THE WILMER APPEALING VOLUNTARY CLOSING PREHENSOR: A DESIGN ANALYSIS AND OPTIMIZATION

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ABSTRACT

The WILMER Appealing Voluntarily Opening Prehensor was redesigned as a Voluntarily Closing Prehensor. However many areas of concern remained after the design was finalized, including axis distortion and only a 0.5 force transmission ratio. This project first corrected the axial distortion issue of the original design, and then redesigned the mechanism to increase the force transmission ratio. A mechanism with sliding levers was designed, which provided a maximum 1.4 force transmission ratio at the maximum opening, and 0.32 transmission when the Prehensor is fully closed. This design remains more efficient that the original design for 85% of the opening range. It is only in the last 7.5mm where the transmission ratio goes bellow the original 0.5. Unfortunately due to manufacturing delays and time mismanagement, a prototype was not finished, however results are promising.

INTRODUCTION

BACKGROUND

The Delft Institute of Prosthetics and Orthotics (DIPO) at the Biomechanical Engineering Department of the Faculty of Mechanical, Maritime, and Materials Engineering at the Delft University of Technology develops innovative prostheses and makes them commercially available under the WILMER brand name. One such prosthesis currently on the market is the WILMER Appealing Prehensor. This is a voluntarily opening (VO) split hook prosthesis designed for children from ages 4 to 7 years old.

Although, conventional split hook prostheses are more functional than hand prostheses (Smit, 2012), parents often reject the split hook due to its unappealing appearance (Plettenburg, 2006). The WILMER Appealing Prehensor preserves all the functionality of the split hook, while considering improving on the appearance. This prosthesis features a smooth transition between Prehensor and forearm, interchangeable covers, and integrated mechanism and operating cable. It also resists sand, water, and dirt (Plettenburg, 2006). It can be seen in Figure 1.

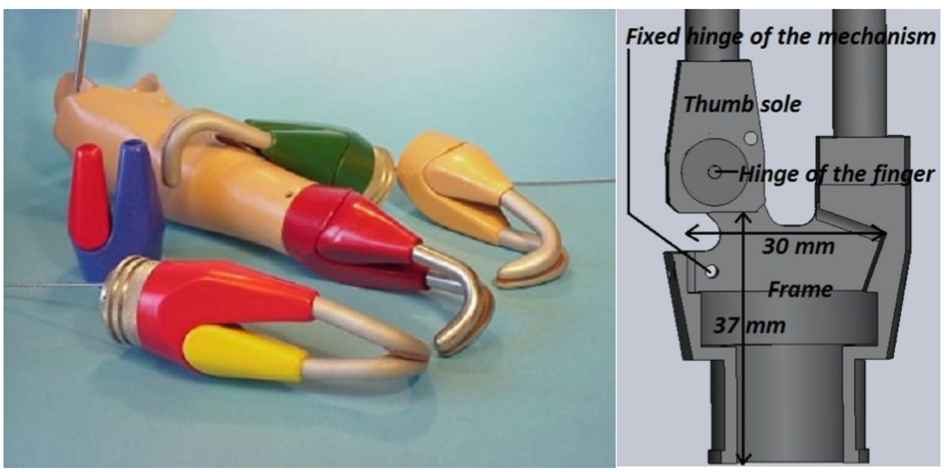

FIGURE 1 - THE WILMER APPEALING PREHENSOR

As it is designed as a VO prosthesis, the pinch force is provided by a spring. Not only does this limit the applied pinch force, but it also increases the activation force needed to operate the prosthesis when compared to a voluntarily closing (VC) design (Carlson, 1988). Therefore, VO prostheses are not only less efficient, but also increase muscle fatigue. With this in mind, DIPO set out to redesign the WILMER Appealing Prehensor as a VC prosthesis (Tweezer).

The redesign task was carried out as a master's thesis project by Alireza Tousi (a student at the time). This task had severe geometrical limitations as the mechanism designed had to comply with the limited space inside the already existing enclosure. Working with such constrains meant it was difficult to maximize the transmission ration of the activation and pinch force. This current project, analyses the design choices made by Tousi and seeks to improve on the original design with the hopes of maximizing the force transmission ratio.

PREVIOUS DESIGN

Tousi went through three different design concepts and finally arrived at the simple four-bar mechanism seen in Figure 2.

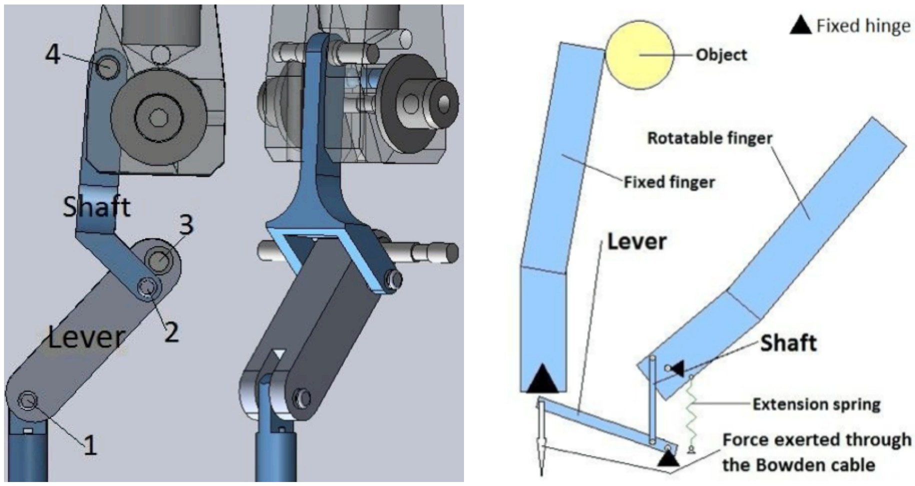

FIGURE 2 - ORIGINAL DESIGN BY TOUSI

The cable connects at point 1 in the lever, and the axis is located at 3. A shaft then connects just before the hinge on lever two and transfers the force to the "thumb hinge" on point 4. The "thumb hinge' then rotates to close the finger when force is applied on the cable. This configuration yields a 0.5 force transmission ration, where about half of the applied force is translated into pinch force.

Before analyzing the efficacy of the design done by Tousi, first the criteria used to guide the original design process must be carefully considered. These considerations are; desired pinch force, opening width, activation force, total weight, and cable excursion. The original criteria defined a minimum of 10 Newton for the pinch force, an opening width of 50 mm, an activation force of 23.5 Newton, a total weight of 120 g, and a cable extension of up to 26.5 ± 5 mm.

There is scarce literature concerning the pinch force for children in the 4 to 7 years old age group. Tousi originally reported a literature survey done by Shaperman et al. (Shaperman, 1995) on the strength of children 2 to 4 years old, as well as an evaluation of the pinch force of children with prosthesis by Van Lunteren (Van Lunteren). Shaperman reported a pinch force of 9 to 18 N on children aged 2 to 4 years old, while Van Lunteren reported a continuous pinch force of 10 N to be enough. Tousi decided to go with a minimum of 10 N as it is the standard value used for the design of children prosthesis. Further review of literature did not yield better studies, so the original assessment holds true. However, to err in the side of caution, a minimum pinch force of 15 N is used in this project.

Literature is also limited on the minimum opening width required by children to perform activities of daily life (ADL). Although Tousi reported two studies on this topic (Lunteren A. V., 1983) (Nieuwendijk, 2010), the main consideration in this regard is the geometrical constrains of the original VO Prehensor. As the dimensions of the existing housing, as well as cosmetic cover, must be maintained, it is important then to maintain the original opening width of 50 mm.

When defining the criterion for maximum activation force, it is important to differentiate between the peak force exerted by the muscle and maximum continuous force. Again, limited literature is available in this subject when it comes to children. Originally a study by Shaperman was reported (Shaperman, 1992) where the strength of 14 unilateral congenital bellow-elbow limb amputees between the ages of 3 and 6 was measured for different shoulder movements. As the force in the direction of the cable pull is of concern here, the shoulder girdle elevation is to be considered. A maximum force of 62 N was reported. Monod (Monod, 1985) reports that 18% of the maximum generated force can be used continuously without muscle fatigue, as well as 38% of the force for intermittent contractions. Therefore, it is safe to assume an initial activation force of 23.5 N and a continuous activation force of 11 N, which is in line with Tousi's original assessment.

Scarce data is available on the weight of children's hands, however Tousi reported a study by Chandler (Chandler, 1975) where the mean weight of the hands of six adults was calculated to be 387 ± 76.5 g. Taking into account the volume ration between the size of the hands of children and adults, a weight of 121.2 ± 24 g was arrived at by Tousi. Considering also the weight of the original Prehensor (125 g), his original criteria of 120 g is adequate.

Finally, no studies have been found in the maximum cable excursion for children. However, as originally reported, Taylor (Taylor, 1954) measured this in adults. It was found that adults had a maximum cable excursion of 53 ± 10 mm. Considering limb lengths of children and adults, a ratio of 0.5 was taken by Tousi, arriving at a maximum excursion of 26.5 ± 5 mm for children. This estimate was found adequate for the design criteria.

With these considerations in mind, the drawbacks of the original design are analyzed. As stated previously, only half of the activation force is converted into pinch force. Therefore to achieve the constant desired pinch force of 15 N, a constant 30 N of force are required. This is almost three times the desired continuous activation force. Furthermore, as is can be seen in Figure 3, there is a 3.85 mm gap on either side of axis 3 where lever one connects. As the force is applied in the middle of the axis, deformation occurs and thus friction increases. These are the two main problems with the current design, and therefore, are the focus of this project. First a redesign of the original mechanism is made to address the problem with the axis deformation, and second a redesign is done in order to increase the force transmission ratio.

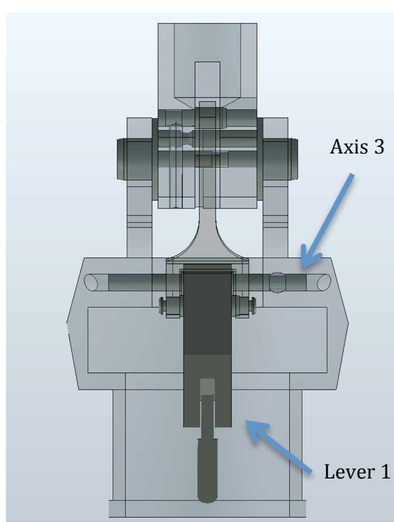

FIGURE 3 - CROSS SECTION

Methods

There were many constraints when optimizing the design, including the design criteria described above, improving the efficiency of the design by Tousi, and constraining the mechanism to fit inside the existing enclosure (Figure 1). The first design described is a simple improvement of the design by Tousi. Then a complete redesign is explained, which focus on improving the force transmission ratio.

Design 1 – an incremental improvement

As previously mentioned, a major flaw in Tousi's original design is the axial deformation incurred on Shaft 3 (Figure 3). A simple redesign was made, where Lever 1 was bifurcated (Figure 4), connecting to the outside of the shaft (between the shaft and the body), with bearings in between. Axis three was then divided into two separate axes on either side. This design provides better support, and minimizes axial distortion and thus friction. Detailed drawings can be found in Appendix 1-A.

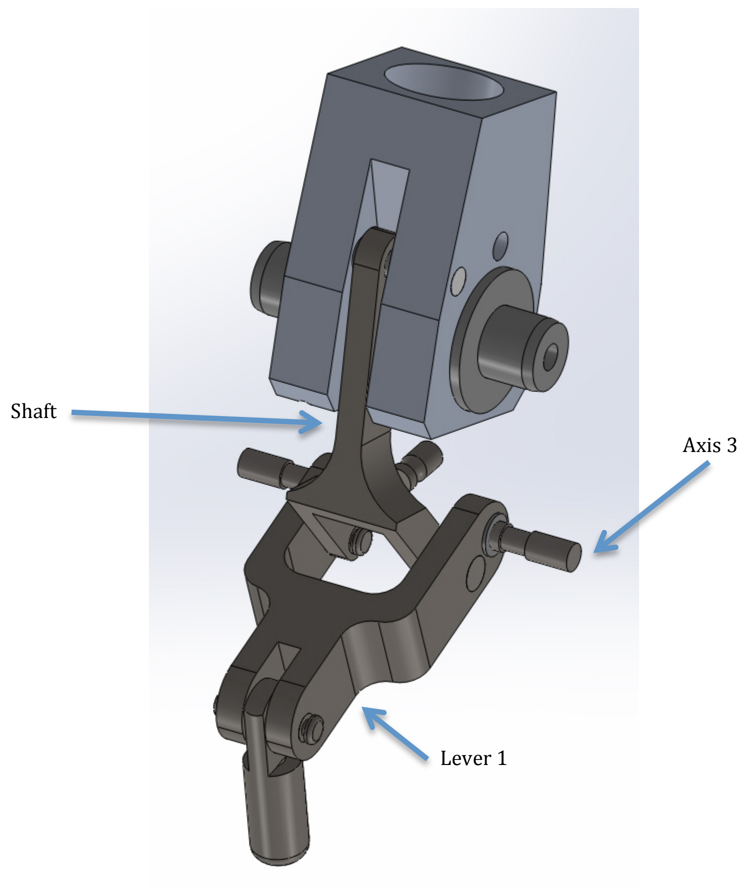

FIGURE 4 - REDESIGNED MECHANISM

DESIGN 2 – BETTER TRANSMISSION RATIO

Once the main design flaw with Tousi's original mechanism was corrected, it could be easily seen that to improve the force transmission ratio, a complete redesign was needed. There are three main limitations which complicate the design process; first, the limited space inside the original enclosure limits the length of levers and thus limits mechanical advantage; second, the distance of the end effector to the hinge (i.e. the finger) (Figure 5) is large (~66 mm) and mechanically disadvantageous; third, the mechanism needs to be robust against sand, water, and dirt, as well as fatigue. This limits the use of mechanically advantageous features such as gears as they are susceptive to dirt and sand. Also a system of pulleys would be unreliable and prone to failure due to fatigue.

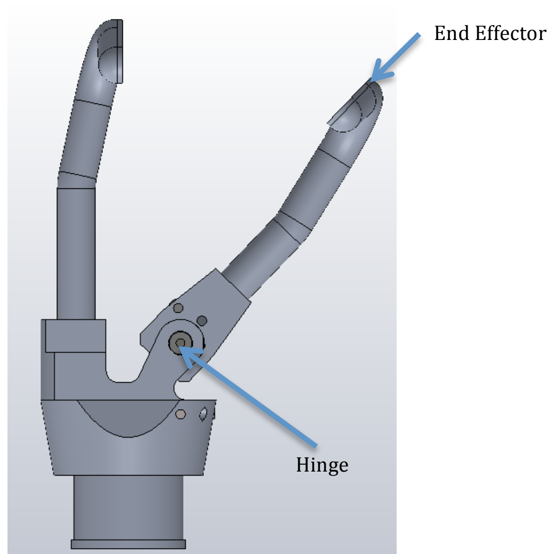

FIGURE 5 - TWEEZER DESIGN

With these considerations in mind, the departure from the classic four-bar mechanism seemed necessary. As the length of the lever or position of the hinges could not be changed due to the restricted space, more levers are a possible solution. However, the size limitation hinders the positioning of multiple levers, and therefore a novel solution had to be found. Thus the prismatic joint was introduced in the connection between levers and the first version of the sliding lever was conceived (Figure 6).

The mechanism is further detailed in Figure 7 A and B. When the mechanism is open, Lever 1 connects to Lever 2 very close to the pivot point (hinge). This provides great mechanical advantage. As the prehensor closes, the connection point moves farther away from the hinge, and the mechanical advantage decreases. It can also be seen in (A) that the cable connector is almost perpendicular to Lever 2, and so most of the force is being applied in the correct direction. In (B) the connector is basically parallel, and therefore almost no force is applied in the correct direction. It is clear then that the position of the axis of rotation must be optimized in order to maintain an angle as close to 90° as possible between the cable connector and Lever 2. Furthermore, the prismatic joint in Lever 1 is too fragile, and it would be prone to deformation over time. The prismatic joint must be redesigned.

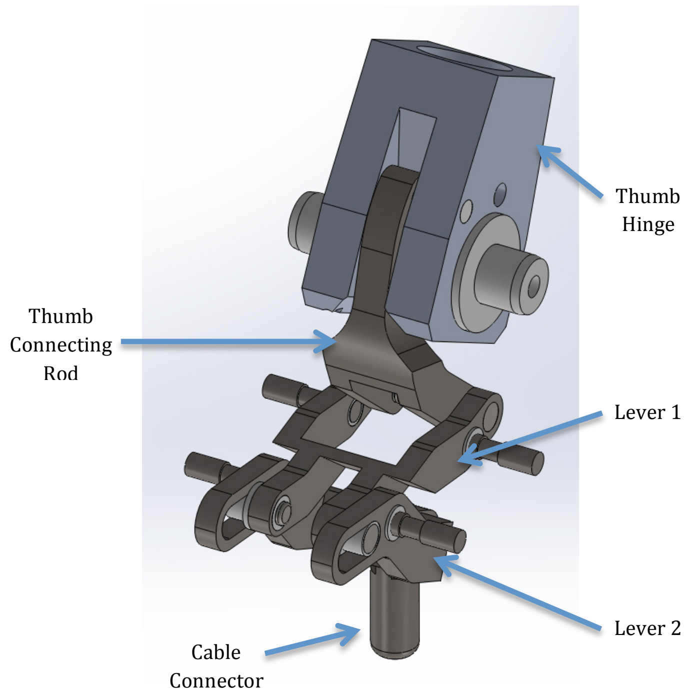

FIGURE 6 - SLIDING LEVER 1.0

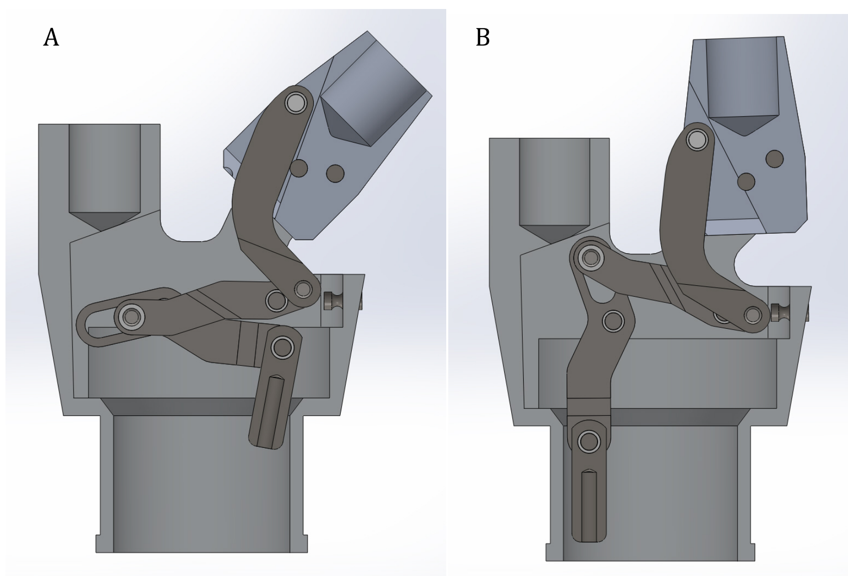

FIGURE 7 – SLIDING LEVER 1.0 (A) OPEN, AND (B) CLOSED POSITIONS

Figure 8 shows the redesigned sliding lever. Lever1 and Lever 2 were designed to be more robust and resistant against fatigue. The use of bearing was considered along the sliding shaft on Lever 2, however it was decided against, as it would add to complexity, as well as susceptibility to dirt. Furthermore, the tight fit between the sliding shaft and linear bearings will not easily become damaged by dirt. In this design, the same issue occurs as before where at the open position; Lever 1 connects to Lever 2 close to the pivot point, providing great mechanical advantage. As the prehensor closes, the connection point moves farther away from the hinge, and the mechanical advantage decreases. It can also be seen in Figure 9 that the position of the axes of rotation have been optimized, and the cable connector remains much closer to 90° (+70° to -12° deviation), increasing the force transmitted. Detailed drawing can be found in Appendix 1-B.

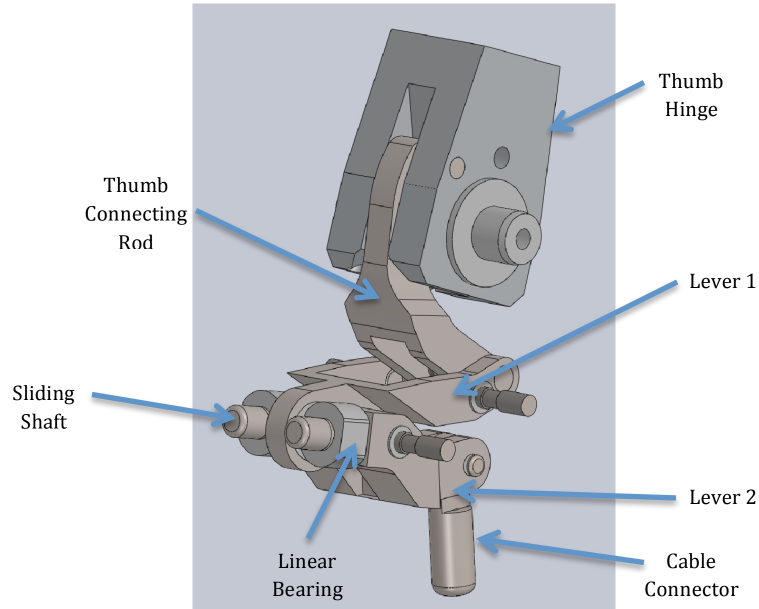

FIGURE 8 - SLIDING MECANISM 2.0

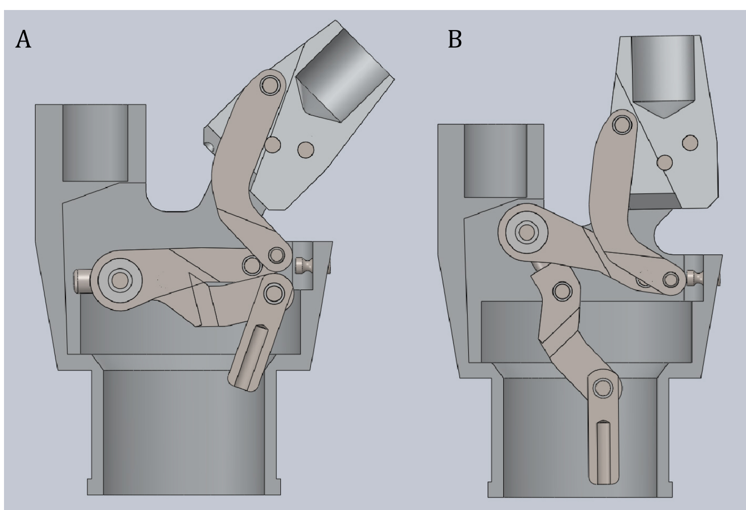

FIGURE 9 - SLIDING LEVER 2.0 (A) OPEN, AND (B) CLOSED POSITIONS

RESULTS

As the first redesign had very similar properties to the original mechanism, the results will concentrate in the second design, where the performance of the mechanism is remarkably different. The design will be compared across all five original criteria to access its efficacy as well as a Failure Modes and Effects Analysis (FMEA). As an aside, a prototype was sent for manufacturing, however due to delays and problems with time constrains, it was not functional at the time of this writing.

PINCH FORCE

A MATLAB model was made to determine the pinch force at an activation force of 11N (Appendix 2). Due to the sliding lever mechanism, the force transmission is not linear, but varies with the opening of the prehensor as well as the angle of the cable to Lever 1. It was found that the pinch force ranges from 15.2 N when the prehensor is at 50 mm opening to 3.4 N at 0 mm opening. This can be seen in Figure 10. For the first 85% of the operational range of the prehensor (50 to 42.5 mm) the performance of this design is superior to that of the original design. In the last 7.5 mm however its efficiency decreases to 1.6 times lower than that of the original design.

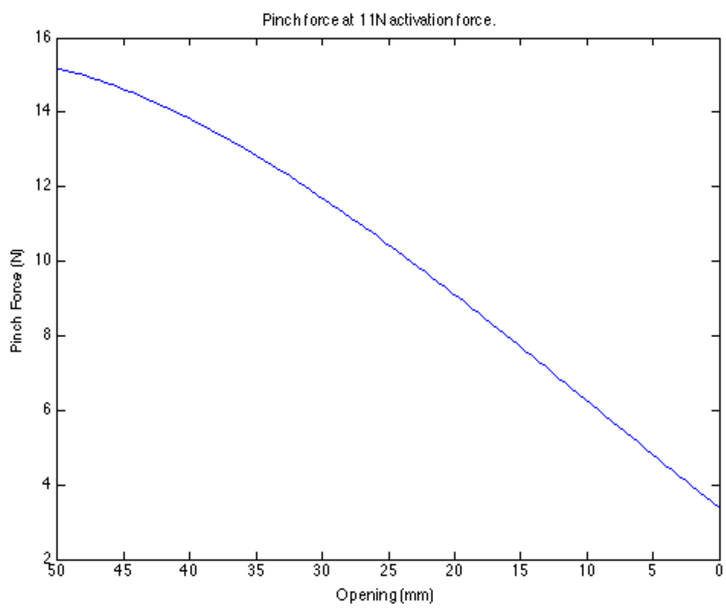

FIGURE 10 - PINCH FORCE AT A CONSTANT 11 N ACTIVATION

ACTIVATION FORCE

A MATLAB model was made (Appendix 2), to determine the activation force necessary to maintain 15 N of pinch force. Again, due to the sliding lever mechanism as well as changes in the cable angle to Lever 1, the force transmission is not linear. It was found that the activation force ranges from 10.8 N when the prehensor is at 50 mm opening to 48.9 N at 0 mm opening. This can be seen in Figure 11. Here, the activation force exceeds the peak activation force at 75% of the operational range (37.5 mm), therefore we see that 15 N cannot be exerted when the prehensor is closed more than 37.5 mm.**Error! Reference source not found.**

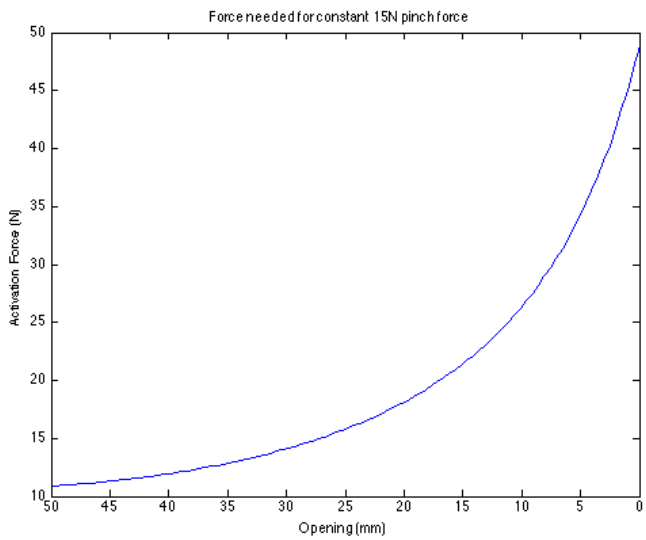

FIGURE 11 - ACTIVATION FORCE NEEDED TO MAINTAIN 15 N PINCH

OPENING WIDTH, CABLE EXCURSION AND WEIGHT

Due to the restriction imposed by the original enclosure, not much was changed that impacted the range of motion of the mechanism. This mechanism has an opening width of 50.72 mm. The measured cable excursion in SolidWorks was 11 mm, which is well below the design criteria. The weight as estimated by SolidWorks is 72.2 g without taking into account the cosmetic cover. This is 33.46 g lighter than the original mechanism without the cosmetic cover, therefore meets the design criteria.

FMEA

The forces acting on each part were derived by a MATLAB model (Appendix 2). Is order to achieve a high factor of safety, all calculations were made at three times the maximum desired pinch force (45 N). It was determined that all parts could be made of 7075-T6 aluminum, except for Lever 1, Lever 2, the Thumb Connecting Rod, and all their associated axis which are manufactured of Ti-6Al-4V titanium. Also, all bearings are made from Polychlorotrifluoroethylene (PCTFE). All parts had a minimum factor of safety (FOS) above 1. Figure 12 shows a of sample FMEA analysis. All other major parts can be found in (Appendix 3).

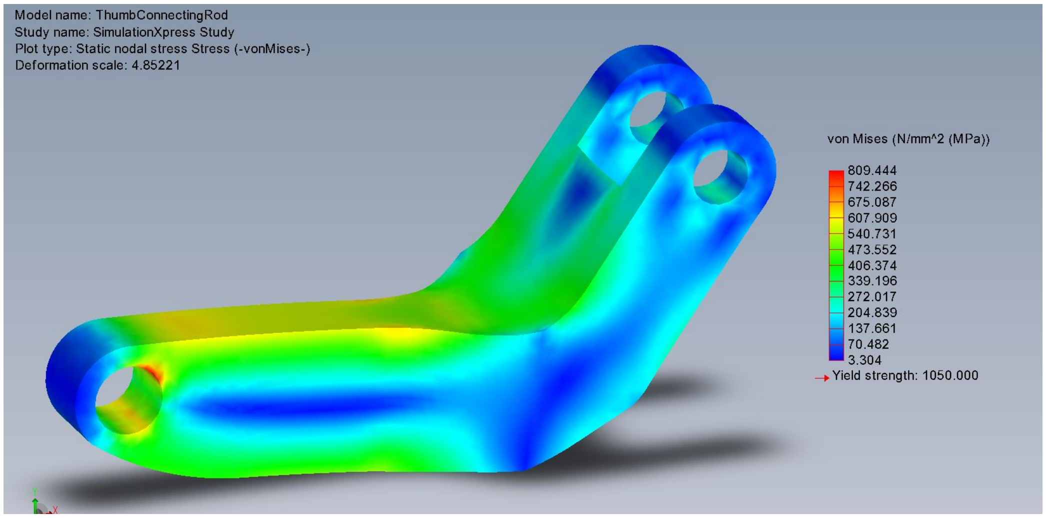

FIGURE 12 - THUMB CONNECTING ROD FMEA

Discussion

A new mechanism was designed for the WILMER Appealing VC Prehensor. Although unconventional, the design improves on all delineated criteria; for most of the operational range, the pinch force remains above the determined 15 N, the activation force remains below 15 N, the prehensor can open more than the minimum 50 mm, and the cable excursion and weight are far below the set criteria. Additionally it meets the constraints of the original design, resulting in the same outward appearance as original design.

What is interesting to note however is the non-linearity of the force transmission. Due to this there will be an increased learning curve for the user in order to properly be able to adjust the activation force to achieve the desired pinch force. Furthermore, the shorter cable excursion diminishes the fine control of the opening of the prehensor compared to the original design. Also with the increase in complexity, this design is more prone to failure. However, it should still be relatively immune to sand, water and dust.

Another point to be addressed in a future study would be to better understand the average grip size for ADLs. As with this design the further closed the prehensor is, the less efficient it becomes, perhaps it is the case that the smaller opening are not used as often and therefore that range is not as important. Or the opposite might be true, which would render this design extremely inefficient.

It is difficult to make true predictions to the real efficacy, as friction is difficult to account for. As stated before, a prototype was sent to production. However due to holidays, it was delayed. Then as other tasks arose, the priority of building the prototype was lowered. When time finally came to build it, there were some manufacturing mistakes that were unfortunately too late to correct. At the time of this writing, the prototype is still non functional. It is recommendable that future studies correct these mistakes and further test the prototype.

It is also noteworthy to include the fact that a locking mechanism was considered for this project to maintain the prehensor closed at a specific position. However such systems already exist in the market (Sure-Lok Cable System by TRS ®), which are simple and work well. Besides, there is anecdotal evidence that locking systems for VC prosthesis are unnecessary for daily use.

Conclusion

The design by Alireza Tousi, was analyzed in this project. All the original design criteria were checked and found to be valid, and all criteria were optimized to create a more efficient mechanism. The activation force was lowered from 22.5 to 10.8 N to produce a 15 instead of 10 N pinch force; the cable excursion was lowered by 7 mm, which is much less than the criteria of 26.5 mm; the total weight was lowered by 33.46 g; the transmission ratio was improved for 85% of the operational range; the minimum opening width was met at 51 mm; and the external dimensions were maintained. Although a functional prototype was not finished, these results show promise and encourage the realization of a prototype for testing.

This internship project was a good learning experience. I learned the value of better managing time, as well as the necessity of constant communication with supervisors, both for project updates and advice. If I were to repeat this experience, I would have taken further advantage of their wisdom to guide me along this project. I highly recommend future students consider this in all their endeavors, and seek out projects as this to further their personal growth.

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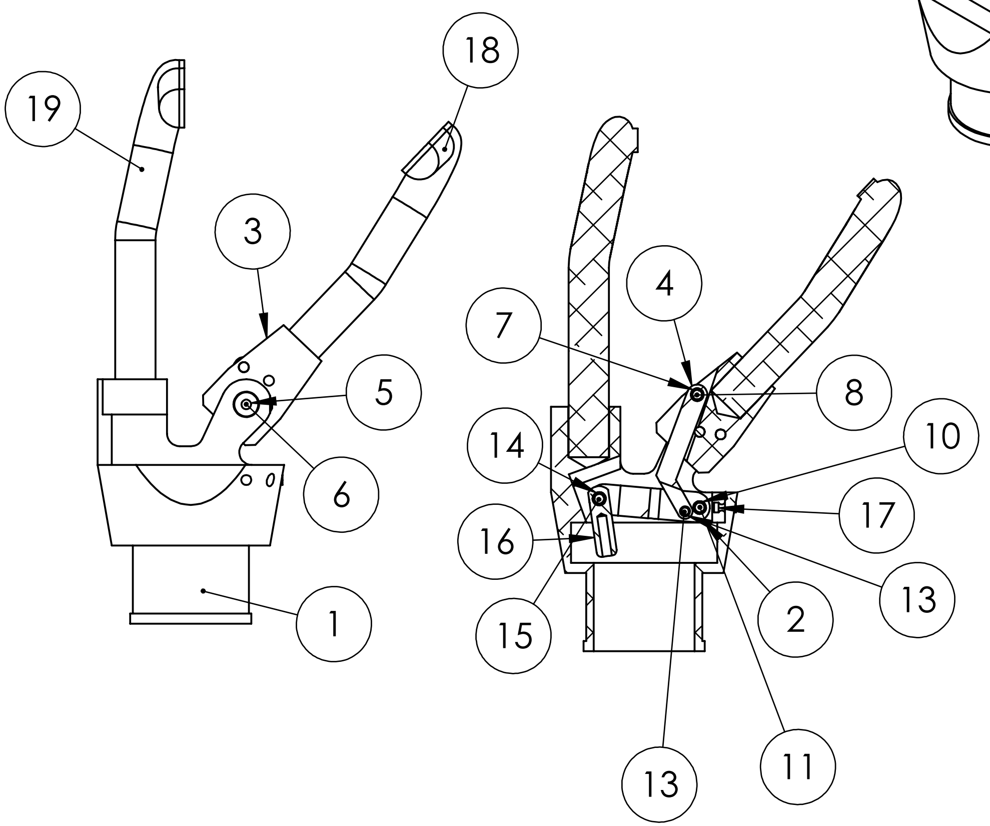
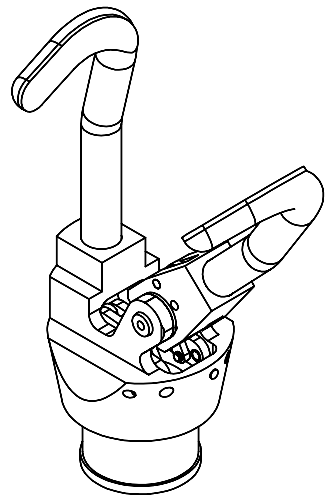
APPENDIX 1-A

Mechanism redesign 1





BOM Table		
ITEM NO.	PART NUMBER	QTY.
1	Body	1
2	LeverMain	1
3	ThumbHinge	1
4	ThumbConnectingRod	1
5	ThumbHingeBearing	2
6	ThumHingeAxis	1
7	ThumbHingeTorqueShaftBearing	1
8	ThumbHingeTorqueShaft	1
9	ThumHingeSpringPin	1
10	MainLeverShaftBearing	2
11	MainLeverAxis	2
12	LeverThumbRodAxisBearing	2
13	LeverThumbRodAxis	2
14	CableConnectorBearing	1
15	CableConnectorAxis	1
16	CableConnector	1
17	BodySpringPin	1
18	ThumbL	1
19	FingerR	1

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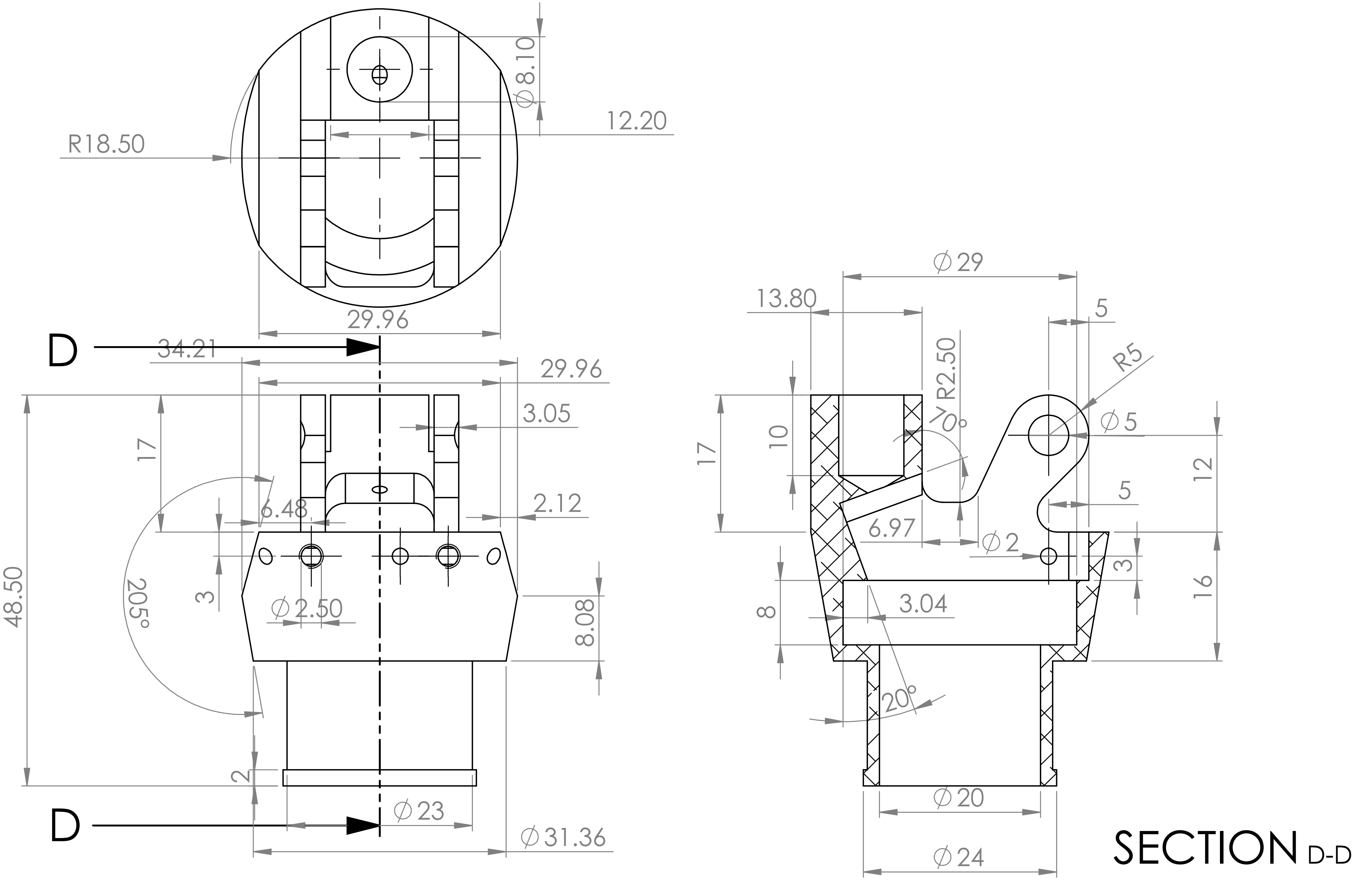

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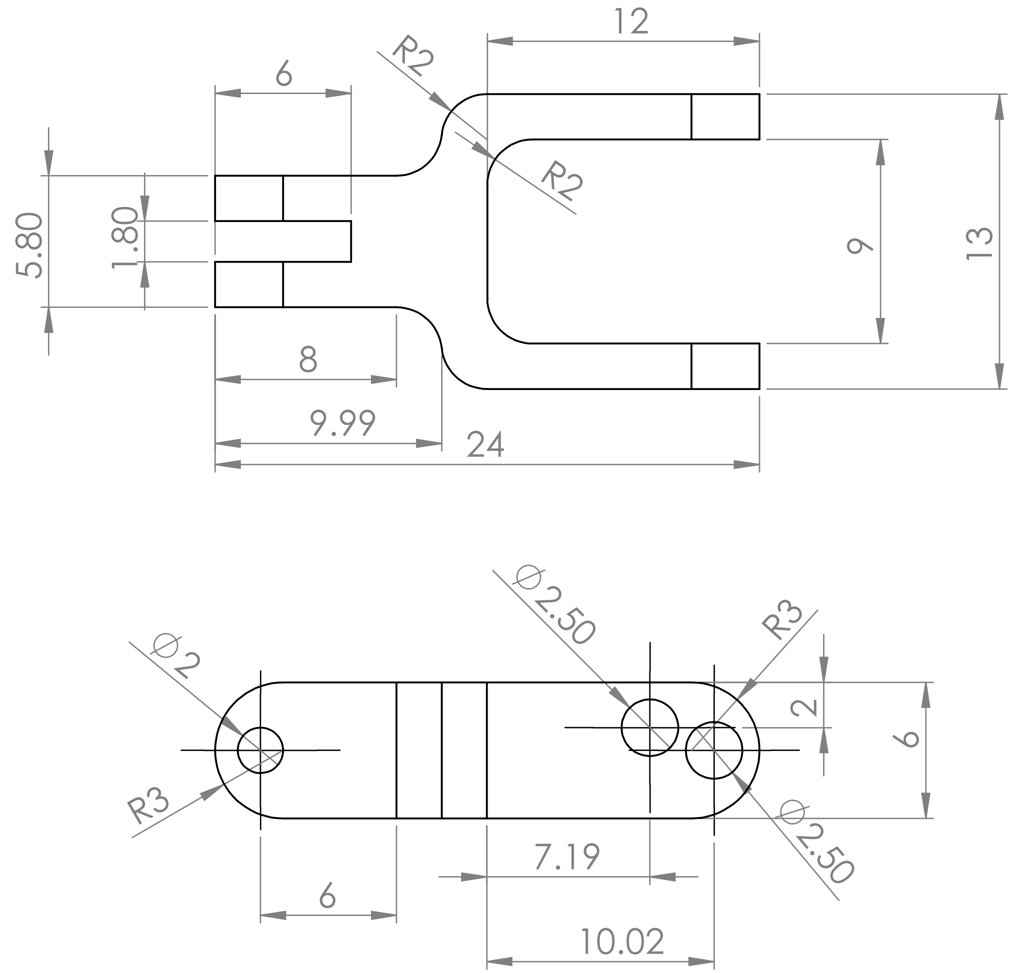
SolidWorks Student Edition.
For Academic Use Only.



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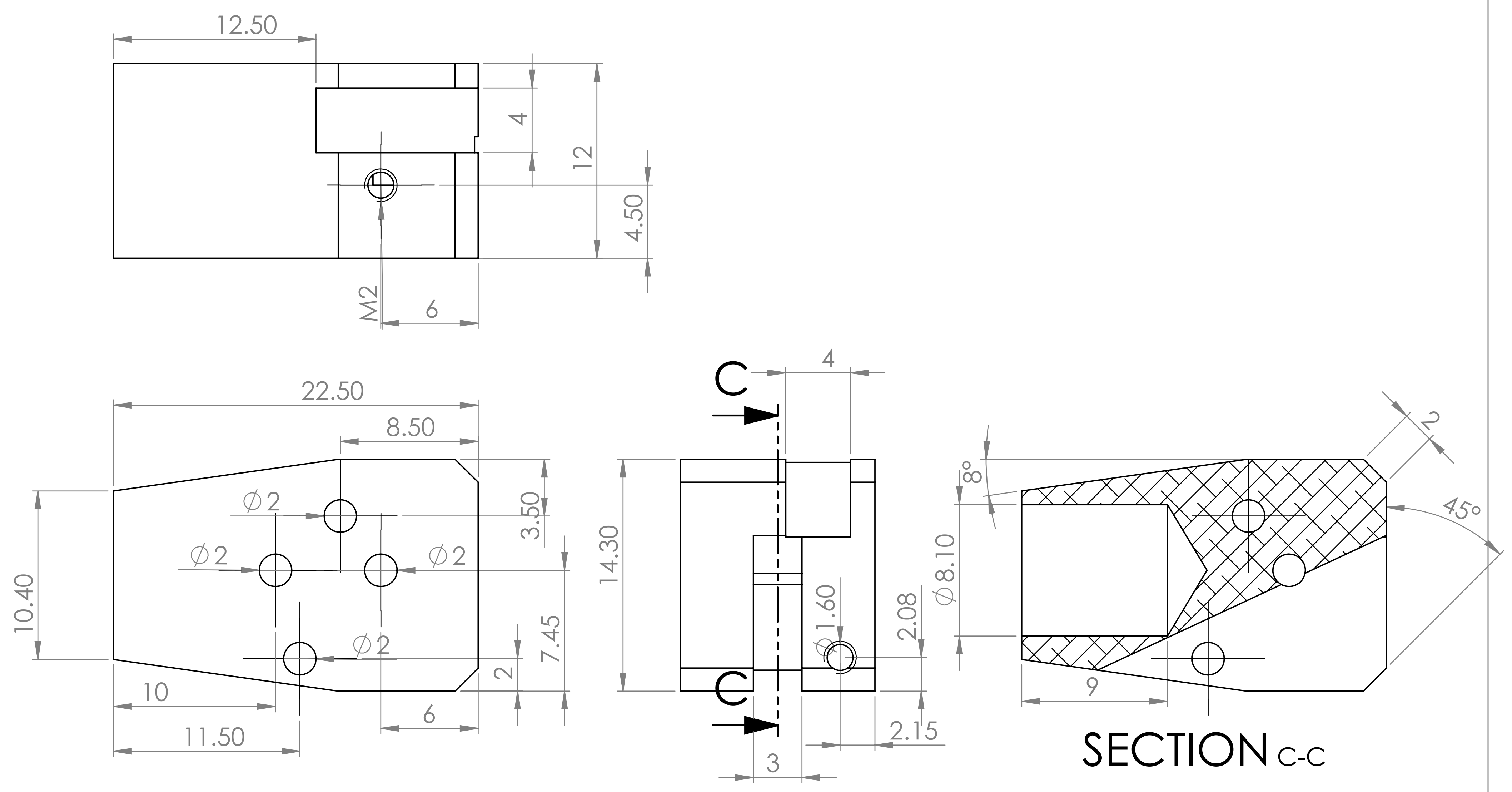

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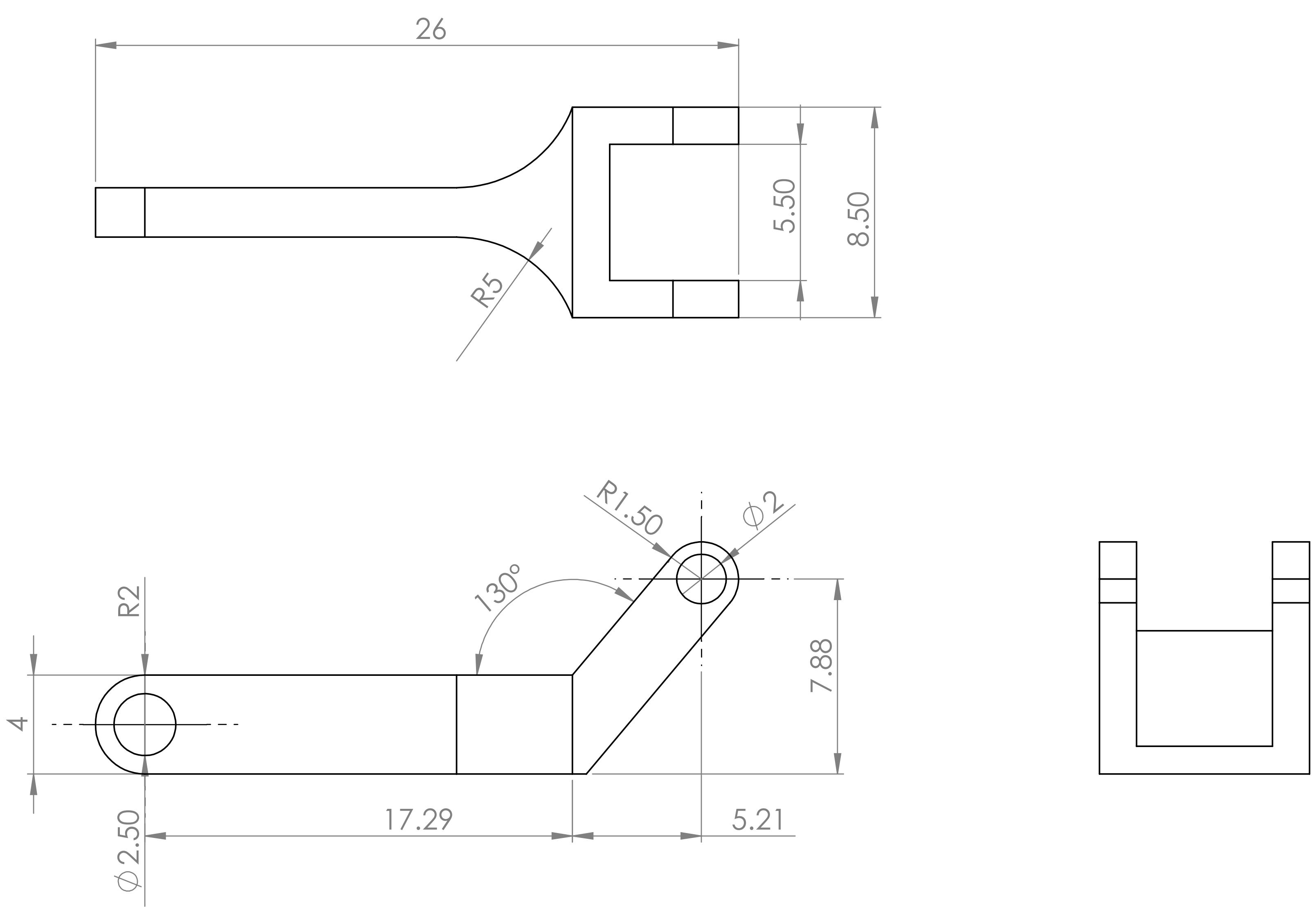

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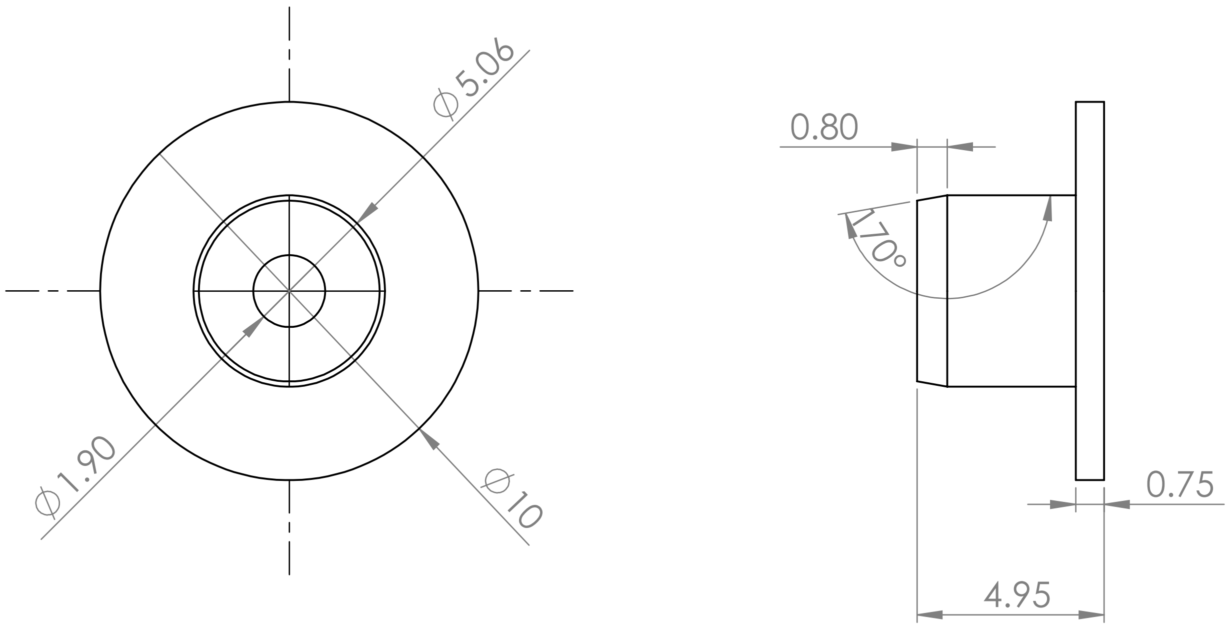

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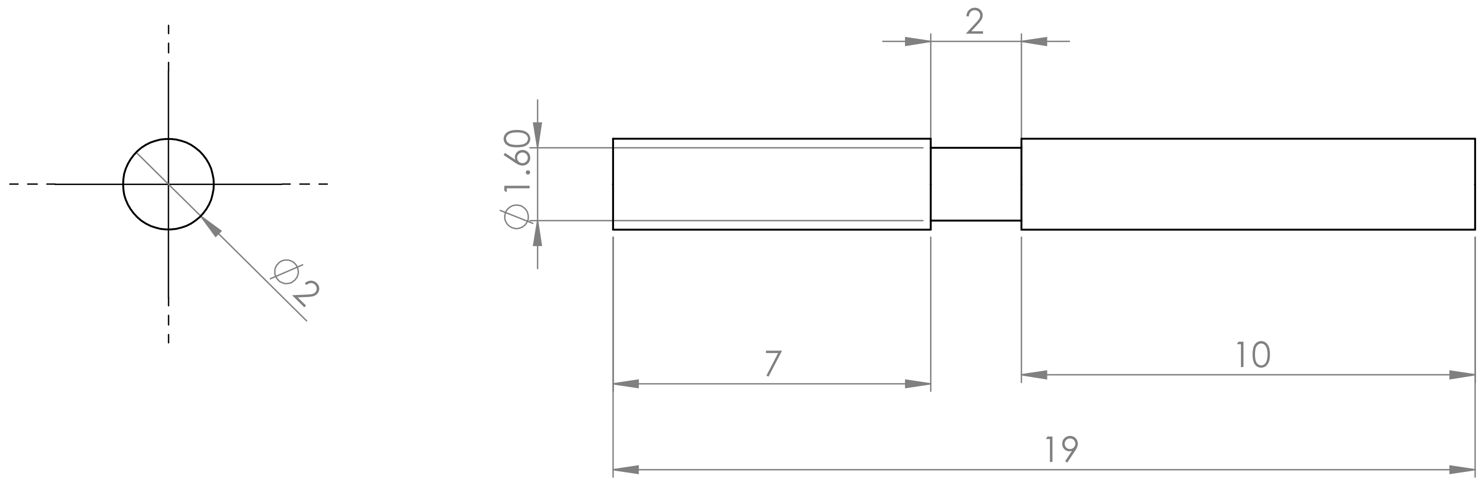

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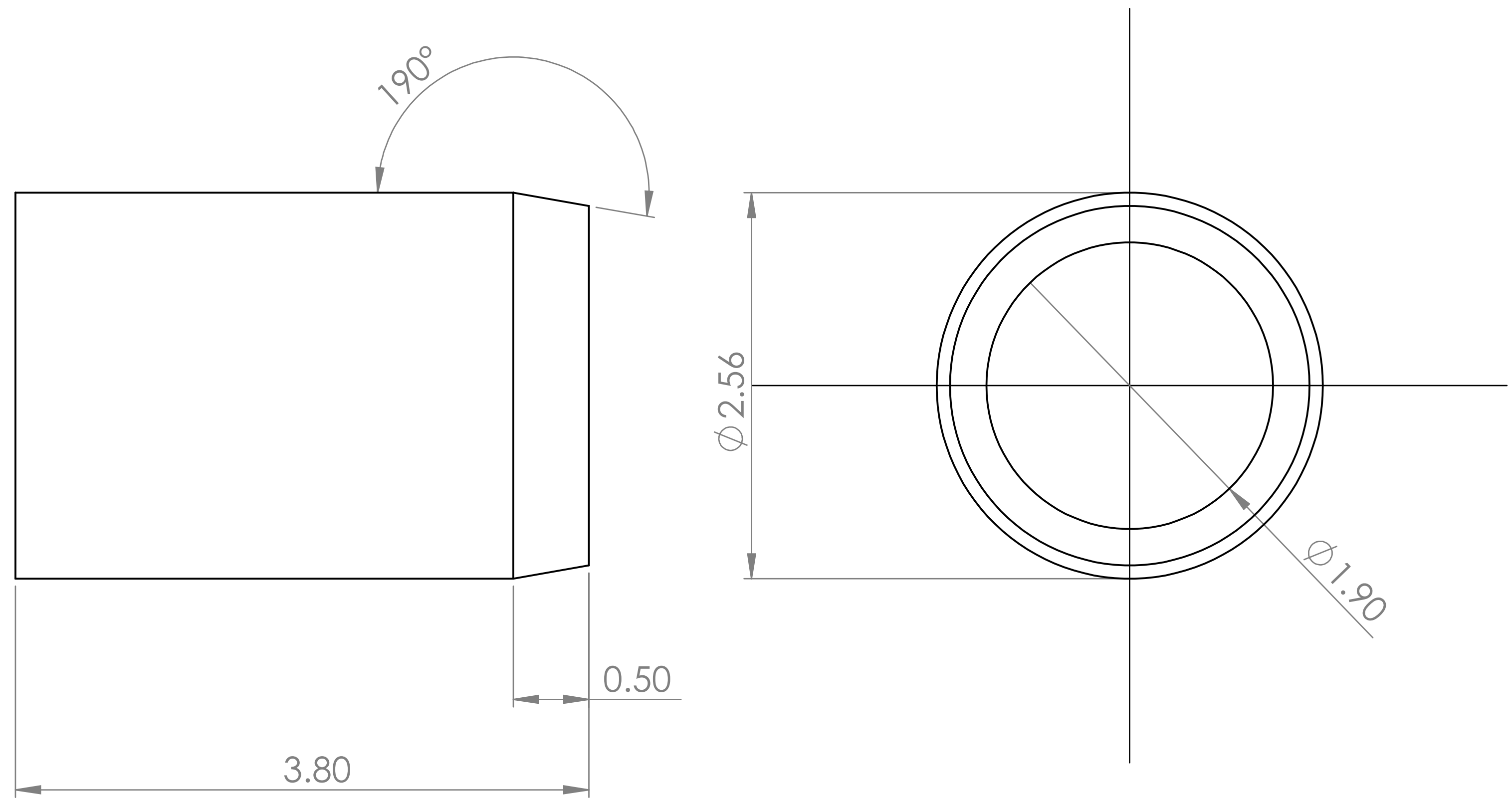

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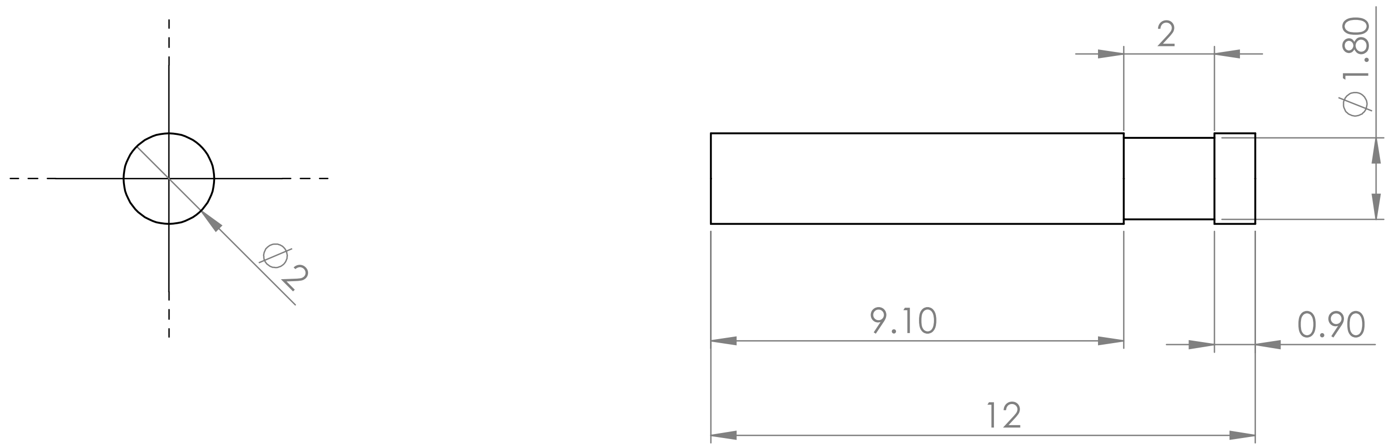

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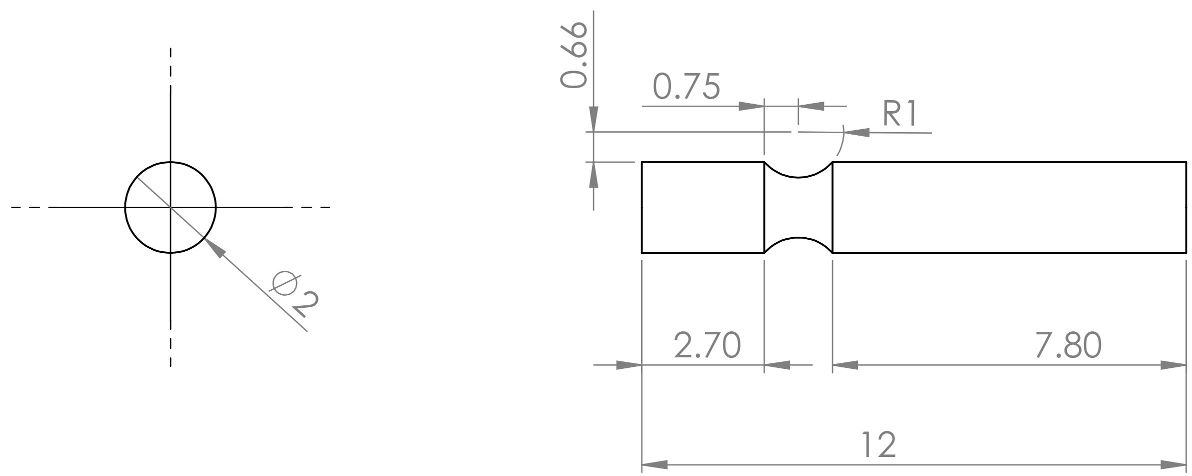

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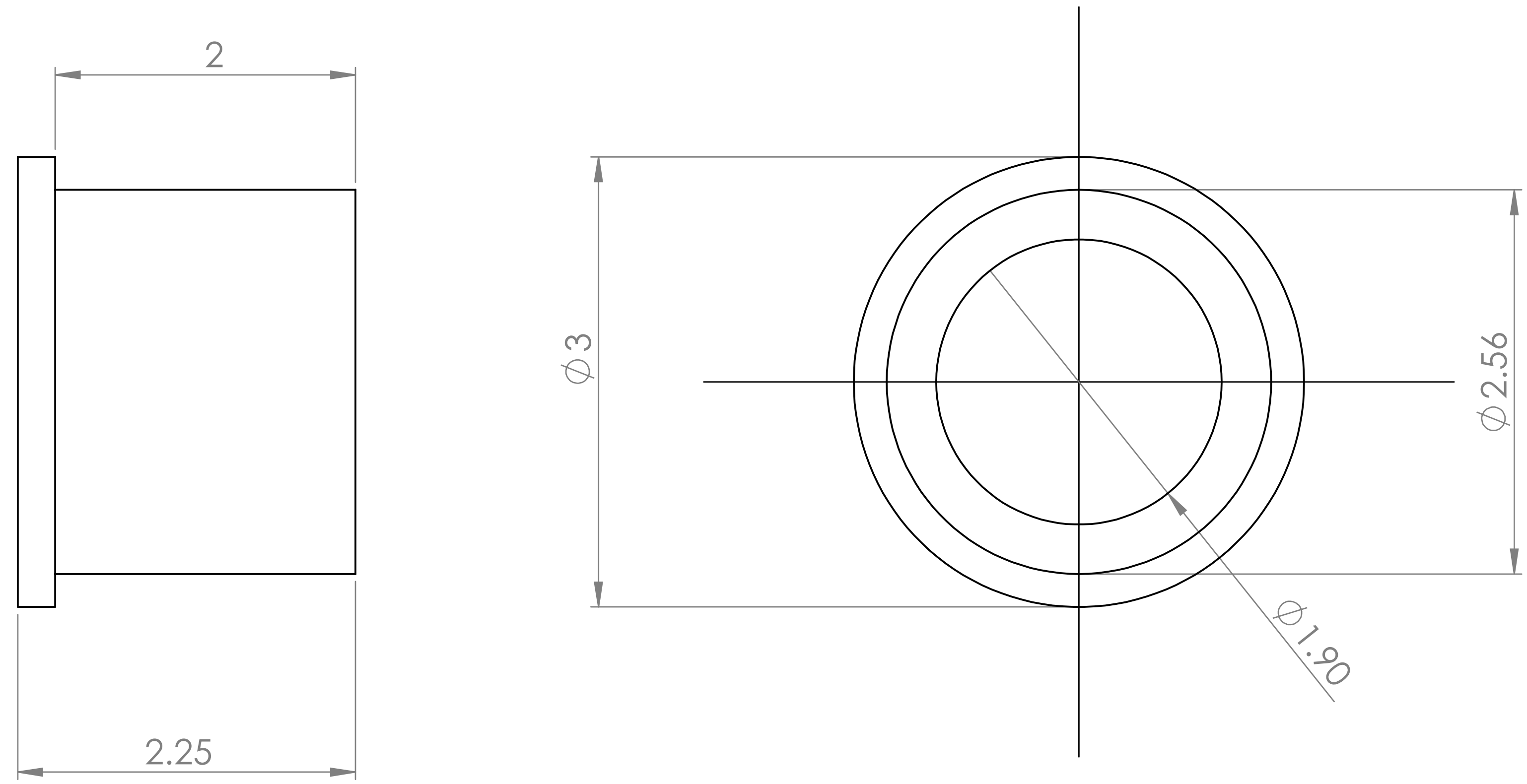
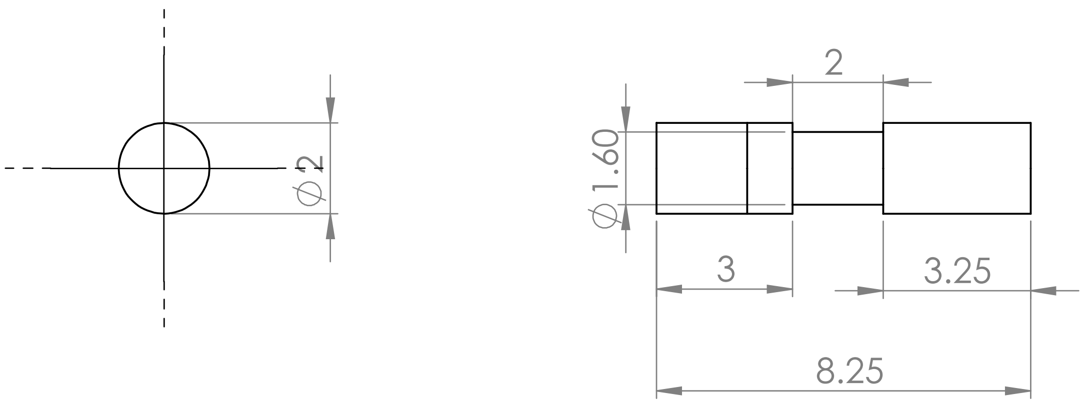
		Drawn by: Roberto Moratore Jr	Format A4	

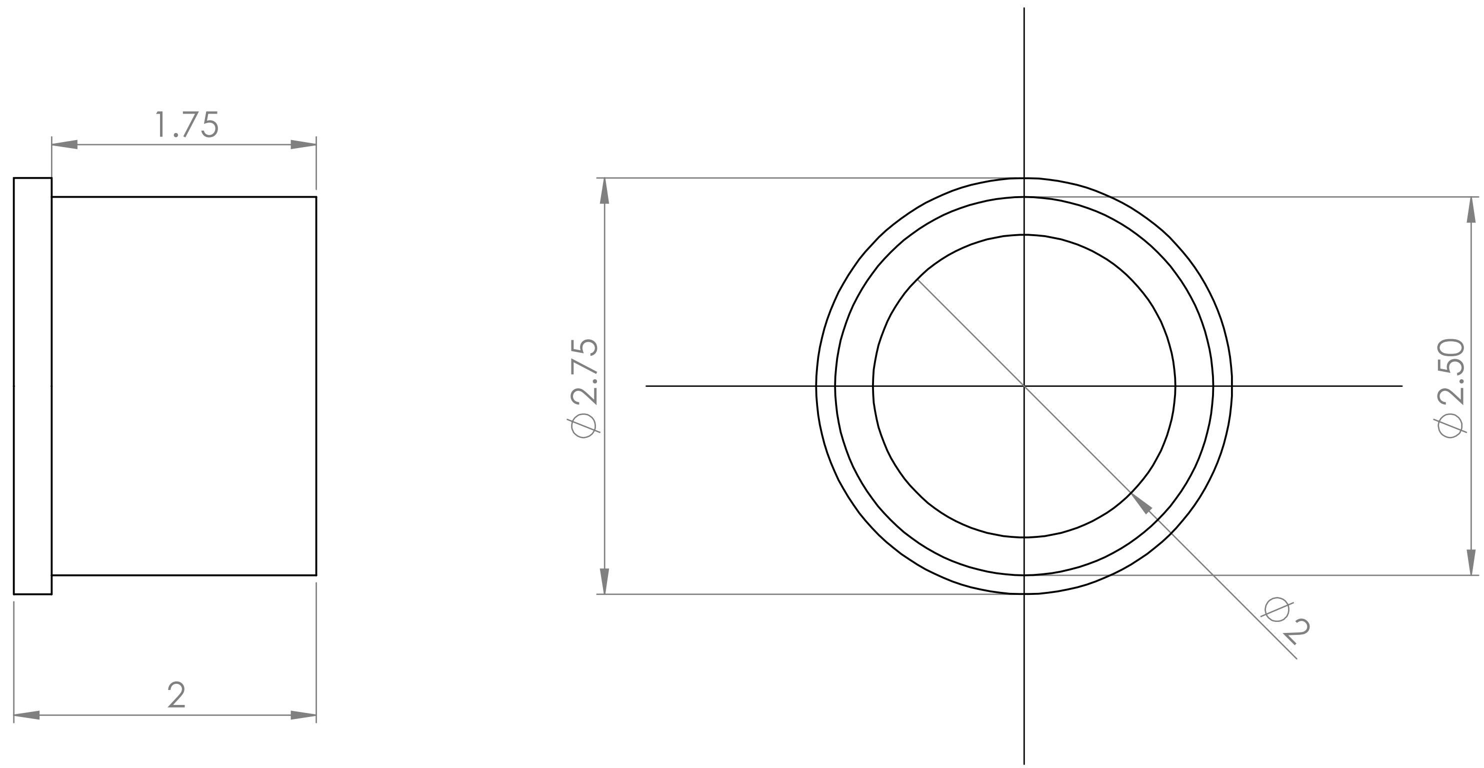


TU Delft
Biomedical Engineering

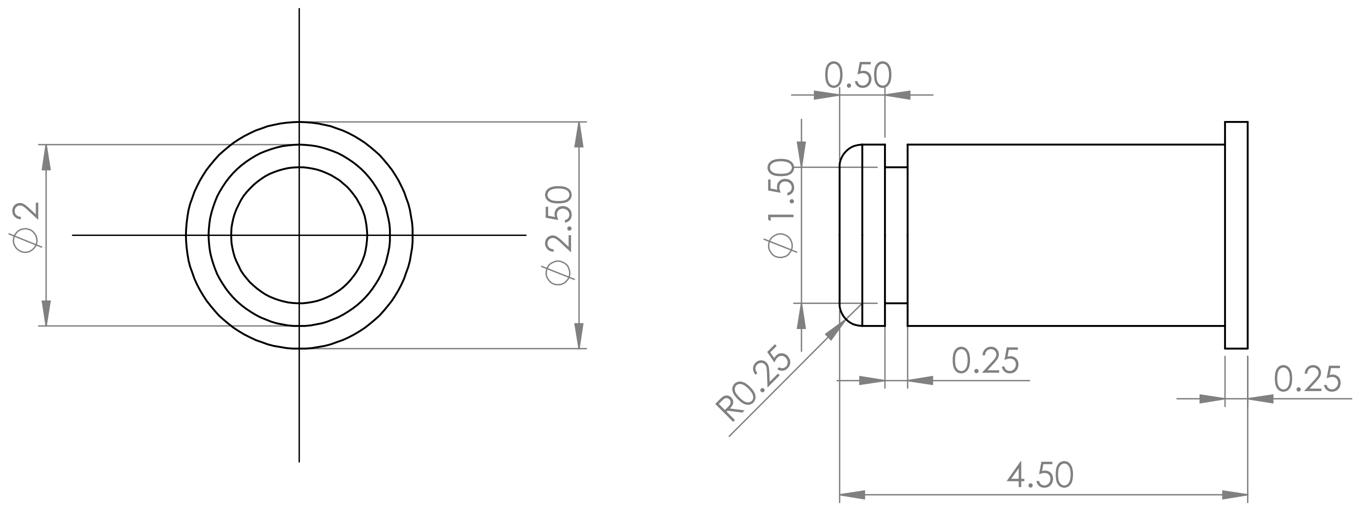
Part Name: Lever Bearing	Date: 6/28/13		Material: PCTFE (Eriflon)
Scale: 2:3	Units: mm	Format A4	Sheet No: 11 of 20
Drawn by: Roberto Moratore Jr			



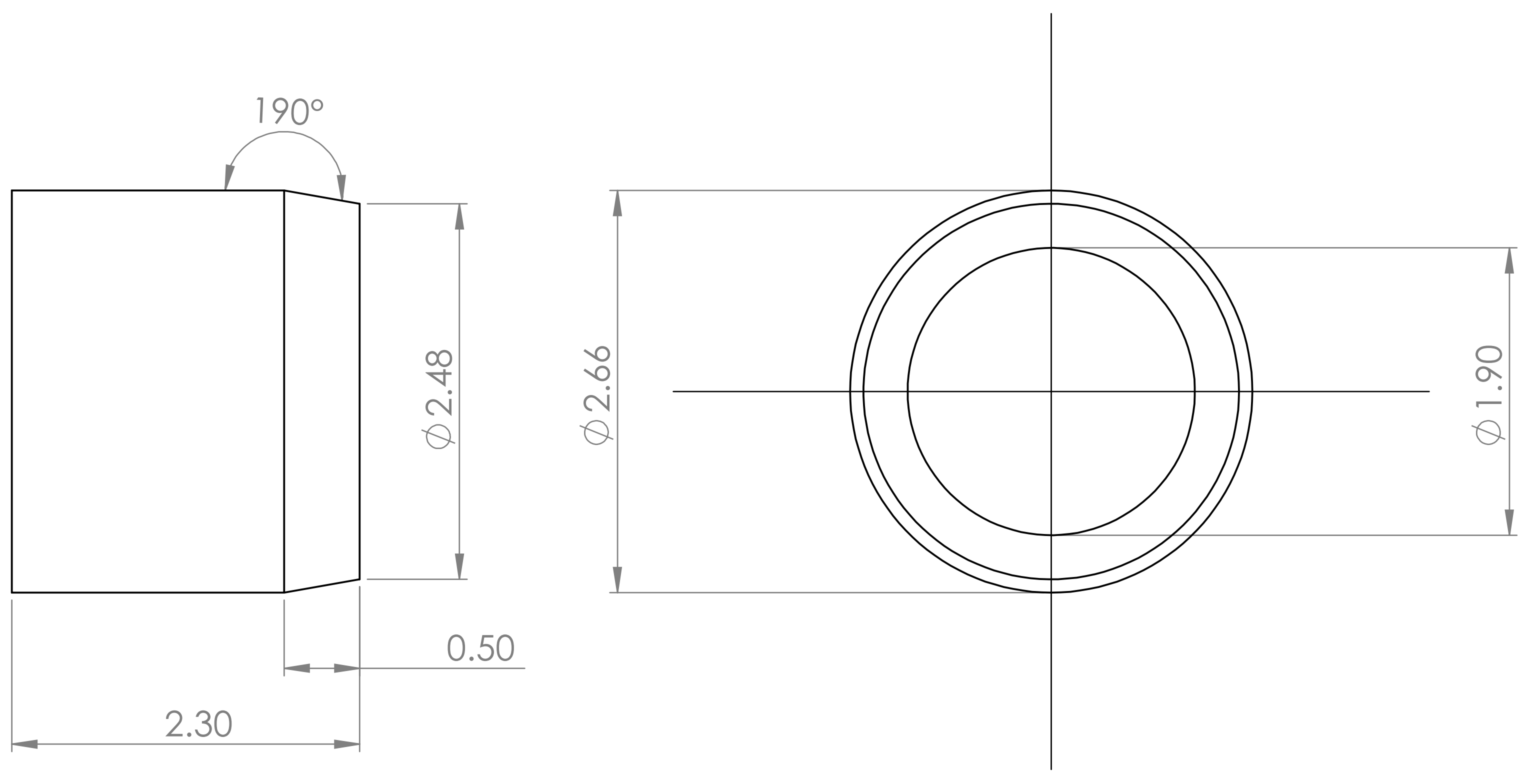
TU Delft Biomedical Engineering	Part Name: Lever Axis		Date: 6/28/13	Material: Ti-6Al-4VSolution treated an
		Scale: 6:1	Units: mm	Sheet No: 12 of 20
		Drawn by: Roberto Moratore Jr	Format A4	



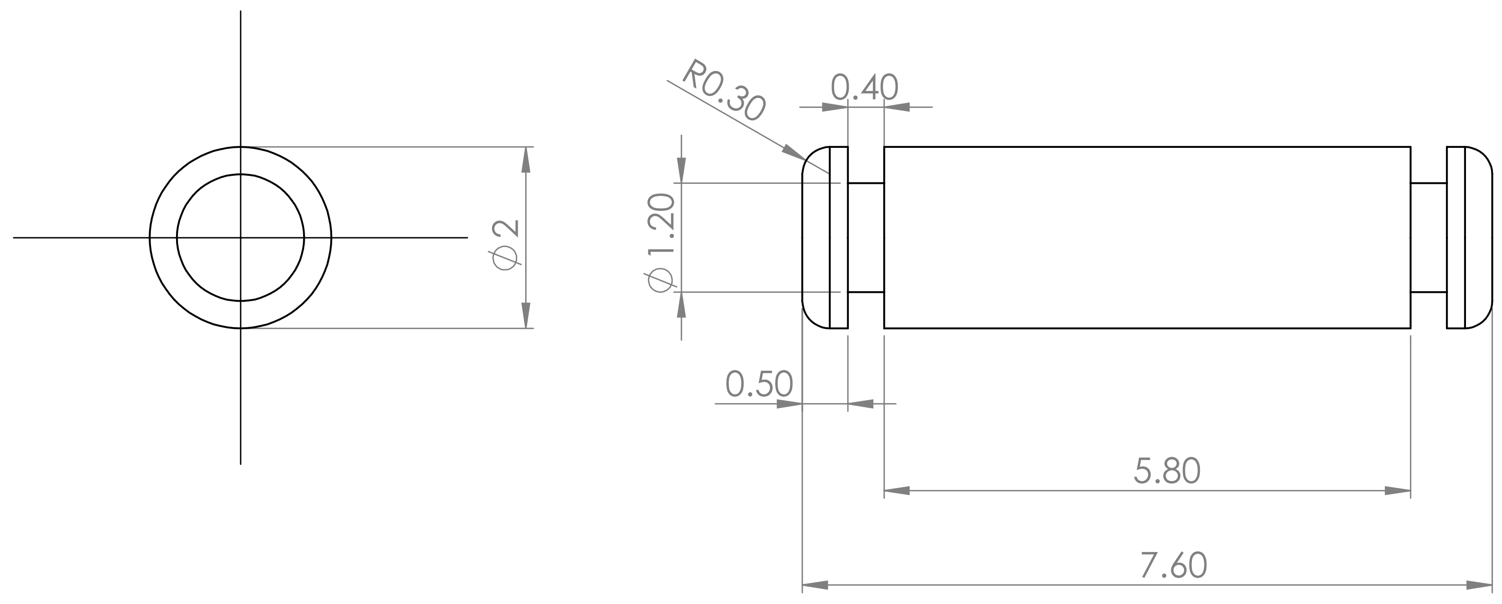
TU Delft Biomedical Engineering	Part Name: Lever Thumb Rod Bearing		Date: 6/28/13	Material: PCTFE (Eriflon)
		Scale: 2:3	Units: mm	Sheet No: 13 of 20
		Drawn by: Roberto Moratore Jr	Format A4	



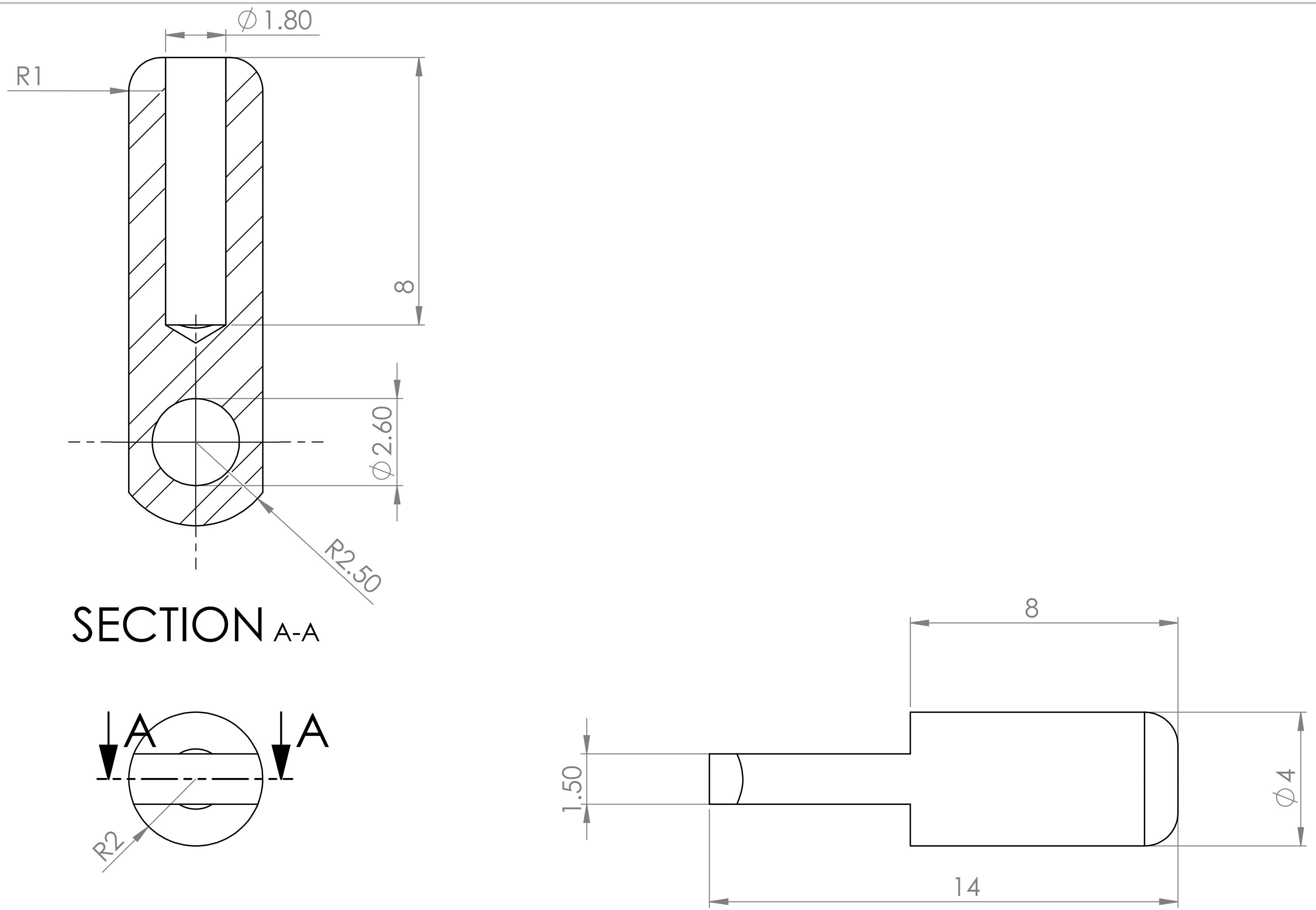
TU Delft Biomedical Engineering	Part Name: Lever Thumb Rod Axis		Date: 6/28/13	Material: Ti-6Al-4VSolution treated and
		Scale: 12:1	Units: mm	Format A4	Sheet No: 14 of 20
		Drawn by: Roberto Moratore Jr			



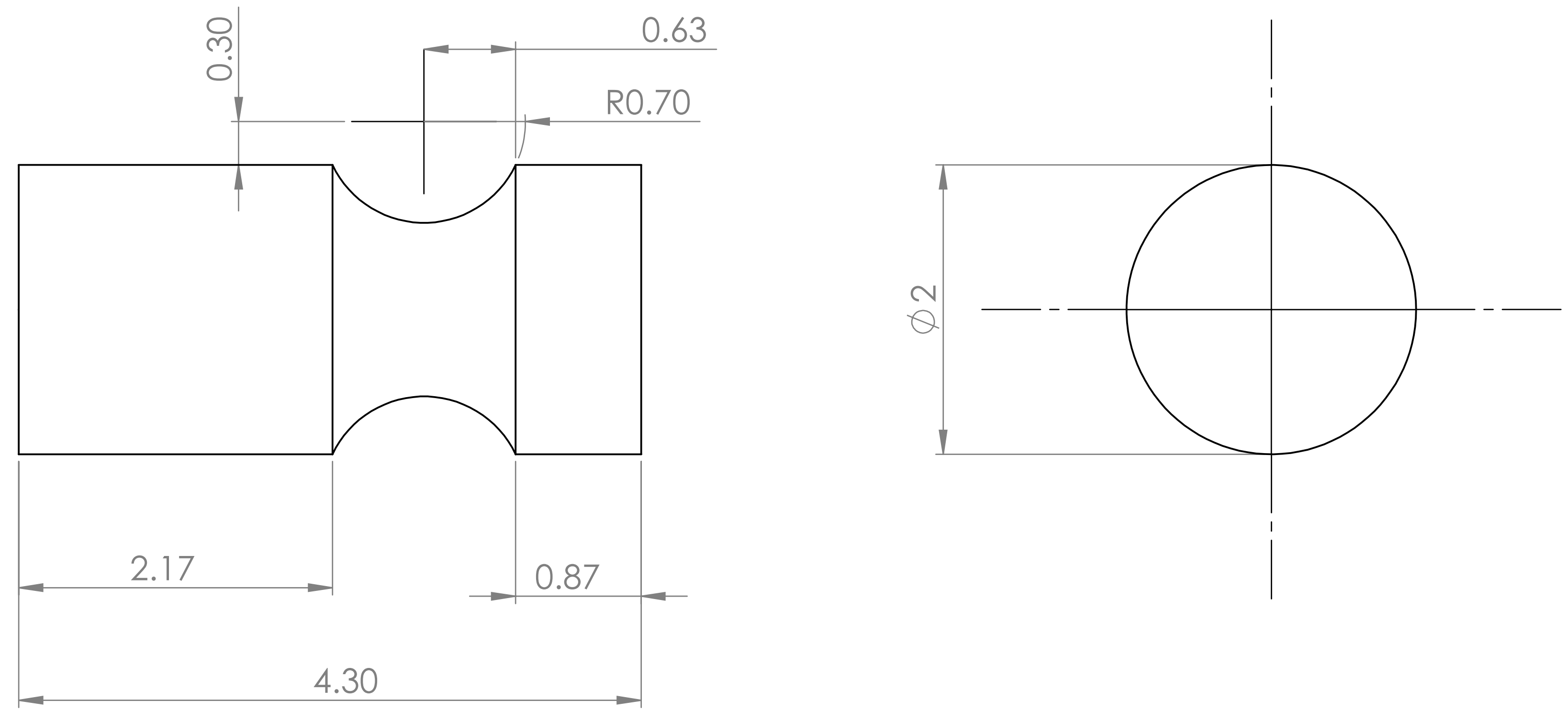
TU Delft Biomedical Engineering	Part Name:		Date: 6/28/13		Material: PCTFE (Eriflon)
		Scale: 2:3	Units: mm	Format A4	Sheet No: 15 of 20
		Drawn by: G. Smit			



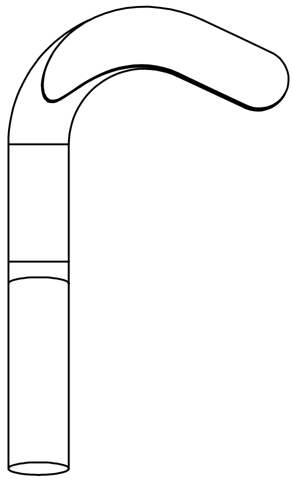
TU Delft Biomedical Engineering	Part Name: Cable Connector Axis		Date: 6/28/13	Material: AISI 304
		Scale: 12:1	Units: mm	Sheet No: 16 of 20
		Drawn by: G. Smit	Format A4	

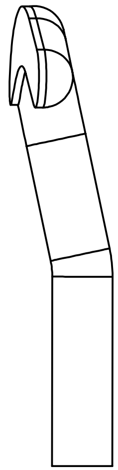


TU Delft Biomedical Engineering	Part Name: Cable Connector	Date: 6/28/13	Material: AISI 304
		Scale: 6:1	Units: mm
		Drawn by: Roberto Moratore Jr	Format A4
			Sheet No: 17 of 20

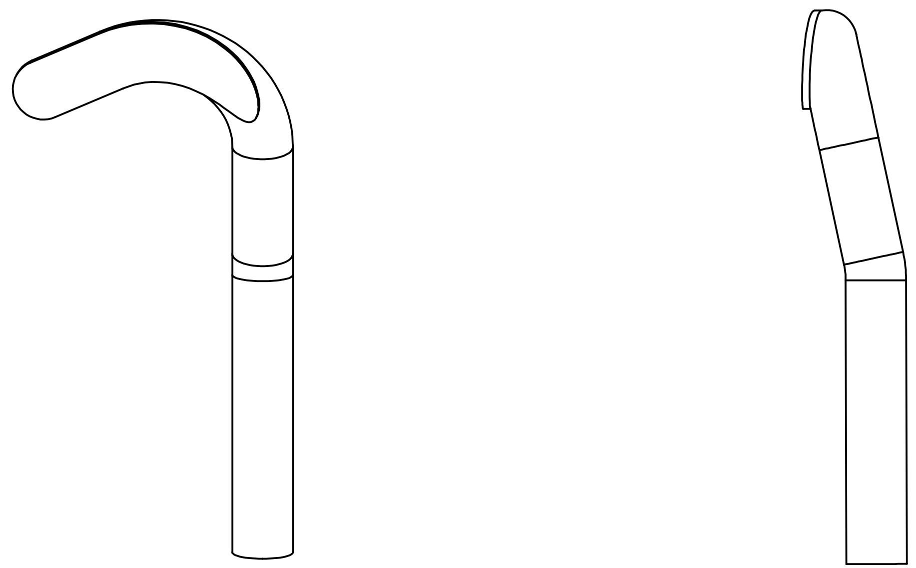


TU Delft Biomedical Engineering	Part Name: Body Spring Pin	Scale: 2:3	Date: 6/28/13	Material: AISI 304
		Drawn by: G. Smit	Units: mm	Format A4
				Sheet No: 18 of 20





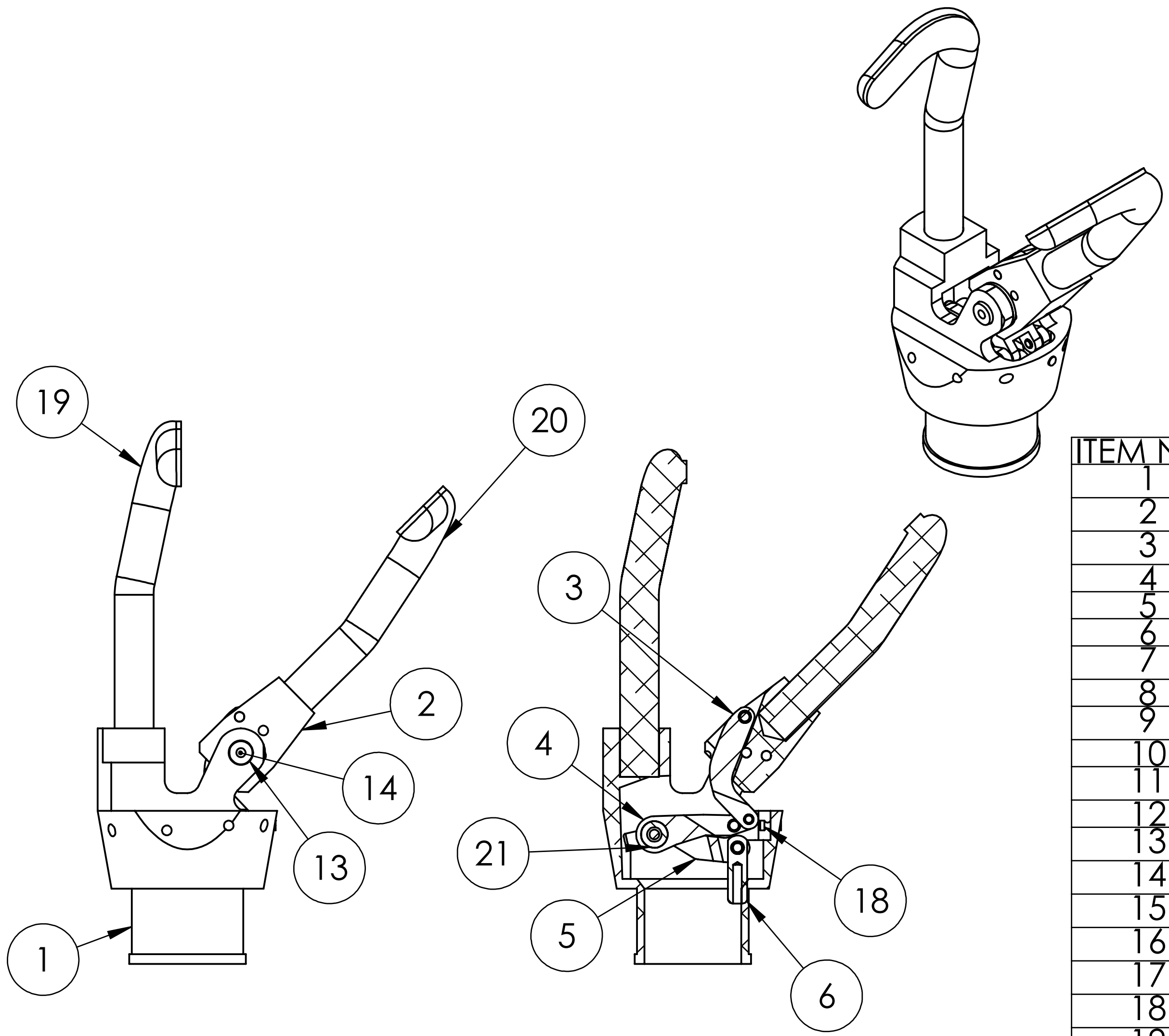
TU Delft Biomedical Engineering	Part Name: Thumb (Left)		Date: 6/28/13		Material: 5154-O, Rod (SS)
		Scale: 1:1	Units: mm	Format A4	Sheet No: 19 of 20
		Drawn by: G. Smit			



TU Delft Biomedical Engineering	Part Name: Finger (Right)	Date: 6/28/13		Material: 5154-O, Rod (SS)
		Scale: 1:1	Units: mm	Format A4 / Sheet No: 20 of 20
		Drawn by: G. Smit		

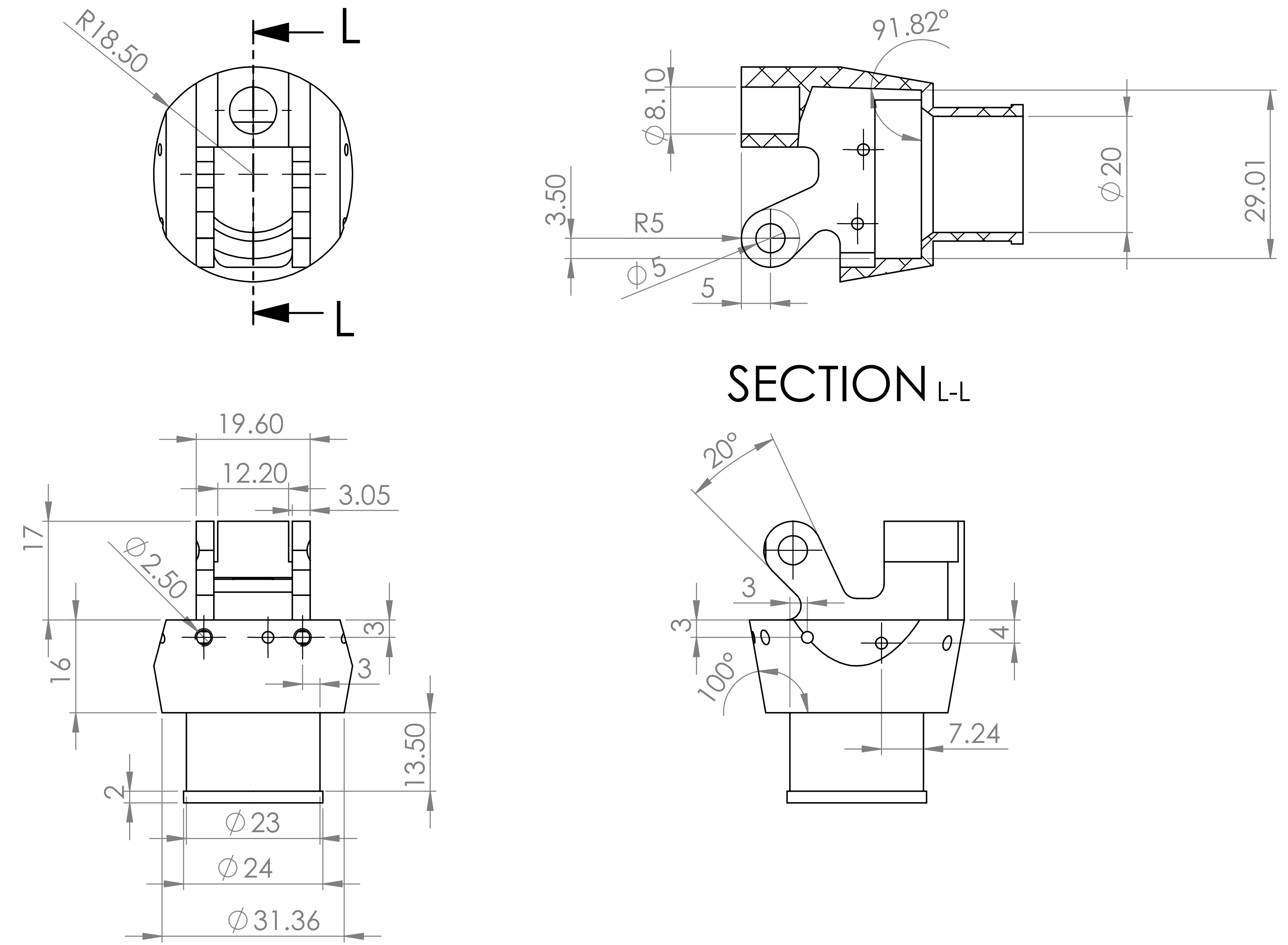
APPENDIX 1-B

Mechanism redesign 2

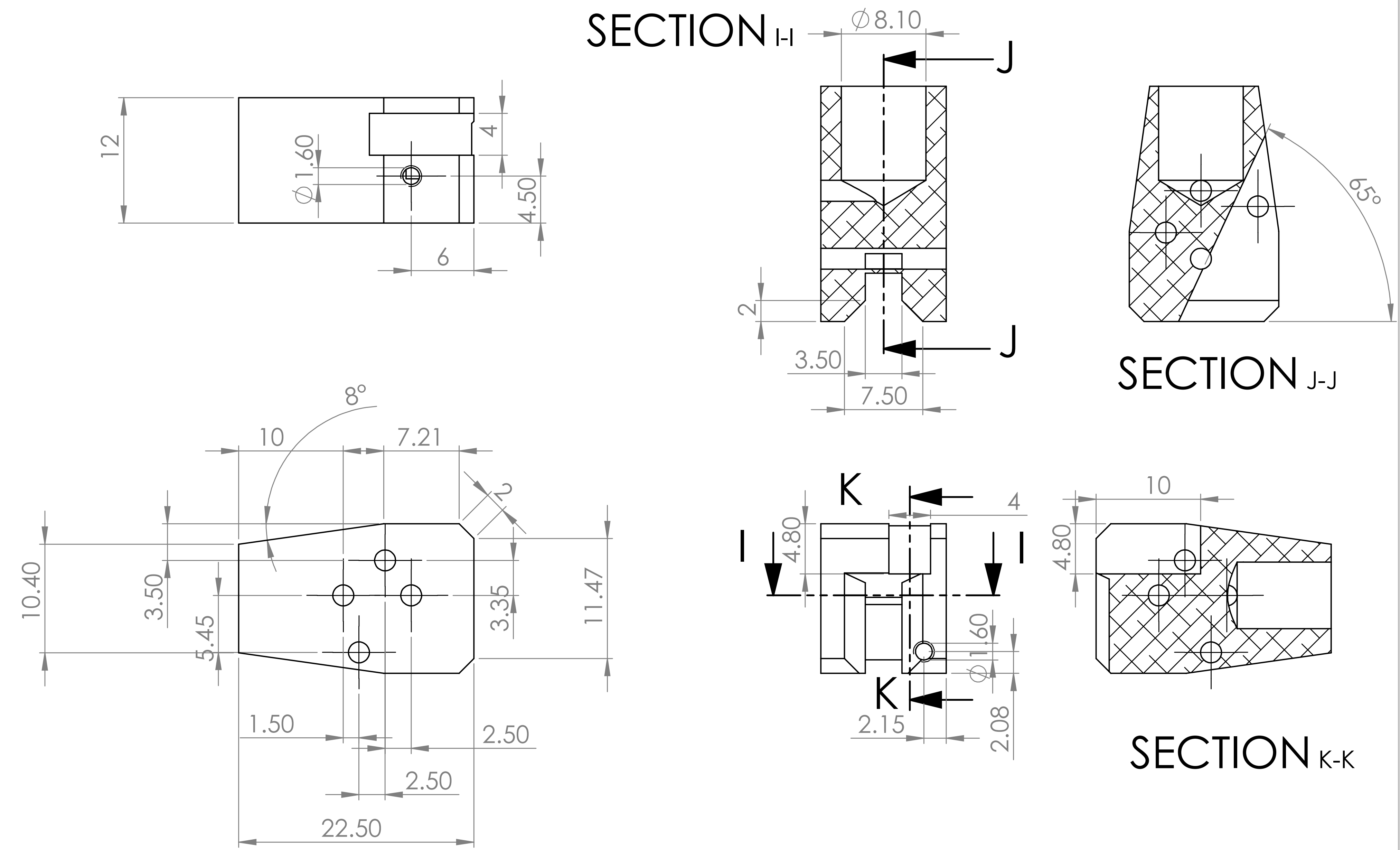


ITEM NO.	PART NUMBER	QTY.
1	Body	1
2	ThumbHinge	1
3	ThumbConnectingRod	1
4	Lever1	1
5	Lever2	1
6	CableConnector	1
7	CableConnectorBearing	1
8	CableConnectorAxis	1
9	LeverThumbRodAxisBearing	2
10	LeverThumbRodAxis	2
11	LeverShaftBearing	4
12	LeverAxis	4
13	ThumbHingeBearing	2
14	ThumHingeAxis	1
15	ThumbHingeTorqueShaftBearing	1
16	ThumbHingeTorqueShaft	1
17	ThumHingeSpringPin	1
18	BodySpringPin	1
19	FingerR	1
20	ThumbL	1
21	CenterBearing	1
22	LinearBearing	2
23	BearingShaft	1

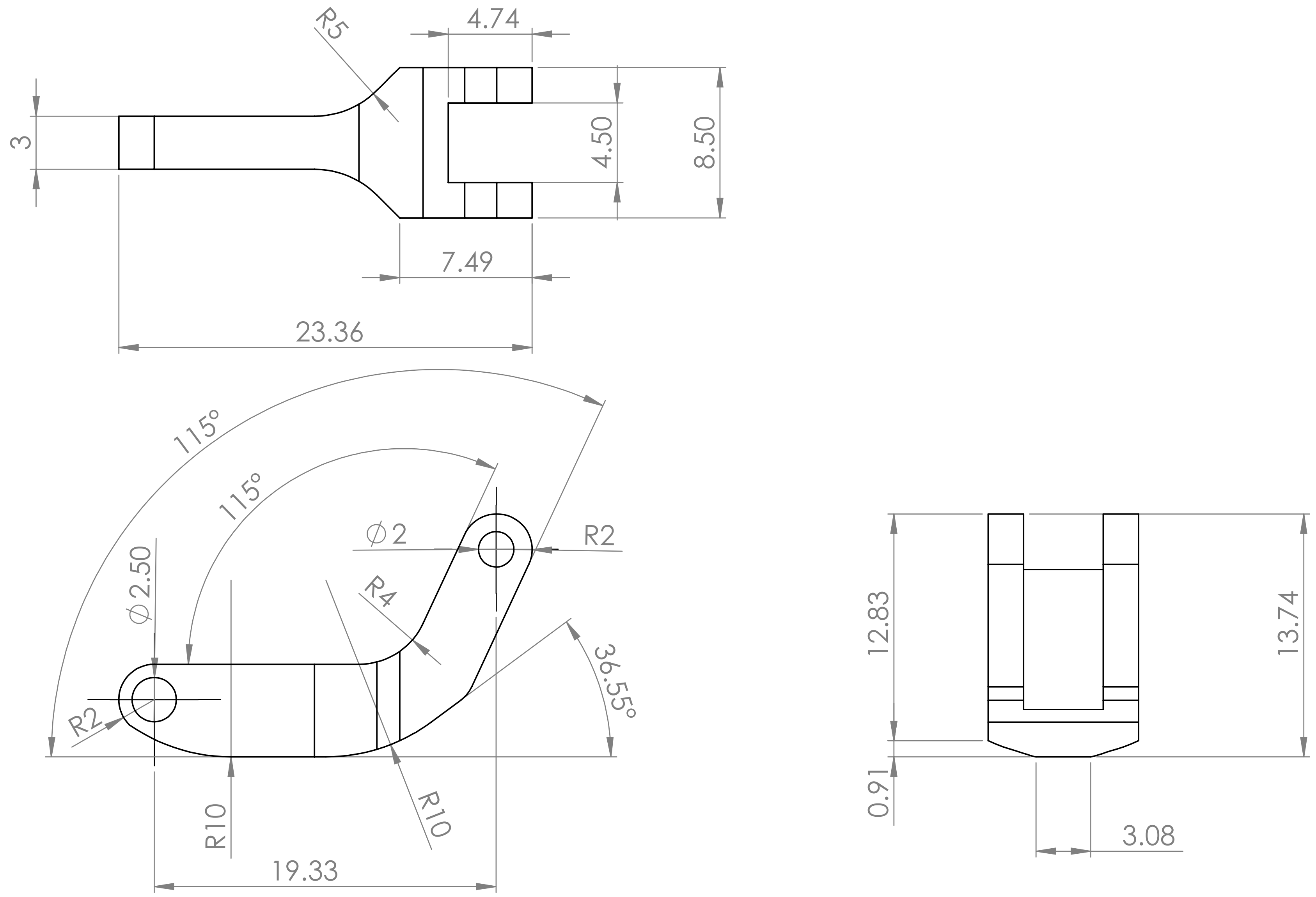
TU Delft Biomedical Engineering	Part Name: Tweezer Assembly		Date: 7/1/13	Material: Material <not specified>
		Scale: 2:3	Units: mm	Format A4 / Sheet No: 1 of 24
		Drawn by: Roberto Moratore Jr		



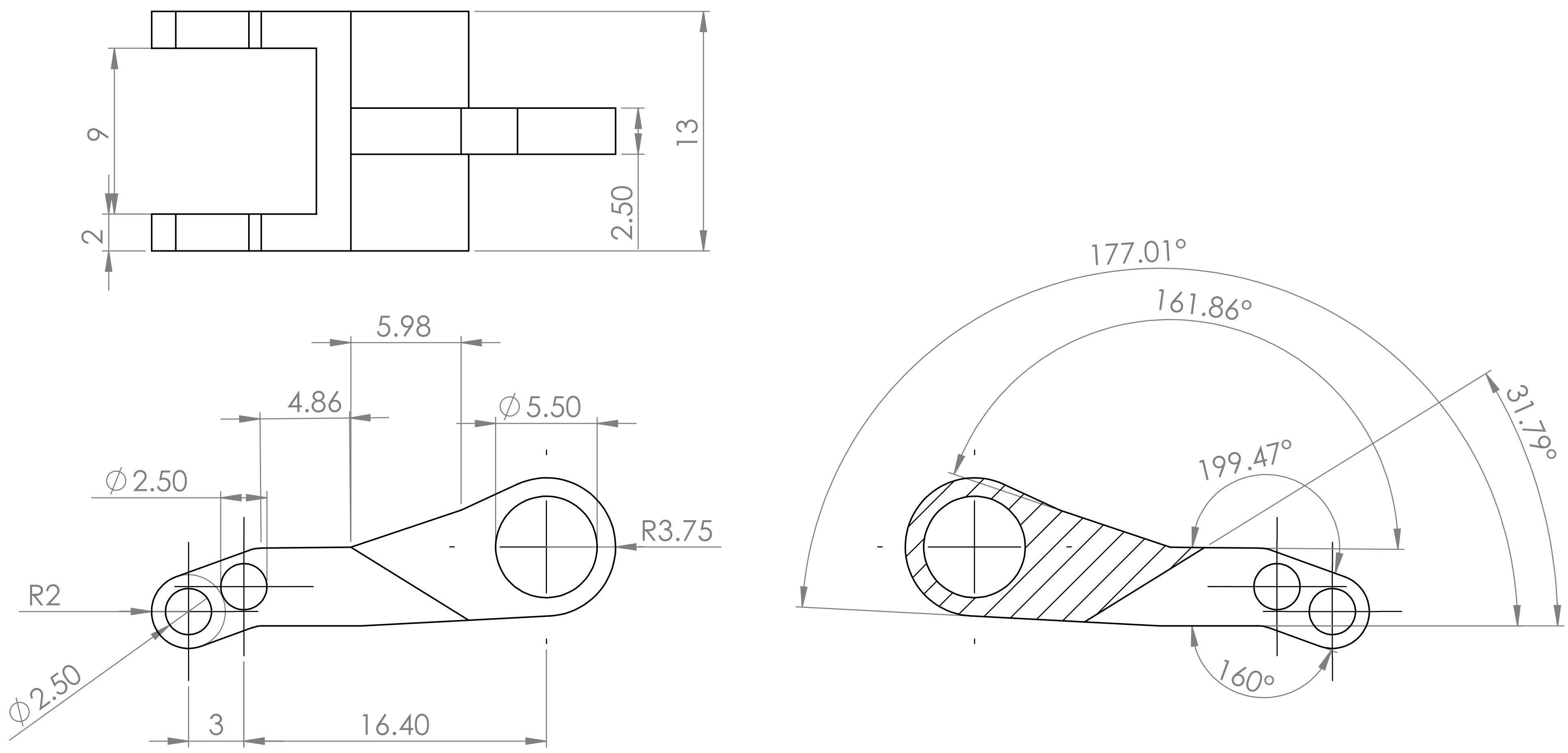
TU Delft Biomedical Engineering	Part Name: Body	Date: 7/1/13	Material: 7075-T6 (SN)
		Scale: 1:1	Units: mm
		Drawn by: Roberto Moratore Jr	Format A4	Sheet No: 2 of 24



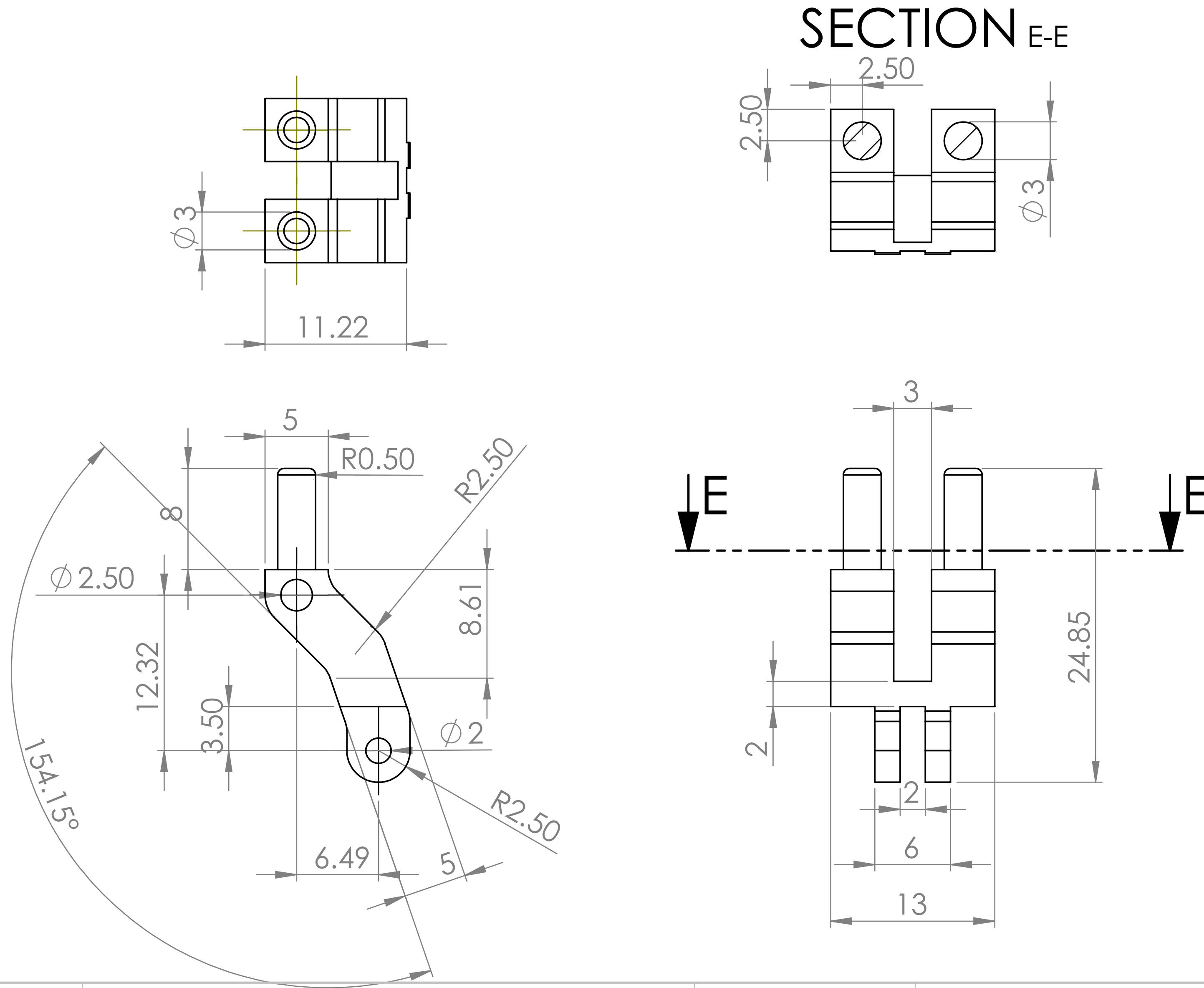
TU Delft Biomedical Engineering	Part Name: Thumb Hinge SolidWorks Student Edition. For Academic Use Only.		Date: 7/1/13	Material: 7075-T6 (SN)
		Scale: 2:1	Units: mm	Format A4
		Drawn by: Roberto Moratore Jr		Sheet No: 3 of 24



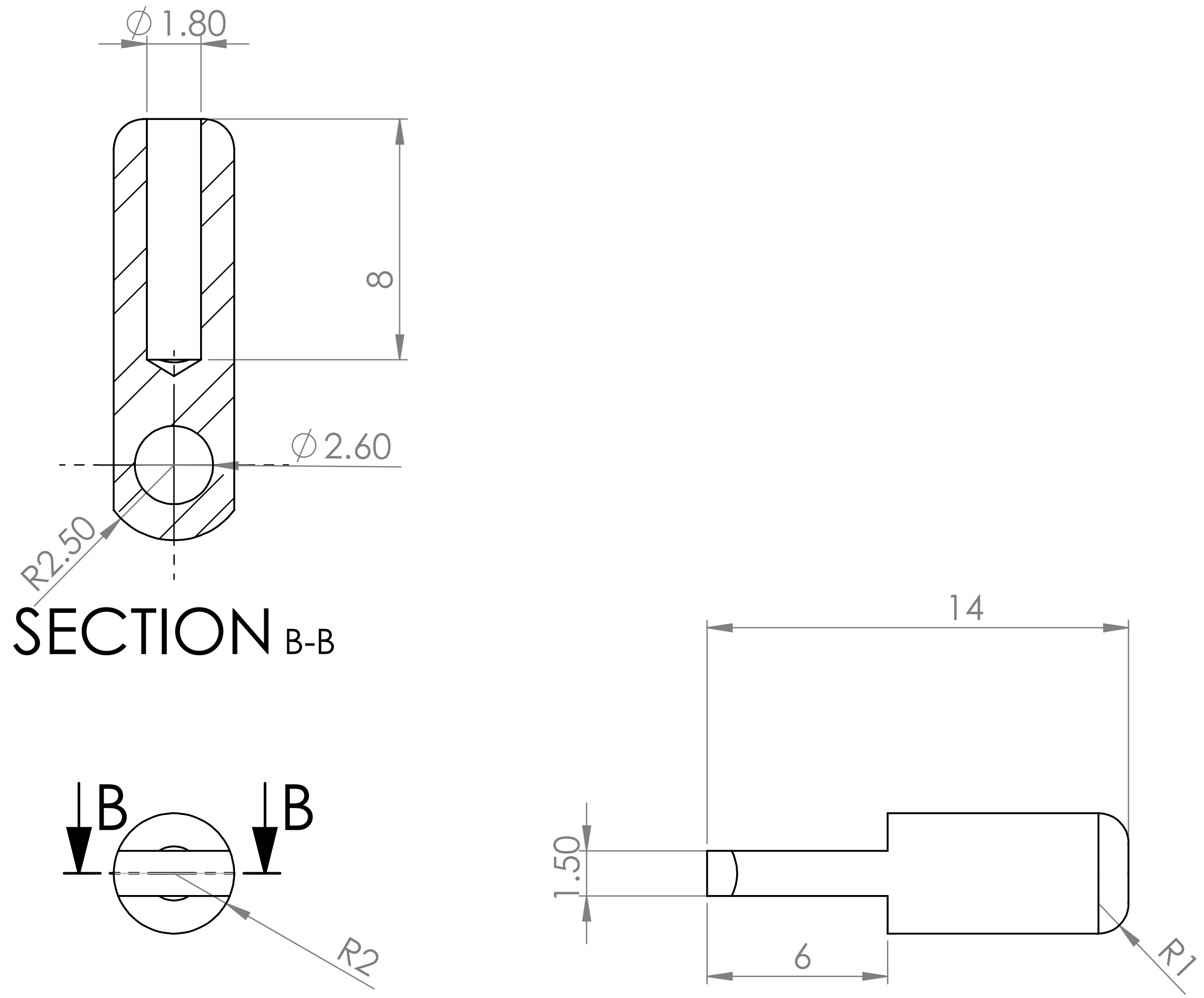
TU Delft Biomedical Engineering	Part Name: Thumb Connecting Rod		Date: 7/1/13	Material: AISI 304
		Scale: 3:1	Units: mm	Format A4 / Sheet No: 4 of 24
		Drawn by: Roberto Moratore Jr		



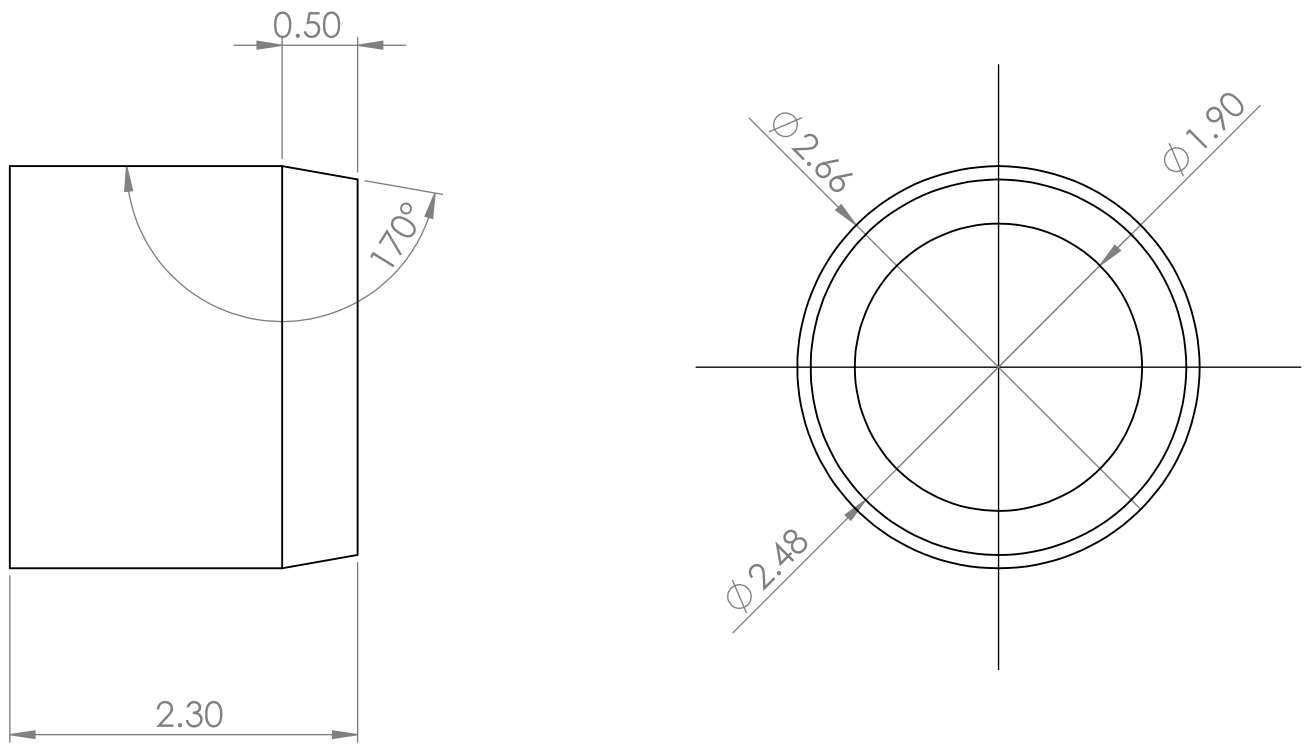
TU Delft Biomedical Engineering	Part Name: Lever 1		Date: 7/1/13	Material: Ti-6Al-4VSolution treated and
		Scale: 3:1	Units: mm	Format A4	Sheet No: 5 of 24
		Drawn by: Roberto Moratore Jr		



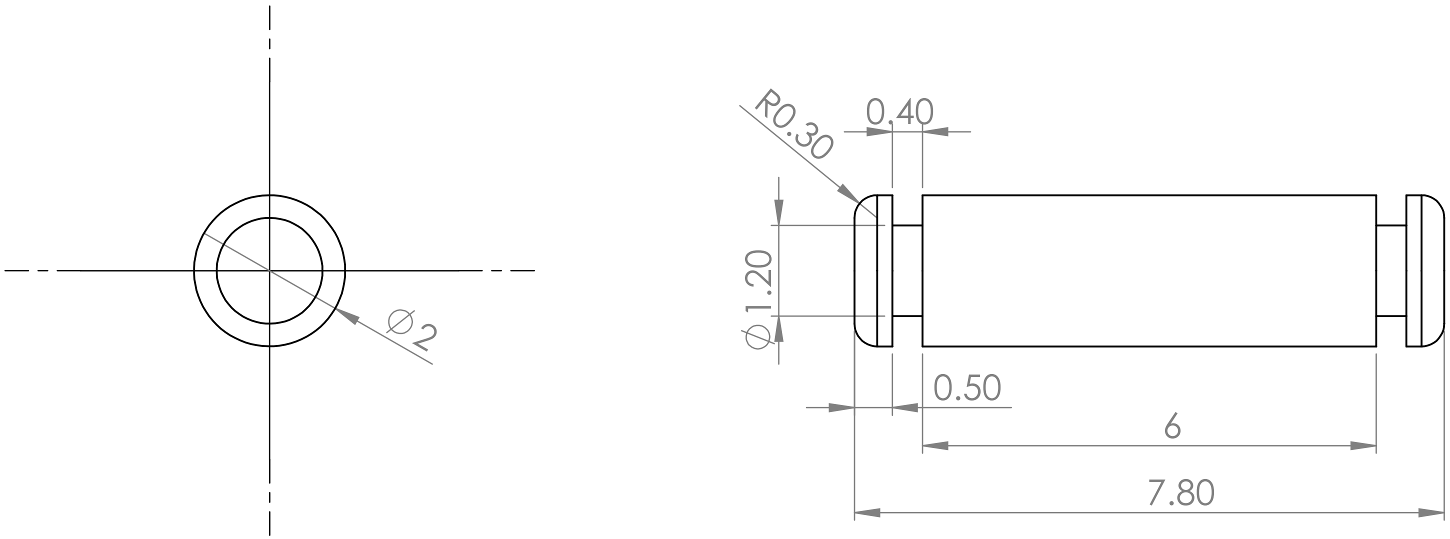
TU Delft Biomedical Engineering	Part Name: Lever 2		Date: 7/1/13	Material: Ti-6Al-4VSolution treated and
		Scale: 2:1	Units: mm	Format A4	Sheet No: 6 of 24
		Drawn by: Roberto Moratore Jr			



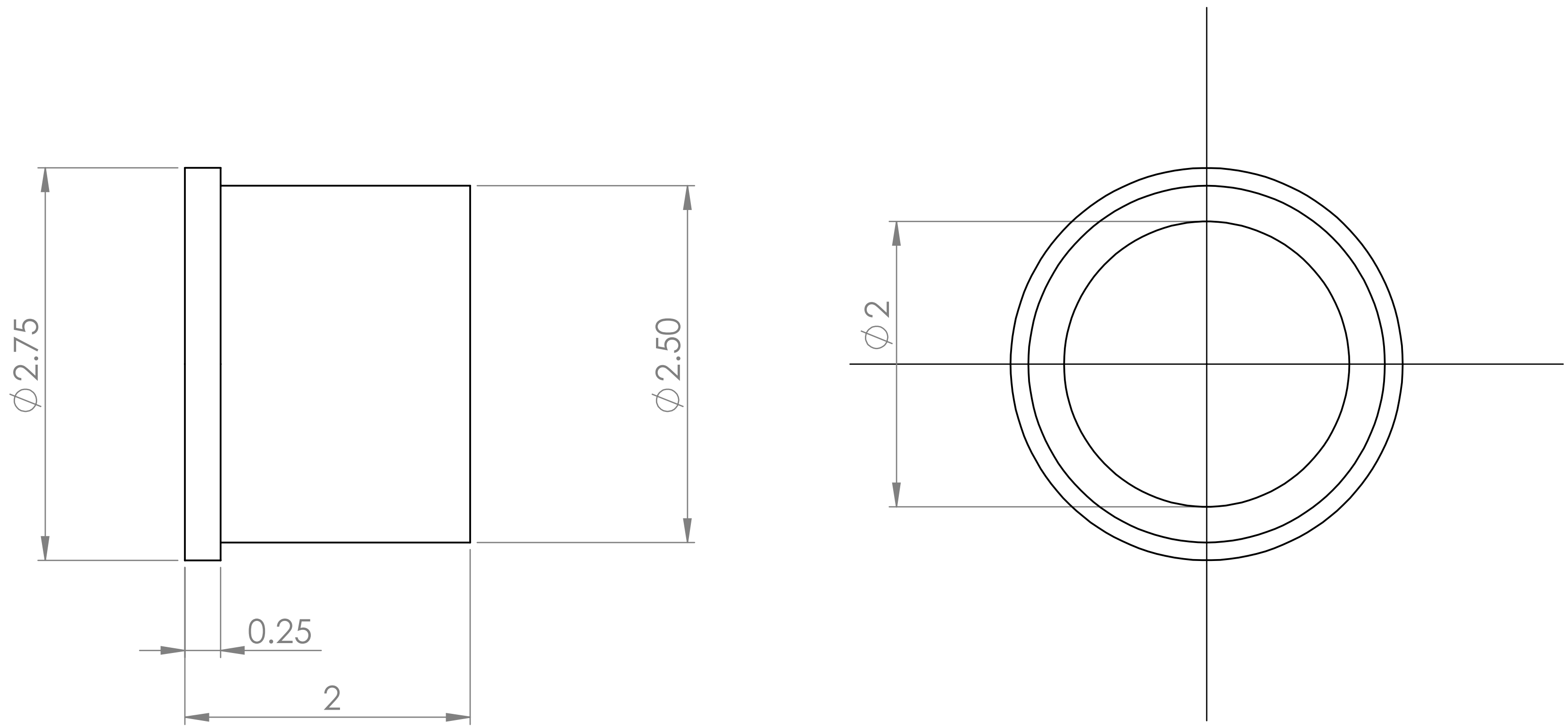
TU Delft Biomedical Engineering	Part Name: Cable Connector		Date: 7/1/13	Material: AISI 304
		Scale: 4:1	Units: mm	Format A4	Sheet No: 7 of 24
		Drawn by: Roberto Moratore Jr			



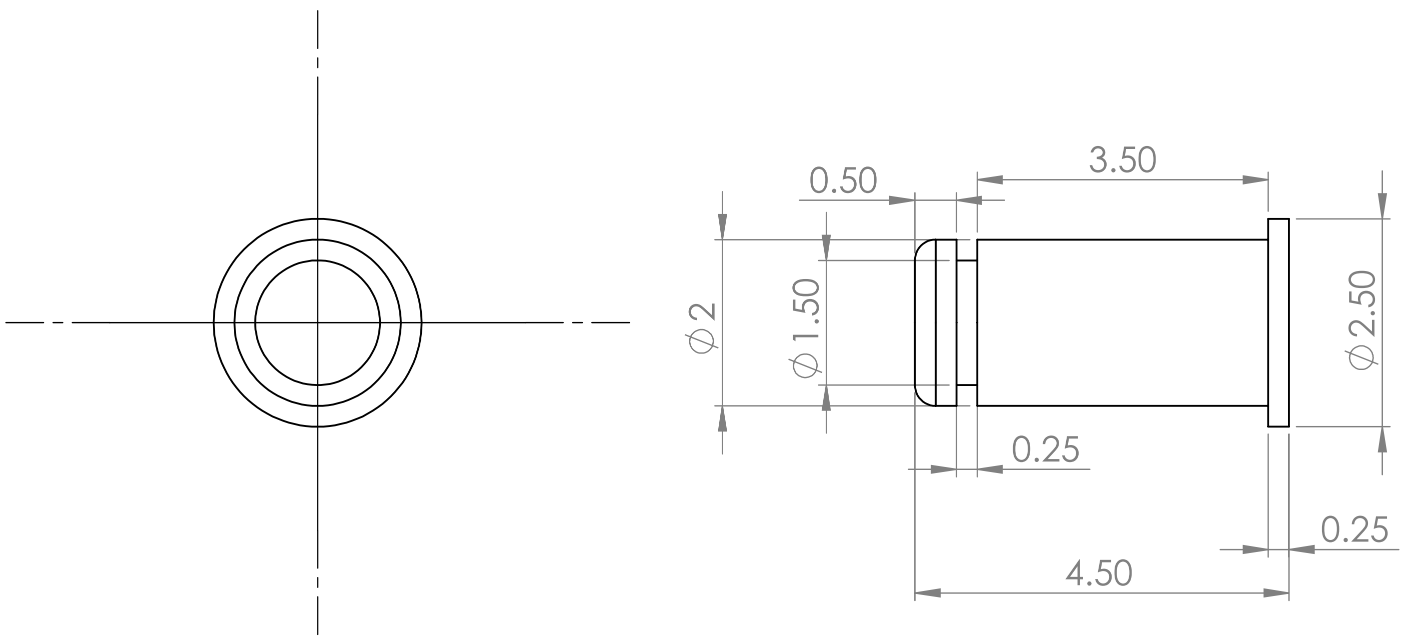
TU Delft Biomedical Engineering	Part Name: Cable Connector Bearing		Date: 7/1/13	Material: PCTFE (Eriflon)
		Scale: 20:1	Units: mm	Format A4	Sheet No: 8 of 24
		Drawn by: Roberto Moratore Jr			



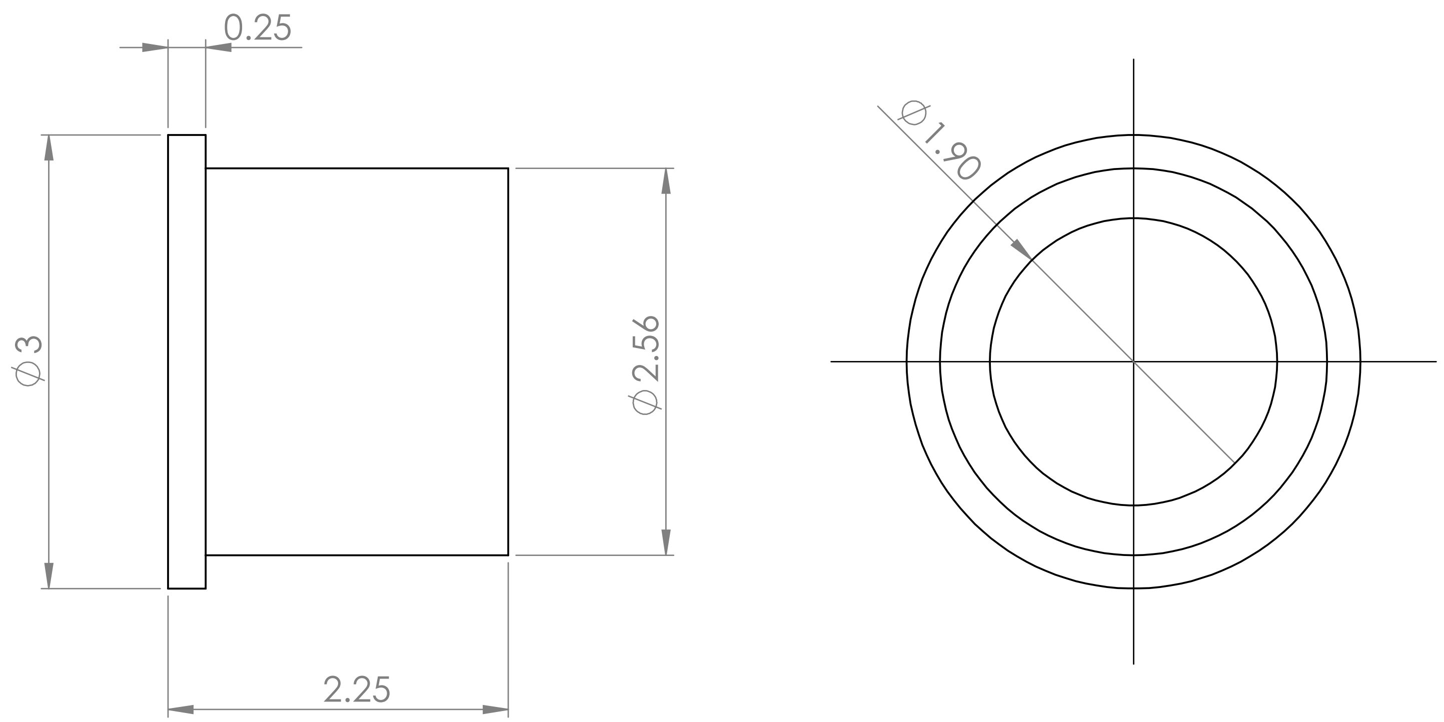
TU Delft Biomedical Engineering	Part Name: Cable Connector Axis		Date: 7/1/13	Material: AISI 304
		Scale: 10:1	Units: mm	Format A4	Sheet No: 9 of 24
		Drawn by: Roberto Moratore Jr		



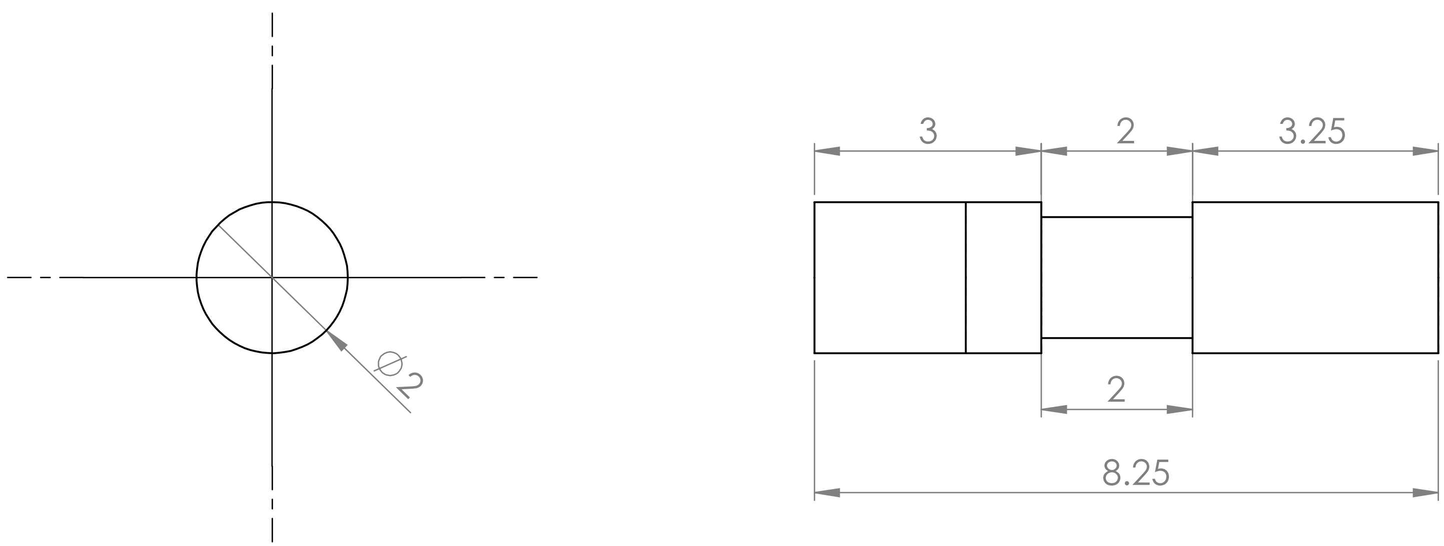
TU Delft Biomedical Engineering	Part Name: Lever Thumb Rod Bearing		Date: 7/1/13	Material: PCTFE (Eriflon)
		Scale: 20:1	Units: mm	Format A4 / Sheet No: 10 of 24
		Drawn by: Roberto Moratore Jr		



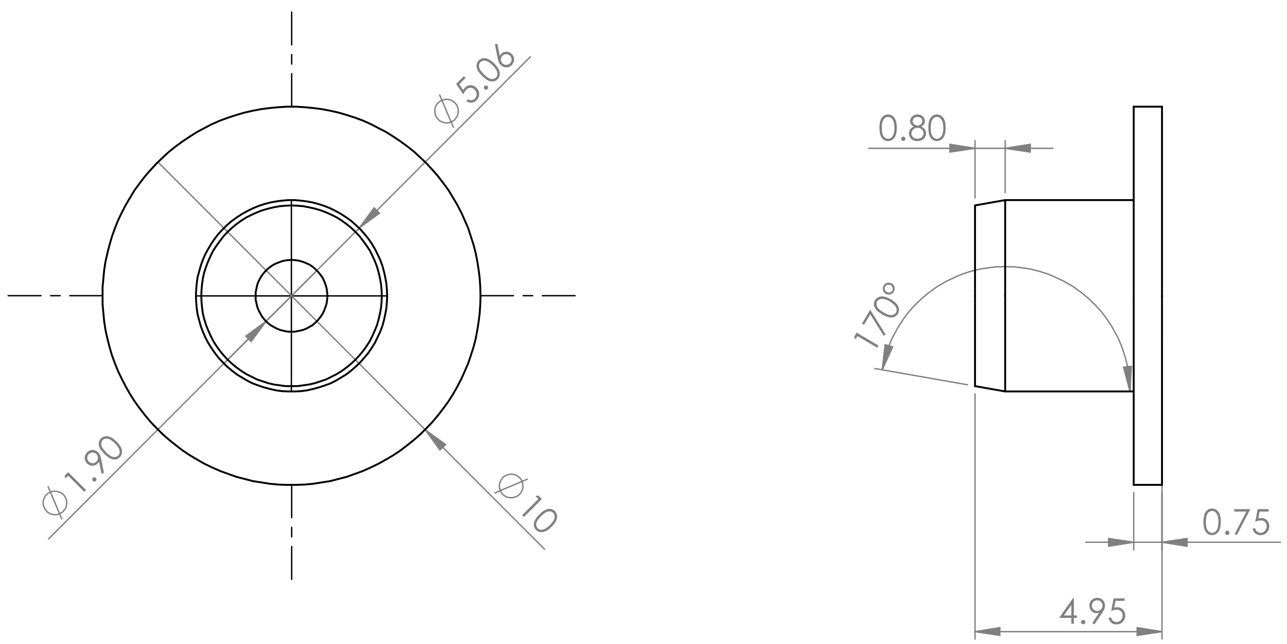
TU Delft Biomedical Engineering	Part Name: Lever Thum Rod Axis		Date: 7/1/13	Material: Ti-6Al-4VSolution treated and
		Scale: 11:1	Units: mm	Format A4	Sheet No: 11 of 24
		Drawn by: Roberto Moratore Jr		



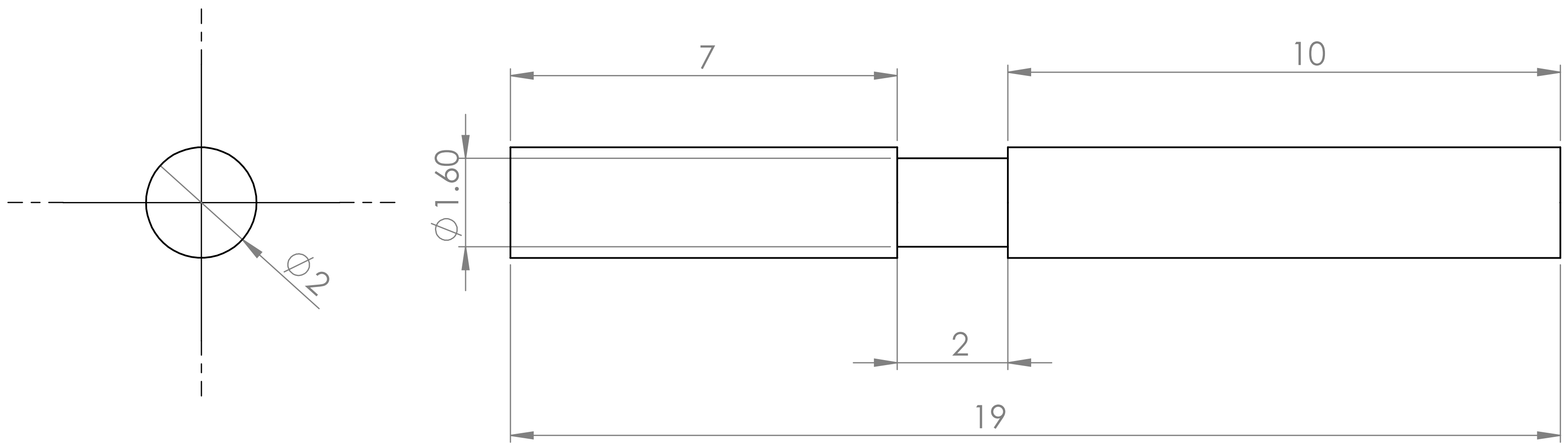
TU Delft Biomedical Engineering	Part Name: Lever Shaft Bearing		Date: 7/1/13	Material: PCTFE (Eriflon)
		Scale: 20:1	Units: mm	Sheet No: 12 of 24
		Drawn by: Roberto Moratore Jr	Format A4	



TU Delft Biomedical Engineering	Part Name: Lever Axis		Date: 7/1/13	Material: Ti-6Al-4VSolution treated an
		Scale: 10:1	Units: mm	Format A4	Sheet No: 13 of 24
		Drawn by: Roberto Moratore Jr		

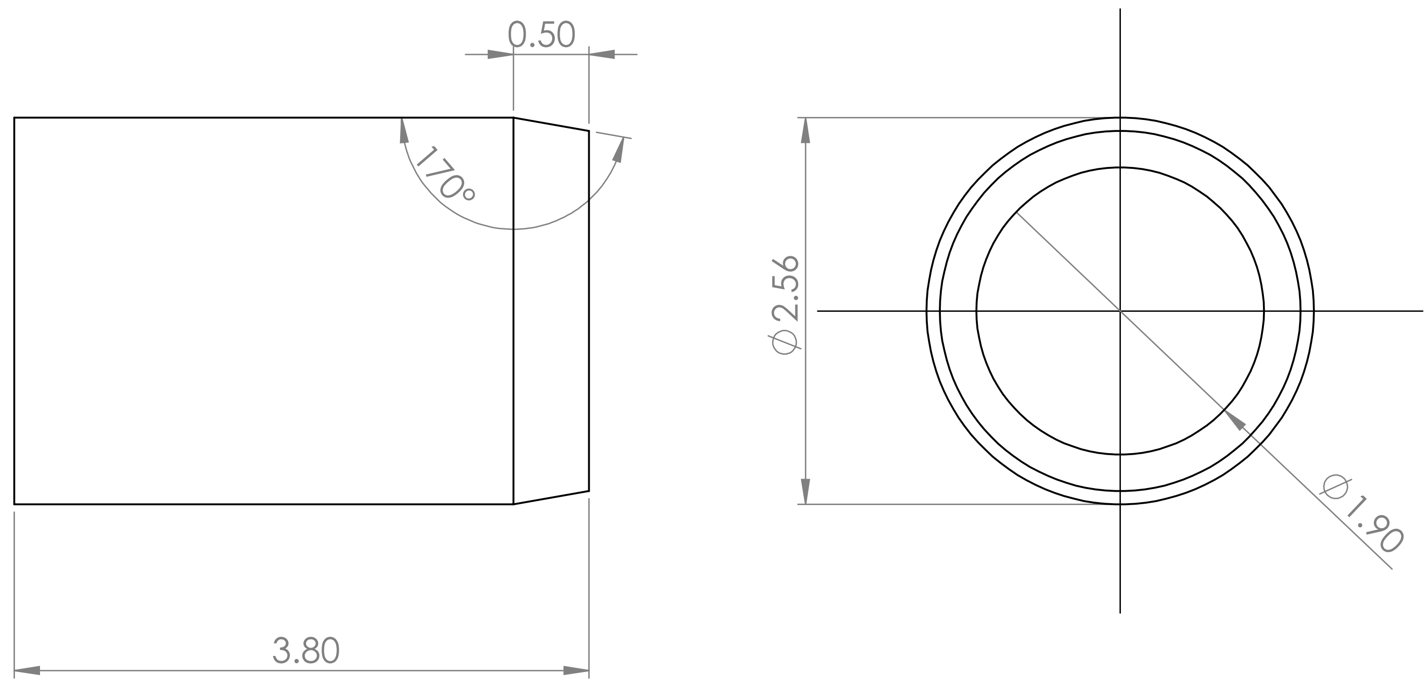


TU Delft Biomedical Engineering	Part Name: Thumb Hinge Bearing		Date: 7/1/13	Material: PCTFE (Eriflon)
		Scale: 5:1	Units: mm	Format A4	Sheet No: 14 of 24
		Drawn by: G. Smit		

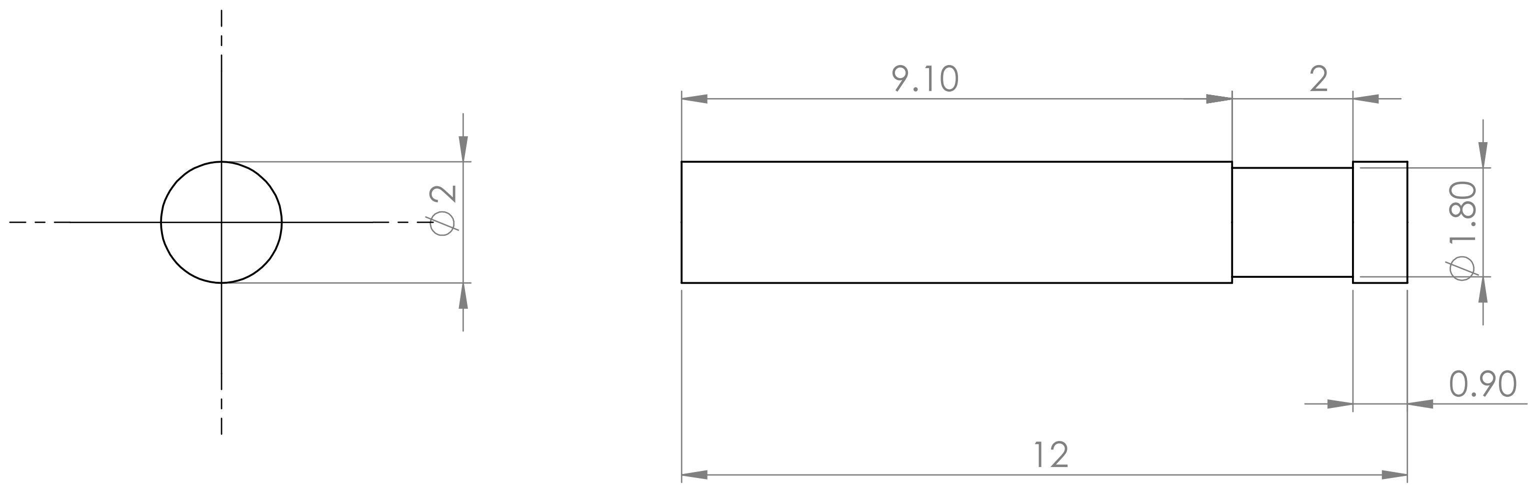


TU Delft
Biomedical Engineering

Part Name: Thumb Hinge Axis		Date:	7/1/13	Material:	AISI 304
	Scale: 8:1	Units:	mm	Format A4	Sheet No: 15 of 24
	Drawn by: G. Smit				



TU Delft Biomedical Engineering	Part Name: Torque Shaft Bearing		Date: 7/1/13	Material: PCTFE (Eriflon)
		Scale: 20:1	Units: mm	Format A4	Sheet No: 16 of 24
		Drawn by: G. Smit		



TU Delft Biomedical Engineering	Part Name: Torque Shaft		Date: 7/1/13		Material: Ti-6AL-4V
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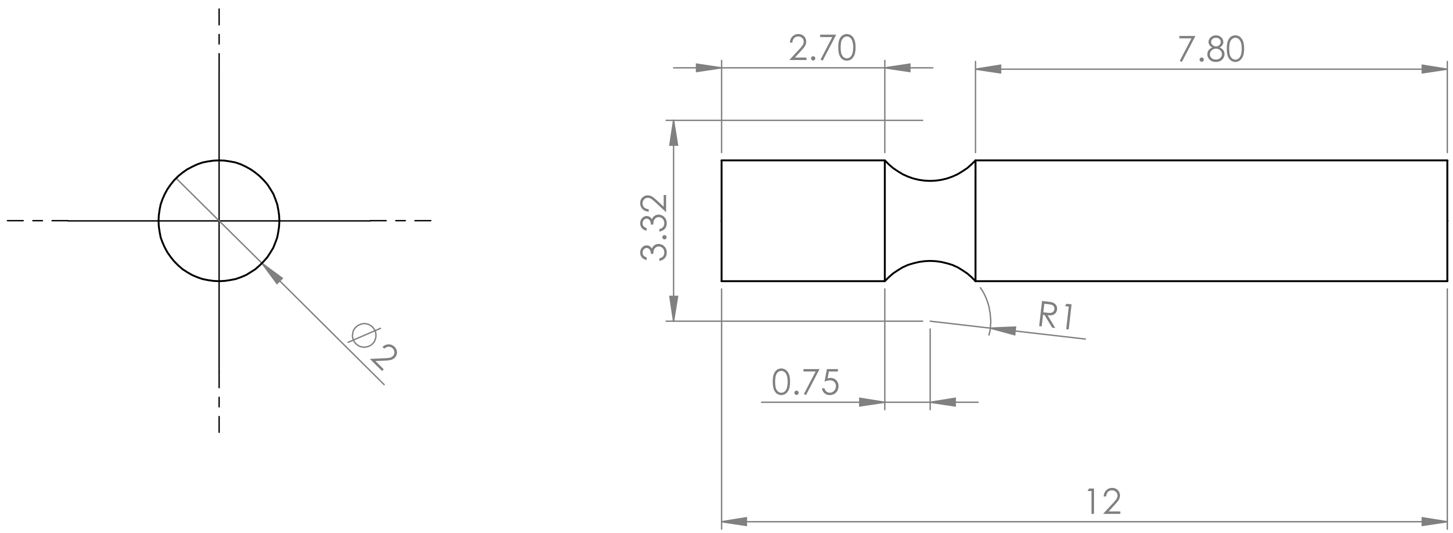
		Drawn by: G. Smit			



TU Delft Biomedical Engineering	Part Name: Thumb Spring Pin		Date: 7/1/13	Material: AISI 304
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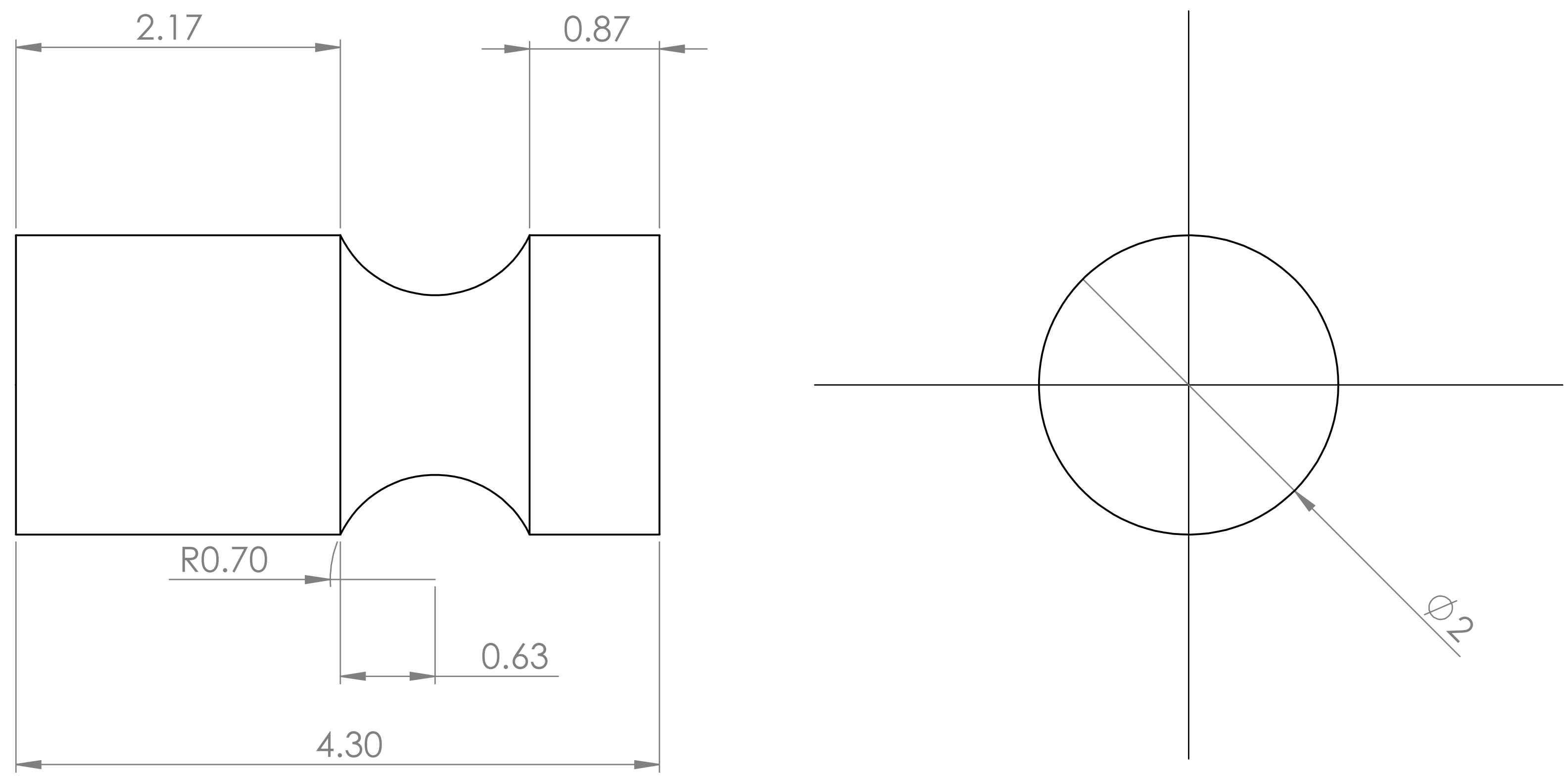
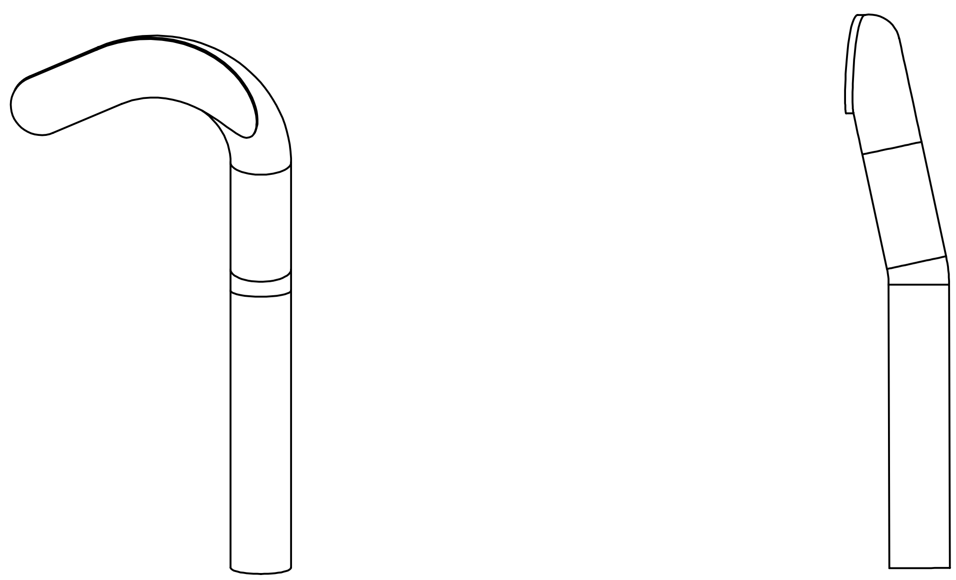
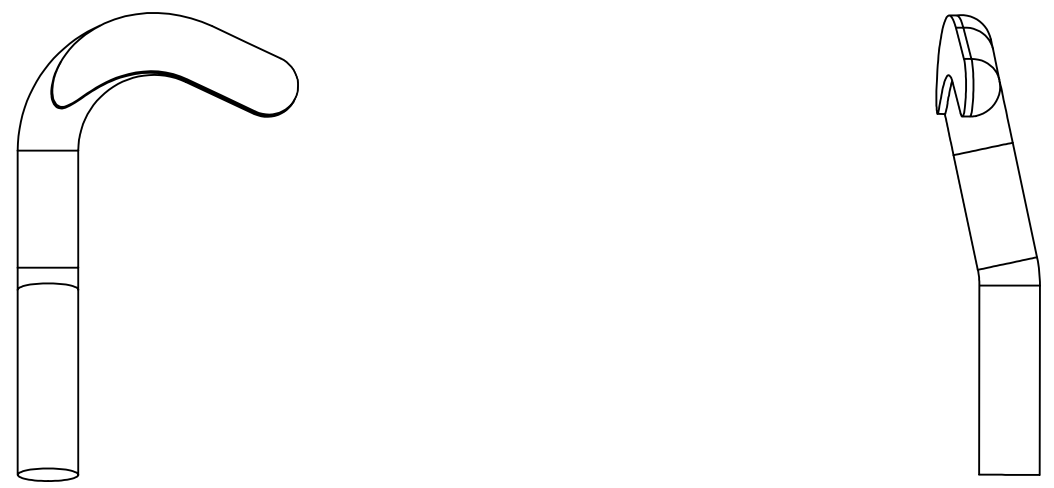
		Drawn by: Roberto Moratore Jr	Format A4	



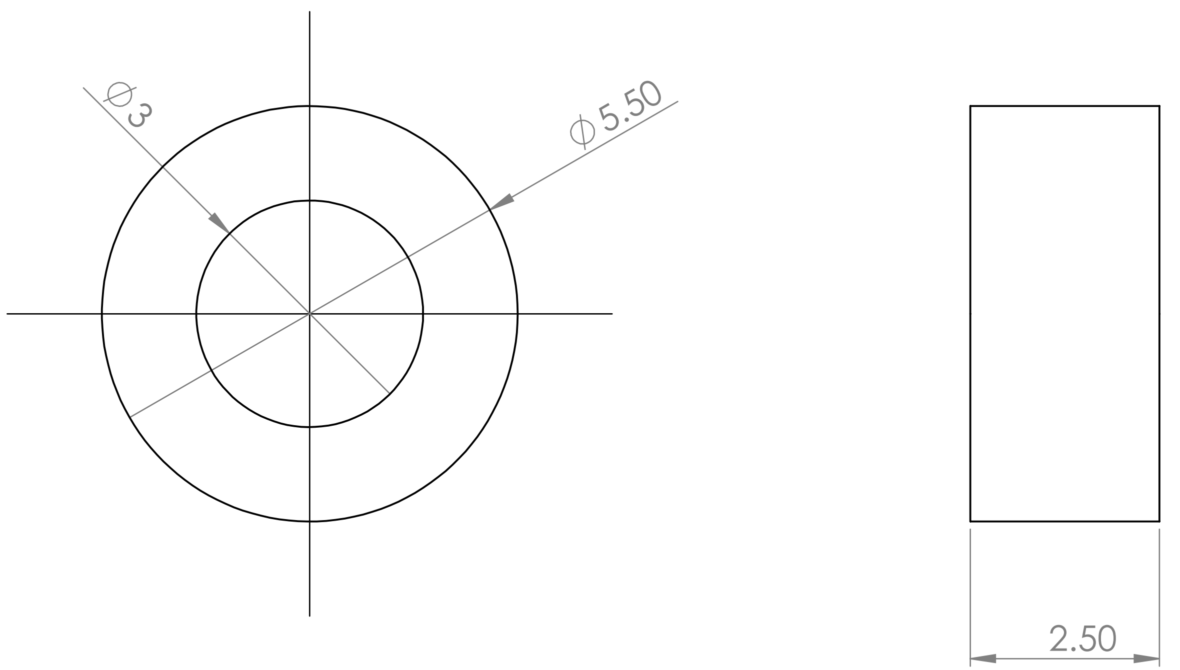
TU Delft Biomedical Engineering	Part Name: Body Spring Pin		Date: 7/1/13	Material: AISI 304
		Scale: 20:1	Units: mm	Format A4	Sheet No: 19 of 24
		Drawn by: Roberto Moratore Jr			



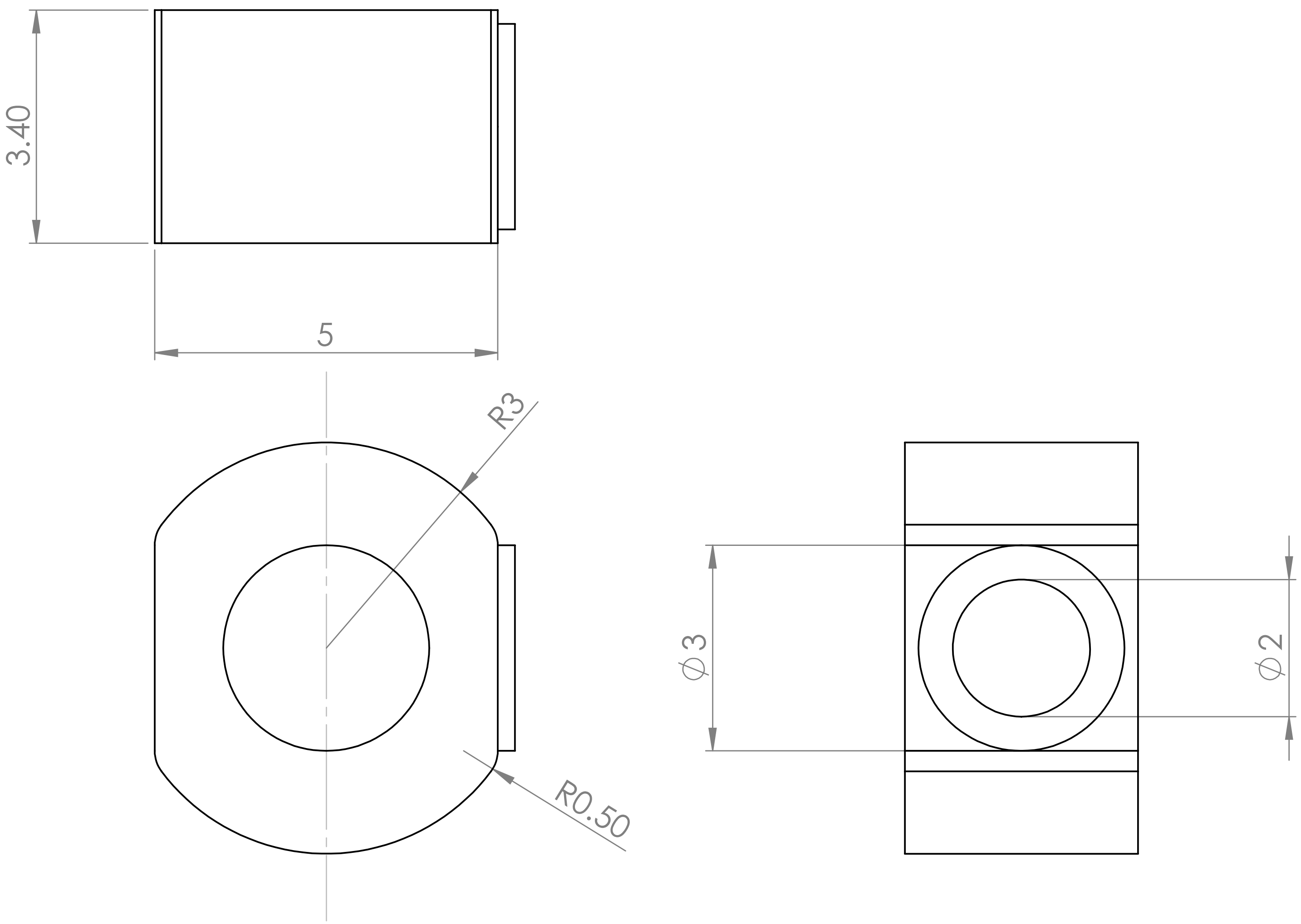
TU Delft Biomedical Engineering	Part Name: Finger (Right)		Date: 7/1/13	Material: 5154-O, Rod (SS)
		Scale: 1:1	Units: mm	Format A4	Sheet No: 20 of 24
		Drawn by: G. Smit		



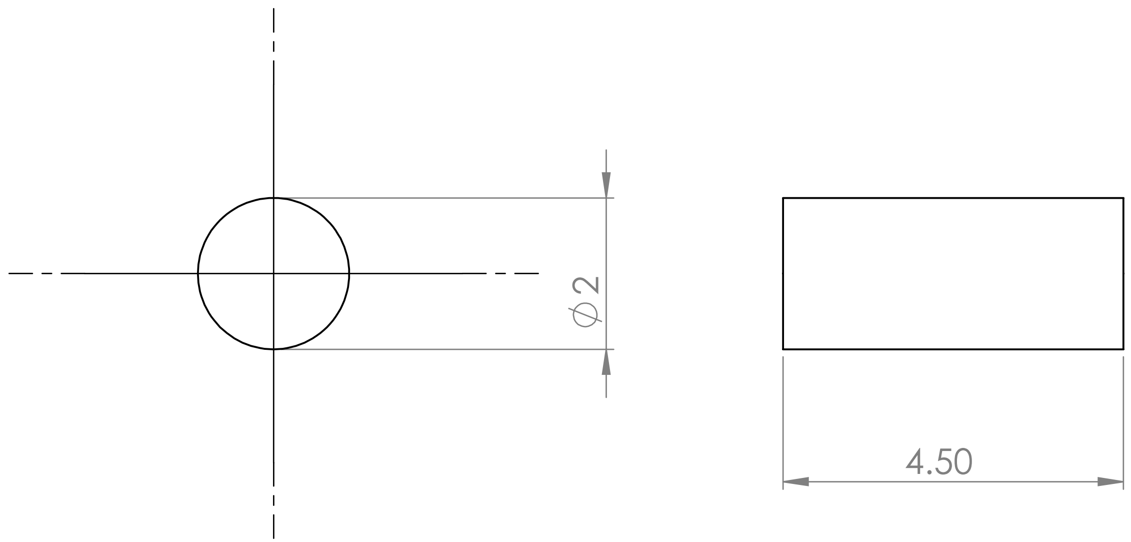
TU Delft Biomedical Engineering	Part Name: Thumb (Left)		Date: 7/1/13	Material: 5154-O, Rod (SS)
		Scale: 1:1	Units: mm	Format A4 / Sheet No: 21 of 24
		Drawn by: G. Smit		



TU Delft Biomedical Engineering	Part Name: Center Bearing		Date: 7/1/13		Material:
		Scale: 10:1	Units: mm	Format A4	Sheet No: 22 of 24
		Drawn by: Roberto Moratore Jr			



TU Delft Biomedical Engineering	Part Name: Linear Bearing	Scale: 10:1	Date: 7/1/13	Material: PCTFE (Eriflon)
		Drawn by: Roberto Moratore Jr	Units: mm	Format A4
				Sheet No: 23 of 24



TU Delft Biomedical Engineering	Part Name: Bearing Shaft		Date: 7/1/13	Material: AISI 304
		Scale: 10:1	Units: mm	Format A4	Sheet No: 24 of 24
		Drawn by: Roberto Moratore Jr			

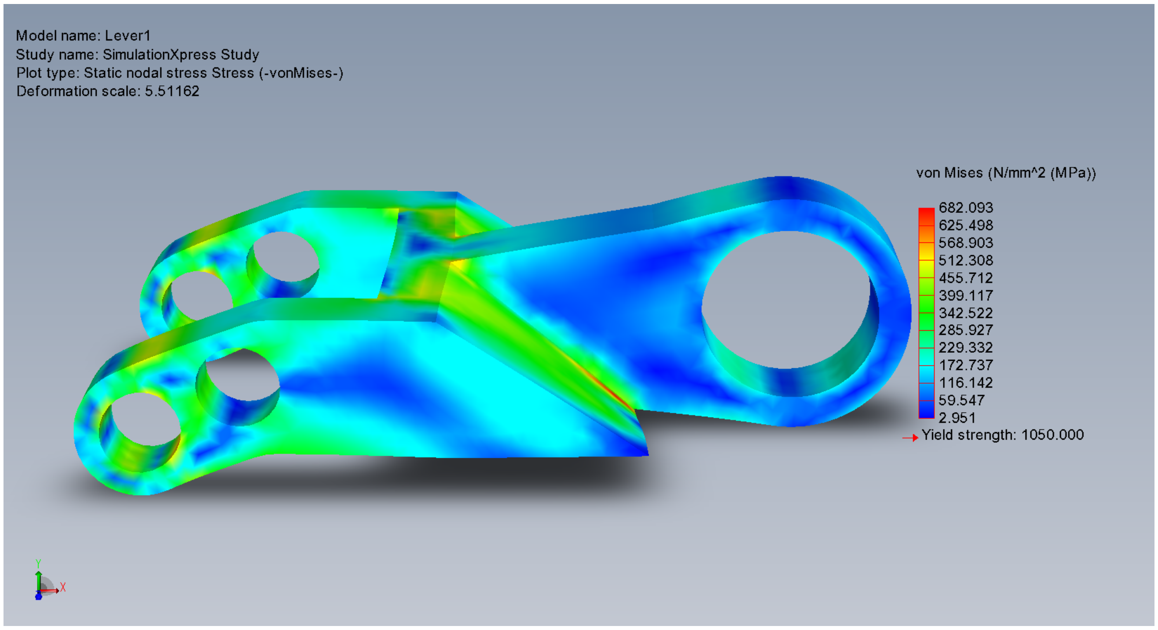
APPENDIX 2

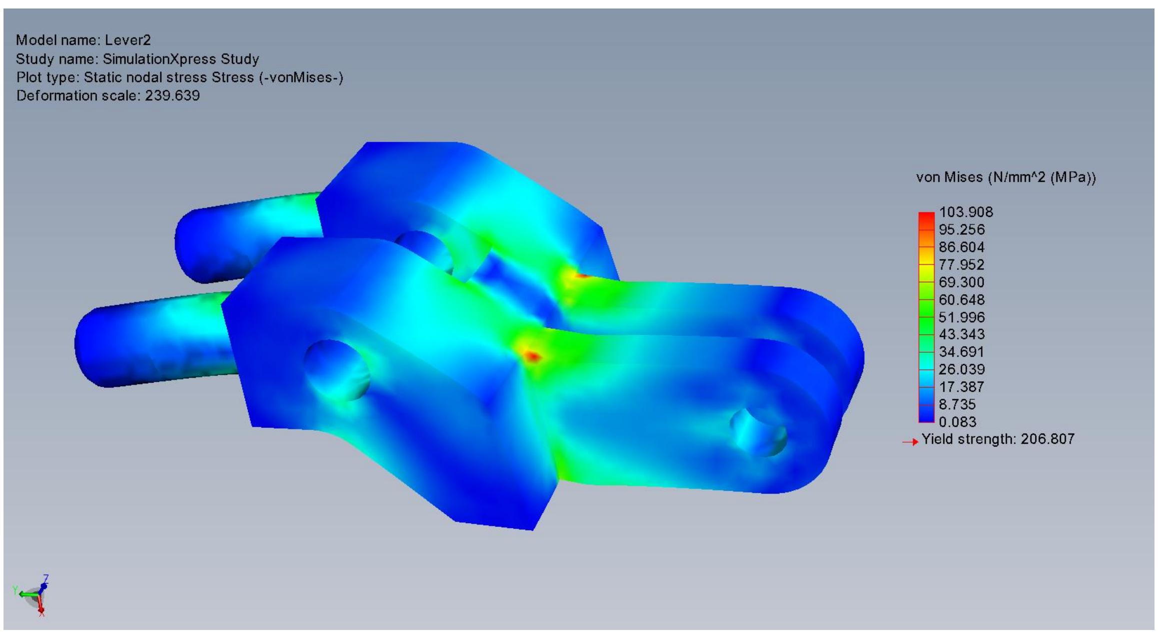
MATLAB Model

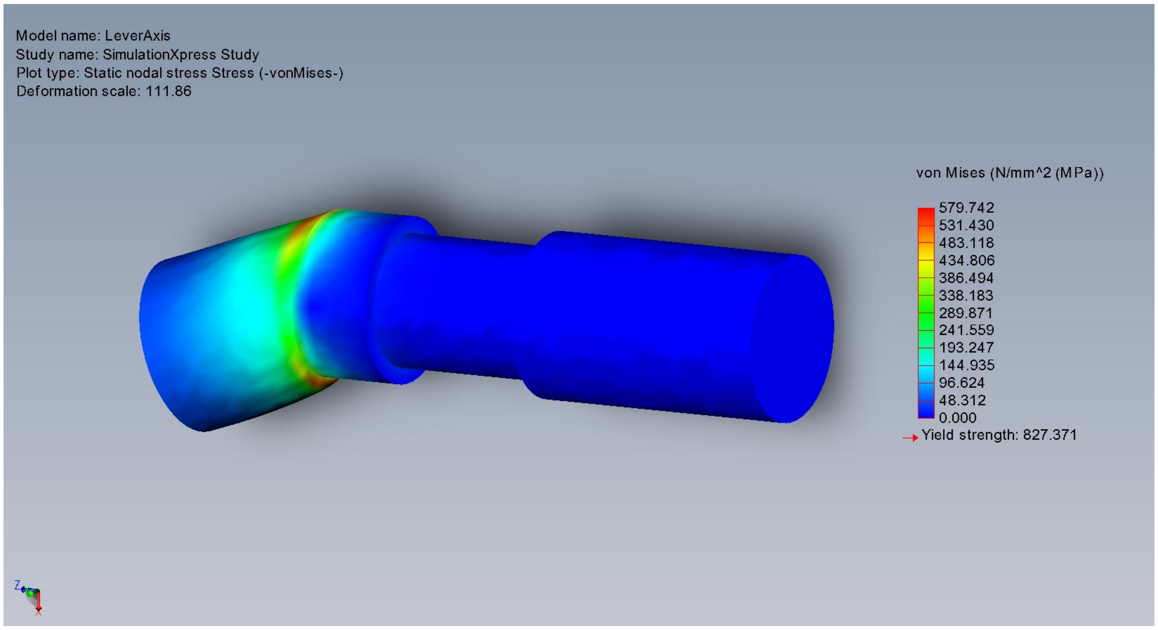
```
force=11;
l1=13.64;
l2=linspace(5.62,9.15,100);
l3=16.54;
l4=3.29;
l5=7.40;
l6=63.76;
cablang=deg2rad(linspace(102.94,20.66,100));
opening=linspace(50,0,100);

for i=1:100
    f1(i)=force*sin(cablang(i));
    f2(i)=(l1*f1(i))/l2(i);
    f3(i)=(l3*f2(i))/l4;
    f4(i)=(l5*f3(i))/l6;
end

plot(opening,f4)
set(gca,'XDir','Reverse')

for i=1:100
f_3(i)=(15*l6)/l5;
f_2(i)=(f_3(i)*l4)/l3;
f_1(i)=(f_2(i)*l2(i))/l1;
force_(i)=f_1(i)/sin(cablang(i));
end
```

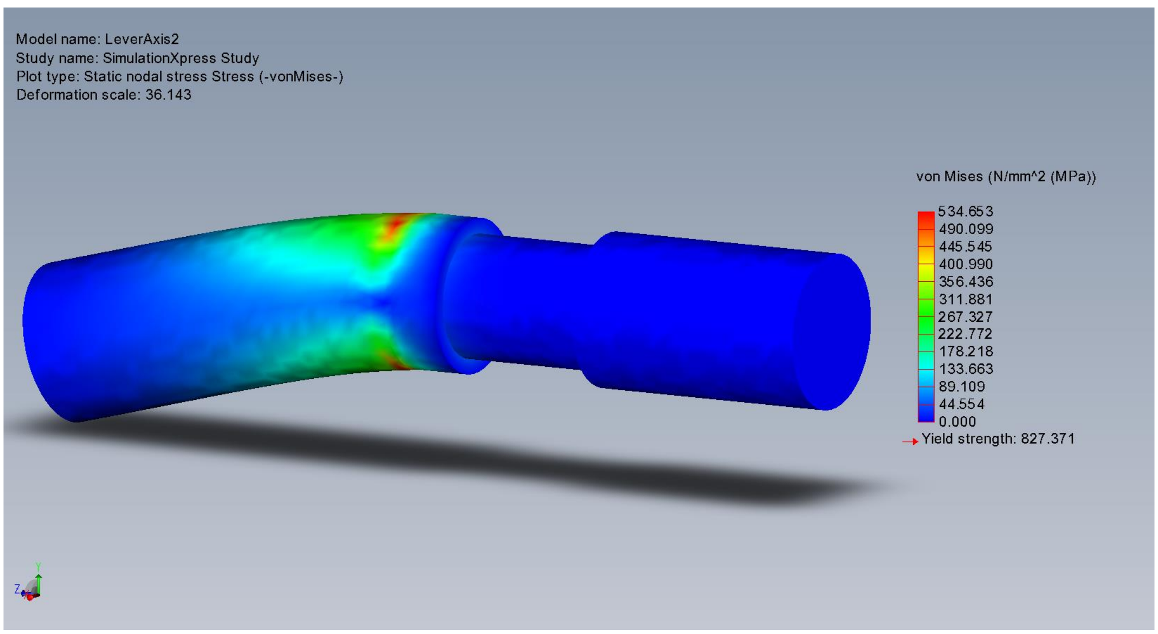
APPENDIX 3

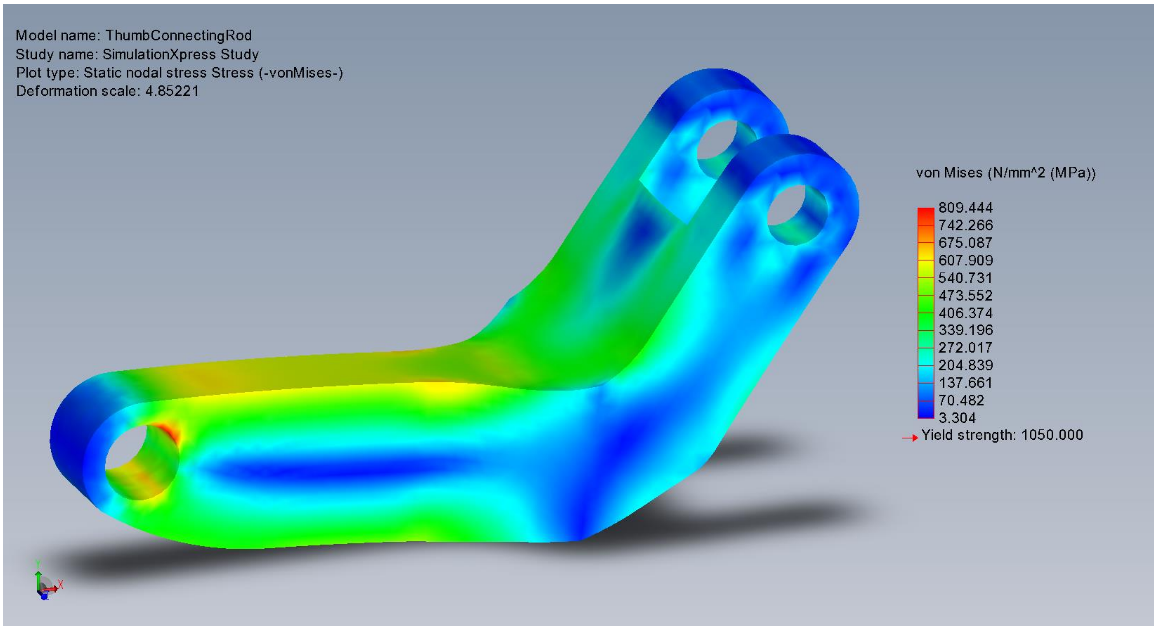
FMEA Analysis






Model name: LeverAxis
Study name: SimulationXpress Study
Plot type: Static nodal stress Stress (-vonMises-)
Deformation scale: 111.86
von Mises (N/mm^2 (MPa))
579.742
531.430
483.118
434.806
386.494
338.183
289.871
241.559
193.247
144.935
96.624
48.312
0.000
Yield strength: 827.371


Model name: LeverAxis2
Study name: SimulationXpress Study
Plot type: Static nodal stress Stress (-vonMises-)
Deformation scale: 36.143
von Mises (N/mm^2 (MPa))
534.653
490.099
445.545
400.990
356.436
311.881
267.327
222.772
178.218
133.663
89.109
44.554
0.000
Yield strength: 827.371


Model name: ThumbConnectingRod
Study name: SimulationXpress Study
Plot type: Static nodal stress Stress (-vonMises-)
Deformation scale: 4.85221
von Mises (N/mm^2 (MPa))
809.444
742.266
675.087
607.909
540.731
473.552
406.374
339.196
272.017
204.839
137.661
70.482
3.304
Yield strength: 1050.000