Mech 488 - 152
KINEMATICS AND MACHINE DESIGN LABORATORY
LABORATORY REPORT FOR LAB #4

PROSTHETIC KNEE JOINT DESIGN PROPOSAL

Prepared for
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Abstract

The knee complex naturally embedded in human anatomy joins the femur, tibia, fibula, and patella through the patellofemoral joint and the tibiofemoral joint. A healthy knee joint complex allows locomotion with minimum energy requirements from the muscles and stability, accommodating for different terrains. By biomedical standards, the knee complex also transmits, absorbs, and redistributes forces caused during the activities of daily life. Kinematic studies show that the knee joint allows for six degrees of freedom; three rotations and three translations. Rotations within the natural knee joint allow for up to 160 degrees of flexion-extension, 6-8 degrees of varus-valgus extension, and 25-30 degrees of internal-external flexion rotation. As for translation, the knee complex allows for approximately 5-10 mm of anterior-posterior, 2-5 mm of compression, and 1-2 mm of medio-lateral translation. Through the advancements of biomedical engineering led by mimicking human kinematics, prosthetics have been developed to replace the knee joint without losing functionality or range of motion. The purpose of this initial report is to detail and justify the design of a prosthetic knee and also provide a bill of materials required to produce a functioning prototype. The goal of the project is to develop a prototype that will act as a baseline design for a knee complex that can be developed into an embeddable human prosthetic that maintains the required structural integrity and factors of safety at a reasonable cost.

Table of Contents

Introduction

Prosthetics have been intertwined in human history dating back to the ancient Romans and Egyptians. Through the 1500s to the 1800s human prosthesis became more popularized due to more widespread warfare. It wasn't until the American civil war that major technological leaps were made in prosthesis by trying to mimic human motion rather than just providing placeholder limbs. Through the 20th century, as the studies of kinematics and biomedical engineering became more intertwined, prosthetics made major advancements. Noted inventor Ysidreo M. Martinez changed the trajectory of prosthetics in the 1970's as he shifted the focus of his work to improving gait and reducing friction rather than just attempting to replicate the motion of natural limbs. Today, prosthetics combine aesthetics, wholeness, and function in an attempt to normalize prosthetic patients' lives as much as possible. Considering modern advances within the scope of this project requires that engineers not only focus on the kinematics and force requirements of a knee joint but also the element of human integration. To effectively accommodate those in need of prosthetics, the knee joint presented in this report should meet engineering requirements, appear aesthetically, and come at a low price point.

Methods

Design

In the genesis of the prosthetic knee design, considerations were made for both a four-bar mechanism and a rolling cam mechanism. Using a cam mechanism offers advantages through its compact and simple design, but disadvantages appear based on the necessary accuracy of cam machining and the regulation of motion. Adversely, a four bar mechanism does not require the same degree of machined accuracy and also offers substantial reliability and low maintenance. Based on these arguments and comparing first drafts of designs, a decision was made to proceed with a compact four-bar mechanism.

The four-bar design is popularly used in knee joint prosthetics because the linkages mirror the anatomical components of the human knee. For reference, the base link imitates the tibia and fibula which connects the knee to the lower portion of the leg. The crank link represents the tibiofemoral joint which attaches the femur and tibia and drive the majority of the motion within the knee complex. The coupler link is located at the top of the knee complex and imitates the motion and properties of the femur bone in the upper leg. Lastly, the follower link functions as the patellofemoral joint by providing protection and limiting mobility similar to the human function of the patella. The follower links allow for the complete design to be more compact due to their curved nature. The radius of the curve was also a major design focus because the curvature is intended to limit the flexion as the knee is bent - a larger radius allows for greater range of motion and a smaller radius more strictly limits the range of motion.

Designing the knee complex based on realistic kinematic function requires a knowledge of the functional range of motion (ROM) of a human knee. Based on figures presented in class, different activities require different ranges of knee flexion. Designing our prototype to a high degree of usability, a flexion of 109 degrees was achieved. This allows for all normal activities to be performed and also features a few degrees of hyperextension, similar to a real knee. If desirable, further adjustments in knee design to achieve a better range of motion will only require a change of radius in the follower link.

The regulation of motion was an important aspect at the forefront of the design process. The goal was that the prosthetic joint would individually regulate its range of motion rather than relying on linear actuators/regulators in other regions of the prosthetic leg (i.e., calf or thigh). As the theoretical leg is extended the prosthetic knee is held at an acceptable degree of hyperextension by an extrusion on the outside of the coupler link. Once the knee is bent the joint must be regulated in the other direction in order to prevent an unnatural range of motion. Here, the flexion is regulated as the internal diameter of the curved follower is stopped by the extruded head of the central thin head socket screw responsible for connecting the base and crank links.

Through several drafts the goals of the design came to fruition but still required material and fastener specifications. The design requirements indicate that the joint must function under the weight of a 250 lb male; therefore, to promote strength and cost effectiveness, it was decided that the links of the mechanism would be 3D printed with PETG filament. Fastener selection was based on tolerance and fits of the pivot points and will be discussed more in the results section of this report. Lastly, in order to best promote an adaptable solution, considerations were made to reduce friction as much as possible without severely increasing the price of production. To do so, dry-running flange sleeve bearings were integrated into the design to add structural support at pivot points while drastically reducing the contact friction during motion.

Analysis

The analysis of the knee joint prototype was based on the loads experienced in the knee of a 250 lb. man. This load was determined by the parameters of the project and was projected onto the knee through digital FEA software. Initial experimentation was used to determine how the forces would distribute throughout the four bar linkage and whether or not the distribution was concurrent with the force distribution in a natural knee joint. The FEA study also functions as a static and kinematic stress investigation - highlighting points of high von mises stresses, factor of safety, and deformation. The FEA studies were done in several configurations, at maximum, minimum and midpoint knee joint flexion.

Additional measures were made to explore the range of potential of the artificial knee. In order to understand what magnitude of forces are applied to the knee during strenuous activity, research was done to find the peak loadings within the knee joint during vertical jumping and push jerking. According to a study done by the National Library of Medicine findings concluded that, “The knee experienced mean peak loadings of 2.4-4.6 × body weight at the patellofemoral joint, 6.9-9.0 × body weight at the tibiofemoral joint, 0.3-1.4 × body weight anterior tibial shear and 1.0-3.1 × bodyweight posterior tibial shear” [1]. In order to prove the integrity of the artificial knee under abnormal stresses, the FEA studies were done at five times the given body, or 1250 lbs. of force.

During testing, the ground link (link attached to the lower leg) was fixed from the inside of the curvature and the vertical flat face. The applied force was then assigned to be distributed evenly across the two-coupler links along the top of the joint (links attached to the upper leg). With these parameters set within our FEA analysis, the studies were run and results are provided in the following section.

Results

Design

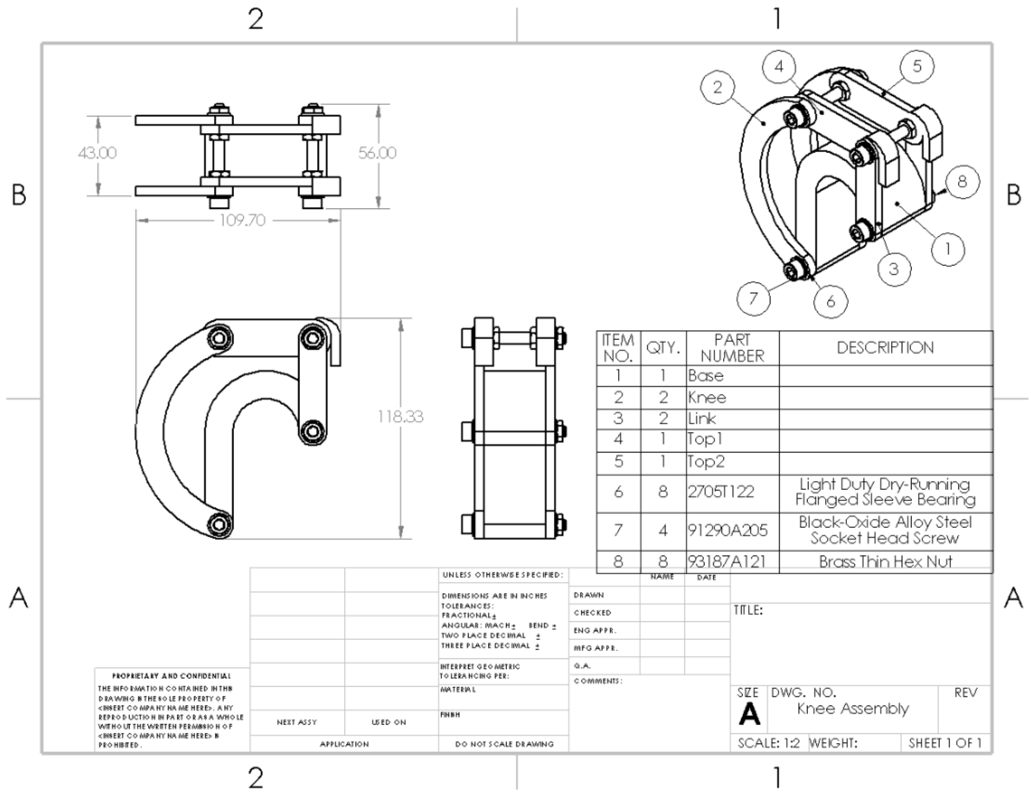

Figure 1: Assembly drawing of knee design.

Shown in Figure 1 is the finalized prototype design of our knee mechanism. The design incorporates a 4 bar linkage mechanism to achieve the desired range of motion. Item 1, is our base component as it was modeled as our fixed component. This part is the part that would attach to the “calf” of the user. Item 2, is our “kneecap” for aesthetic reasons and also functions as our stopper for the knees range of motion. When the mechanism is rotated to an angle of 109 degrees, from a base angle of 0 degrees when upright, the inner part of the knee hits item 3, our link. Item 3, is one of our linkages, it additionally, serves as our stopper for our range of motion in conjunction with items 4 & 5. This stops our knee from hyperextending past our 0 degrees upright by the catch on parts 4 & 5 hitting the side of our link, item 3. Items 4 & 5, are our tops which would attach to the user's “thigh”. This could’ve been achieved via a singular part but since we are 3D printing the prototype, it was split into 2. This was to simplify the printing process and not require the use of support material. The thickness of the parts except for the base was determined by the flanged sleeve bearings so as to be able to mate 2 parts with one. The thickness of the base was determined from the length of our screws so as to minimize the tail of the screw past the nut. The outsourced parts from McMaster, the bolt, nut and flanged sleeve bearing were chosen to minimize the cost and complexity of the design.

Bill of Materials

The Bill of Materials (BoM) for the knee prototype can be seen below in Figure. For this prototype, $50 was allotted for McMaster Carr parts as well as a $25 budget for 3D printed materials. As seen in the BoM for this prototype, all parameters fall well within these budgetary constraints. Due to this initial drawing package being a prototype, more cost efficient parts were chosen for assembly and rotational movement. A more complex linkage mechanism including bearings or properly machined materials will be chosen for the final design package in order to ensure a comfortable fit and movement for the consumer's knee. The gram quantity for PETG material used in 3D printing is an initial estimate using a 3D image slicing software; PETG material was chosen as well as using the design's dimensional constraints to obtain the cost for these parts. All designs are initial and will be reviewed and properly adjusted as material is chosen as the final product is revised and completed.

Prosthetic Knee Joint						
Alex Briones, Thomas Simon, & River Kramer						
Part Title:	**Part #**	**Part Link:**	**Pcs/Pkg:**	**Quantity:**	**Cost/Qty:**	**Cost:**
Alloy Steel Socket Head Screws	91290A205	https://www.mcmaster.com/catalog/128/3410	10/Pkg.	1	$7.58	$7.58
Metric Brass Thin Hex Nuts	93187A121	https://www.mcmaster.com/catalog/128/3504	10/Pkg.	1	$4.57	$4.57
Light Duty Dry-Running Flanged Sleeve Bearings	2705T122	https://www.mcmaster.com/catalog/128/1338	1/Pkg.	8	$1.58	$12.64
3D Printed links for 4-Bar	N/A	https://cloud.3dprinteros.com/#/projects/projects	1 gram	66	$0.07	$4.62
					Total Cost:	$29.41

Figure 2. Initial Prosthetic Knee Prototype Bill of Materials

Part	**Quantity**	**Reference**	**Price**
6M Socket Head Screws	1 Pkg. Pkg. Qty: 10	Alloy Steel Socket Head Screws (Part #: 91290A205)	$7.58/pkg.
6M Thin Head Hex Nut	1 Pkg. Pkg. Qty: 10	Metric Brass Thin Hex Nuts (Part #: 93187A121)	$4.57/pkg.
Dry-Running Flanged Sleeve Bearing	8 pcs.	Light Duty Dry-Running Flanged Sleeve Bearings (Part #: 2705T122)	$1.58/pc.
PETG Filament for 3D Print	60 grams	3D Printed links for 4-Bar	$0.07/gram

Figure 3. Chart for Organization of McMaster and 3D Print Orders

Once the prototype is reviewed and agreed upon, a final design concept will be decided upon. This final design will require a complete review of material type, overall part dimensions, product cost, and safety factor of the prosthetic based upon FEA's run under general loading conditions. The material type will be decided upon based on three general factors; these include loading capabilities of materials chosen, cost of these materials, and the materials biocompatibility with the human body. Part dimensions will also be driven by the general loading conditions as well as material type to ensure the part will not fail under human loading conditions. These are assumed to be five times the human body mass for this application. As mentioned prior, product cost will be driven primarily by material choice, but a general estimate for manufacturing as well as fasteners to assemble this part will be factored in. Finally, the FEA results will be used to ensure that all choices from above result in a prosthetic with a factor of safety much greater than one to ensure longevity and user comfort for the user's lifetime.

Analysis

For the analysis and actual deployment of knee replacement we will be doing so with proven medical grade materials. For the linkages and fasteners, we will be using Ti-6Al-4v, an alpha-beta titanium alloy with a high specific strength and excellent corrosion resistance. For the bushings mating the fasteners and linkages together we decided on high density polyethylene which has a high strength to density ratio as well as being corrosion resistant.

For our Finite Element Analysis (FEA), we choose three positions over the range of motion of our knee. They are shown in the following 3 figures of the factor of safety, von mises stress and displacement. On the left-hand side shows the knee in its standing position. In the middle shows the knee halfway through its range of motion. Lastly, on the right shows the knee in its sitting position. Additionally, the analysis was done with a loading of 1250 pound-forces which would simulate the extreme case of loading on the knee. With the loading being applied to the larger cane shaped linkage which would attach to the calf and the fixed link being the shorter linkages which would attach to the femur.

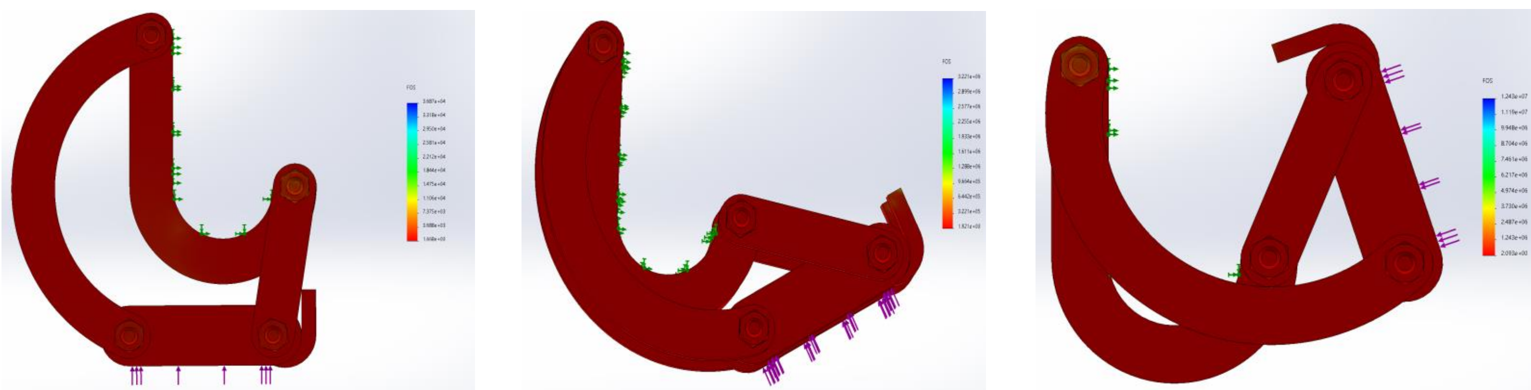

Figure 4: Factor of Safety over a range of motion

For our knee over the range of motion from standing and sitting we see minimum factors of safety of 1.668, 1.921 and 2.093 which are more than adequate considering the loading applied during the FEA. We additionally see a uniform factor of safety across the knee in all three ranges of motion.

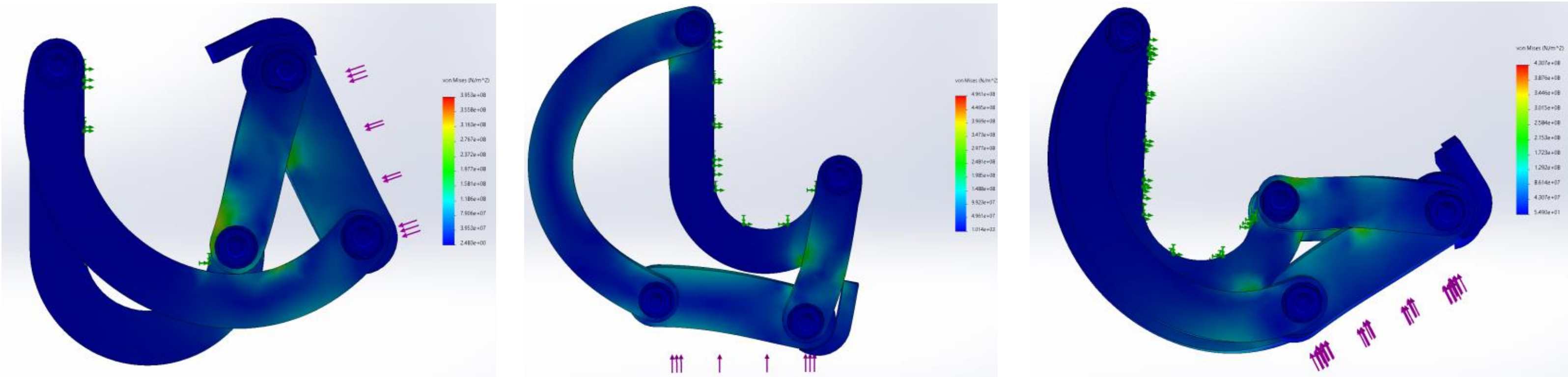

Figure 5: Von Mises Stress over a range of motion

For our knee over the range of motion from standing and sitting we see maximum von mises stress of 395 MPa, 496 MPa and 430 MPa which are quite high but adequate considering the loading. We also see a fairly uniform von mises stress of 2.5 Pa, 1 kPa and 55 Pa respectively. Additionally, we see spots of higher stress mainly at the connection between the fastener and the linkages. They are seen in green in figure 5 with the values being approximately 200 MPa, 250 MPa and 250 Mpa.

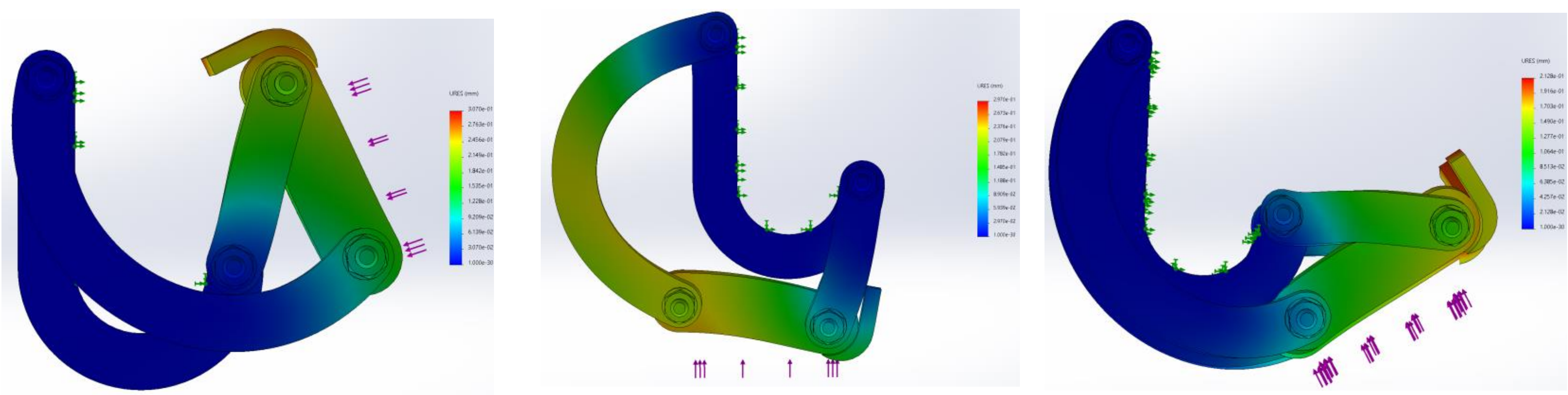

Figure 5: Displacement over a range of motion

For our knee over the range of motion from standing and sitting we see maximum displacement of 0.31 mm, 0.3 mm and 0.21 mm. The maximum displacement is mostly seen at the connection between the wing and crank link. We see fairly uniform displacement shown in dark blue on the sugar cane shaped linkage 1*10^-10 mm which is our minimum.

Discussion

Throughout the design, dimensioning, cost tracking, parts ordering, assembly, testing, and analysis of the artificial knee, our team of engineers feels comfortable recommending our final product as a functional first prototype that should be used for continuous improvement. The knee joint functions seamlessly while opening. The closing motion of the knee is also smooth and only has marginal error when the movement of the crank link is snagged by the outer edge of the ground link. This problem could easily be solved in further prototyping by rounding out the square edges of the ground link where it causes interference. The finished prototype also features rounded crank and ground links. The shapes of these links not only emulate the protective nature of the natural kneecap, but they also allow for a more compact four bar that can still achieve 109 degrees of motion. The use of bushings, or sleeve bearings, is an integral component within our prototype that drastically reduces the friction within the joints. It is recommended that the bushings are included in future prototyping. The selected hardware has also proved to be reliable throughout the testing of the prototype. All materials purchases in an effort to achieve a prototype came in under budget.

As for the analysis of the knee joint, each series of exaggerated stress testing concluded acceptable results that lead our engineering team to believe that the artificial knee will confidently withstand all normal conditions. Throughout the full range of motion, the maximum factor of safety experienced is 2.093. This factor of safety is acceptable for reliable materials where severe loadings and conditions are not present. The results of the Von Mises Stress tests feature no concerning stress concentrations and fail to exceed 250 MPa. The curvature of several of our links and the lack of notches helps distribute loads and minimize yielding. These results for induced stresses are acceptable. Lastly, the results of the displacement testing simulation indicate that deformation due to 1250 lbs. of force will be no more than 3 mm. This result is acceptable for a first prototype, but our team recommends that materials engineers explore options other than titanium for the artificial knee joint.

References

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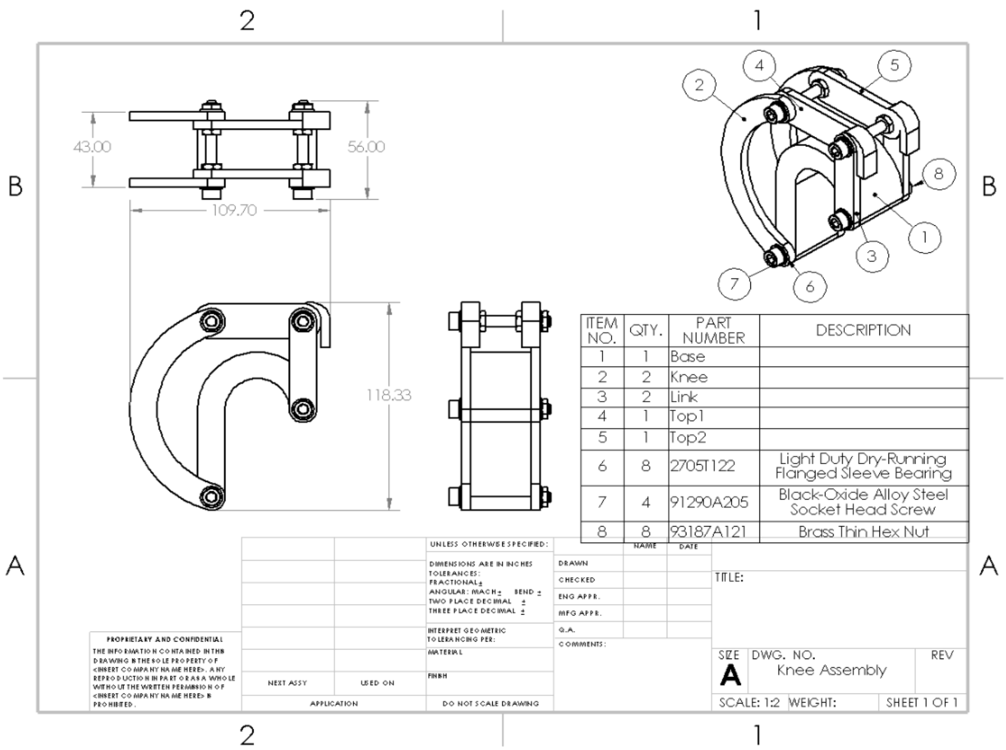
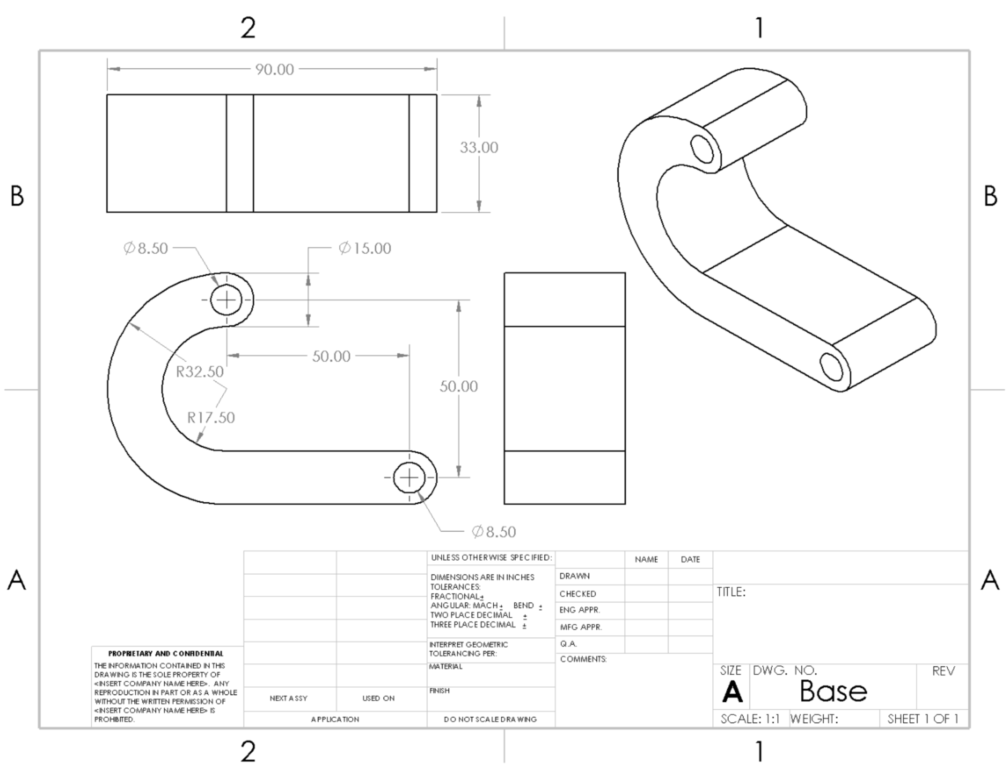
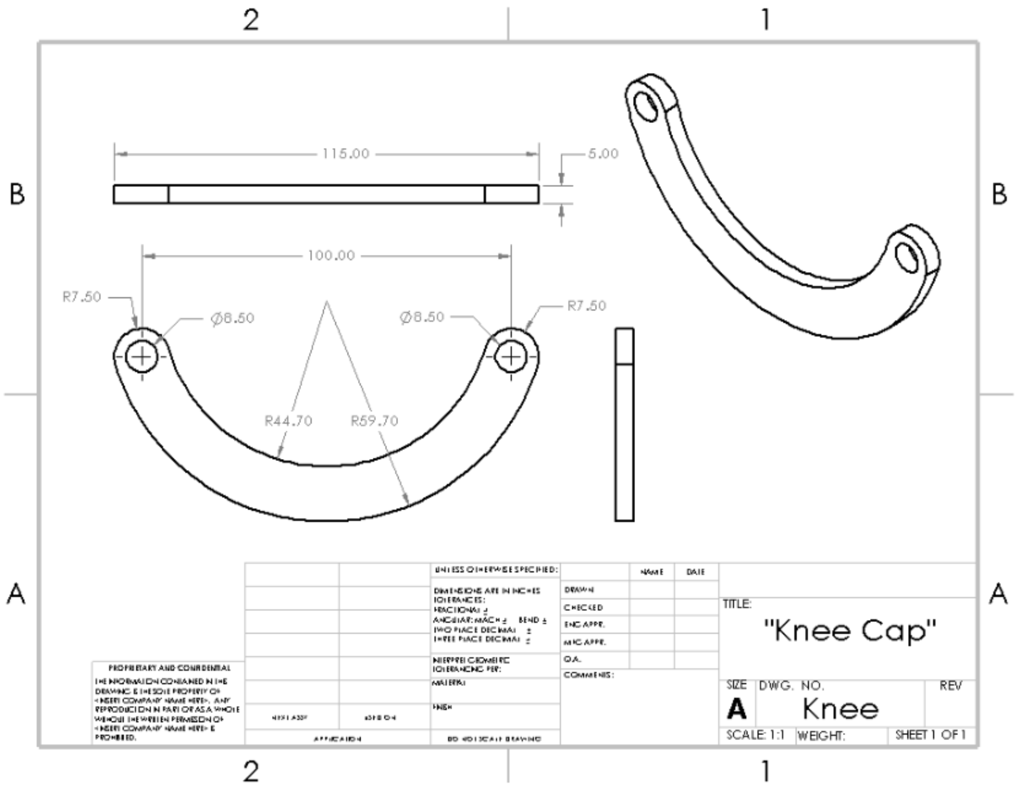
Appendix

Engineering Drawings







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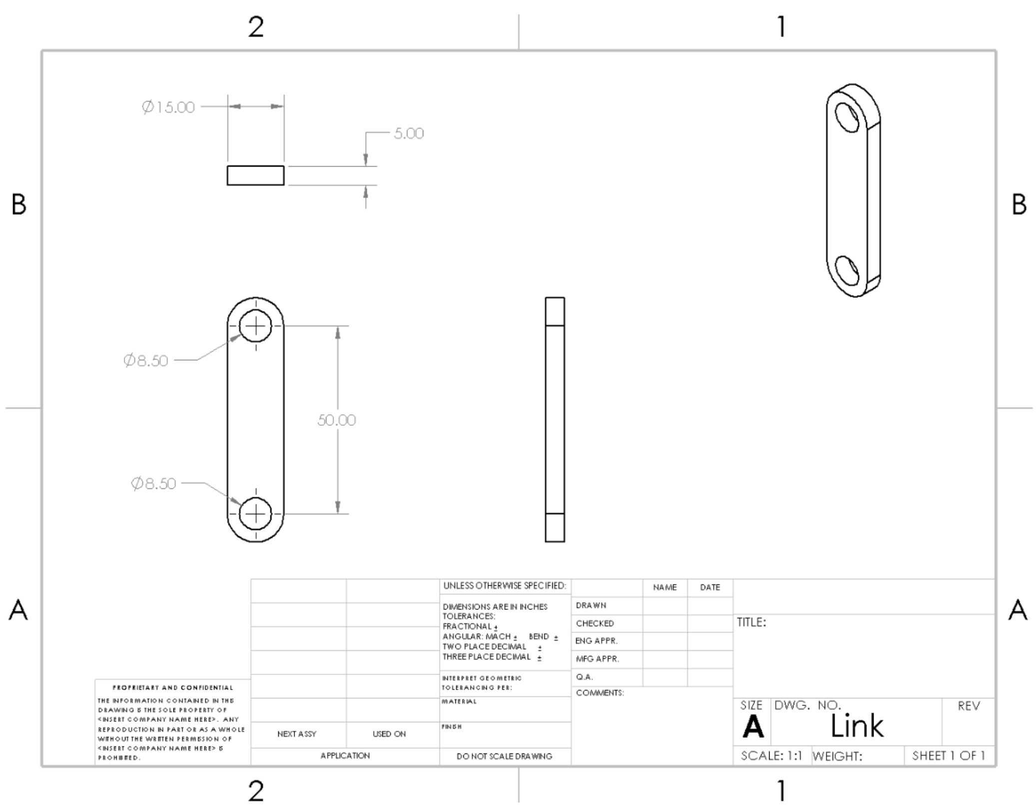

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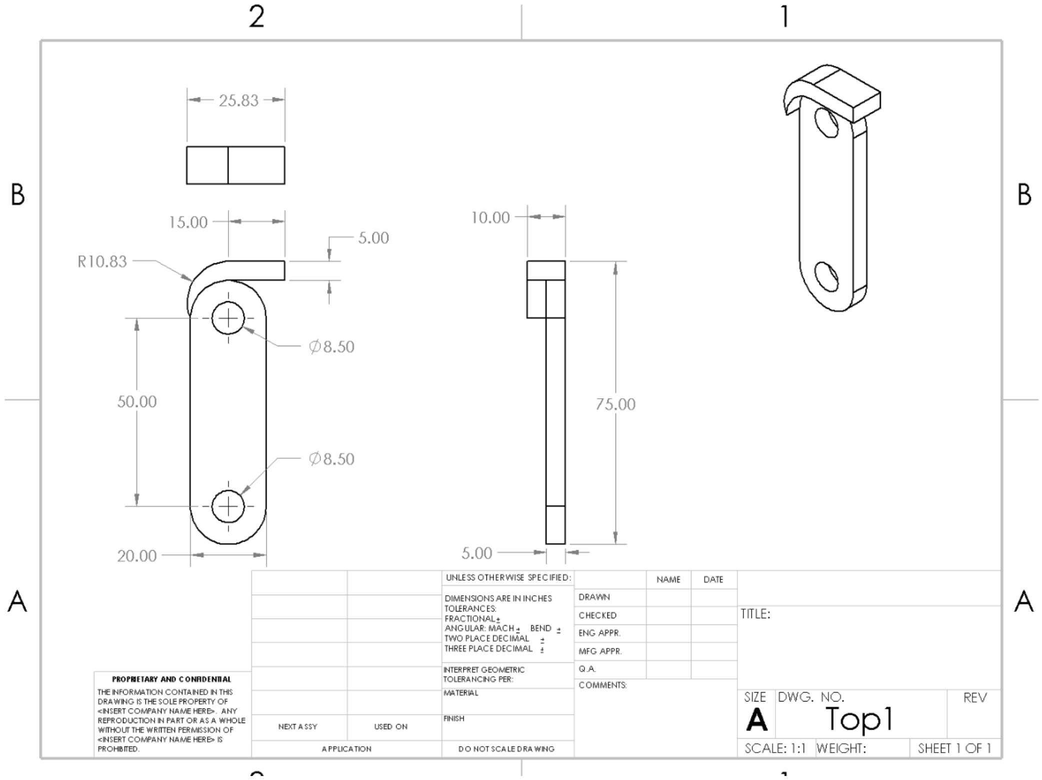

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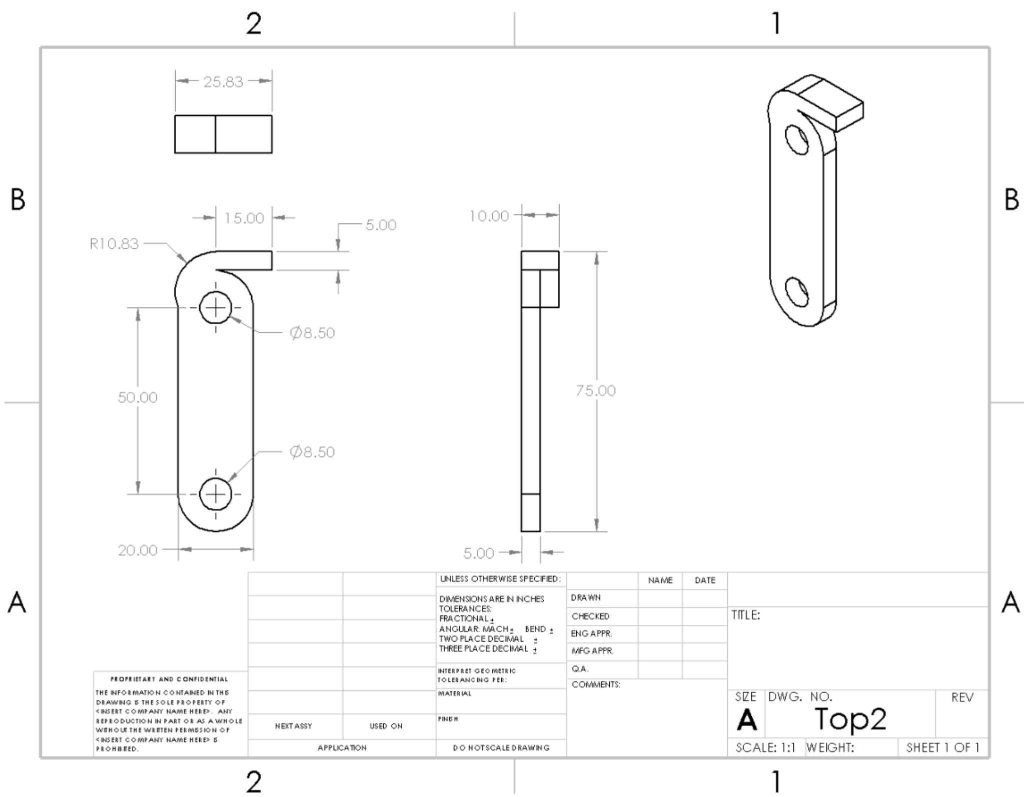

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