# LEGO KNEE

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## Introduction

There is currently a need for a high performance prosthetic knee that can be inexpensively manufactured to international standards. The Stanford knee, originally developed in 2008 by a group of Stanford students including Joel Sadler (now collaborating with us), was a response to this need. It was praised by its users at Jaipur Foot Organization, the world's largest limb fitting organization, as well as others *(e.g. Time Magazine's* Top 50 Inventions for 2009) for its high gait performance in combination with a much lower cost (about $30) than any comparable designs on the market.

However, we believe that the design can still be improved radically in performance and price. Our innovative redesign leads to a lighter, slimmer, easier to manufacture, and less material consuming knee prosthesis without changing the already optimized kinematics. In addition, we are working on an alignment system and planning on adding pneumatic damper that will improve the gait of many patients. Therefore, our knee prosthesis should be able to provide unmatched performance in the low-to-medium cost segment.

An alignment system is an essential improvement to the Stanford knee because men and women typically have different leg angles. Also, natural gait depends on the proper position of the knee and foot. Furthermore, changing the angle of the leg changes the load on the hips. Therefore, by adding an alignment system to our design, the gait of the patient will improve significantly.

A main characteristic of a knee joint is its kinematics. The Stanford design, along with many others on the market, uses a four bar mechanism. In this design, the instantaneous center of rotation changes during gait, very similar to an actual human knee. This yields dynamic damping during swing phase due to the changing of rotational inertia of the lower limb.

Our team currently has two designs with the same four bar mechanism and the same kinematics as the Stanford knee. The first design is asymmetric. We have decreased the width of the previous design and eliminated a linkage (decreasing it from five to four). The second design is symmetric as it maintains the five linkages like the Stanford knee. During the summer, our team will be testing both prototypes and will decide which is stronger.

## Our Designs

### *Initial Prototype: Single Four Bar Linkage Knee*

One of the first designs we created is an asymmetric model consisting of a single four-bar linkage. The initial prototype for this design was made from two pieces of high density polyethylene, along with two thin steel linkages. These were attached together using four quarter-inch bolts, secured with four correspondingly sized lock washers. This prototype was capable of approximately $90^{o}$ of flexion. The assembled model is shown in Figure 1.

***Figure 1: Prototype of Single Four Bar Linkage.*** *This prototype is a rough model used to better conceptualize the costs and benefits of using a knee with a single four bar linkage. It was manufactured using solely a band saw, power sander, and drill press. The prototype is based on the work of the Stanford team, following the polycentric design with similar measurements.*

From this model, we discovered that the torsional forces exerted on knees during common loading are large enough to bend the pieces of thin metal we used. We checked this by using the force of our hands to move the knee, pulling on it as the weight of a heavy foot might during swing phase. This caused the knee to temporarily misalign. This bending happens when only a single linkage is present. Team advisers therefore recommended making metal linkages thicker or adding more linkages. Additionally, large washers could be placed at the sides to add more stability.

Schematic drawings of this design's top and bottom components are shown in Figures 2 and 3. To manufacture the prototype, measurements were made on a block of high density polyethylene with area 5cm by 5cm. The large outer curve was then traced out using a preconstructed curve of the desired radius. Necessary straight cuts were then made on a vertical band saw, as well as a rough profile of the curve. We used a drill press to create the holes and countersinks, and then smoothed the outer curve's profile using a power sander. The design was constructed entirely from flat pieces so that a water jet could be used, when available, to recreate the same knee design with very high precision.

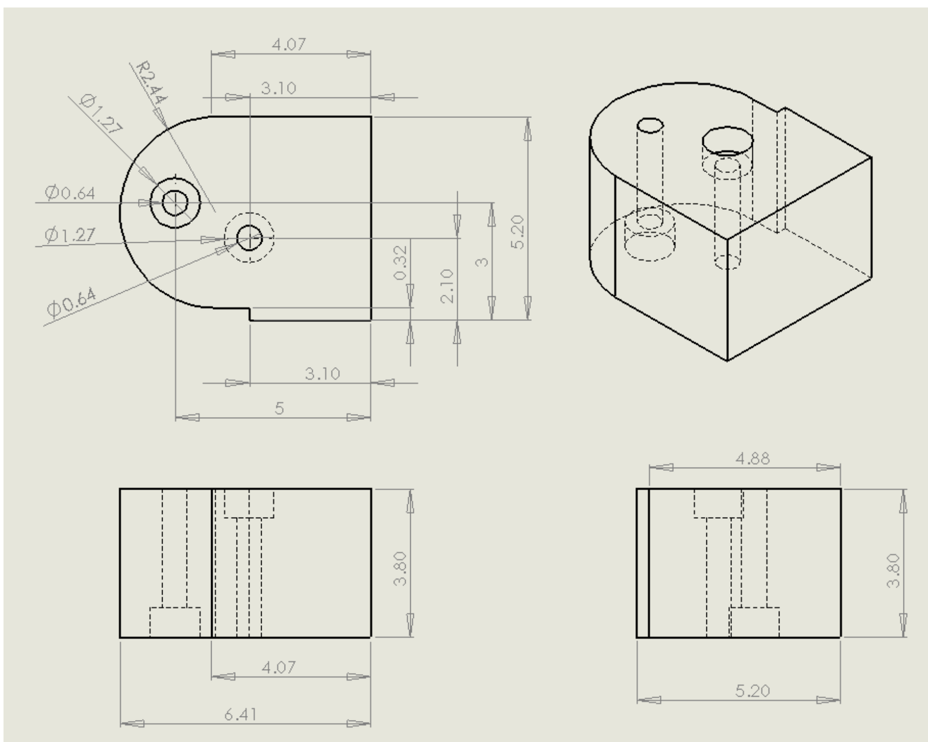


***Figure 2: Upper Portion of Single Linkage Knee.*** *Shown here is a three-section view of the knee's upper portion. This block may be fabricated using a band saw, power sander, and drill press, or alternatively a water jet and drill press. As shown by the dashed lines, countersunk holes are included to reduce the knee thickness. If it is deemed useful to include washers between the bolts and the plastic component, the countersunk holes could be enlarged. Adding washers might make it possible to tighten the bolts more without adding as much friction in the joint.*

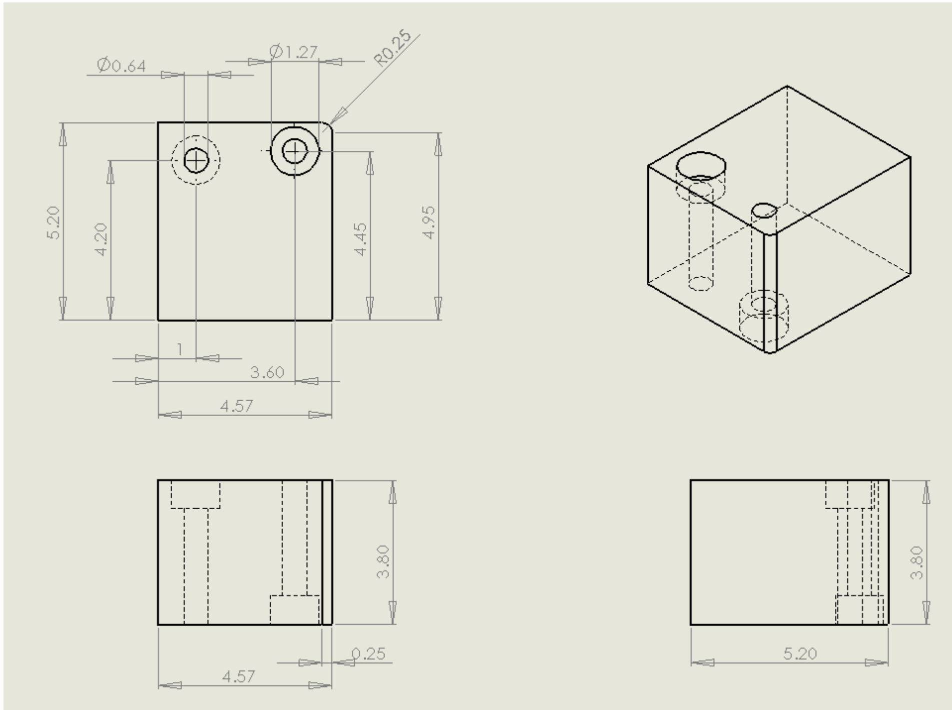


***Figure 3: Bottom Portion of Single Linkage Knee.*** *Shown here is a three-section view of the knee's bottom portion. The accompanying physical part was manufactured via the same processes as the knee's upper portion.*

Shown in Figures 4 and 5 are the designs for the metal linkages used to construct the single linkage prototype. These were manufactured from a soft steel alloy. To create the linkages' curves, we traced out the measurements on a sheet of steel. A rough curve profile was created using a band saw before smoothing with a power sander. As with the plastic top and bottom of the knee, this design can also be recreated using a water jet, mill, or other tools.

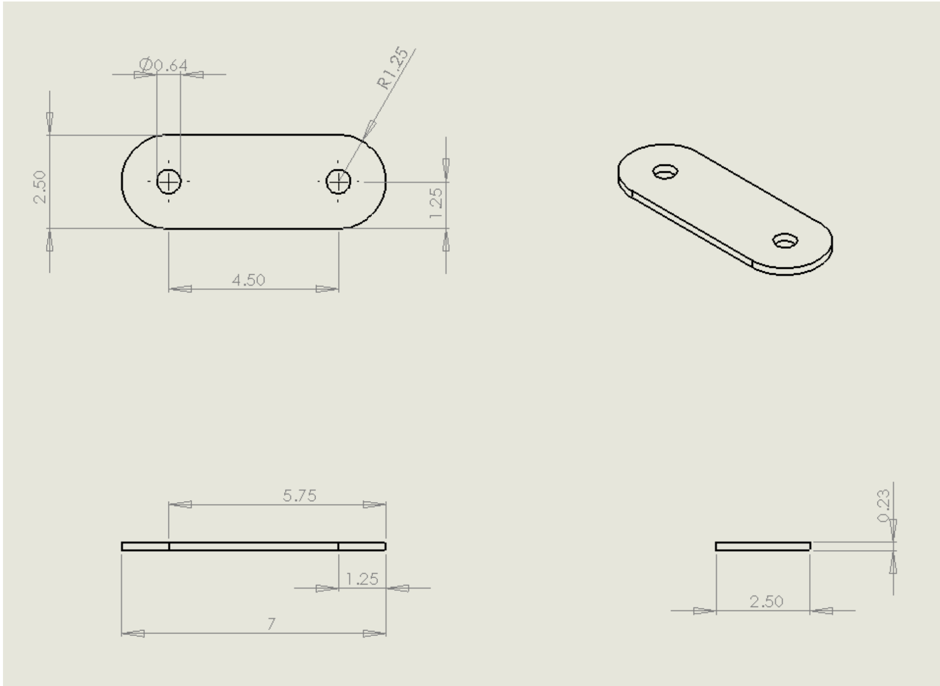


***Figure 4: Larger Knee Linkage.*** *This linkage was created from a piece of sheet steel using a band saw, drill press, and power sander. This linkage is placed on the front right side of the knee when viewed head on, as shown in Figure 6.*

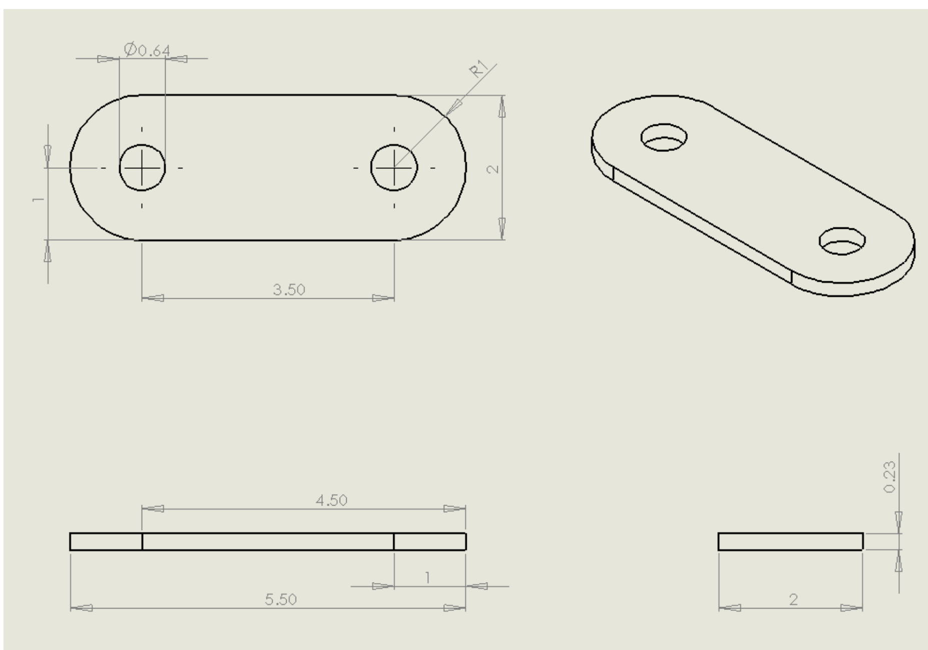


***Figure 5: Smaller Knee Linkage.*** *This smaller linkage was created similarly to the large one. It is placed on the back left side of the knee when viewed head on, as shown in Figure 6.*

Once manufactured, the parts shown in Figures 2 through 5 can be assembled using four bolts with accompanying lock nuts. We used ¼" diameter bolts in the prototype; however, it remains to be determined which bolt diameter is most appropriate for the knee, given the tradeoffs of cost and strength. The final assembled model should appear as shown in Figure 6. Note that bolts that are too long may be shortened using a saw or rotary tool.

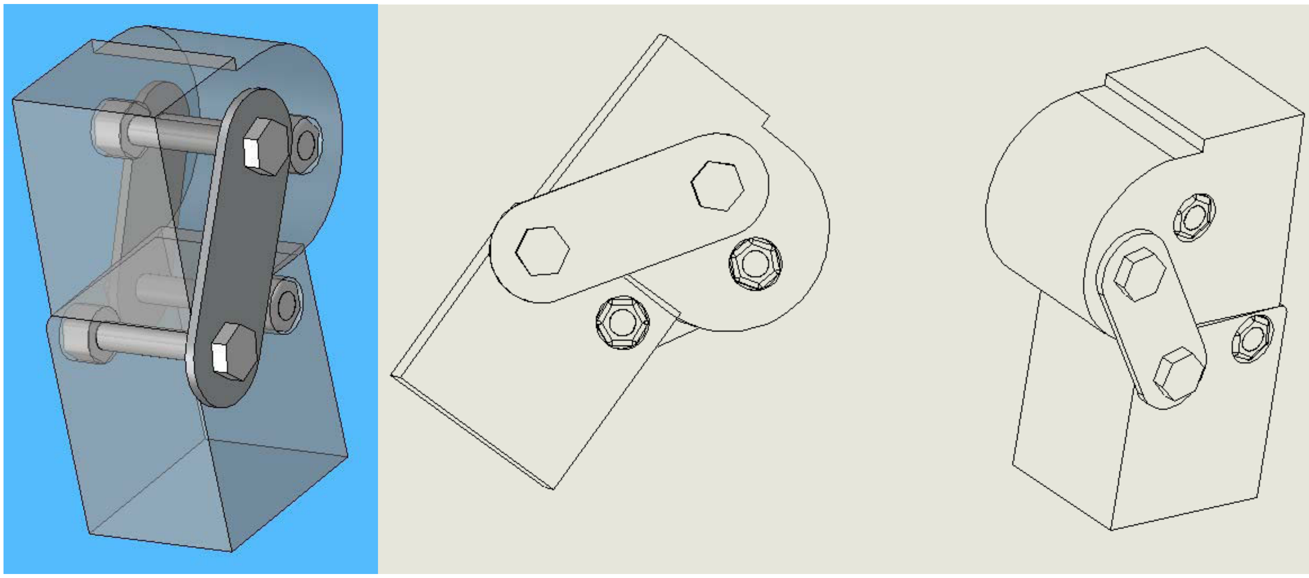

***Figure 6: Completed Assembly for Single Linkage Knee.*** *This assembly includes two high-density polyethylene blocks, two steel linkages, four bolts, and four lock nuts. The pieces to be manufactured are described in Figures 2 through 5.*

Based on the performance possible with this design, we decided to follow two courses of action. One is to strengthen the linkages and consider other ways of adding stability without width, which will be undertaken and tested this summer. The second is to add extra linkages, which was pursued during the end of the class this fall. The resulting multiple linkage prototype is described in Figures 7 through 10.

## *Advanced Prototype: Multiple Linkage Knee*

The second prototype we built is shown in Figure 7. In it, we took into account some of the disadvantages of earlier prototypes and attempted to improve on them. This prototype, while it was manufactured similarly to the single linkage design, was machined to smaller tolerances. As a result, it is quite stable and capable of 160 degrees of rotation. Other differences include the addition of 20 washers and the fact that, due to the additional linkages, only two of the bolt holes were countersunk. We also decided to construct the linkages from aluminum instead of steel, due to aluminum's lower density. We will be testing the impact of these and other changes during the summer.

Note that the linkages shown below are not symmetric. As can be seen in Figure 7, one of the linkages may seem to be missing. The reason for this design decision is that a damper may later be placed in the empty location. Alternatively, another aluminum linkage could be added. The impact of this symmetry decision and the material choices will be a focus of summer testing. However, the current design still rotates well with minimal flexion. Prototype details are shown in Figure 7, while drawings for manufacturing are shown in Figures 8 and 9.

***Figure 7: Prototype of Multiple Linkage Knee.*** *This knee was manufactured similarly to the single linkage knee. The primary differences were adding twenty thin washers for spacing, changing the linkages to aluminum, and including only two countersunk holes.*

The top and bottom components of the knee are manufactured similarly to those used in single linkage prototype. As before, they can be created using a band saw, drill press, and sander; or a water jet and drill press for the countersunk holes. Likewise, the dimensions are the same except for the presence of two rather than four countersinks, shown in Figures 8 and 9. Because the linkages are the same as those used previously, the diagrams for those are not repeated.

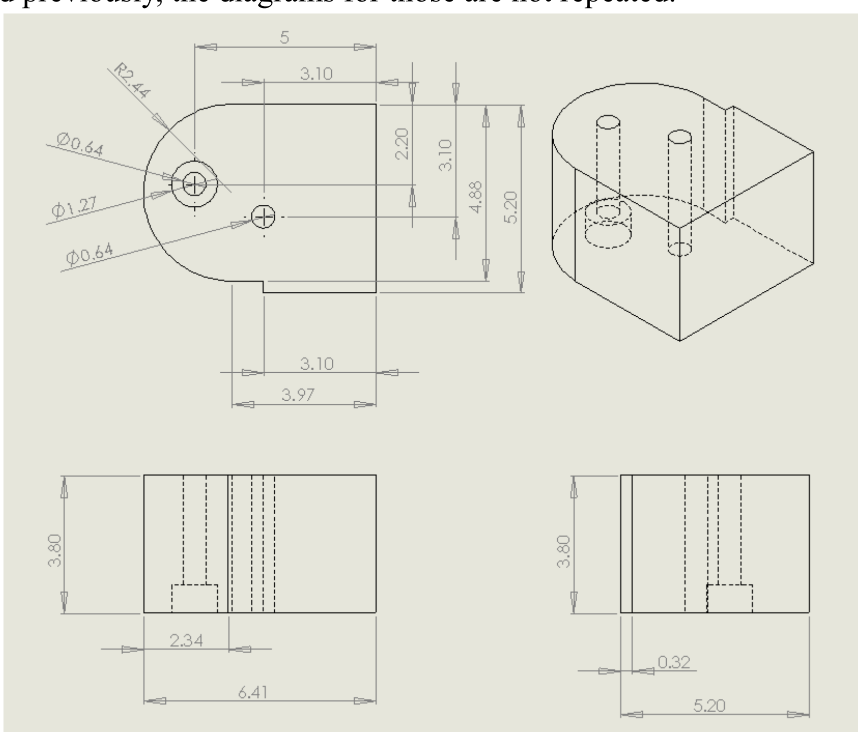


***Figure 8: Upper Portion of Multiple Linkage Knee.*** *Shown here is a three section view of our latter prototype's upper half. It is the same as that for the first prototype, except it contains two fewer countersunk holes.*

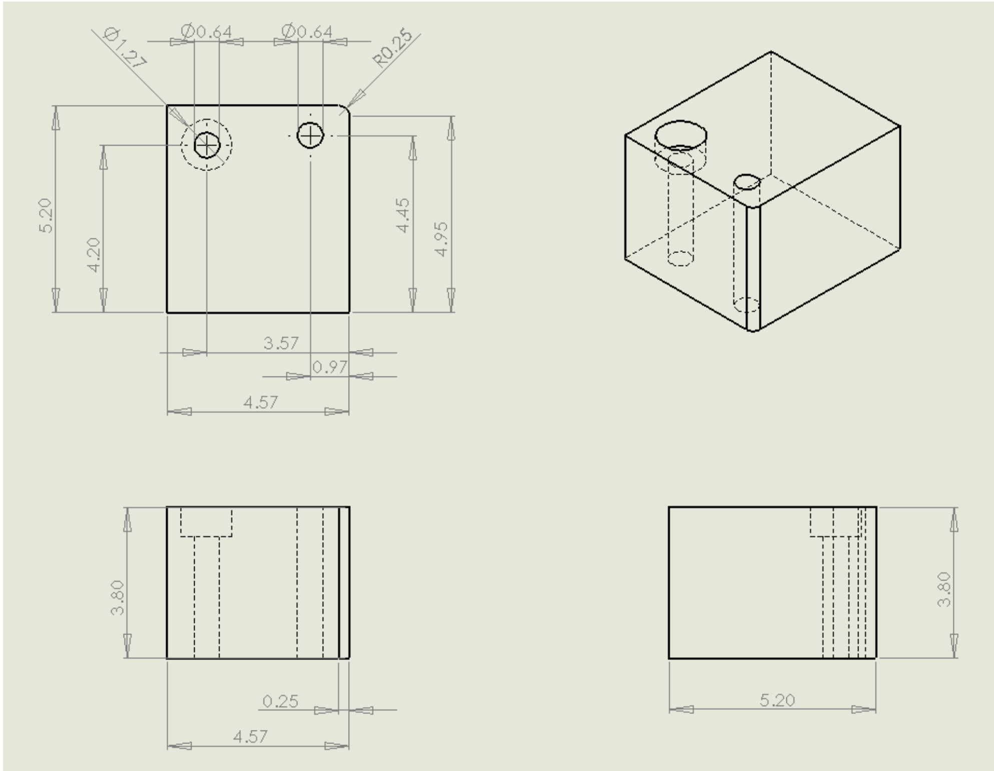


***Figure 9: Lower Portion of Multiple Linkage Knee.*** *Shown here is a three section view of our latter prototype's lower half. It is the same as that for the first prototype, except it contains two fewer countersunk holes.*

Pictured below in Figure 10 are a SolidWorks assembly and drawing showing the final knee construction. In it are the same linkages as those used for the initial knee design, except the linkage material is aluminum. Additionally, linkages of various materials and thicknesses may be included, depending on the result of tradeoffs between price, strength, and durability. We will be investigating the best balance of these tradeoffs this summer.

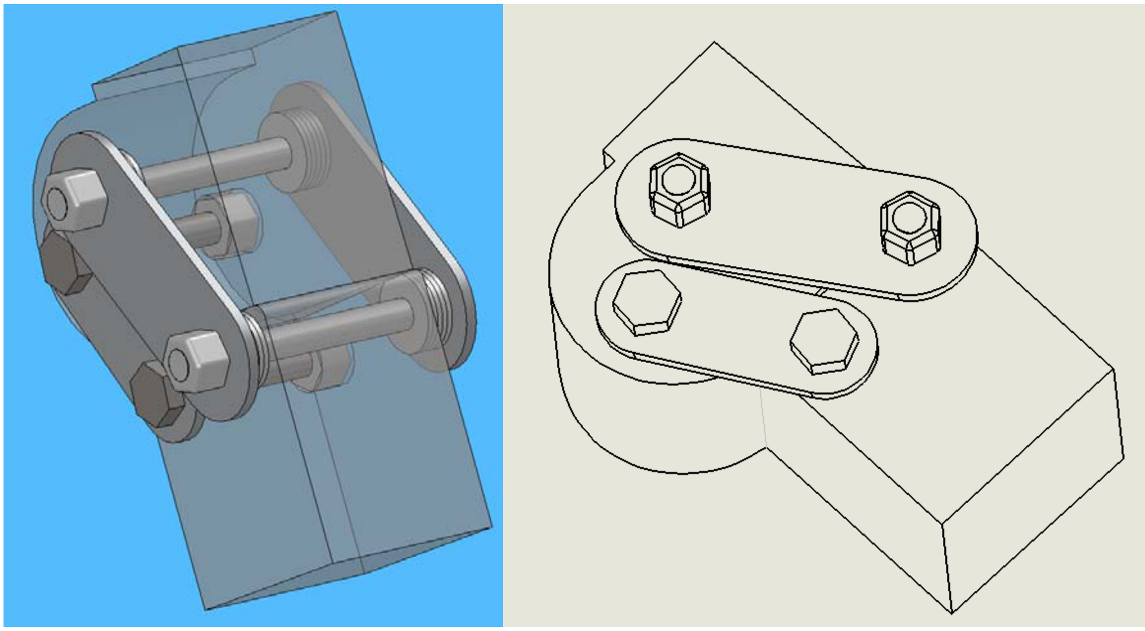

***Figure 10: Completed Assembly for Multiple Linkage Knee.*** *This assembly includes two high-density polyethylene blocks, two steel linkages, four bolts, and four lock nuts. The pieces to be manufactured are described in Figures 4,5,8,and 9. Note that two out of eight holes are countersunk, and that the design currently includes only three linkages. We will be investigating the effects of adding another linkage or damper in the same location this summer.*

## First Alignment Prototype

Pictured here is the first alignment system we created to be used with our knee designs. It is an undersized (not to scale) model we used to determine the movement properties and constraints of such an alignment system. The design consists of one quarter-inch diameter bolt with accompanying nut, two large washers, and a short ring machined from Delrin. The ring is meant to be placed inside a pylon having the same inner diameter. The bolt is meant to be inserted into the top of a knee, and then the nut can be tightened once the desired alignment position has been determined. Then the ring can be secured afterwards in the pylon at the top of the knee, using epoxy, smaller bolts, or other fastening methods.

The alignment system shown in Figure 11 currently provides approximately 1.5 cm of vertical and horizontal placement flexibility, combined with full $360^{o}$ rotation. Although the current bolt size may not be strong enough to support a person’s full body weight, a similar but larger system could be successfully used with a larger pylon to provide additional alignment. During the summer, a larger version of the system will be tested, including the use of a thicker bolt and pylon, combined with longer rings of various kinds of plastic.

***Figure 11: Initial Alignment System.*** *In the alignment system pictured here, a short ring of Delrin is used to support a moveable bolt, which is to be screwed into the top of a prosthetic knee joint. The alignment system is then tightened in the desired position and fastened to the end of a pylon.*

Shown below in Figure 12 is a three-section view of the plastic ring used in the alignment system. This ring can be manufactured by drilling a hole directly into appropriately sized stock, or by using a water jet to create concentric rings of the desired sizes. The dimensions shown below in centimeters describe the small model we created. They could be scaled up proportionally to match the size of the desired pylon and alignment system.

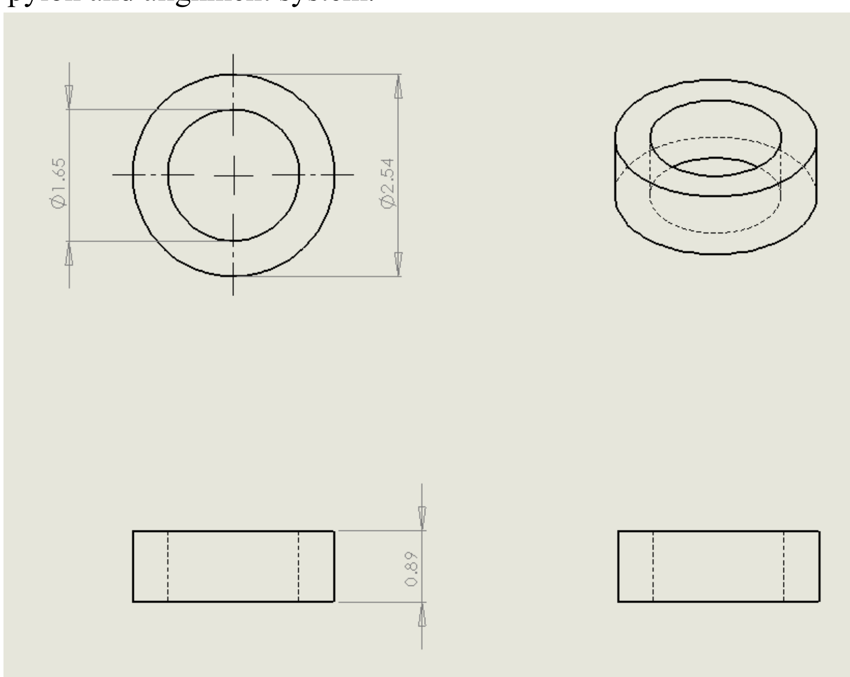


***Figure 12: Three Angle View of Alignment Ring.*** *The above drawing shows the construction of our initial alignment ring prototype. Dimensions, shown in centimeters, should be proportionally scaled according to the necessary size of the alignment system. The alignment ring can be manufactured using a drill press in one inch stock, as well as in a water jet from thick sheet plastic.*

Shown in Figure 11 is the completed assembly of the initial alignment system we created. The assembly is to be secured in a pylon above and screwed into a knee device below. We hope to scale and test the system this summer, as well as investigate its possible combination with more advanced alignment systems. In a later form, the prototype could potentially offer more freedom in alignment positioning.

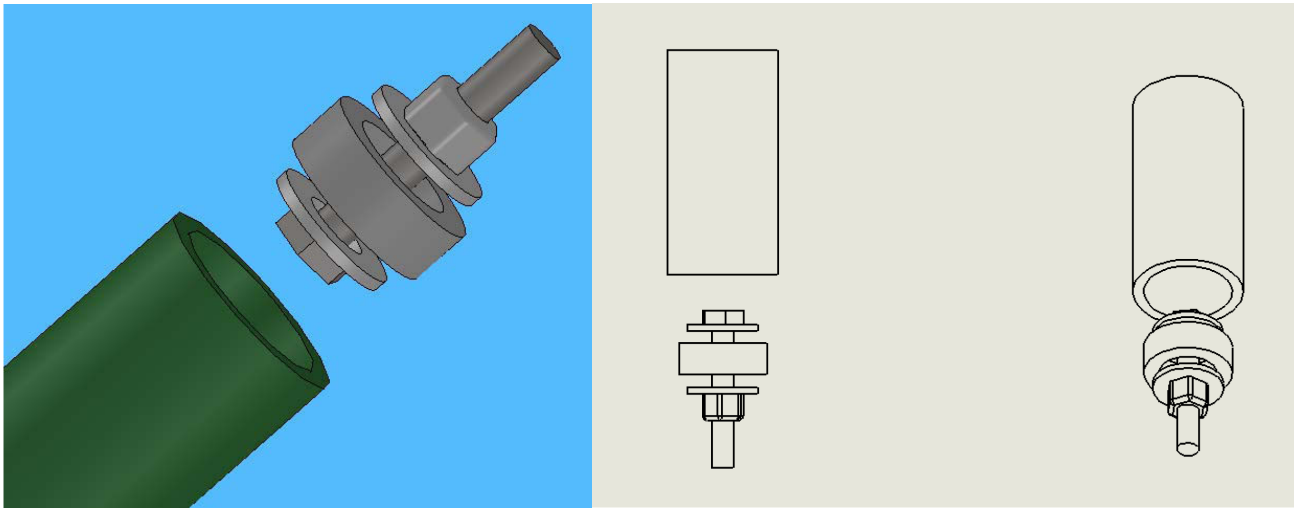

***Figure 11: Initial Alignment Assembly.*** *Shown here is the completed assembly for the initial knee alignment system. It is created from a ring of plastic, two washers, and a nut and bolt.*

## Second Alignment Prototype

The second alignment prototype functions quite differently from other alignment systems we have seen. For this reason, we believe that although it has great potential, it would need to go incredibly rigorous testing, both for safety and to determine user appeal. This prototype, shown in Figure 12, shows a rough prototype of the system. It is again a small model used to determine the degrees of motion provided by such a system. This model was successful in that it shows the system allows for height adjustment, $360^{o}$ of rotation in the horizontal plane, and approximately $30^{o}$ of rotation from the vertical plane in any horizontal direction.

***Figure 12: Second Alignment System.*** *This alignment system, machined from a single piece of one inch tube stock, allows for both linear vertical and angular positioning.*

This alignment system's construction is quite simple to make. To create the plastic piece pictured in Figure 13, we began by taking a piece of one inch tube stock and using a drill to make a large hole in the center. Then, using a band saw, we cut the piece of tube stock in half down the center. This created a flat edge for each half, on which we drew a circle. We used a power sander to remove the material external to the circle. After this, we glued the two pieces back together, creating the prototype shown above. Note that this plastic piece has cross-sections with different shapes, two of which are circular and one of which is a square. Because of the piece's particular construction, it is possible to use tube stock instead of solid stock to save material. It is also possible to create the same design using a water jet if it is available. In that case, instead of drawing a circle and using a power sander to remove the external material, a water jet would be used to remove the excess.

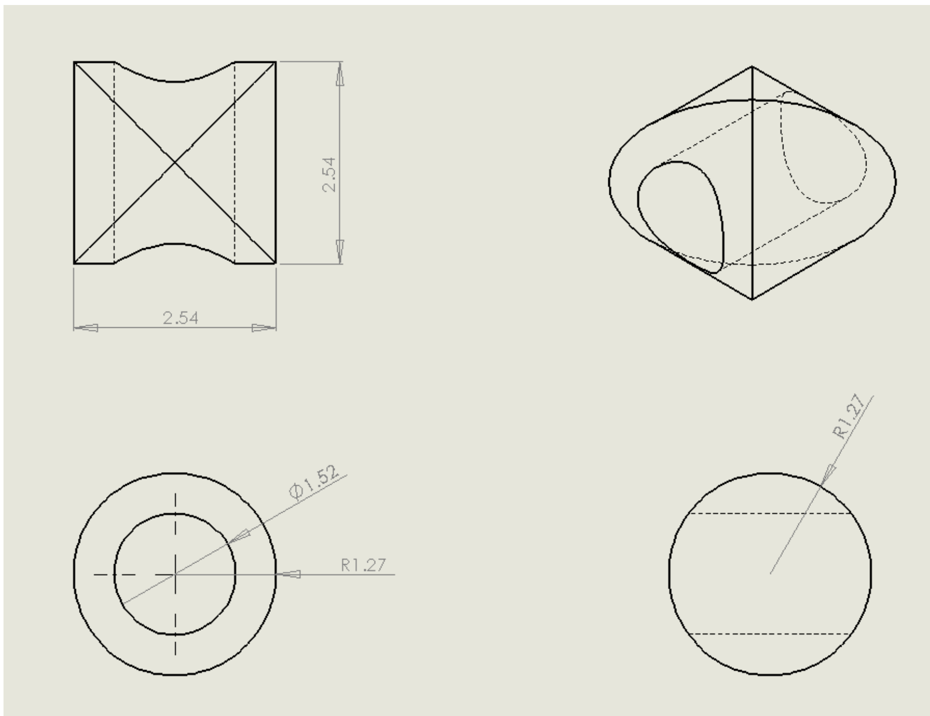


***Figure 13: Plastic Slider for Second Alignment System:*** *This piece allows the sliding inner bolt to attain 30$^o$ of angular alignment in the vertical direction and 360o in the horizontal direction. By altering the slider's placement in the pylon, additional degrees of vertical alignment may be attained. The piece may be manufactured using a band saw, drill press, and sander, or using primarily a water jet. As for the previous prototype, dimensions should be proportionally scaled to match the required pylon and need for load bearing.*

Figure 14 shows the completed assembly for the second alignment prototype. The required pieces are a plastic slider to be manufactured, two washers, a matching nut and bolt, and a pylon to fit the slider piece.

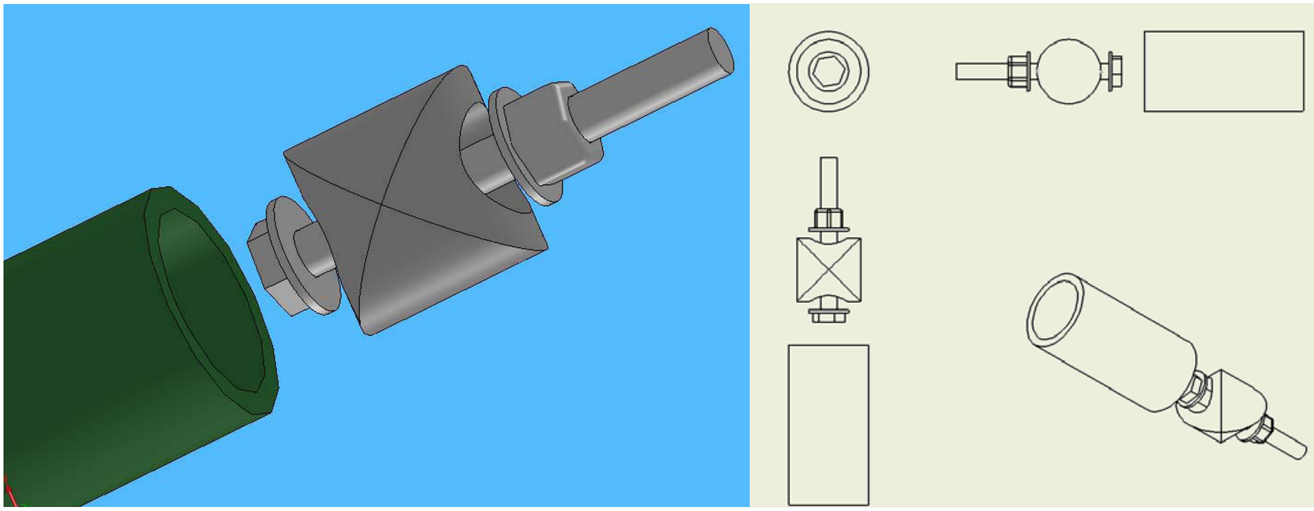

***Figure 14: Second Alignment Assembly.*** *This assembly requires only six pieces and can be easily tightened before positioning within the pylon. We plan to test the effectiveness of larger versions of the assembly this summer.*

# Advantages

Both designs have the following major advantages:

## *Simpler Manufacturing*

Four bar designs like the one by the Stanford team contain parts that have a fairly complex three dimensional structure. This requires repositioning the parts during the manufacturing process in order to access all necessary areas with the tools. Also, a mill is required for creating the grooves, which increases the cost substantially.

Since our design is composed entirely of flat sheets, it can be easily manufactured with a saw, drill, and sander. A laser cutter or water jet can also be used. Both are substantially less expensive than a mill and available at FabLabs in many developing countries

## *Slimmer design*

Since we use less material, we further reduce costs, the weight of the prosthesis, and impact on the environment. In addition, the slimmer design will allow for a life-like cosmetic cover. The Stanford Knee's wide design (shown in Figure 2) currently exceeds the width to fit with the aesthetic covers used by Jaipur Foot. We solved this problem by reducing the number of required layers to three, as well as providing insets for the bolts.

# The Manufacturing Process

The major improvement to the Stanford knee is the simplification of the manufacturing process. The Stanford design requires advanced machinery that is not accessible everywhere on the globe. For this reason, we have decided to simplify the manufacturing process to three simple steps.

1. Make cuts to the materials with a saw based on the established measurements.
2. Using a ¼ drill bit make a hole on the place mentioned on the measurements section.
3. Sand the edges until a complete rotation is possible.

The idea behind this simplification is that anybody with the materials and the basic tools can construct this Lego Knee. In the future, an instructional YouTube video on the manufacturing process of the knee may be created.

### *Materials List*

1. High Density Polyethylene
2. Screws
3. Spacers and Nuts
4. Aluminum

### *Tools*

1. Saw
2. Drill
3. Sander

However, if a water jet is available, it may also be used. Each part may be water-jetted.

### *Cost*

The projected manufacturing cost for the knee is $14. The breakdown of the cost is as follows:

1. Bolt, Nuts, and Washers: $4
2. Metal and Plastic: $5
3. Labor: $5

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