objects with gripper | 4 | Redesign tongs to have a better geomety | 5 | 160 | Minimize twisting actions using the gripper | | | | | |
| Gripper-Wrist | System overheating | Device failure / burns | 3 | Overusing | 7 | Add fins to housing | 3 | 63 | Avoid overusing | | | | | |
| Full system | Gripper tongs won't move | Inconvenience for user | 1 | Oxidization of components | 3 | Implementation of plastics and aluminum | 4 | 12 | Minimize usage in dusty environment | S Lusky, 11-30-20 | Used nylon gears and plastic brackets | 1 | 2 | 2 |
| | Wrist won't move | Inconvenience for user / Over heating | 2 | Oxidization of components | 3 | usage of plastics and aluminum for parts material | 3 | 18 | Avoid contamination by water or other liquids | JFoote, 11-30-20 | Used nylon gears and plastic plates | 0 | 0 | 0 |

# VERIFICATION

Verification of the design was conducted to compare our achieved specifications to our desired specifications that we defined based on our user requirements. The verification of the design's specifications is shown in Table 21. Most of the specifications were able to be verified either through the CAD model or through engineering analyses. In the table, a green check means that the desired specification has been met, a red X means that the desired specification has not been met, and a yellow question mark means that the specification still needs to be measured. All engineering specifications will be measured again on the physical prototype once it has been fabricated for accuracy.

**Table 13:** Verification of engineering specifications

| User Requirements | Engineering Specification | Desired | Achieved | Verification Method | Status |
|---|---|---|---|---|---|
| Size of the median adult male hand | Hand length | 19.5 cm | 19.7 cm | Measure CAD model dimensions | ✓ |
| | Hand width | 9 cm | 10.8 cm | Measure CAD model dimensions | ✗ |
| | Hand thickness | 3.5 cm | 6.6 cm | Measure CAD model dimensions | ✗ |
| Lightweight | Prosthesis weight | ≤ 500 g | 530.5 g | Evaluate CAD model mass | ✗ |
| Wrist range of movement, torques and speeds are similar to those of an average adult human wrist | Flexion-Extension ROM | 74-70 deg | 45-45 deg | Wrist analysis | ✗ |
| | Radial-Ulnar ROM | 27-40 deg | 45-45 deg | Wrist analysis | ✓ |
| | Flexion-Extension torque | 10 N-m | 10 N-m | Wrist analysis | ✓ |
| | Radial-Ulnar torque | 10 N-m | 10 N-m | Wrist analysis | ✓ |
| | Flexion-Extension speed | 120 deg/s | 120 deg/s | Wrist analysis | ✓ |
| | Radial-Ulnar speed | 120 deg/s | 120 deg/s | Wrist analysis | ✓ |
| Gripper strong enough to securely grasp objects | Force capacity | 160 N | 160 N | Ball screw and motor analysis | ✓ |
| | Capability to grip common objects | Hammer, Coke Can, Solo Cup, Pencil, M&M, Phone, Grocery Bag | - | Evaluated while testing physical prototype | ? |

To verify that the design was similar to that of the median adult male hand, the length, width, and thickness dimensions were determined using the measuring tool in SolidWorks. The achieved length was only slightly over our desired length, so we agreed that the status could be marked with a green check. The achieved width was 1.8 cm over the desired width. The achieved hand thickness was 3.1 cm over the desired thickness, a significant difference. The main reason for this difference was the way that the gripper subsystem needed to be positioned with respect to the wrist subsystem.

The lightweight requirement was evaluated using the mass properties tool in Solidworks. The mass of 530.5 g that we achieved was surprisingly close to our target of being under 500 g. The components that contributed the most towards the overall mass were the motors, ball screws, and aluminum components such as the gripper baseplate and tongs. We were able to limit much of the weight by using 3D printed plastic where the material properties of aluminum were not necessary.

The wrist subsystem was developed specifically with the ROM, torque, and speed specifications in mind. Because of this, we were able to develop a wrist that has capabilities very similar to those of an average adult male wrist. The flexion-extension and radial-ulnar are both able to achieve 45-45 deg ROM. This has to do with the limited space available for the tie-rods to move while avoiding contact with other wrist components.

The gripper subsystem was also developed specifically with the grip strength in mind. We performed gripper force, motor torque, and motor speed requirements to exactly meet the desired 160 N gripping force. The final specification, the capability of the gripper to grip common objects, requires a physical prototype in order to be tested. To determine whether the gripper will satisfy this condition if it can securely grasp each object without the object dropping, and if it can maintain this grip while the wrist moves to the maximum bounds of its ROM in each DOF.

## DISCUSSION AND RECOMMENDATIONS

**Lessons Learned**

Because we were designing a prosthesis that none of our members had personal experience with, the majority of our design process was reliant on learning from others, from both a medical and engineering standpoint. Our design was heavily influenced by the insight from one of our main stakeholders, Megan Diemer, who, as a prosthetist was able to pass along the first-hand knowledge she had about what makes a good prosthesis from the perspective of the user. Through our weekly meetings, much of what we learned surprised us as our preconceived notions of what we thought would be beneficial were not consistent with what she recommended. An example of this was the discussion of including an additional joint in the gripper to simulate finger movements in a hand. Our initial thought behind this was to go for replicating the missing movement a finger could provide, such as wrapping around an object's surface. What we actually found out from Megan was that people who use an upper limb prosthesis often prefer to use hooks because of the simplicity that they provide, and because the slim profile of hooks allow people to easily see what they are doing. Oftentimes a prosthesis with articulated movements that replicate those of normal fingers can block the user's view of what they are holding, and without haptic feedback it makes it difficult to perceive the interaction between the prosthesis and the objects in space. This knowledge proved valuable to us and informed our decision to go with a simpler gripper design that maximized the view of what the user is holding.

This extended into the lessons we learned from the engineering challenges we were faced with as well. Our project set out to create a prosthesis with a novel wrist design, and while our team was able to break new ground with our 2 degree of freedom wrist design, we also were able to learn a lot about the process involved in doing so. Our project began in the summer a few weeks before the semester started, where we spent that time doing extensive amounts of research and reading about wrist designs in industry, existing prosthesis solutions,  as well as about the human hand and wrist. We were able to gain insight into what worked in existing solutions and their downsides, as well as mechanism designs in industrial robotics and other engineering applications that could be modified into a wrist application. One of the biggest lessons we learned came during the selection of a transmission for the gripper and wrist mechanisms. Instead of simply searching online and examining technical specifications of motors and lead screws until we happened upon a perfect match, we were able to learn how to use a MATLAB script provided to us by our stakeholder Revanth Damerla's lab that searched a database of Maxon motors based on inputs of dimensions, power intake, speed and torque that were indicated from specifications of possible lead screws (pitch, diameter, etc.). This process relied on heavy documentation and made the process far more meticulous and organized, which was important for a product that required us to establish good engineering practices.

**Design Strengths**

The main strengths of this design are that the gripper can match and even exceed the gripping forces of other heavy-duty gripper prostheses on the market, that the wrist closely replicates the wrists natural ROMs, torques, and speeds, and its low weight. Many heavy-duty grippers only allow 1-DOF, such as the Greifer [16]. In this respect, our design has been a success in incorporating multiple DOFs with the possibility of incorporating a pronation-supination DOF in series with the existing 2-DOF parallel wrist mechanism. The mass of our prosthesis is impressive because it is only slightly above the mass of the average male hand. This means that the user will not feel off-balance because our prosthesis creates an approximately even weight distribution with the user's other hand.

**Design Weaknesses**

The gripper portion that roughly represents the "hand" of the prosthesis is able to achieve the strength and speed requirements we had set based on human standards. Unfortunately, meeting this goal required more space than we had anticipated. While the final length is very close to that of the average adult male's hand, the height and width are both more than 20% greater than the average dimensions. This is due to the arrangement of motors and gripper tongs, specifically, the way in which they are mounted together. Adding width here ensures that the gears have proper meshing, but this arrangement takes up more space than we had hoped. Beyond the gripper system as a standalone element, the relationship between the gripper and the wrist deserves mentioning as something that stands to be optimized. The integration between the two subsystems had not been fully thought out by the semester's end, with some elements "floating" in the space between the two major assemblies.

**Recommendations for Future Work**

This project was created under the assumption that it would be one in a series of projects that would culminate in a 3 DOF wrist that could be tested to discover the ultimate utility of flexion/extension and radial/ulnar deviation in the wrist. Because of this, we will leave in this report a list of recommendations for further improvements on our design from small details to larger design concepts.

**Recommendations - Gear Inserts and Wrist End Supports**

Some of the details yet to be fully realized in our design are how the gears in our design will be rigidly attached to our ball screws. The hub of the gears cannot simply be secured with a set screw as having the gear oriented such that the hub of the gear is closest to the screw only increases the moment arm of the mechanism and would reduce our efficiency. We recommend creating an insert that can act as a sleeve around the shape of the motor hub and can be press-fitted into the gear and then secured more rigidly with a set screw on the hub. This allows the face of the gear to be closest to the ball screw and ensure maximum efficiency.

One last detail is the support for the upper end of the wrist support rods and ball screws. The analysis and base design for this part can be taken directly from the work done on the gripper supports and the part may be made of the same *Formlabs Rigid 4000* 3D printing material.

**Recommendations - Housing**

Housing for this mechanism is highly desirable especially once testing with study subjects begins. As a user is handling the object it will be susceptible to accidental damage as the user may knock it into things while learning to control it and manipulate objects. Additionally, things can easily be caught inside the intricate system and could cause jamming while also being difficult to extract. For housing material, we recommend a material that is strong, easily customizable, and lightweight. Our material recommendation is carbon fiber as it is commonly used as a housing material according to the prosthetist, Megan Deimer, from the University of Michigan Hospitals. It is no wonder that this material is commonly used as it is incredibly light for the amount of durability it possesses and working with epoxy impregnated carbon fiber sheets is a highly customizable process which is necessary in the field of prosthetics as oftentimes amputees have different needs when it comes to prosthetic connection and requirements.

**Recommendations - Pronation/Supination DOF**

As a prototype with the goal of determining the utility of a prosthetic wrist with flexion/extension and radial/ulnar deviation, the final degree of freedom, pronation/supination was notably absent. If the studies conducted using our 2-DOF prosthesis demonstrate significant improvements to users' capabilities, the next step would be to implement this final degree of freedom for additional testing. Pronation/supination abilities could be applied by adding a thin brushless motor with a large diameter attached to a planetary gear transmission placed behind the wrist assembly. This structure would extend into the forearm region to minimize the lever arm created by the additional weight acting on the user's arm. It is unlikely that our current design would serve to fully replace a human hand, but with the addition of pronation and supination, this prototype would more accurately reflect the natural biomechanics of the wrist and hand.

## CONCLUSION

This report outlines the work that has been completed during the Fall 2020 semester on this project, including the extensive review of literature and existing products in the field, a description of the design process that we undertook, a design that addresses the stakeholder requirements to the best of our abilities currently, as well as a outline for the future work that will be required in order to complete this project to a full-scale working model. The primary objective was to design a novel 2 degree of freedom wrist with a powered gripper, with the goal of replicating the dimensions and capabilities of the average male hand and wrist. Amidst the backdrop of a primarily remote semester during the COVID-19 pandemic, we believe we have been able to work out a solution that in its current state will prove valuable to the future work that will be done to complete the project, with the recommendations and findings we have provided in this report.

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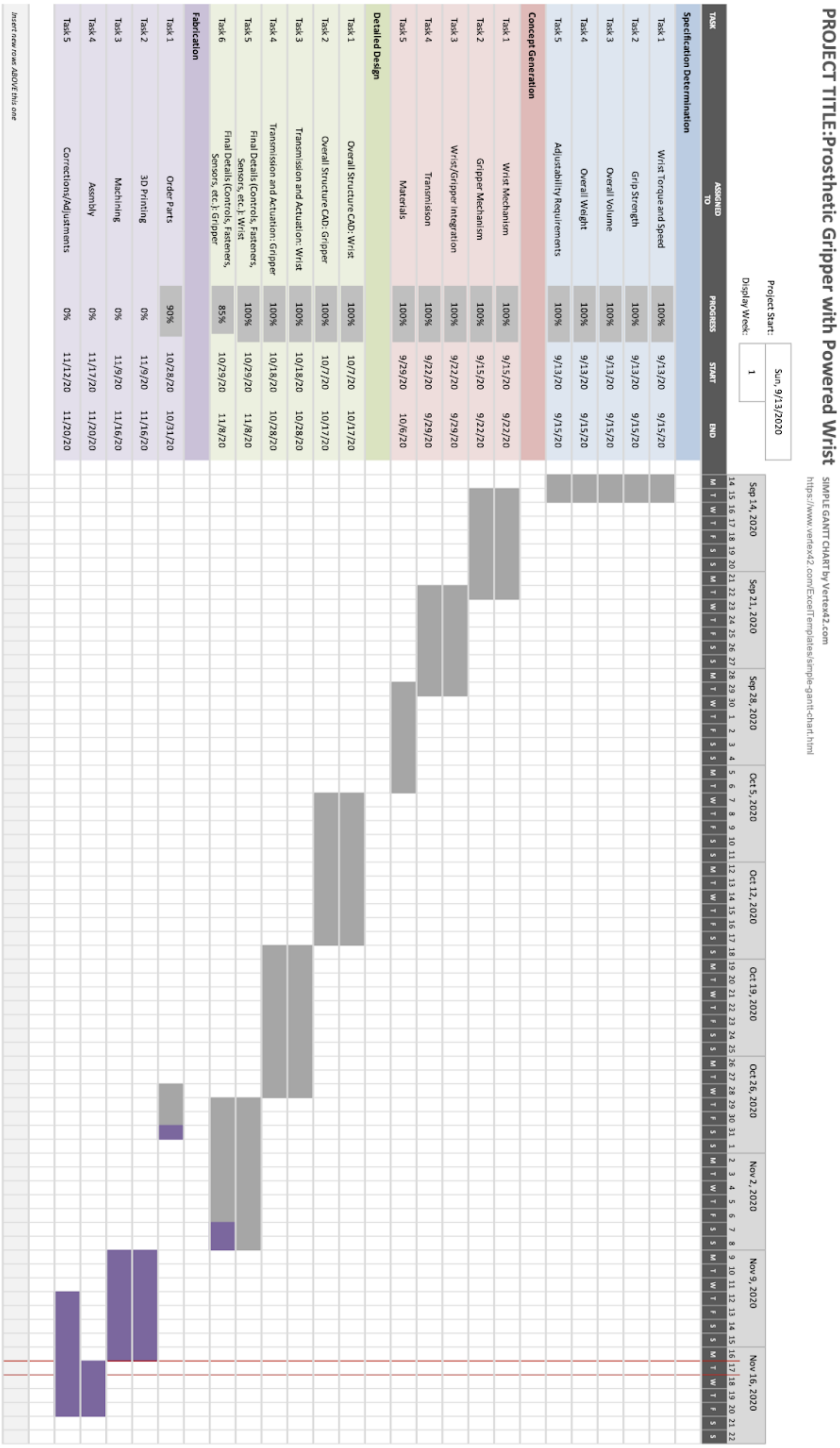
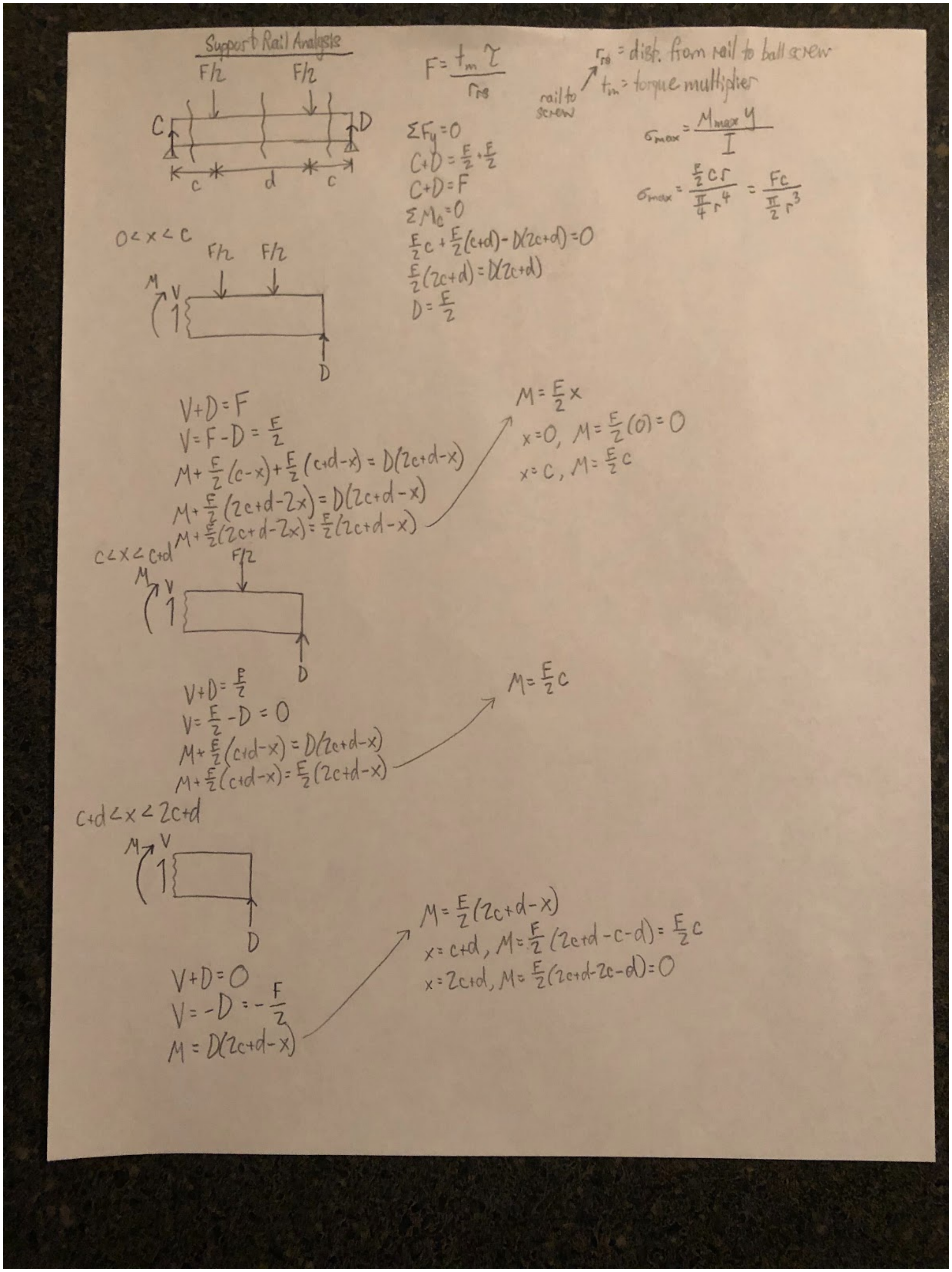
# APPENDIX

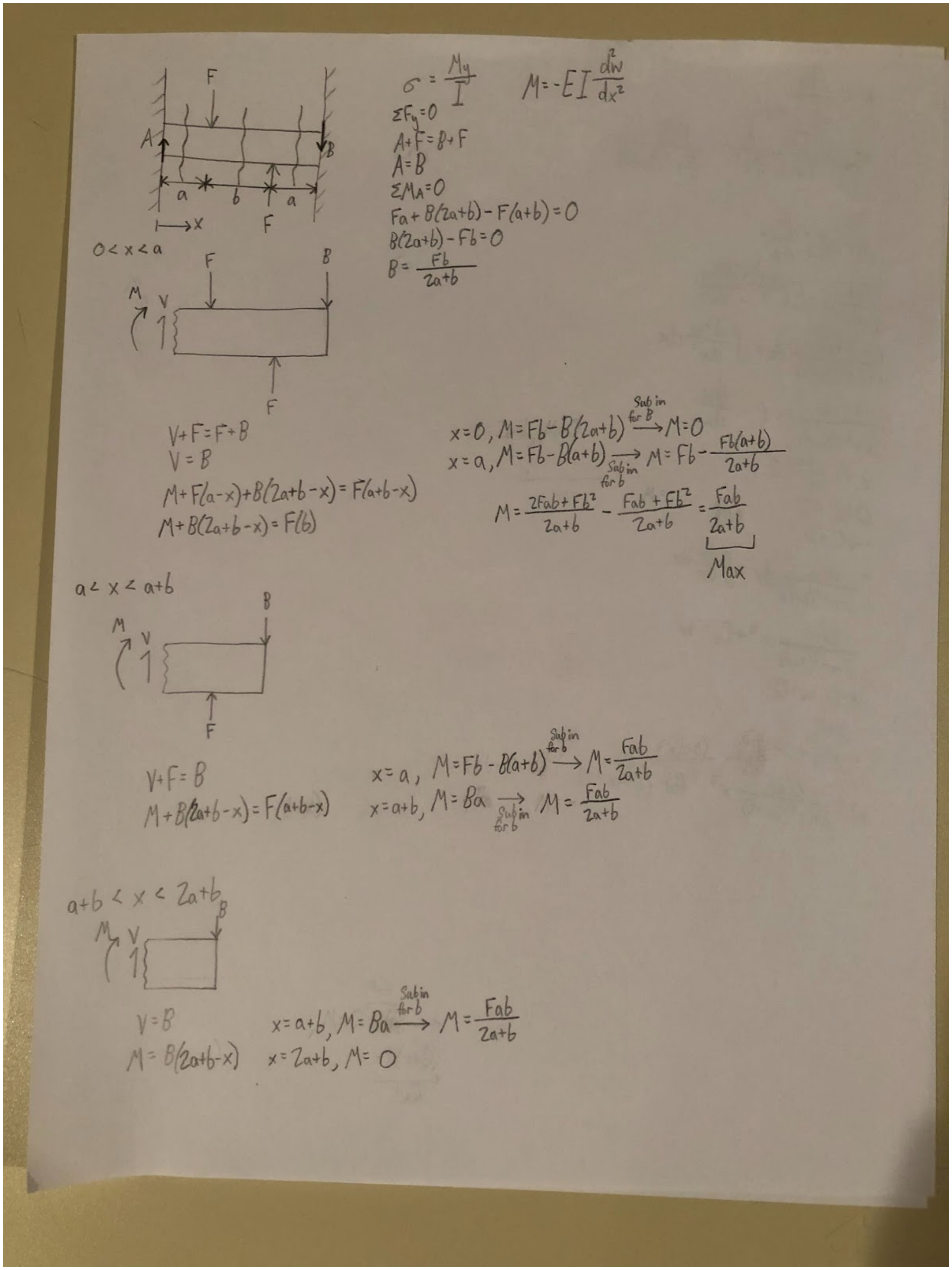
## Appendix A - Gantt Chart



## Appendix B - Support Rail Analysis



**Appendix C - Pivot Pin Analysis**



$$\sigma = \frac{My}{I}$$

$$\sigma_{max} = \frac{Fab}{2a+b}\frac{r}{\frac{\pi}{4}r^4} = \frac{Fab}{\frac{\pi}{4}r^3(2a+b)}$$

$$M = -EI\frac{d^2w}{dx^2}$$

$$\frac{Fab}{2a+b} = -E\left(\frac{\pi r^4}{4}\right)\frac{d^2w}{dx^2}$$

$$\int \frac{-4Fab}{E\pi r^4(2a+b)}\,dx = \int \frac{d^2w}{dx^2}\,dx$$

$$\frac{-4Fab}{E\pi r^4(2a+b)}x + C_1 = \frac{dw}{dx}$$

$$x=0,\ \frac{dw}{dx}=0$$

$$0+C_1=0$$

$$\rightarrow C_1=0$$

$$\int \frac{-4Fab}{E\pi r^4(2a+b)}x\,dx = \int \frac{dw}{dx}\,dx$$

$$\frac{-2Fab}{E\pi r^4(2a+b)}x^2 + C_2 = w$$

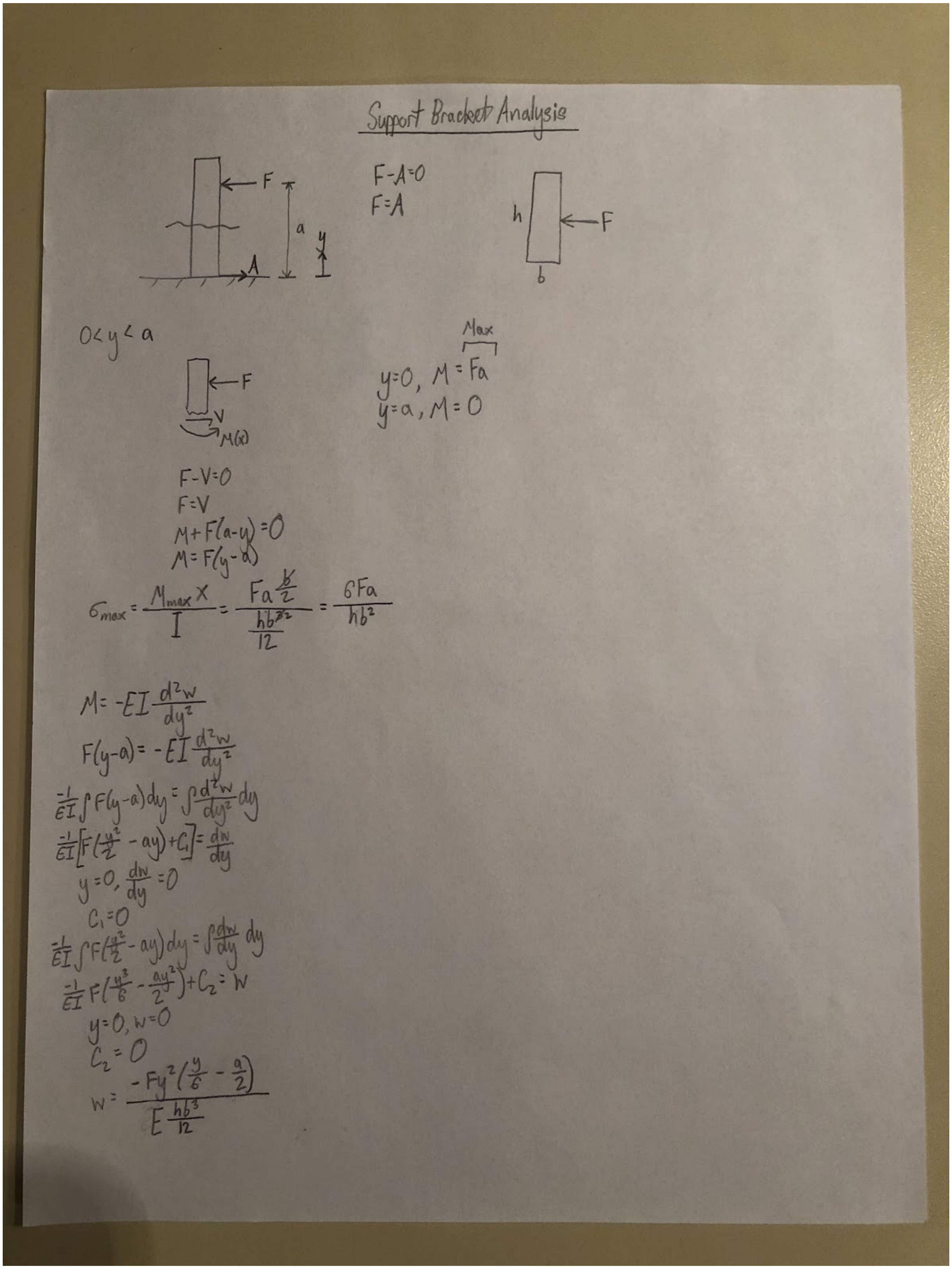
$$x=0,\ w=0$$

$$0+C_2=0$$

$$\rightarrow C_2=0$$

$$w = \frac{-2Fab}{E\pi r^4(2a+b)}x^2 \quad \text{for } (0<x<a)$$

**Appendix D - Support Bracket Analysis**



Support Bracket Analysis

F, a, y, A

$F - A = 0$

$F = A$

h, F, b

$0 < y < a$

F, V, M(x)

$y = 0,\ M = \underbrace{Fa}_{Max}$

$y = a,\ M = 0$

$F - V = 0$

$F = V$

$M + F(a-y) = 0$

$M = F(y-a)$

$$\sigma_{max} = \frac{M_{max}\,x}{I} = \frac{Fa\frac{b}{2}}{\frac{hb^3}{12}} = \frac{6Fa}{hb^2}$$

$$M = -EI\frac{d^2w}{dy^2}$$

$$F(y-a) = -EI\frac{d^2w}{dy^2}$$

$$\frac{-1}{EI}\int F(y-a)\,dy = \int\frac{d^2w}{dy^2}\,dy$$

$$\frac{-1}{EI}\left[F\left(\frac{y^2}{2} - ay\right) + C_1\right] = \frac{dw}{dy}$$

$y = 0,\ \frac{dw}{dy} = 0$

$C_1 = 0$

$$\frac{-1}{EI}\int F\left(\frac{y^2}{2} - ay\right)dy = \int\frac{dw}{dy}\,dy$$

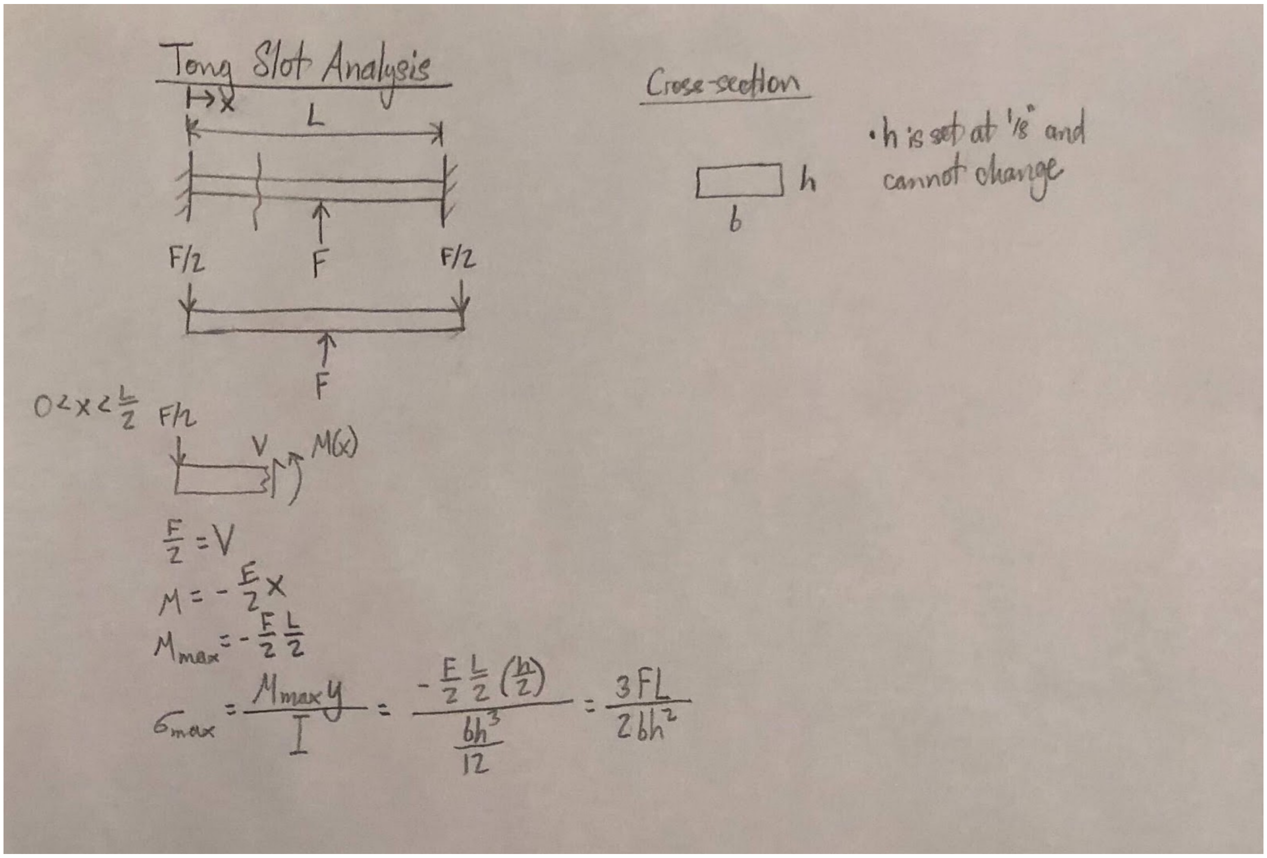
$$\frac{-1}{EI}F\left(\frac{y^3}{6} - \frac{ay^2}{2}\right) + C_2 = w$$

$y = 0,\ w = 0$

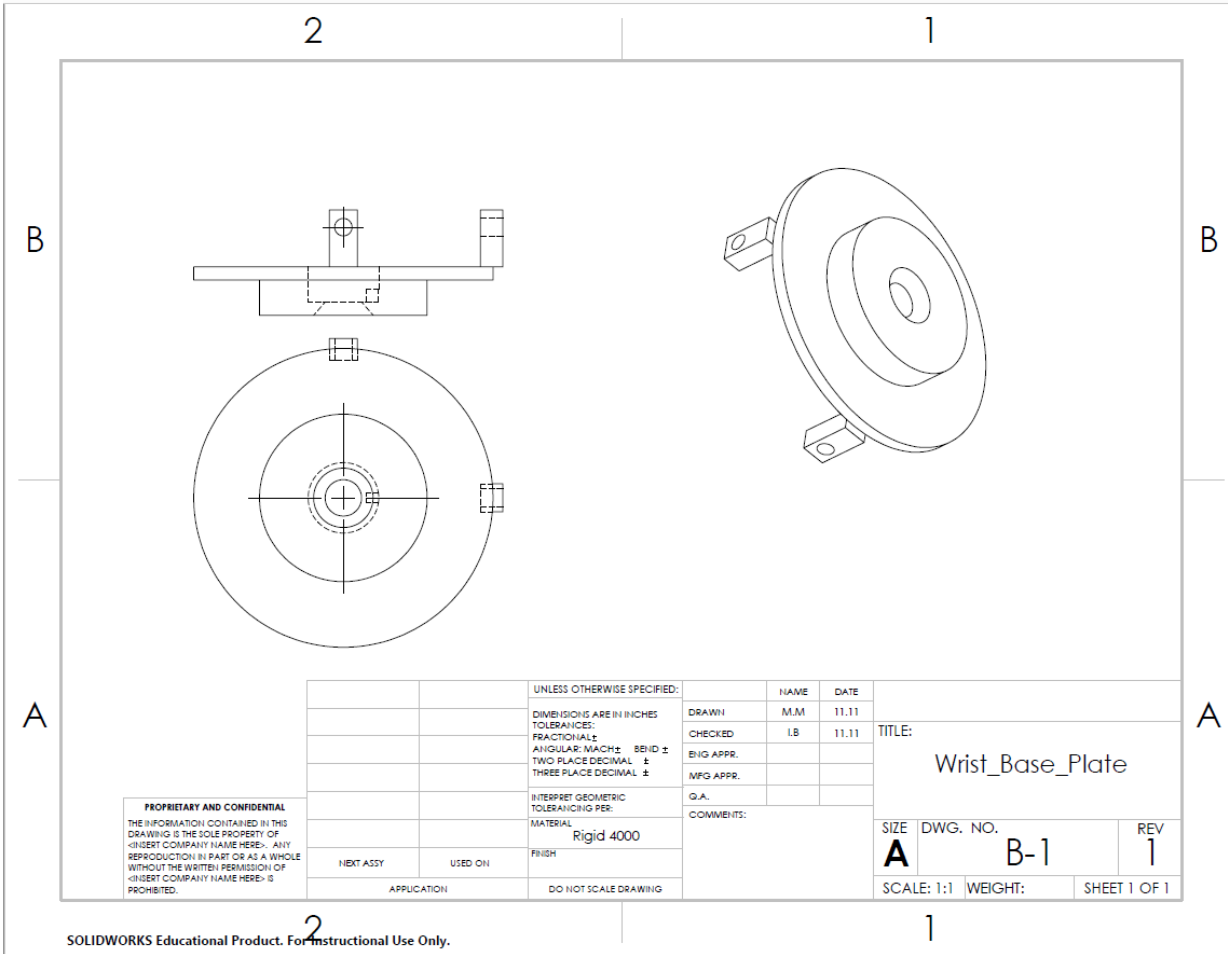
$C_2 = 0$

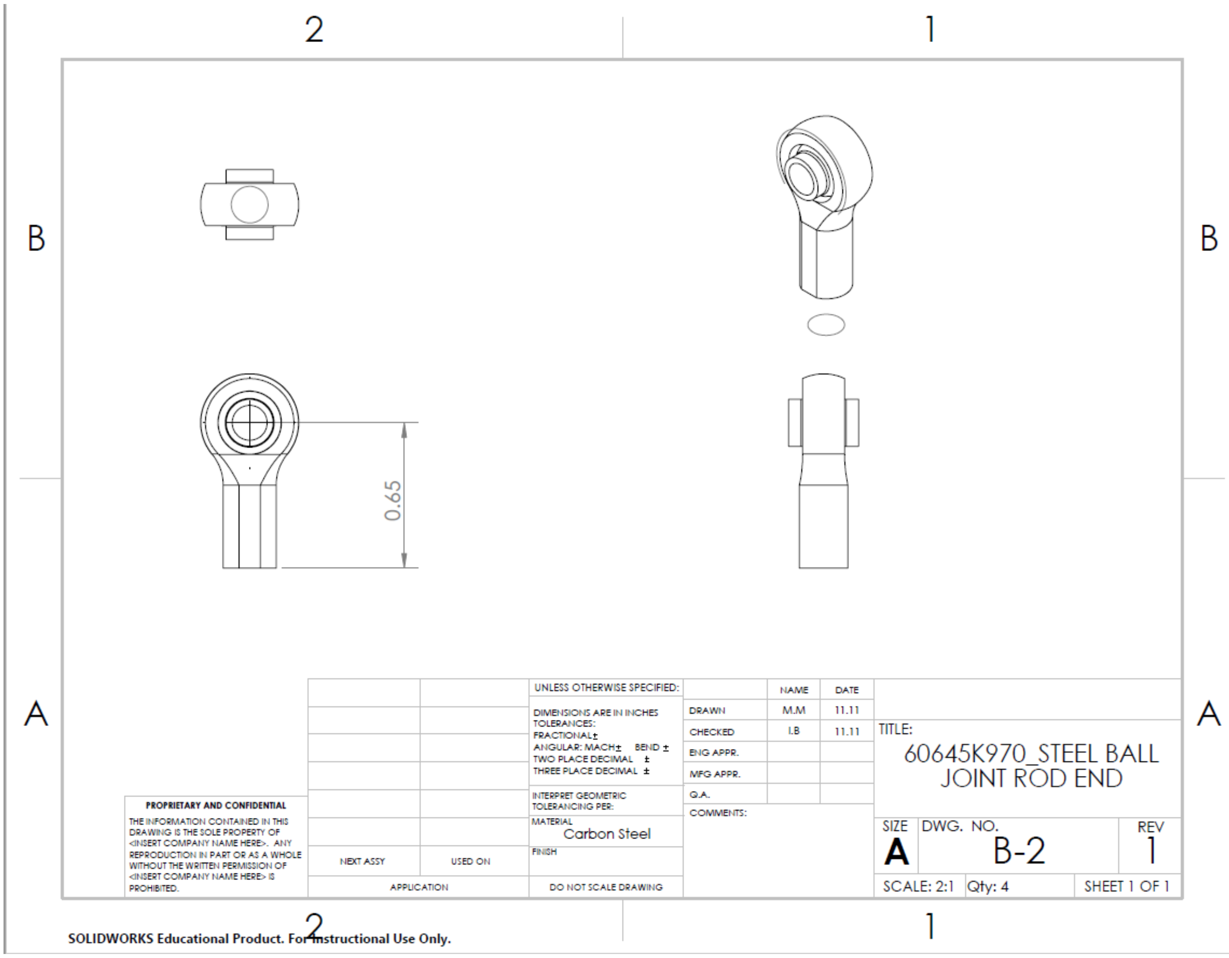
$$w = \frac{-Fy^2\left(\frac{y}{6} - \frac{a}{2}\right)}{E\frac{hb^3}{12}}$$

**Appendix E - Tong Slot Analysis**



## Appendix F - Drawings and Manufacturing Plans



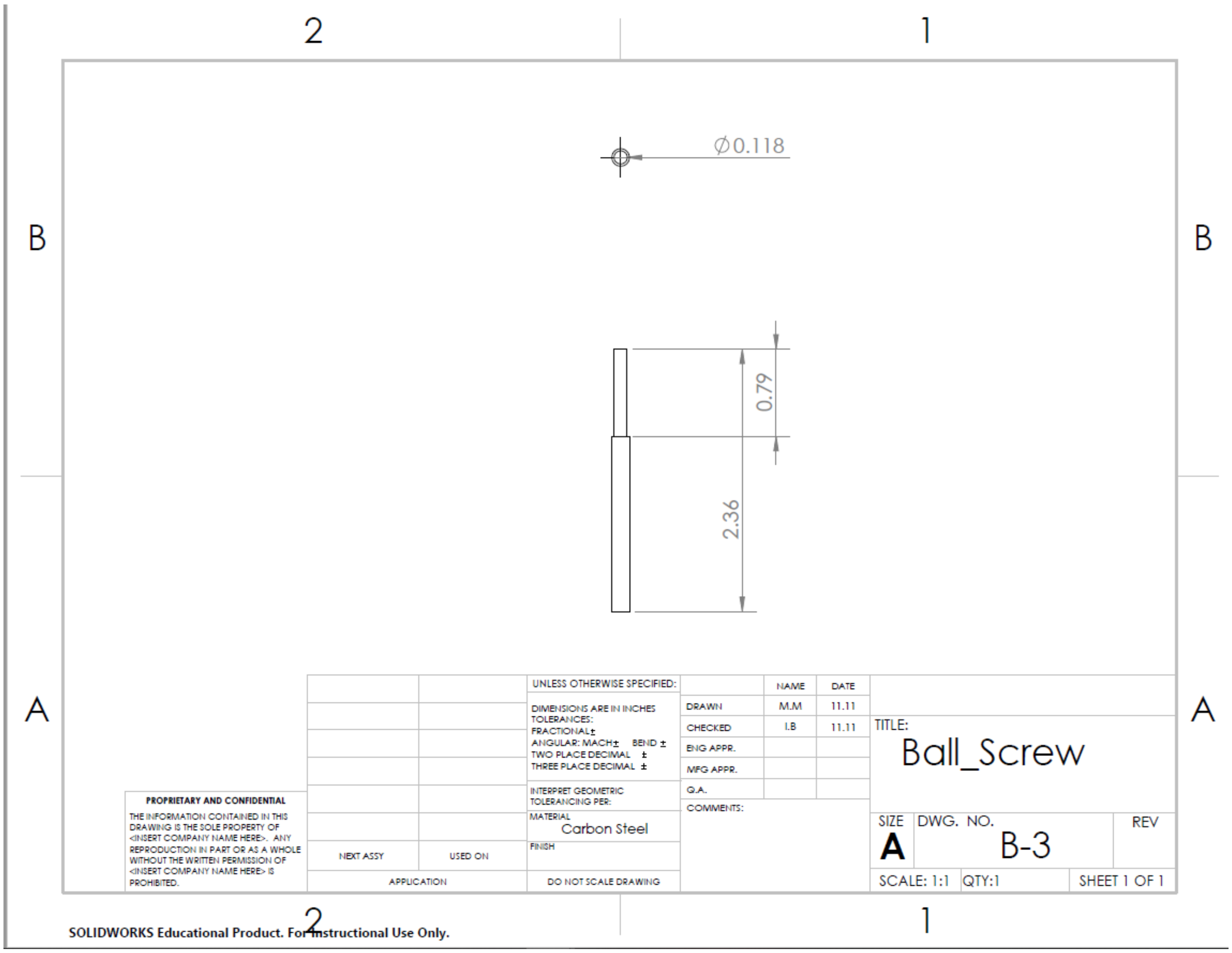



# Manufacturing Plan

**Part: Ball Joint**

**Raw Material Stock:**

| Step | Process Description | Machine | Fixture | Tool(s) | Speed (RPM) |
|---|---|---|---|---|---|
| 1 | Secure ball joint in vise | Vise | | | |
| 2 | Install an apropriate end mill and lower down the z-direction until it touches the part | Mill | | | 700 |
| 3 | Remove material until porpriate length is obtained | Mill | | | 700 |
| 4 | Deburr part to clean sharp edges | file | | | |

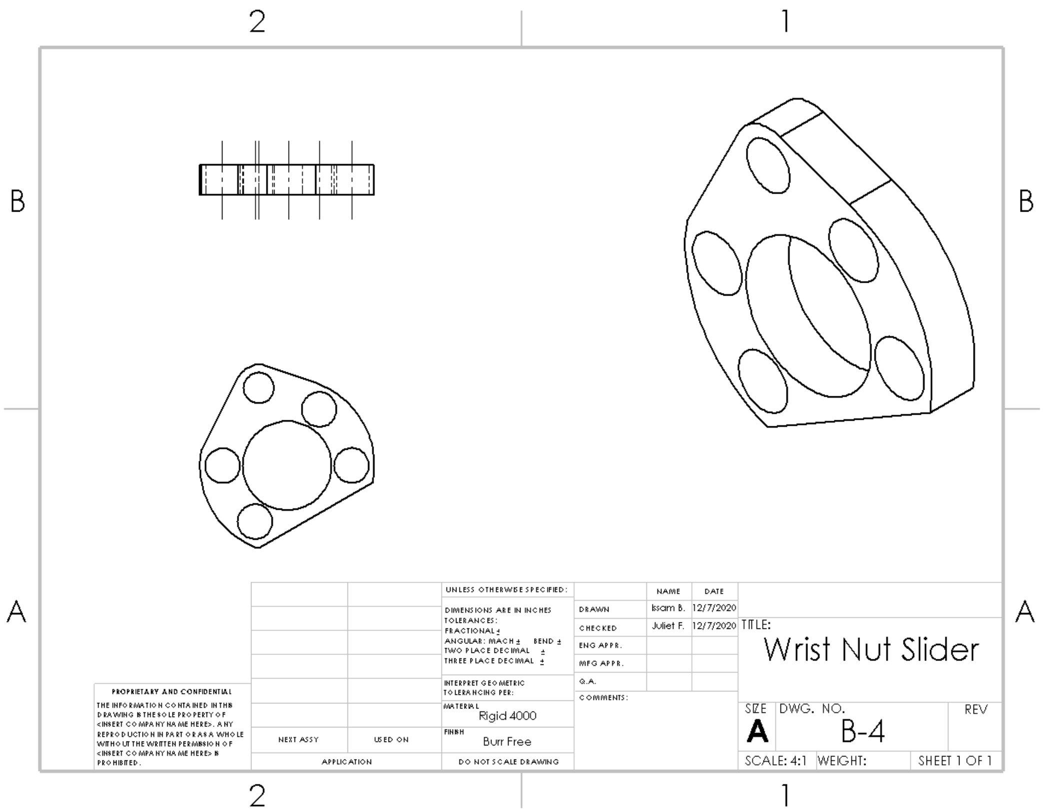



# Manufacturing Plan

**Part: Ball_Screw**

**Raw Material Stock:**

| Step | Process Description | Machine | Fixture | Tool(s) | Speed (RPM) |
|---|---|---|---|---|---|
| 1 | Secure ball screw In the lathe from jornal side | Lathe | | | 1000 |
| 2 | Zero out the lathe machine once it touches the part | Lathe | | | 1000 |
| 3 | lathe down one side to appropriate size for 0.79 in long | Lathe | | | 1000 |
| 4 | Deburr part to clean sharp edges | file | | | |


2
1
B
A
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Rigid 4000
FINISH
Burr Free
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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NAME
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Juliet F.
12/7/2020
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MFG APPR.
Q.A.
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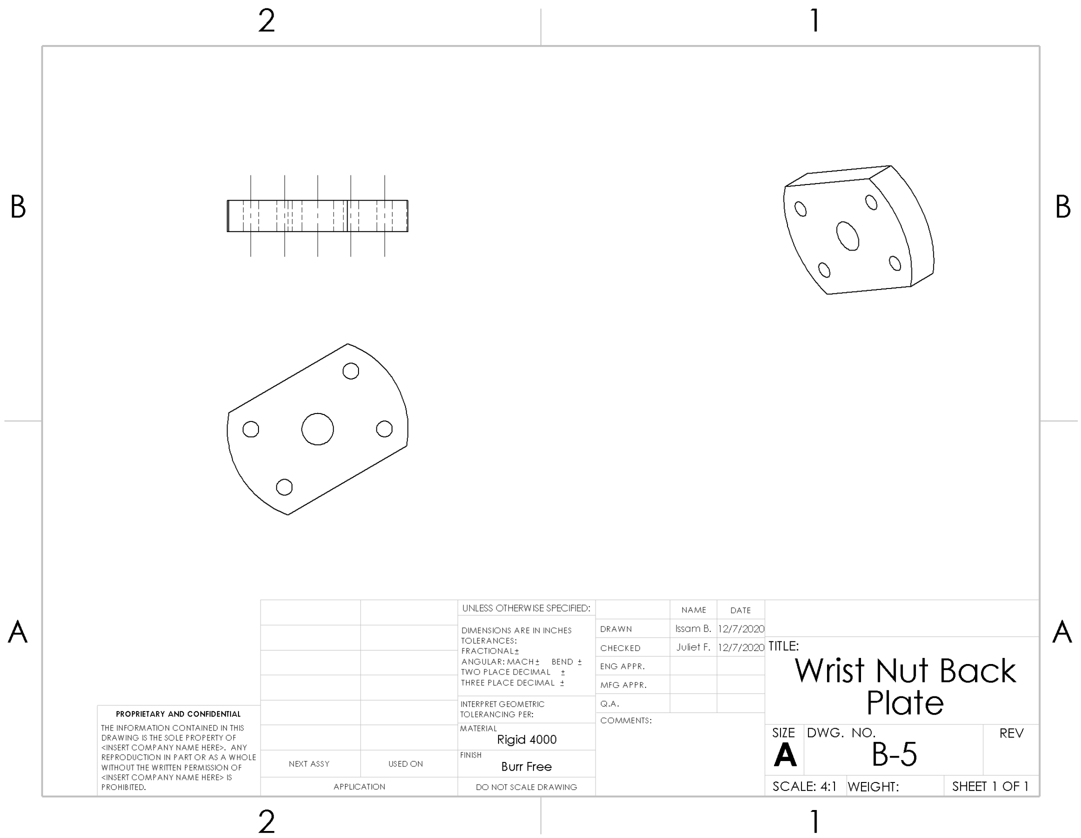
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COMMENTS:
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SIZE
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B-5
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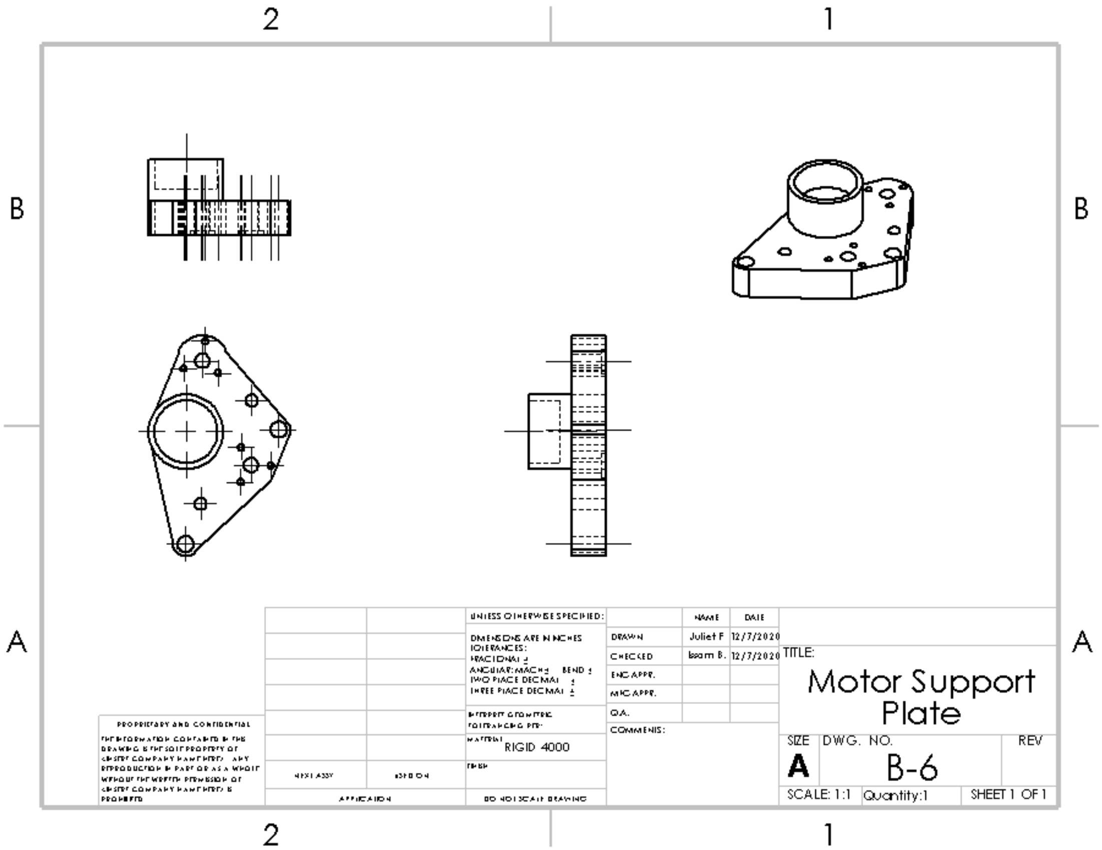

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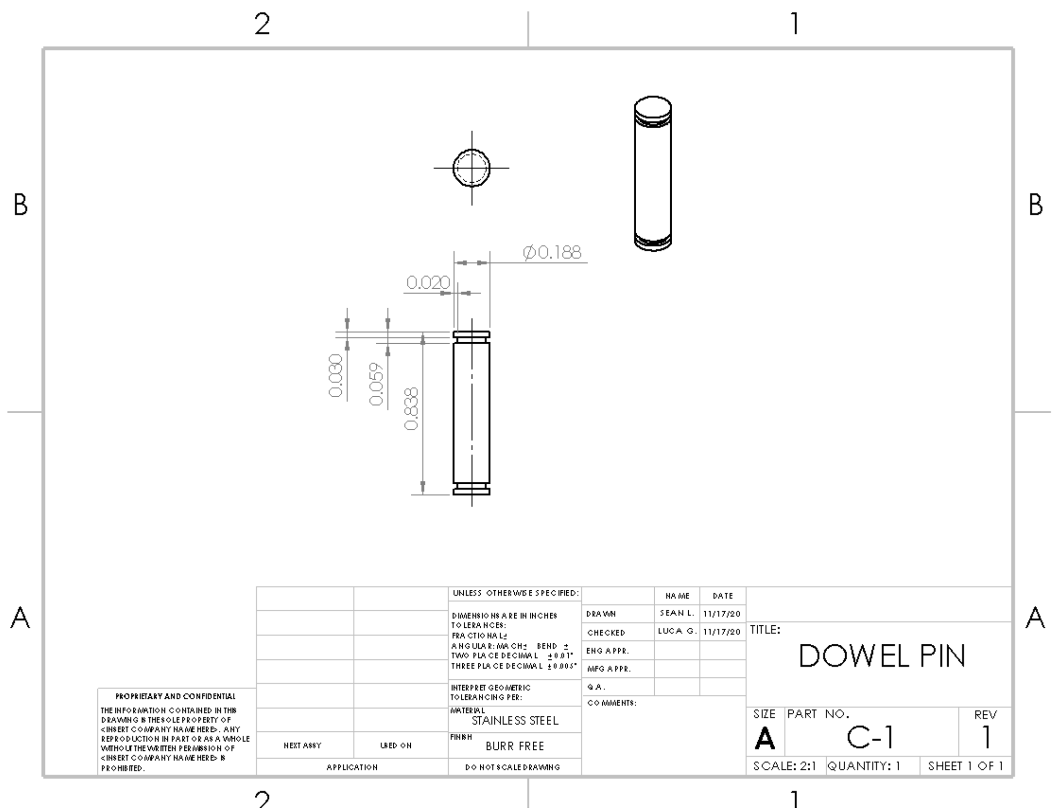


# Manufacturing Plan

**Part: Dowel Pin**

**Raw Material Stock: Stainless Steel**

| Step | Process Description | Machine | Fixture | Tool(s) | Speed (RPM) |
|---|---|---|---|---|---|
| 1 | Cut 3/16" dia. round stock to a length of about 1" | Band saw | Drill press vise | | 300 ft/min |
| 2 | Place part in the collet | Lathe | Collet | | |
| 3 | Face one side | Lathe | Collet | Turning tool | 840 |
| 4 | Face the other side | Lathe | Collet | Turning tool | 840 |
| 5 | Measure using calipers | | | Calipers | |
| 6 | Remove additional material to bring to final length of 0.838" | Lathe | Collet | | 840 |
| 7 | Use groove cutting tool to cut both grooves | Lathe | Collet | | 840 |
| 8 | | | | | |
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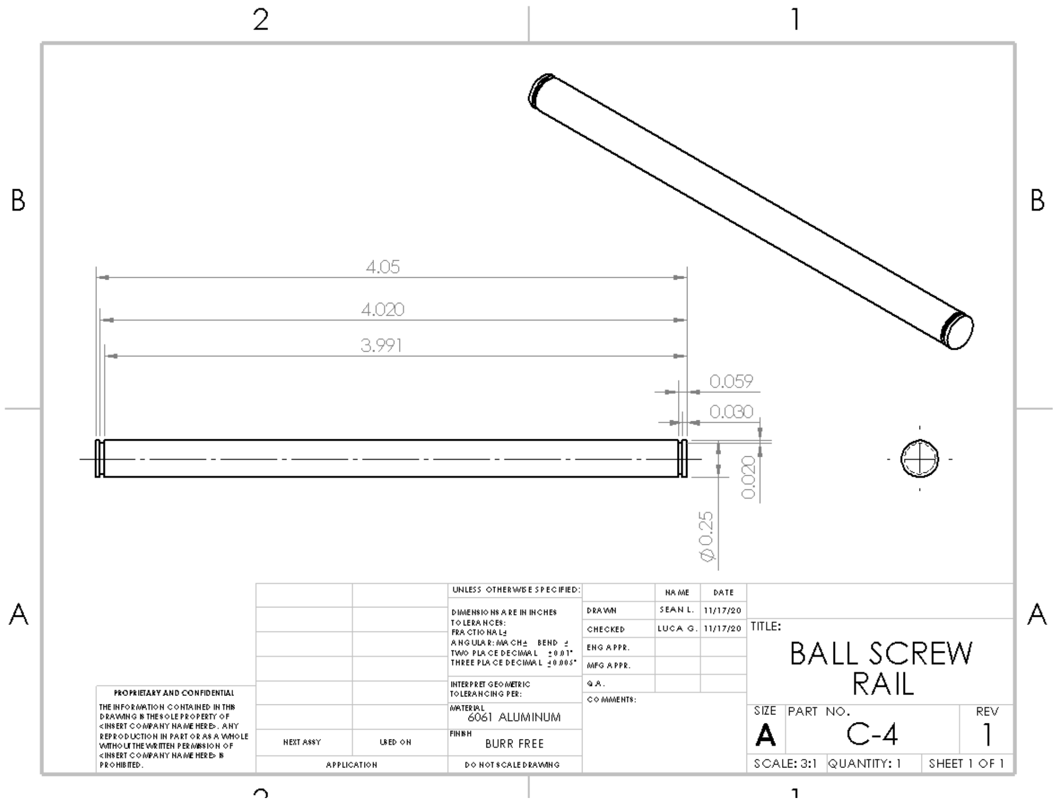


# Manufacturing Plan

**Part: Ball Screw Rail**

**Raw Material Stock: 6061 Aluminum**

| Step | Process Description | Machine | Fixture | Tool(s) | Speed (RPM) |
|---|---|---|---|---|---|
| 1 | Cut 1/4" dia. round stock to a length of about 4.25" | Band saw | Drill press vise | | 300 ft/min |
| 2 | Place part in the collet | Lathe | Collet | | |
| 3 | Face one side | Lathe | Collet | Turning tool | 840 |
| 4 | Face the other side | Lathe | Collet | Turning tool | 840 |
| 5 | Measure using calipers | | | Calipers | |
| 6 | Remove additional material to bring to final length of 4.05" | Lathe | Collet | | 840 |
| 7 | Use groove cutting tool to cut both grooves | Lathe | Collet | | 840 |
| 8 | | | | | |
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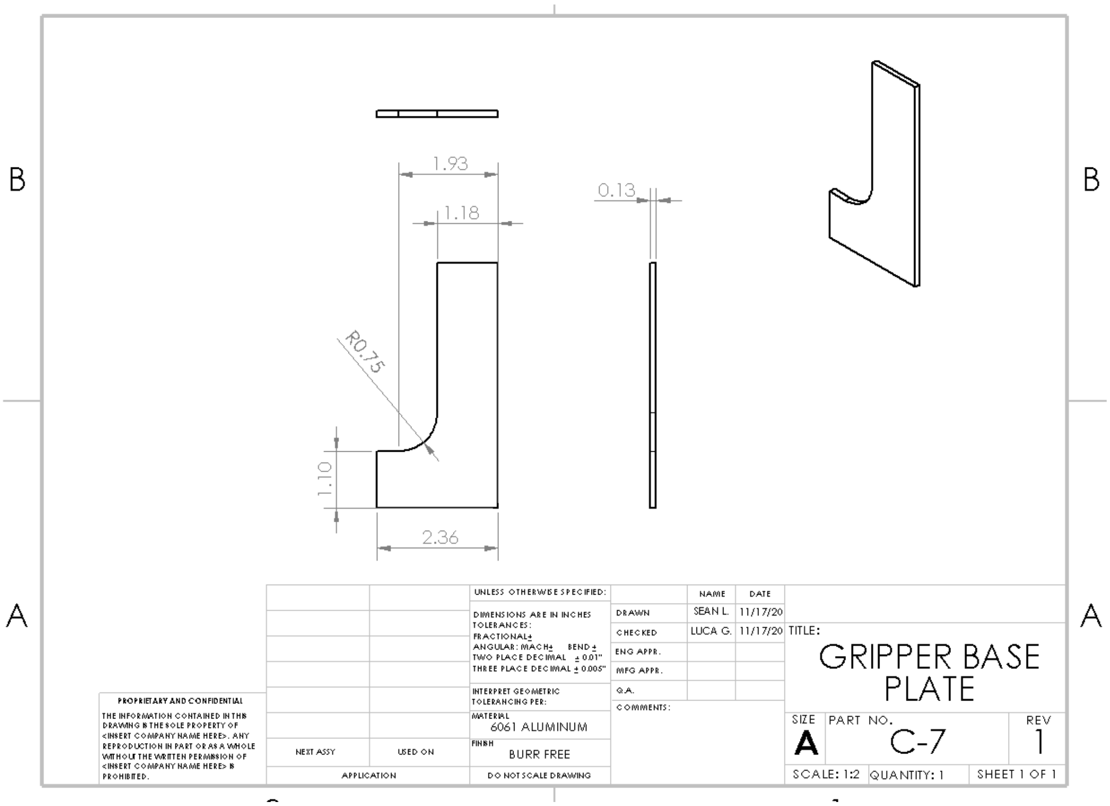


# Manufacturing Plan

**Part: Gripper Base Plate**

**Raw Material Stock: 6061 Aluminum**

| Step | Process Description | Machine | Fixture | Tool(s) | Speed (RPM) |
|---|---|---|---|---|---|
| 1 | Fron view is waterjetted | Waterjet | | | |
| 2 | | | | | |
| 3 | | | | | |
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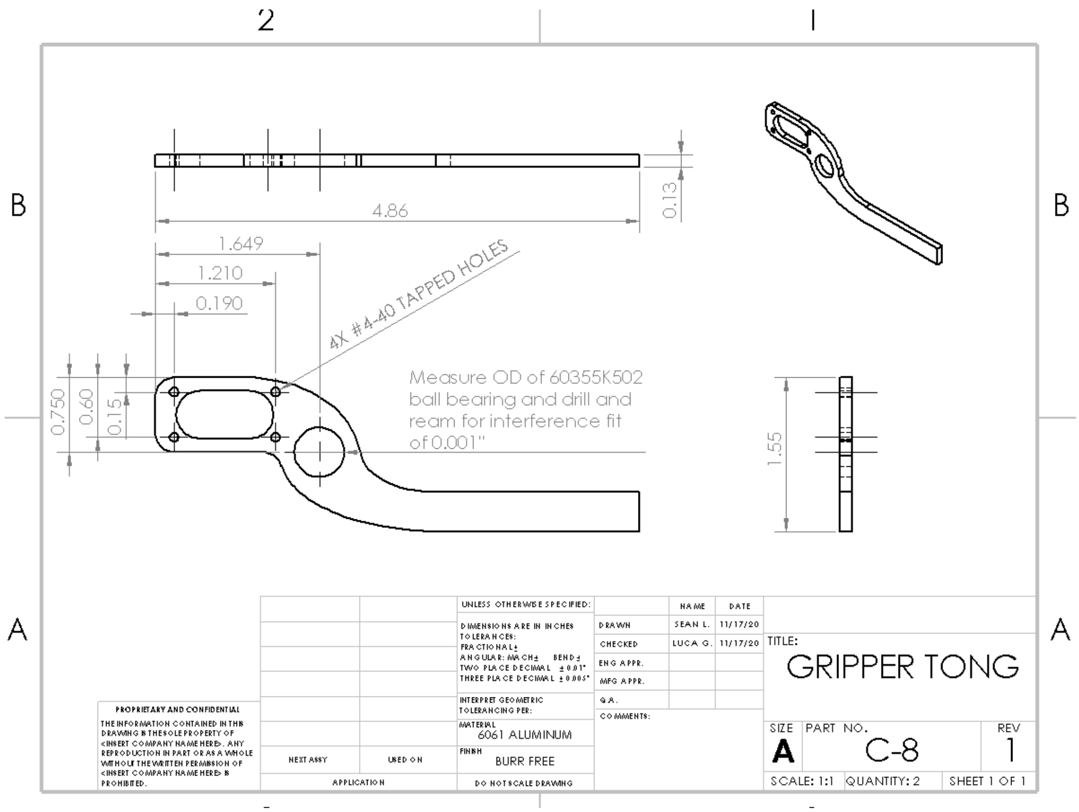


# Manufacturing Plan

**Part: Gripper Tong**

**Raw Material Stock: 6061 Aluminum**

| Step | Process Description | Machine | Fixture | Tool(s) | Speed (RPM) |
|---|---|---|---|---|---|
| 1 | Front view including slot is waterjetted | Waterjet | | | |
| 2 | Secure part to mill using dowels and toe clamps | Mill | Dowels and toe clamp | | |
| 3 | Install edge finder and drill chuck | Mill | Dowels and toe clamp | Edge finder | |
| 4 | Find datum lines for X and Y | Mill | Dowels and toe clamp | Edge finder | |
| 5 | Center drill all holes | Mill | Dowels and toe clamp | Center drill | |
| 6 | Drill the 4X #4-40 tapped holes with a #43 drill bit | Mill | Dowels and toe clamp | #43 drill bit | |
| 7 | Measure the outder diameter of the 60355K502 ball bearing and select appropriate drill bit | Mill | Dowels and toe clamp | Calipers, appropriate drill bit | |
| 8 | Ream hole for interference fit of 0.001" | Mill | Dowels and toe clamp | Reamer | |
| 9 | Tap the 4 holes using the #4-40 tap while the part is still on the mill | | Dowels and toe clamp | | |
| 10 | Take part off of mill and deburr all edges | | | Deburring tool | |
| 11 | | | | | |
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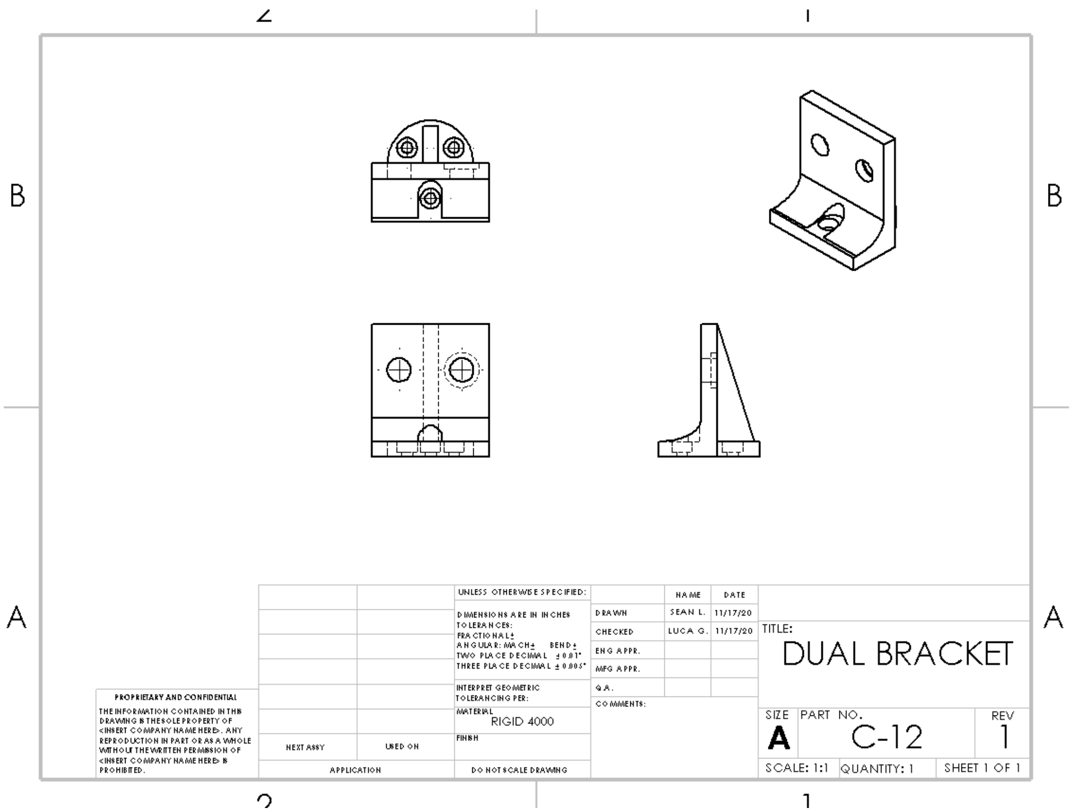
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ANGULAR: MACH± BEND±
TWO PLACE DECIMAL ±0.01"
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SEAN L.
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MFG APPR.
Q.A.
COMMENTS:
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
RIGID 4000
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NEXT ASSY
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APPLICATION
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SIZE
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PART NO.
C-12
REV
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SCALE: 1:1
QUANTITY: 1
SHEET 1 OF 1
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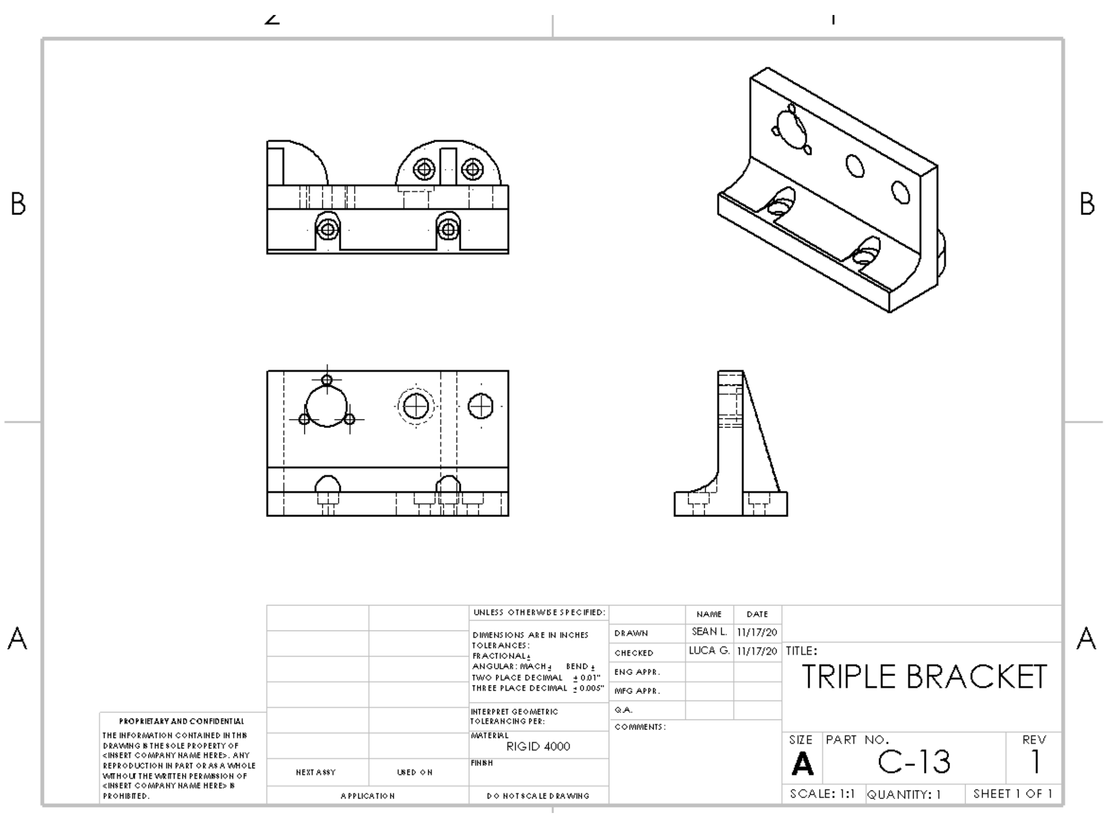
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SIZE
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PART NO.
C-13
REV
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SCALE: 1:1
QUANTITY: 1
SHEET 1 OF 1
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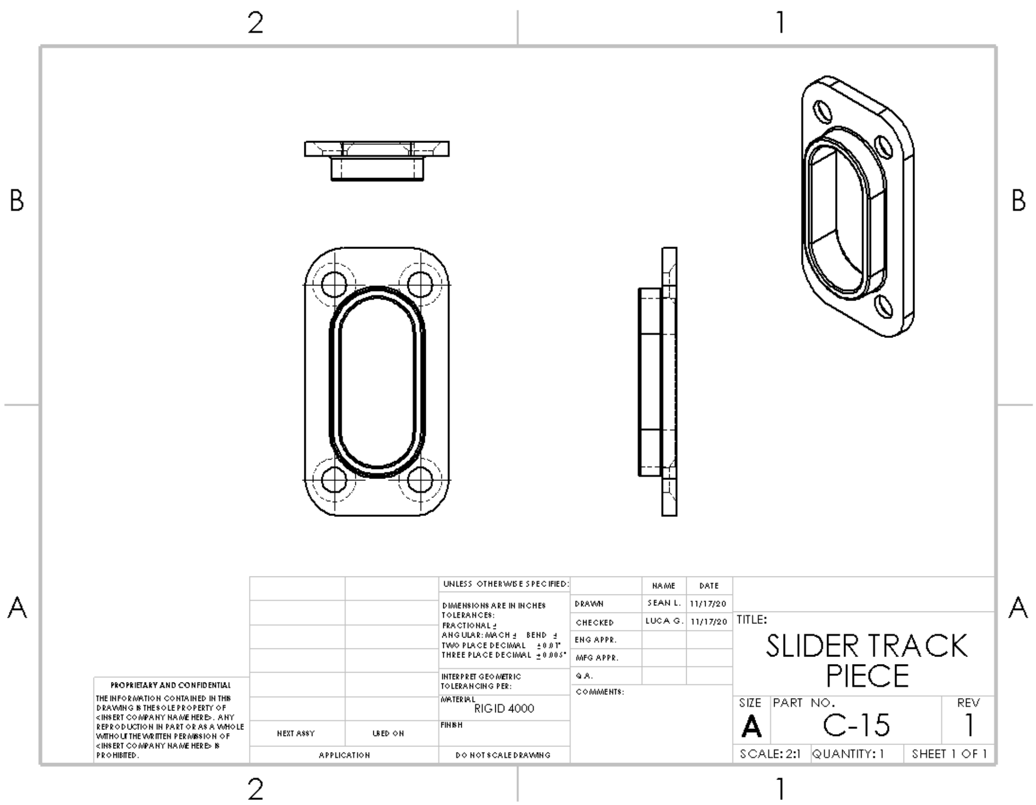

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ENG APPR.
MFG APPR.
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COMMENTS:
TITLE:
SLIDER TRACK PIECE
PROPRIETARY AND CONFIDENTIAL
MATERIAL
RIGID 4000
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USED ON
APPLICATION
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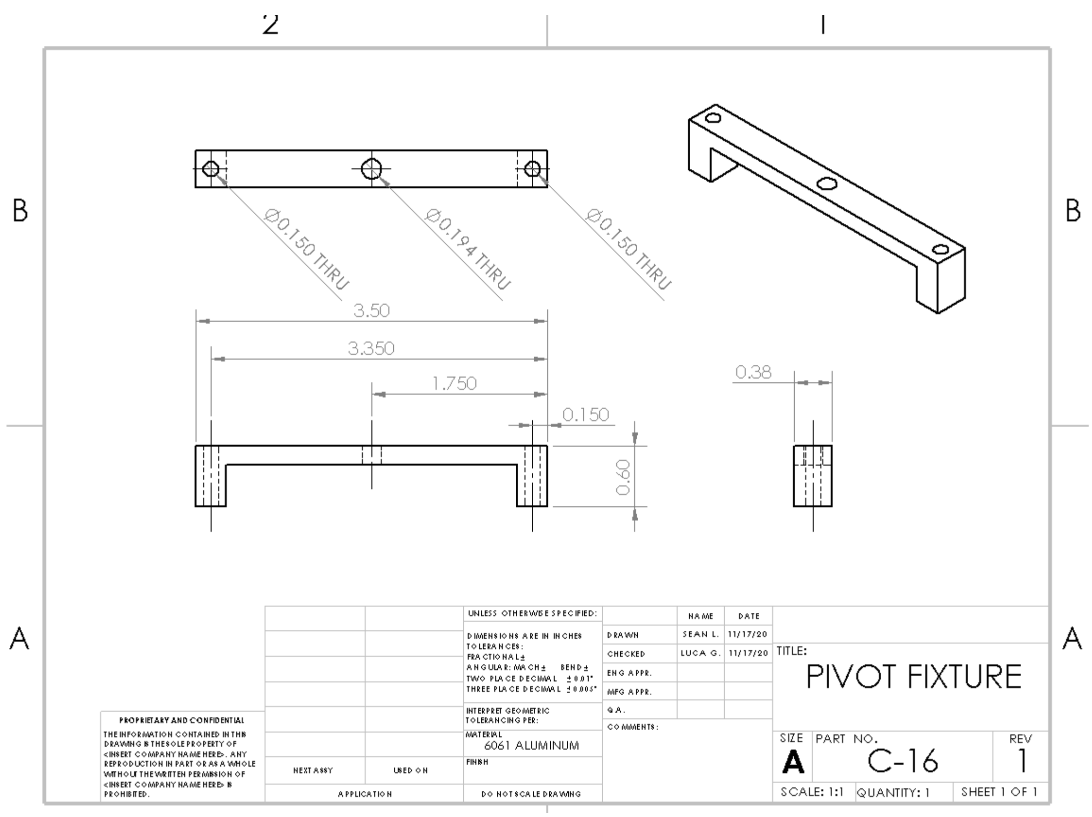
SIZE
A
PART NO.
C-15
REV
1
SCALE: 2:1
QUANTITY: 1
SHEET 1 OF 1

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Ø0.150 THRU
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LUCA G.
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ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
PIVOT FIXTURE
PROPRIETARY AND CONFIDENTIAL
MATERIAL
6061 ALUMINUM
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USED ON
APPLICATION
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SIZE
A
PART NO.
C-16
REV
1
SCALE: 1:1
QUANTITY: 1
SHEET 1 OF 1

# Manufacturing Plan

**Part: Pivot Fixture**

**Raw Material Stock: 6061 Aluminum**

| Step | Process Description | Machine | Fixture | Tool(s) | Speed (RPM) |
|---|---|---|---|---|---|
| 1 | Fron view is waterjetted | Waterjet | | | |
| 2 | Secure part to vise | Mill | Vise | | |
| 3 | Install edge finder and drill chuck | Mill | Vise | Edge finder | |
| 4 | Find datum lines for X and Y | Mill | Vise | Edge finder | |
| 5 | Center drill all holes | Mill | Vise | Center drill | |
| 6 | Drill the 2 x 0.150" dia. holes with a #24 drill bit | Mill | Vise | #24 drill bit | |
| 7 | Drill the 0.194" dia. hole with a #9 drill bit | Mill | Vise | #9 drill bit | |
| 8 | Take part off of mill and deburr all edges | | | Deburring tool | |
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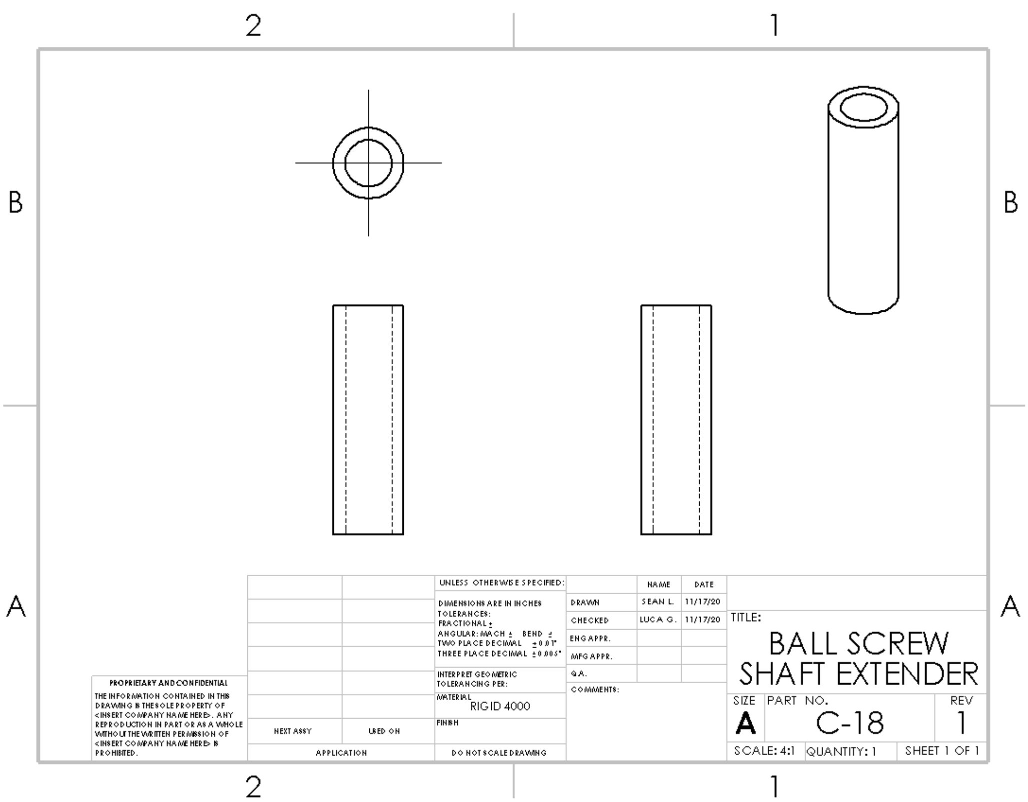

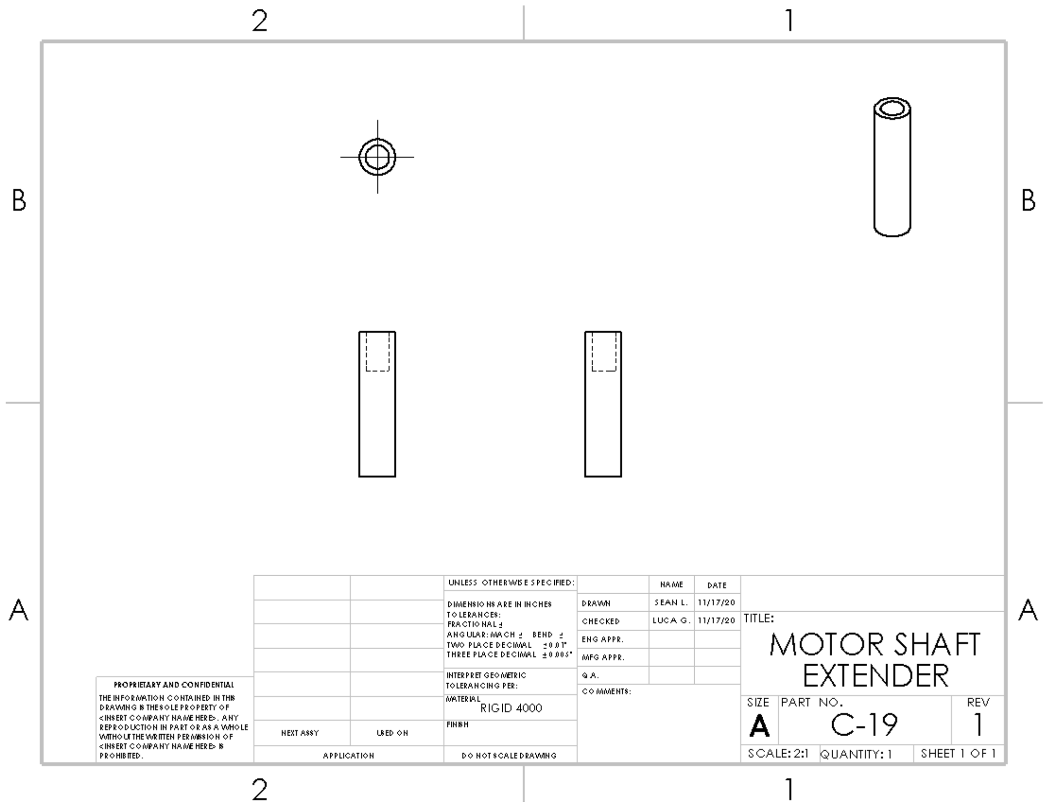

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ANGULAR: MACH ± BEND ±
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THREE PLACE DECIMAL ±0.005"
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MATERIAL
RIGID 4000
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LUCA G.
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ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
MOTOR SHAFT EXTENDER
SIZE
A
PART NO.
C-19
REV
1
SCALE: 2:1
QUANTITY: 1
SHEET 1 OF 1
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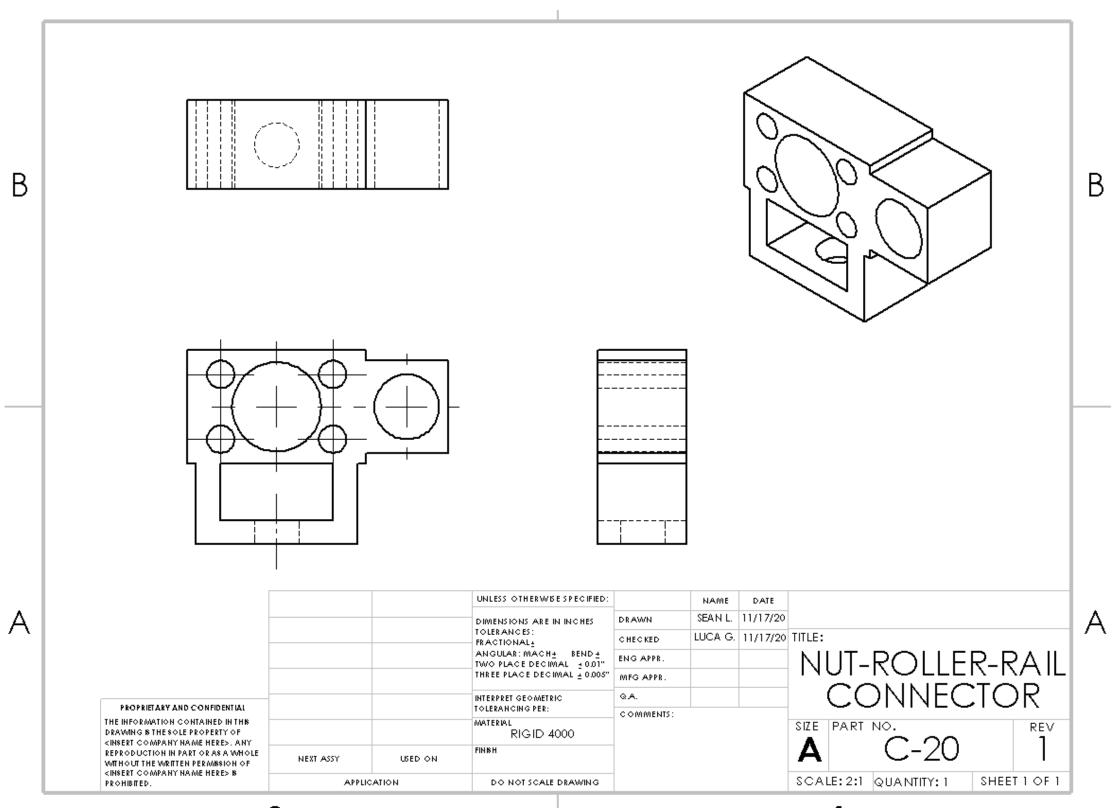

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**Appendix G - Bill of Materials**

| Subsystem | Part Number | Part Name | Material | Quantity | Supplier | Price |
|---|---|---|---|---|---|---|
| Wrist | B-1 | Wrist Base Plate | Rigid 4000 | 1 | --- | --- |
| | B-2 | 60645K970 Steel Ball Joint Rod End | Carbon Steel | 4 | McMaster | $7.50 each |
| | B-3 | SR0402 Ball Screw | Carbon Steel | 2 | KSS | $225 |
| | B-4 | Wrist Nut Sliders | Rigid 4000 | 2 | --- | --- |
| | B-5 | Wrist Nut Back Plate | Rigid 4000 | 2 | --- | --- |
| | B-6 | Motor Support Plate | Rigid 4000 | 1 | --- | --- |
| | B-7 | 18-8 Stainless Steel Threaded Rod, 8-32 Thread Size, 1/2" Long | Stainless Steel | 2 | McMaster | $10.09 / pk. 50 |
| | B-8 | GPX13M1KLSL25D0CPSC Planetary SP STE Ø13 mm, 2-stage | --- | 2 | Maxon | $351.90 each |
| | B-9 | 2664N419 Metal Gear - 20 Degree Pressure Angle | Brass | 2 | McMaster | $15.58 each |
| | B-10 | RS Pro 7906699 Universal Joint | Steel | 1 | Allied | $24.95 |
| | B-11 | A 1N 2-N32028 32 DP, 28 Teeth, 14.5° Pressure Angle Gear | Nylon | 2 | SDP/SI | $3.52 each |
| Gripper | C-1 | Dowel Pin | Stainless Steel | 1 | --- | --- |
| | C-2 | 6mm Ball Screw | Stainless Steel | 1 | Misumi | $200 |
| | C-3 | Ball Screw Nut | --- | 2 | --- | --- |
| | C-4 | Ball Screw Rail | 6061 Aluminum | 1 | --- | --- |
| | C-5 | 60355K502 Ball Bearing | --- | 2 | McMaster-Carr | $6.90 / ea. |
| | C-6 | 97431A280 Side-Mount External Retaining Ring E-Style | --- | 2 | McMaster-Carr | $4.15 / pk. 100 |
| | C-7 | Gripper Base Plate | 6061 Aluminum | 1 | --- | --- |
| | C-8 | Gripper Tong | 6061 Aluminum | 2 | --- | --- |
| | C-9 | 97431A300 Side-Mount External Retaining Ring E-Style | --- | 2 | McMaster-Carr | $5.77 / pk. 100 |
| | C-10 | 90107A011 Flat Washer | --- | 3 | McMaster- | $3.64 / pk. |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | | Carr | 100 |
| | C-11 | 6659K640 Oil-Embedded Flanged Sleeve Bearing | --- | 2 | McMaster-Carr | $2.05 / ea. |
| | C-12 | Dual Bracket | Rigid 4000 | | --- | --- |
| | C-13 | Triple Bracket | Rigid 4000 | | --- | --- |
| | C-14 | A1N2-N32028 Gear | Nylon | 2 | SDP | $3.52 / ea. |
| | C-15 | Slider Track Piece | Rigid 4000 | 2 | --- | --- |
| | C-16 | Pivot Fixture | 6061 Aluminum | 1 | --- | --- |
| | C-17 | Roller | --- | 2 | THK | |
| | C-18 | Ball Screw Shaft Extender | Rigid 4000 | 1 | --- | --- |
| | C-19 | Motor Shaft Extender | Rigid 4000 | 1 | --- | --- |
| | C-20 | Nut-Roller-Rail Connector | Rigid 4000 | 2 | --- | --- |
| | C-21 | 6391K127 Oil-Embedded Sleeve Bearing | --- | 2 | McMaster-Carr | $0.80 / ea. |
| | C-22 | ECXSP16L Motor with GPX16 Gearhead | --- | 1 | Maxon | $400 |

**Appendix H - Engineering Standards**

Engineering standards help improve quality, increase safety, and aid in interfacing different systems. However, this project did not make use of any standards. We researched standard databases using University of Michigan's Art, Architecture, and Engineering Library in the hopes of finding some relevant standards for our engineering analyses, such as our bolt analysis, but were unable to find any standards that were of use to us. Our main focus for this project was the engineering analysis for the prosthesis design, as opposed to the implementation of said prosthesis because this prosthesis is intended to be a single prototype design in a series of projects. Therefore we did not do extensive research into standards regarding the sale and use of prostheses by the public. If this were our object, we would conduct research into Association for the Advancement of Medical Instrumentation (AAMI) standards.

**Appendix I - Engineering Inclusivity**

Our project aims to help individuals with hand and wrist amputations. To ensure that our decisions honored the guidelines of inclusive design, we opted to create a device that responds to the greatest need. According to data from 2005 on upper limb loss in the United States, men accounted for 1,026 amputations, while 542 amputations were performed on women. Furthermore, the age group 18-65 accounted for more than half of the total amputations. [31] For these reasons, our target group is adult men. Based on this, the values that steered our design were taken from average adult male hand and wrist dimensions, mobility statistics, and strength measurements. We acknowledge that our design is not unisex, but are proud to tackle the health issue where it is most severely manifested. Other than aiming for the largest audience, we collaborated with a prosthetist who works at the University of Michigan hospital. She has worked with many amputees and gained professional insight on what typically leads to a successful implementation of a prosthesis. While we didn't work with any amputees personally, Diemer's knowledge provided us with directions to take our design that we otherwise would not have been aware of. It should be mentioned that Diemer's insight may be more valuable than that of a potential product user, given that our design only exists in electronic form, and it would have been very difficult to collaborate with anyone in-person due to social distancing. We hope to be working with amputees in the future, and our project will then take into account the opinions of those primary stakeholders who may end up using a device like ours.

**Appendix J - Environmental Context Assessment**

Our project does make significant progress toward the unmet goal of a 3-DOF prosthetic device, which would vastly improve the quality of life for amputees desiring similar mobility to what they once had. Achieving this goal would help close the gap of accessibility between individuals with upper limb amputations and healthy individuals. A fully functioning system as we expect it to look in its final form should mimic the movements of the human wrist without weighing more than the flesh and bone counterpart. A potential undesirable consequence of the product's success would be the expectation that amputees must replace their limbs with prosthetic alternatives. This could become a toxic point of view in the disabled community, where "owning" one's disability is often seen as admirable. As for the ecological impact of our system, there are a number of factors at play that minimize the $CO2$ emissions and energy created by the manufacturing of our product. Large portions of the structures within our system are 3D printed, which is a very energy efficient method to fabricate high-strength parts. The motors that are used to power the device are high-efficiency, small motors that require very small amounts of electrical energy. If the device pushes beyond the prototype stage, there is a high likelihood that it will be adopted for its low resource requirements, and hopefully, exceptional ease of use and high performance.

**Appendix K - Social Context Assessment**

The social context assessment should be prefaced with the reiteration of our design object, which is that this objective of this project is to produce a single prototype to show the feasibility of a 2 DOF wrist with a gripper that will allow the patient to easily grasp a variety of objects. The prosthesis is not likely to be adopted by the market due to the relatively high cost and the in-progress state of the design. The low demand for prostheses among the general population is likely to prevent the system from being so successful economically that planetary systems will be worse off. Prostheses are generally resilient to disruptions in business as usual because there is always a steady demand by patients for prosthetic devices. One event that might disrupt the market is a sudden loss in wealth or an economic depression. If people have less money, they might opt to forgo a prosthesis, or to purchase a cheaper, static prosthesis that does not have powered actuation.

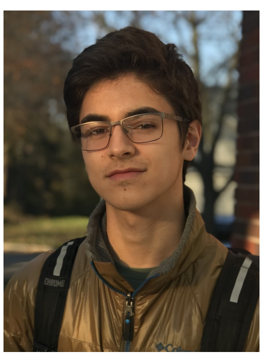
**Appendix L - Ethical Decision Making**

Ethics are at the core of an engineer's work. It inspires confidence among both our colleagues and our stakeholders that we are abiding by a professional code of conduct. All work during this project adhered to the ASME Engineering Code of Ethics [30]. The primary ethical consideration in this project is that the user is entrusting the engineers with ensuring the safety, capability, and durability of the prosthesis. The intended market is not expected to have a background in engineering or design, so it is up to the engineers to provide a quality prosthesis and to be truthful about the relevant information pertaining to the design. As detailed in our Risk Assessment, we have done our best to be truthful about all known risks and modes of failure. One ethical dilemma that this project ran into was that an unenclosed design presented multiple safety. By not including an outer housing in our prosthesis design, we could achieve a lower total weight. However, this would leave the user exposed to risks such as pinch points, as well as exposing the internal components to the environment resulting in increased wear from dust particles, moisture, and impacts. We resolved this dilemma by opting to include a lightweight carbon fiber housing in our plans for this prototype, though we were unable to incorporate the housing into our CAD model at this stage. We discussed this option with resident prosthetist Megan Diemer to better understand how similar methods are used in the fabrication of custom prostheses.

## AUTHORS

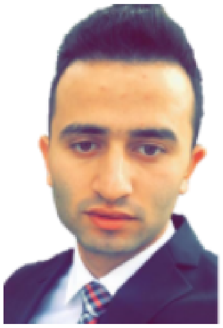
**Issam Bourai, BS (exp. 2021)**
Born in Seattle, WA and raised in Santa Clara, CA, Issam began working on design projects in high school, where his involvement in FIRST Robotics enabled him to learn about engineering in a hands-on environment. Deciding to continue on this path, he decided to enroll at the University of Michigan to study Mechanical Engineering. His areas of experience are applications of solid mechanics and materials engineering, especially in medical devices. Issam is graduating from the University of Michigan in May 2021 with a BSE in Mechanical Engineering with a minor in Materials Science and Engineering.

**Juliet Foote, BS (exp. 2021)**
Juliet was raised in Okemos, MI and was originally accepted into the University of Michigan School of Literature Science and Arts to pursue mathematics and chemistry. After learning of all the incredible opportunities in engineering both at the University of Michigan and in professional life, Juliet chose to transfer to the College of Engineering to pursue Mechanical Engineering, a decision she has never regretted and believed has allowed her to pursue her passion of linking science and creativity in engineering design. Juliet is graduating from the University of Michigan with a BSE in Mechanical Engineering in May 2021.



**Luca Geralds, BS (exp. 2021)**
Raised in New York City, Luca attended Fiorello H. LaGuardia Performing Arts High School as a technical theater major. Here, his lifelong inclination toward mechanical creations and ideas came together through the design and building of large-scale theatrical scenery elements, props, and lighting systems. Becoming very comfortable with power tools of all varieties in LaGuardia's wood shops, Luca felt right at home at the machine shops at the University of Michigan. Initially heartset on biomedical engineering, he still plans on working in this field, but found that mechanical engineering provides the best route to the type of roles he hopes to fulfill in the field of medical device development.

**Sean Lusky, BS (exp. 2021)**
Sean was raised in Sterling Heights, Michigan. He knew he wanted to major in a math or science related field by the time he had finished middle school. He has strong interests in manufacturing processes, product design, and sustainability. Outside of the classroom he enjoys learning history, reading books, camping, and boating. Sean is graduating from the University of Michigan with a Bachelors in Mechanical Engineering in May 2021.



**Maurice (Mo) Miro, BS (exp. 2021)**

Raised in Damas suburb, Syria. He discovered his passion for design after the first design class he completed at U of M. His main area of research is prostheses design. As a Research Assistant at the Neurobionics Lab, he improved the design of the open-source leg (OSL). Before joining the Neurobionics Lab, he interned as a Mechanical Engineer at Meritor in Troy, MI to improve the design of the 4200 transfer case series. Outside of school he enjoys working on cars, mountain biking, playing soccer and reading. Mo is graduating from the University of Michigan with a Bachelors in Mechanical Engineering in May 2021.

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