Fall 2018

Anisotropic Tissue Maker

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Executive Summary

Traumatic brain injury (TBI) is a common injury that is not thoroughly understood. Data of brain mechanics and motion are not abundant during the time of impact. In order to accumulate more data and achieve a better understanding of how the injury occurs tissue mimics can be made. These mimics of the brain are typically made of a gelatin-like substance that can represent material properties of the brain. Using these models can facilitate a fundamental understanding of TBI and does not require the procurement or damaging of living tissue. Currently, some models exist to explain this phenomenon, but they are highly simplified. Most of these tissue models are isotropic, meaning that the material properties are the same in every direction. Data suggest that brain tissue is anisotropic, meaning that the material properties differ in various directions. As a result, the isotropic models do not provide a very accurate representation of brain tissue. To increase the complexity of the model and improve the comparison to brain tissue, anisotropy can be induced. As a result, our group set out to create a device that can efficiently, and consistently create a network of fibers to cure a gelatin-like substance, Sylgard 527, around. By including these threads, or fibers, anisotropy is induced. The fiber matrix is constructed such that all fibers are in one direction and parallel to one another. Sylgard 527 was used because the material has been proven to have tunable properties that can be adjusted to simulate brain tissue. By creating these tissue mimics, a variety of testing can be completed to investigate the material properties and mechanics, which will ultimately bolster the understanding of brain mechanics and TBI.

MEMS 411: MECHANICAL ENGINEERING DESIGN PROJECT
FALL 2018

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1 INTRODUCTION

In order better understand the mechanical behavior of the human brain during impact, a surrogate tissue is required. Difficulties arise when analyzing real brain tissue because living tissue samples are immoral or inconvenient to obtain and ex vivo, or non-living, samples have different material properties. Currently, models of brain tissue exist in Dr. Bayly's lab that are made from a silicone gel and have been proven to demonstrate the material properties of brain tissue. The problem is that this gel behaves as an isotropic material meaning that the material properties are the same regardless of the direction. Data suggest that actual brain tissue has some degree of anisotropy, meaning that the material properties vary depending on the direction. Dr. Bayly is requesting a device that can conveniently and consistently make anisotropic tissue samples. Ideally, we would accomplish this by creating a network or parallel, unidirectional fibers to induce anisotropy then cure the silicone gel around it. Also, it would be beneficial if the device only required a single operator and minimized the excess silicone gel. The robust manufacturing process required for this project should allow for the quick and accurate production of multiple samples, allowing for a more accurate representation of the human brain and its behavior for future research.

2 PROBLEM UNDERSTANDING

2.1 BACKGROUND INFORMATION STUDY

Three (3) Existing Designs:

1. Freeze/Thaw Induced Anisotropy
    a.

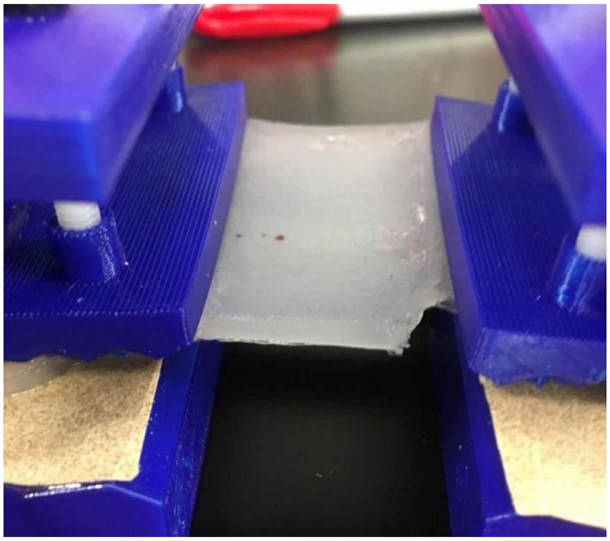


Figure 1: Freeze/Thaw Induced Anisotropy Design

    b. http://iopscience.iop.org/article/10.1088/0031-9155/59/22/6923/meta
        i. This link refers to the fabrication methods employed in Dr. Bayly's lab

    c. One method to induce anisotropy that is used in Dr. Bayly's lab is exposing a polyvinyl alcohol solution to numerous freezing and thawing cycles. After a few cycles, the solution solidifies into a gelatin. At this point, the gelatin is stretched in order to induce anisotropy by unraveling the crosslinks within the PVA gel. As a result, anisotropy is created in one direction and more freeze/thaw cycles are used to preserve the anisotropy. Although this is working for the most part and an inexpensive method to creating anisotropic materials, the fabrication process does not work consistently and there is a lot of variation between samples.

2. Pasta Anisotropic Model
    a.

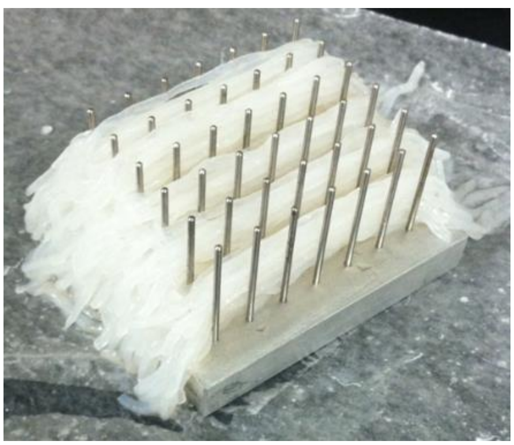


Figure 2: Pasta Anisotropic Model Design

b. A link is not available for this design because this was produced within Dr. Bayly's lab and has not been referenced or published online.

c. Another previous design to induce anisotropy was placing angel hair pasta then forming a gelatin around it. Notably, softer "fibers", or pasta in this case, are ideal to more accurately represent human anatomical structures. The usage of pasta implies that this is an impractical, non-permanent design. Results from the lab suggest that this design did produce anisotropy, but it was not concise and not entirely aligned in a single direction. Lastly, the inclusion of a metal foundation for this device makes it ineligible for testing using magnetic resonance imaging methods. This method of inducing anisotropy is easy and inexpensive, but it lacks accuracy and longevity.

3. Automatic Knitting Device

a.

Figure 3: Automatic Knitting Device Design

b. http://www.skacelknitting.com/addi-Express/

c. This product is a circular knitting device that is remarkably easy to operate sold by addi®. It weighs approximately six pounds and can use up to 46 needles to create larger pieces. The rate at which knitting is done seems to be far superior than human efforts and does not require a high level of expertise. A crank is turned to power the device and a mechanical arm circles the device knitting each string as it passes. Notably, it is possible that setting up this device could be time consuming and potentially a difficult task. This device bolsters an incredibly efficient and accurate method to completing a notorious time and labor-intensive task.

Two (2) patents:

1. Twisting ball panel display
   a. US4126854A
   b.

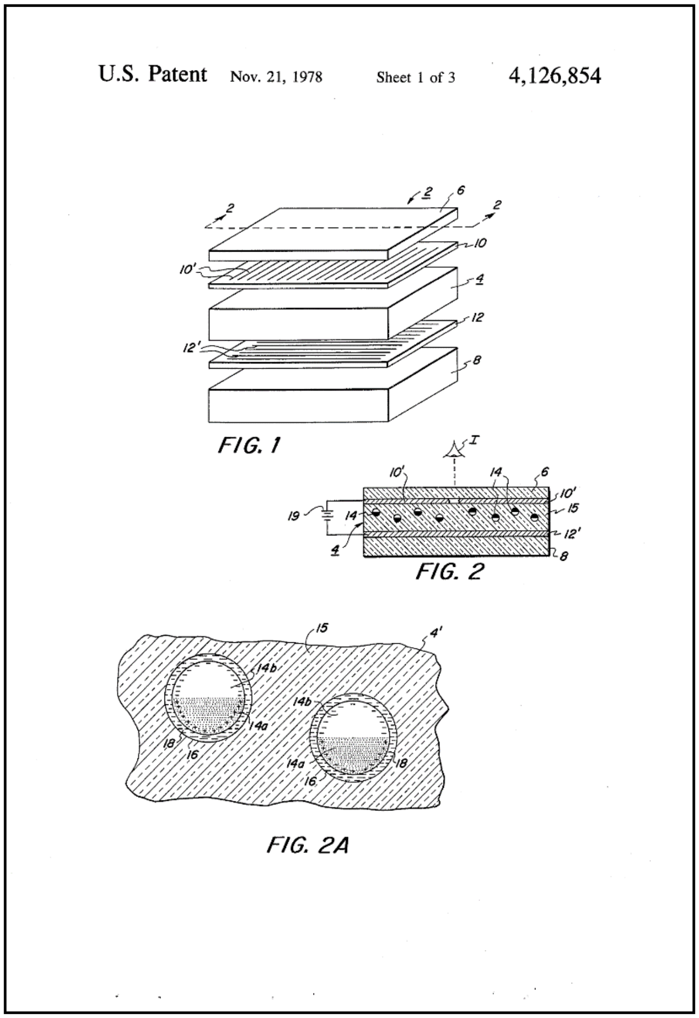


Figure 4: Twisting Ball Panel Display Patent

   c. A system for display panels created using small particles with electrical characteristics inside of a gel, such as Sylgard 182. Using electrical fields, these particles can rotate to create anisotropy that produces a image or pattern that serves a function in optics. The particles serve to provide a characteristic not present in the regular gel.

2. Variable permeability bone implants, methods for their preparation and use
    a. US6187329B1
    b.

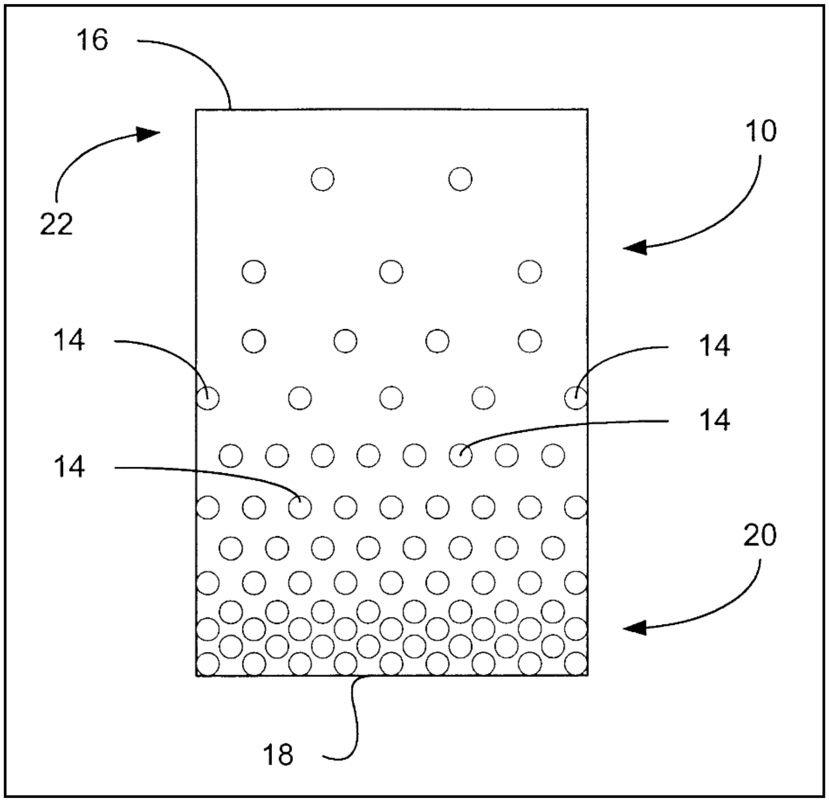


Figure 5: Variable Permeability Bone Implants Preparation and Use Patent

    c. A process designed to create anisotropic bone implants containing a porous agent that allows for the the reduced permeability of bodily fluids. The porous agent is combined into the surrounding polymer and distributed via gravity to change its characteristic. The implant mimics the bone tissue's physical characteristics through a combination of materials and formations.

Two (2) codes or standards:

1. Code of Federal Regulations: Hazardous Substances
    a. HAZARDOUS SUBSTANCES AND ARTICLES: ADMINISTRATION AND ENFORCEMENT REGULATIONS §1500.17 Banned hazardous substances.
    b. This code defines and explains substances that can be hazardous to humans for reasons of chemical composition or physical effects of use. Additionally, it bans various substances that are deemed too dangerous for practical use in most contexts. Where it be paint composition, gel mixture, or a pressurized device, anything created for the anisotropic device must avoid hazardous substances that could endanger the user.

2. Standard atmospheres for conditioning and/or testing -- Specifications
    a. ISO 554:1976

b. The International Organization for Standardization defines a procedure for creating a standard or standards for usage in material testing. This information ensures that tested materials or products are subject to the same environmental conditions and prevent external variables from affecting test results. In the creation of any prototypes, tests will be made to assess and compare product capabilities. It is necessary to have a standardized environment that will be applied to all test models.

2.2 USER NEEDS

Product: Anisotropic Tissue Maker (ATM)
Customer: Dr. Philip Bayly

Notes: The interview took place in Dr. Bayly's office. Together, we talked through his desired outcome, past efforts, and design requirements.

Address: Urbauer 319, Washington University Danforth Campus
Date: September 7, 2018

Table 1: Customer Needs Interview

Question	Customer Statement	Interpreted Need	Importance
What is the desired usage of the product?	A device to create an anisotropic material in one direction.	The ATM must generate specimen that demonstrates anisotropic properties	5
	Will be in a research/clinical environment, used in MRI scanner room	Should function at room temperature without metal components	3
What would you like to see in this product?	Material properties that represent brain tissue	Should have a comparable stiffness to brain tissue	4
	Uniform (not heterogenous) dense fibers, fibers in one direction, and evenly distributed fibers	The fibers should be spaced parallel so there are a couple fibers every millimeter	4
What do they dislike about the current product?	Do not want it to decay or change properties over time	The product must be durable and generate a long-lasting sample	3
	Do not want tension in the fibers but should be taut	The fibers need to be pulled and kept taut without creating tension	4
What do they suggest to improve?	Create a robust manufacturing process that makes it easy to generate samples	Device is easy for lab technician to use	3
What are the dimensional specifications for the sample	Thin, cylindrical samples to accommodate testing environment	Product should be approximately 5.0 cm in diameter and 2.0 cm in thickness	4

Table 2: Interpreted Customer Need

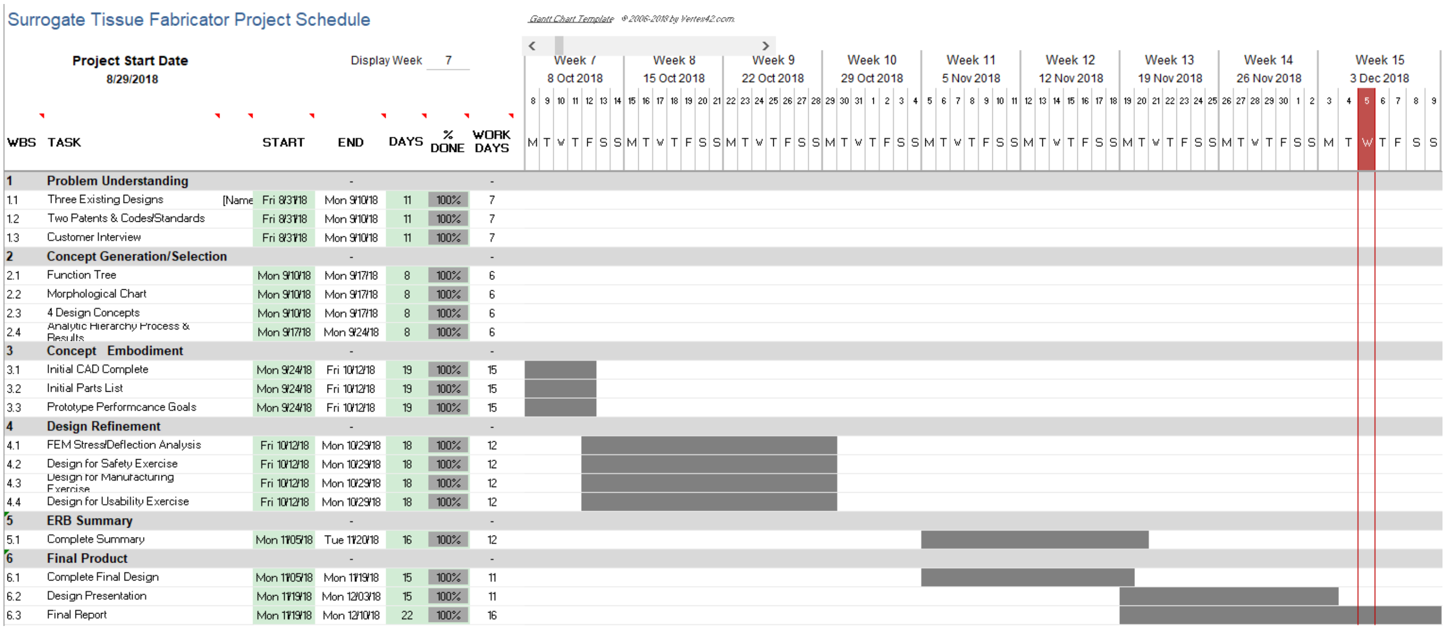
Need Number	Need	Importance
1	Functionality- Generates specimen that demonstrates anisotropic properties	5
2	Accuracy- Generates specimen with properties very similar to brain tissue and dense fiber spacing	4
3	Durability- Device will not break after many iterations	3
4	Repeatability- Can generate specimens with little deviation	4
5	Ease of use- Device is easy for lab technician to use	3
6	Longevity- Specimen generated does not degrade	3
7	Aesthetic- Visually represents brain tissue	1
8	Design Specifications- Product must be about 5.0 cm in diameter and 2.0 cm in thickness	4

2.3 DESIGN METRICS

Table 3: Target Specifications

Metric Number	Associated Needs	Metric	Units	Acceptable	Ideal
1	1,2	Sample Elastic Modulus	kPa	1.0 - 10.0	2.0 - 3.0
2	1,5	Time to weave and set specimen	minutes	30	15
3	8	Total size	centimeters	+- 2.0	5.0 diameter 2.0 thick
4	3,4	Samples made have consistent fiber dimensions	samples	5	20
5	6	How long the samples last in lab setting	weeks	4	16

2.4 PROJECT MANAGEMENT



Surrogate Tissue Fabricator Project Schedule

Project Start Date 8/29/2018 | Display Week 7

WBS	TASK	START	END	DAYS	% DONE	WORK DAYS
1	**Problem Understanding**		-			-
1.1	Three Existing Designs [Name	Fri 8/31/18	Mon 9/10/18	11	100%	7
1.2	Two Patents & Codes/Standards	Fri 8/31/18	Mon 9/10/18	11	100%	7
1.3	Customer Interview	Fri 8/31/18	Mon 9/10/18	11	100%	7
2	**Concept Generation/Selection**		-			-
2.1	Function Tree	Mon 9/10/18	Mon 9/17/18	8	100%	6
2.2	Morphological Chart	Mon 9/10/18	Mon 9/17/18	8	100%	6
2.3	4 Design Concepts	Mon 9/10/18	Mon 9/17/18	8	100%	6
2.4	Analytic Hierarchy Process & Results	Mon 9/17/18	Mon 9/24/18	8	100%	6
3	**Concept Embodiment**		-			-
3.1	Initial CAD Complete	Mon 9/24/18	Fri 10/12/18	19	100%	15
3.2	Initial Parts List	Mon 9/24/18	Fri 10/12/18	19	100%	15
3.3	Prototype Performcance Goals	Mon 9/24/18	Fri 10/12/18	19	100%	15
4	**Design Refinement**		-			-
4.1	FEM Stress/Deflection Analysis	Fri 10/12/18	Mon 10/29/18	18	100%	12
4.2	Design for Safety Exercise	Fri 10/12/18	Mon 10/29/18	18	100%	12
4.3	Design for Manufacturing Exercise	Fri 10/12/18	Mon 10/29/18	18	100%	12
4.4	Design for Usability Exercise	Fri 10/12/18	Mon 10/29/18	18	100%	12
5	**ERB Summary**		-			-
5.1	Complete Summary	Mon 11/05/18	Tue 11/20/18	16	100%	12
6	**Final Product**		-			-
6.1	Complete Final Design	Mon 11/05/18	Mon 11/19/18	15	100%	11
6.2	Design Presentation	Mon 11/19/18	Mon 12/03/18	15	100%	11
6.3	Final Report	Mon 11/19/18	Mon 12/10/18	22	100%	16

Figure 6: Completed Gantt chart

3 CONCEPT GENERATION

3.1 MOCKUP PROTOTYPE

Figure 7: Final Mock-Up View with Stands

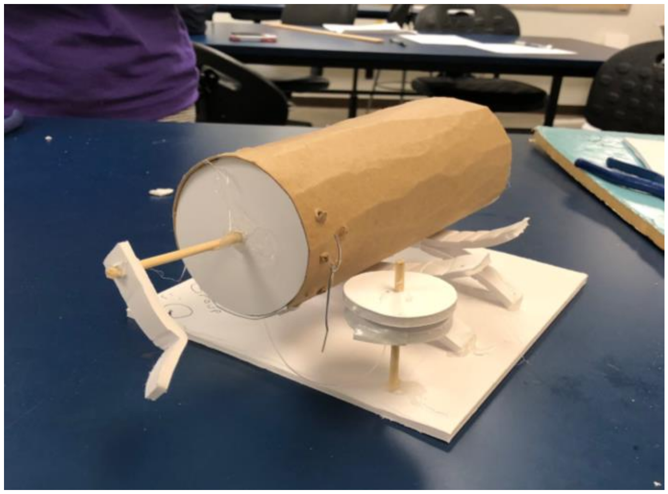


Figure 8: Final Mock-Up Crank and Spool View

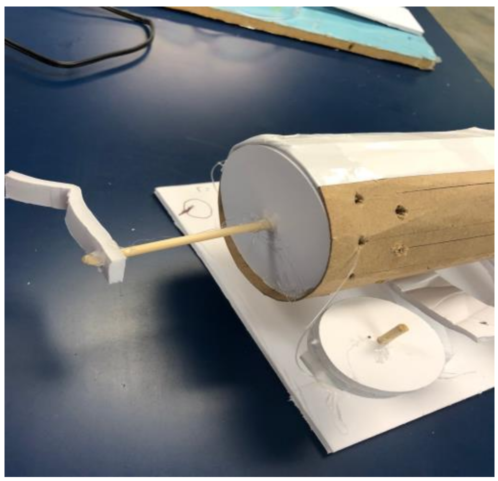


Figure 9: Final Mock-Up Close up of Crank

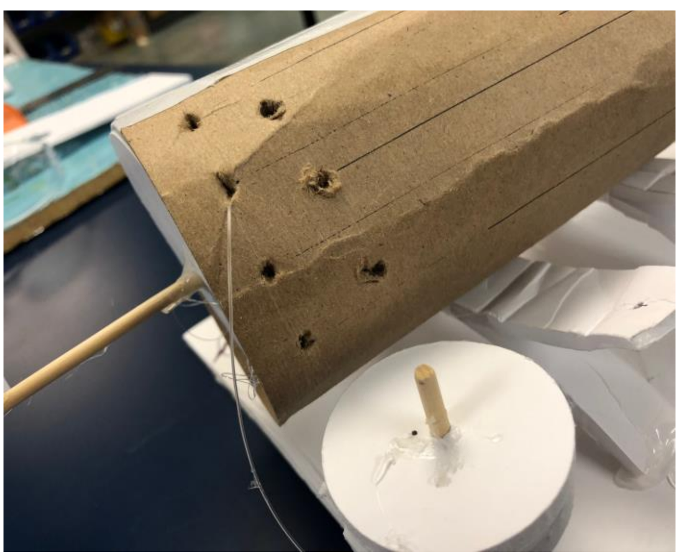


Figure 10: Final Mock-Up Close up Tube

Concluding the mockup of our initial design we realized that the density of fibers required would be difficult in such a small footprint. We scaled up our mockup to show the general idea of how the design works. To weigh down the fibers we used a paper clip to represent a needle. The functionality of the design shows promise if we can 3D print sections of the cylinder with very fine tolerances. Moving forward we will produce a sample with a diameter of approximately 5 cm to allow a more uniform, fiber-dense sample. After we created the crank going straight through the center of the cylinder we realized this was not the ideal design. Methods for bracing the 3D printed sample tube will be addressed, allowing rotation to ensure the proper feeding of fibers into the device. We also noticed we need a spool of some sort to feed our fiber into the device. With these considerations in mind, we created our function tree and morphological.

3.2 FUNCTIONAL DECOMPOSITION

Function Tree:

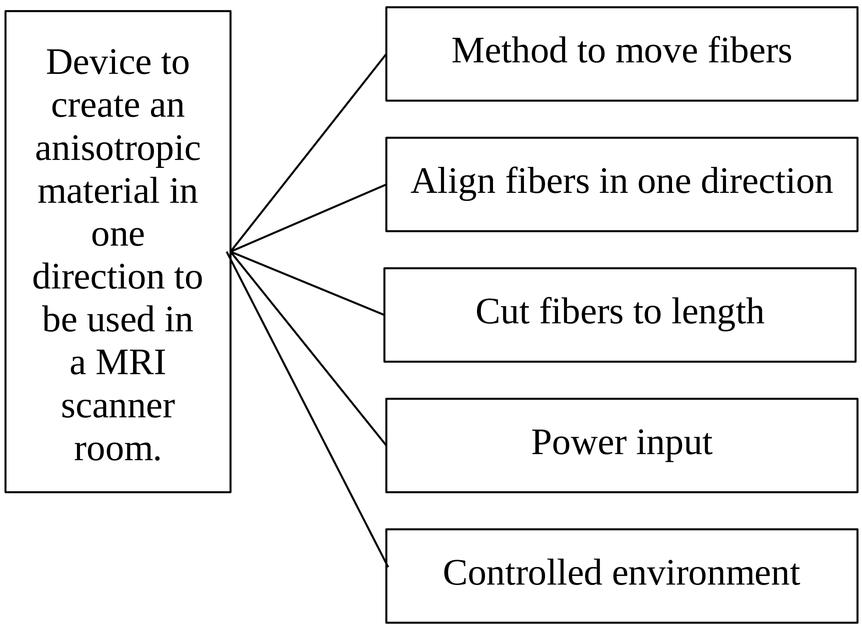
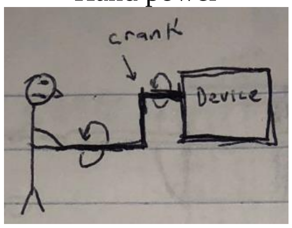
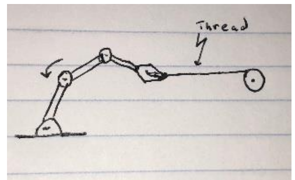
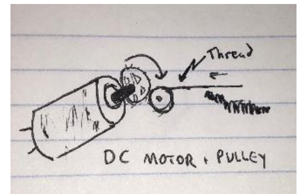
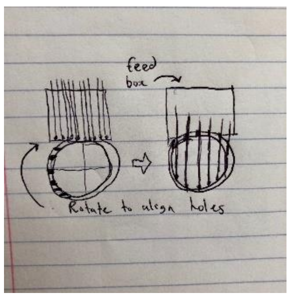
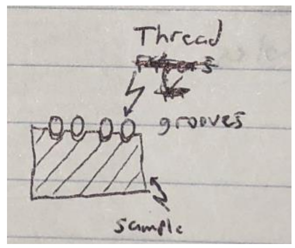
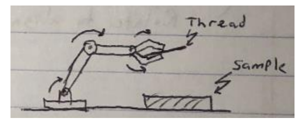
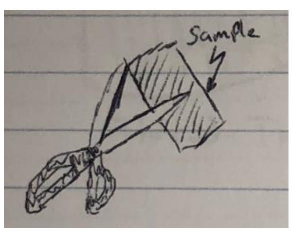
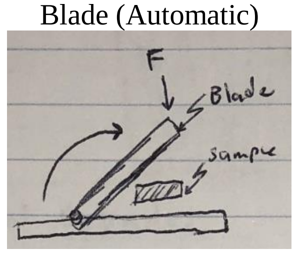
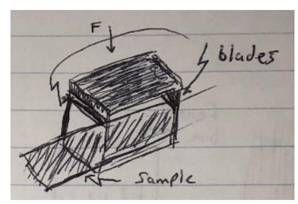
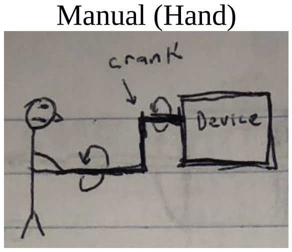
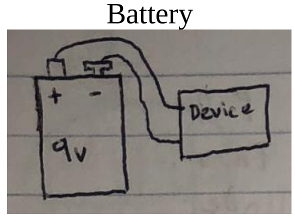
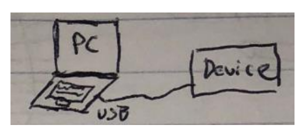
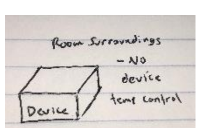
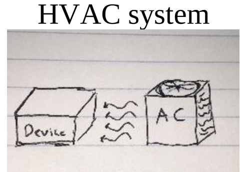
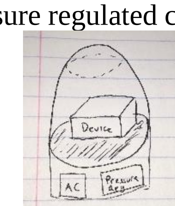


Figure 11: Function tree

Morphological Chart:

Table 4: Morphological Chart

Function	**Option 1**	**Option 2**	**Option 3**
1 - Method to move fibers	Hand power 	Mechanical Arm 	Motor 
2 - Align fibers in one direction	Gravity 	Grooves/Indents 	Mechanical Arm 
3 - Cut fibers to length	Scissors (Manual) 	Blade (Automatic) 	Flame 
4 - Power input	Manual (Hand) 	Battery 	USB 
5 - Controlled environment	Open to environment 	HVAC system 	Pressure regulated chamber 

3.3 ALTERNATIVE DESIGN CONCEPTS

Concept Name: "Push Pop!"

Group Member: Jaryd Huffman

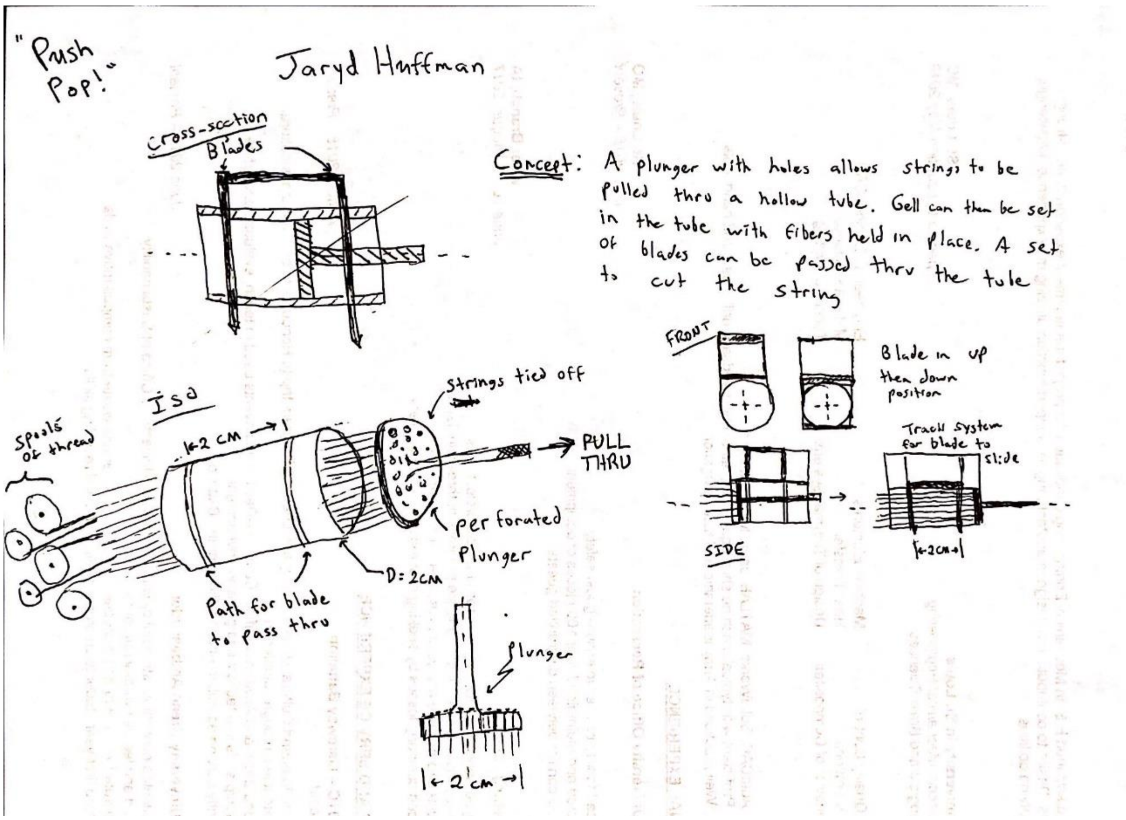


Figure 12: Push-pop design

Description: The Push pop uses a hollow tube and perforated plunger to guide and hold thread within the sample mold. Thread is held externally on spools. The user pulls the plunger until it has reached the end of the tube, arraying the fibers in a parallel fashion, held in light tension. With the cables set, gel can be poured in to set. The tube has channels for a set of fixed blades to pass through and cut the fibers to length.

Solutions:

1. Method to move fibers
2. Cut fibers to length
3. Power input

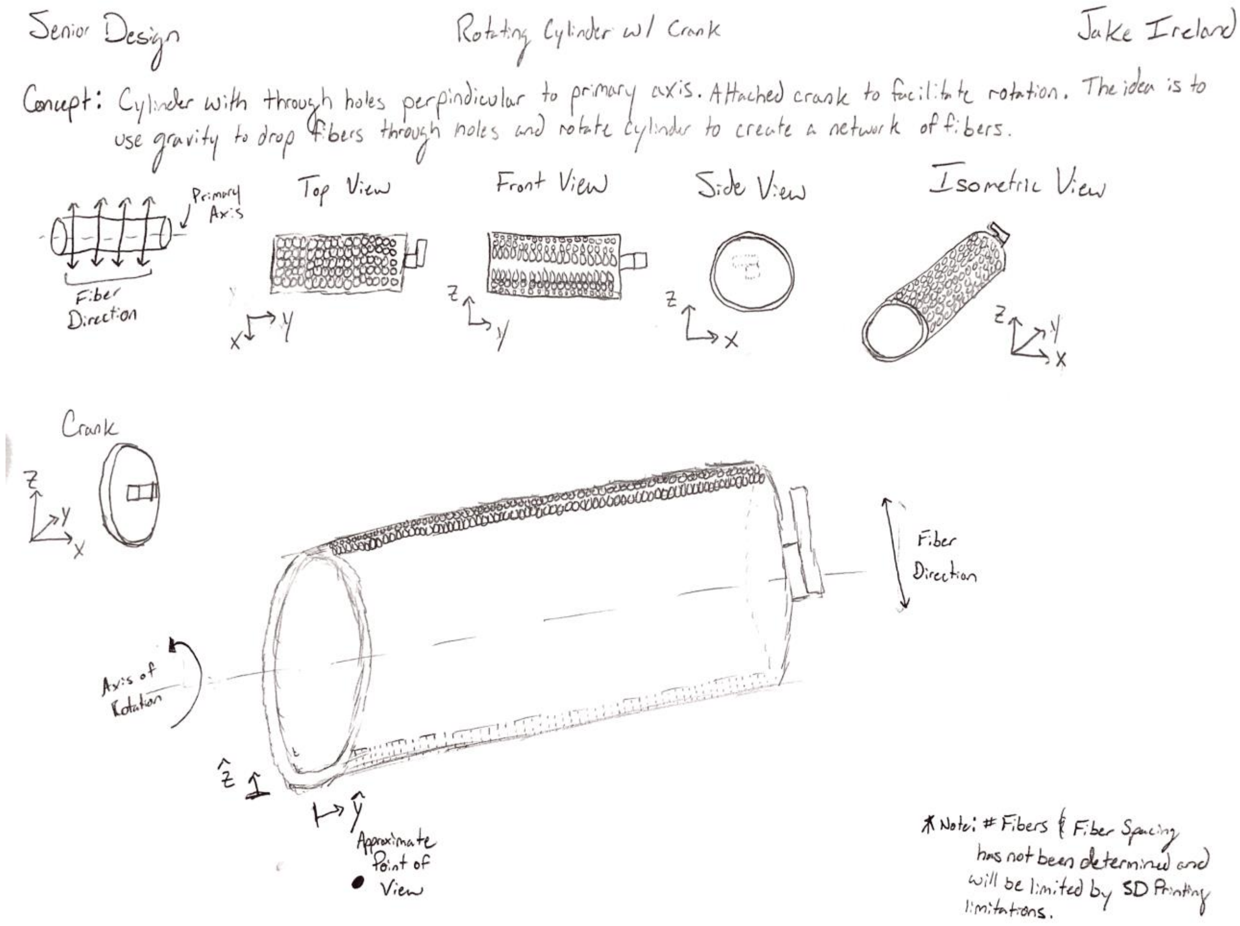


Figure 13: Rotating cylinder with crank design

Description: The Rotating Cylinder with a Crank design is comprised of a hollow cylinder with through holes along the radial direction. A weighted thread can be inserted into a hole on the top of the cylinder and fall through the corresponding hole in the bottom. Next, the cylinder could be rotated using the crank in order to bring the thread back up to the top and continuously use gravity as a resource. The cylinder would also move along its axis of rotation in order to progress the threading of holes and create a network of fibers.

Solutions:

1. Method to move fibers
2. Align fibers in one direction
3. Power input

Concept Name: “Weave and Cut”

Group Member: Daniel Cano Pargas

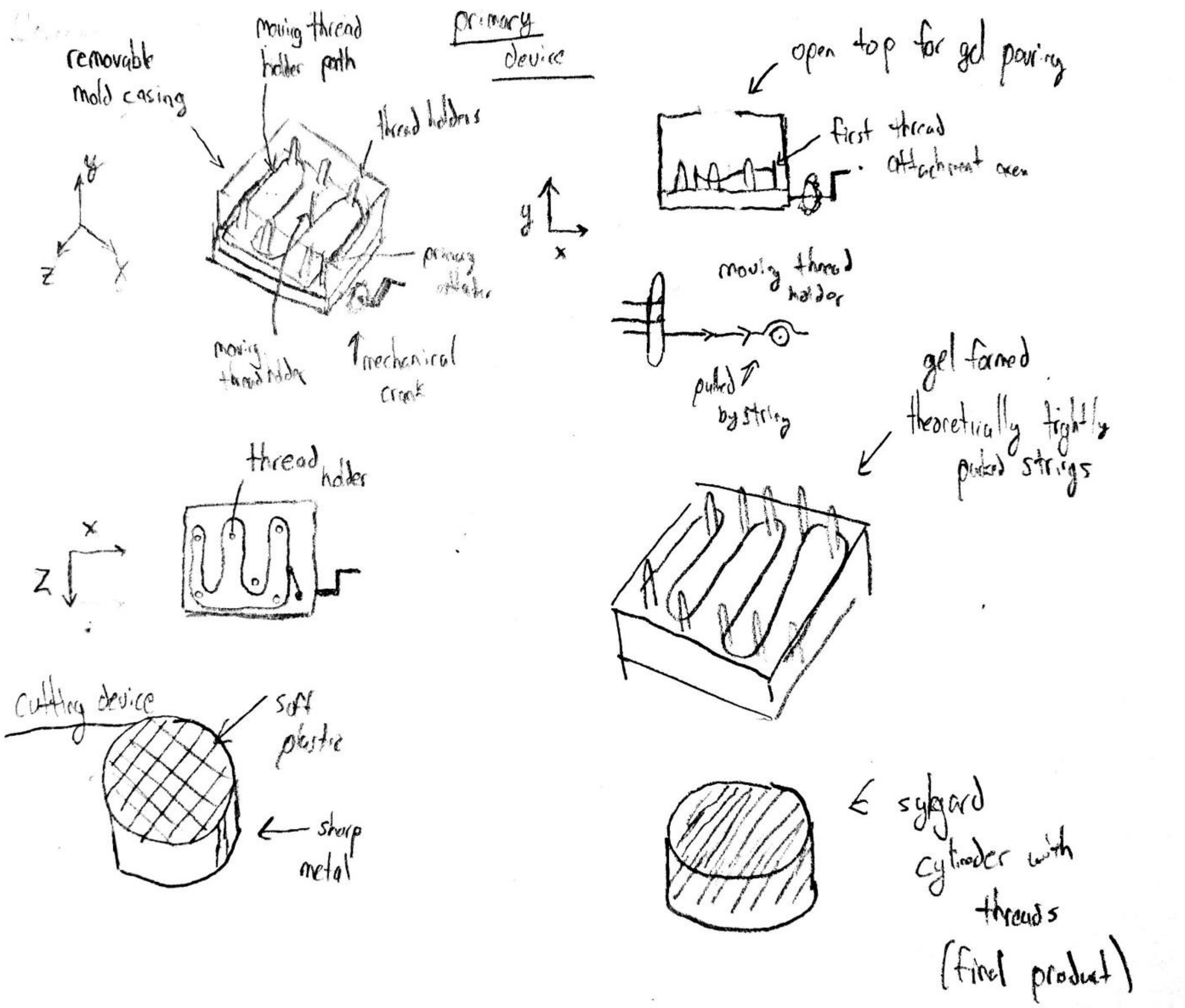


Figure 14: Weave and cut design

Description: Threads are attached to a moving thread holder that is pulled along a track by a sting which is attached to a pulley system rotates by a crank. The threads, or fibers, latch on to stationary thread holders and form straight lines. When the entire system is weaved, a Sylgard gel solution is poured into the open top. After hardening, the removable mold casing is detached, and a cookie cutter type object is used to a cut a cylindrical shape which is the final product.

Solutions:

1. Method to move fibers
2. Align fibers in one direction
3. Cut fibers to length
4. Power input

Concept Name: “Crank, Weave, and Stack”

Group Member: Sarah Mohrmann

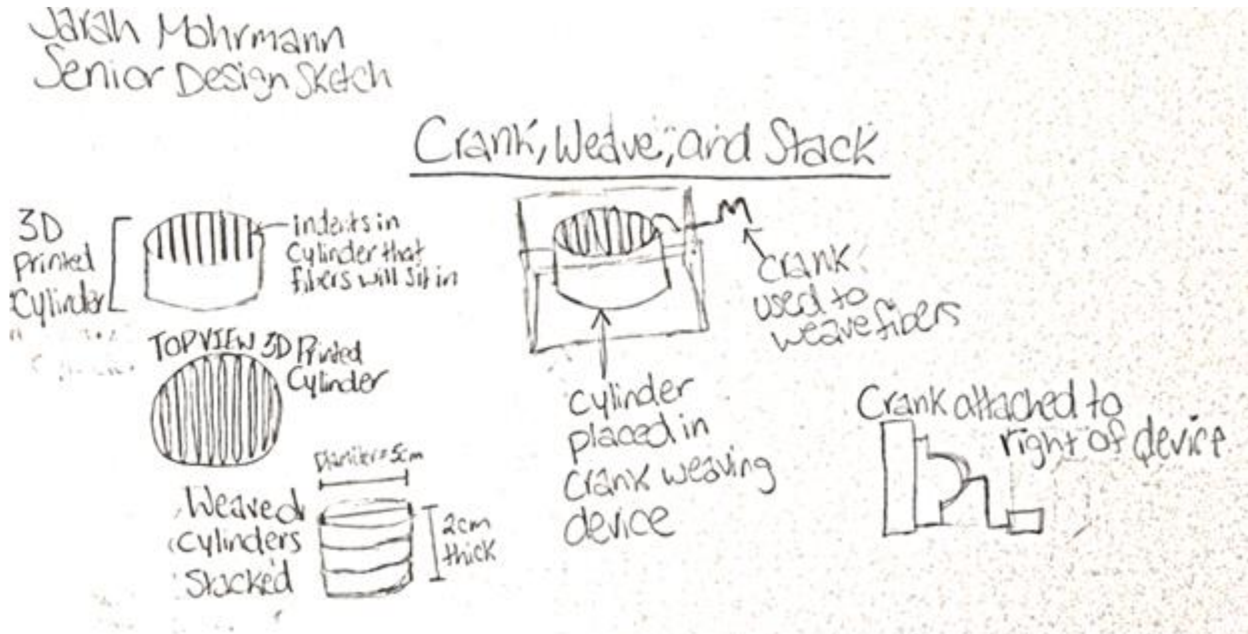


Figure 15: Crank, Weave, and Stack design

Description: The Crank, Weave, and Stack method will use a few 3D printed cylinders with indents/groves for to fibers to be placed in. The thin cylinder will be placed in a device where a crank system weaves the fibers around the groves on top of the cylinder. After multiple cylinders are weaved a Sylgard gel is placed on top of each one to keep the fibers in place. Finally, the cylinders are placed on top of one another to created one cylinder with a diameter of 5 cm with a thickness of 2 cm.

Solutions:

1. Method to move fibers
2. Align fibers in one direction
3. Power input

4 CONCEPT SELECTION

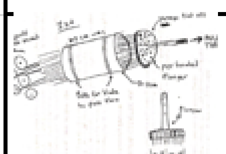
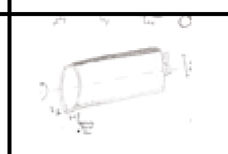
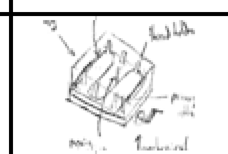
4.1 SELECTION CRITERIA

Table 5: Selection Criteria

	Functionality	Accuracy	Durability	Repeatability	Ease of use	Design Specifications	Row Total	Weight Value	Weight (%)
Functionality	1.00	1.00	3.03	0.33	1.00	1.00	7.36	0.14	13.56%
Accuracy	1.00	1.00	5.00	3.03	1.00	1.00	12.03	0.22	22.16%
Durability	0.33	0.20	1.00	0.14	0.33	0.20	2.21	0.04	4.06%
Repeatability	3.00	0.33	7.00	1.00	3.03	1.00	15.36	0.28	28.29%
Ease of use	1.00	1.00	3.00	0.33	1.00	1.00	7.33	0.14	13.50%
Design Specifications	1.00	1.00	5.00	1.00	1.00	1.00	10.00	0.18	18.42%
						Column Total:	54.29	1.00	100%

4.2 CONCEPT EVALUATION

Table 6: Concept Evaluation

		Alternative Deisgn Concepts							
		oncept #1 "Push Pop		Concept #2 "Rotating Cylinder w/Crank"		Concept #3 "Weave and Cut"		Concept #4 "Crank, Weave, and Stack"	
Using Concept #2 as a reference. (Mockup)									
Selection Criterion	Weight (%)	Rating	Weighted	Rating	Weighted	Rating	Weighted	Rating	Weighted
Functionality - Generates specimen that demonstrates anisotropic properties	13.5634143	3	0.41	3	0.41	3	0.41	3	0.41
Accuracy - Generates specimen with properties very similar to brain tissue and	22.1591584	3	0.66	3	0.66	3	0.66	3	0.66
Durability - Device will not break after many iteration	4.06368186	4	0.16	3	0.12	4	0.16	4	0.16
Repeatability - Can generate specimens with little deviation	28.2928358	3	0.85	3	0.85	3	0.85	3	0.85
Ease of use - Device is easy for lab technician to use	13.501458	2	0.27	3	0.41	4	0.54	5	0.68
Design Specifications - Product must be about 5.0 cm in diameter and 2.0 cm in	18.4194516	3	0.55	3	0.55	3	0.55	3	0.55
	Total score	2.906		3.000		3.176		3.311	
	Rank	4		3		2		1	

4.3 EVALUATION RESULTS

The concept ranked highest by our Weighted Scoring Matrix and Analytic Hierarchy Process was Sarah's "Crank, Weave, and Stack". 6 criteria were taken into consideration: Functionality, Accuracy, Durability, Repeatability, Ease of Use, and Design Specifications. When taking these criteria and their associated weightings, the "Crank, Weave, and Stack" was the clear winner.

Our chosen concept, also known as Concept #4, was like the rest in terms of Functionality, Accuracy, Repeatability, and Design Specifications. In these, there was essentially no deviation from the reference concept, also known as Concept #2. Where our chosen concept excelled was its durability, requiring very few parts and maintenance, and its ease of use, needing nothing more than a crank to function effectively.

Although it is similar to Concept #3, the chosen concept addresses its competitor's difficulty in threading multiple fibers to a single piece by instead creating a system where multiple gel forms are stacked. In this same fashion, the concept maintains an equal functionality without compromising simplicity. Its form is already cylindrical and there's no additional pulling, threading, popping, or cutting. For the weight and importance of our device, it exceeds all others.

4.4 ENGINEERING MODELS/RELATIONSHIPS

1. Beam Loading

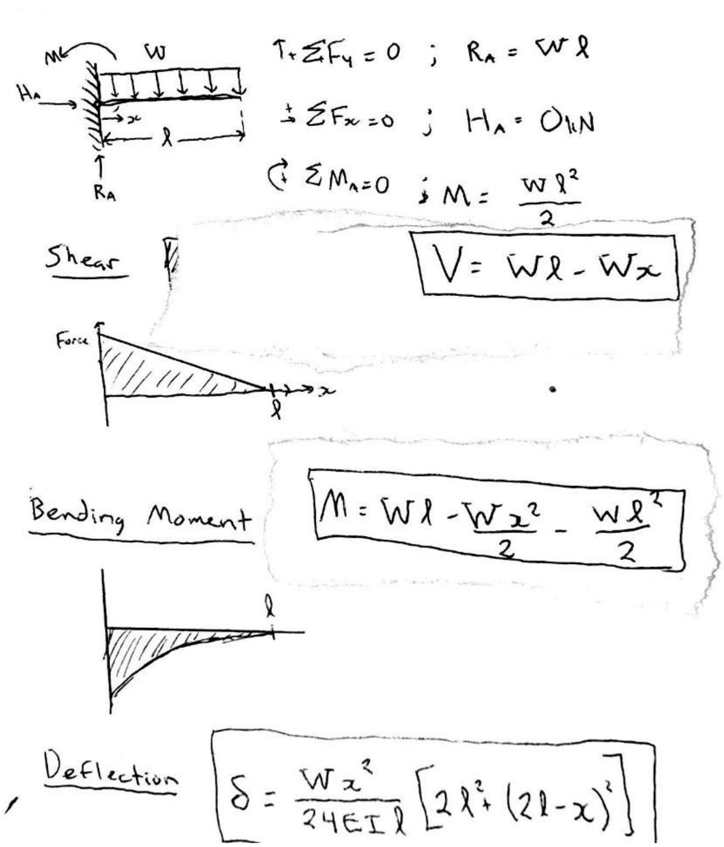


Figure 16: Beam Loading Models

Where V is shear force, W is distributed load, length is l, position is x, moment is M, deflection is δ, modulus of elasticity is E, and moment of inertia is I.

This model will help our team analyze how much stress and deflection we can expect on our devices pins as we thread fiber. These equations will allow us to set dimensions of pins in accordance with how much force we expect to apply to the fiber. This will ensure we do not use pins that are too large to prevent unwanted deflection, saving time and resources.

2. Composite Stiffness

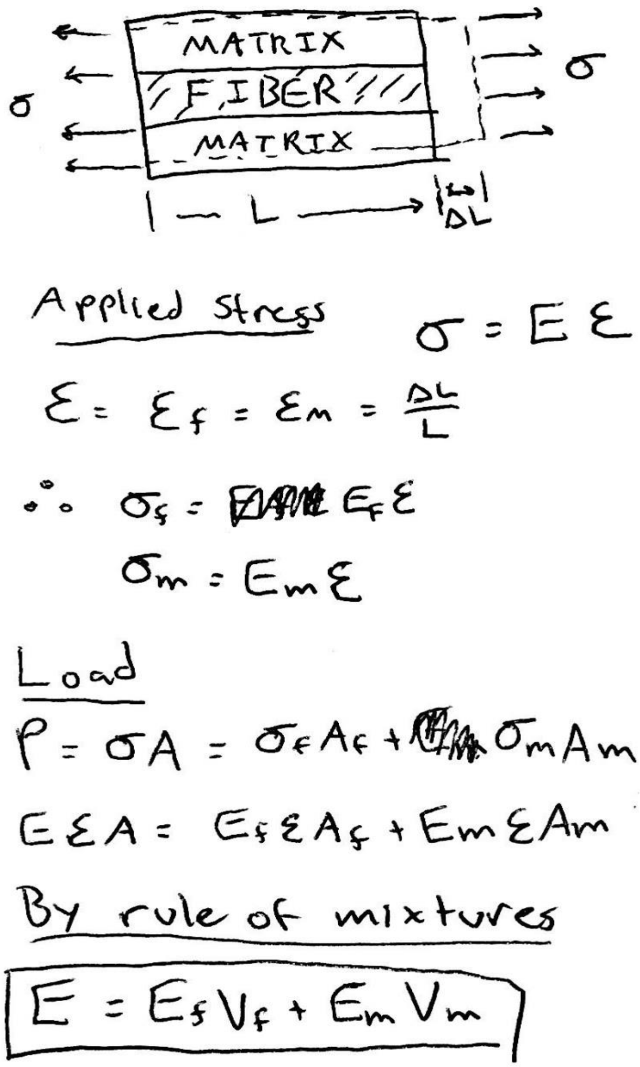


Figure 17: Composite Stiffness model

Where σ is stress, E is modulus of elasticity or stiffness, length is L, strain is ε, load is P, area is A, and volume is V. Superscript f represents the fiber and m represents the matrix or gel.

This engineering model uses composites knowledge to allow us to determine the composite stiffness or modulus of our design. Since the deformation of the fiber and the gel matrix is equivalent we can solve for the stress in both the fiber and the Sylgard gel using a known modulus. With this information in hand, we can find a composite stiffness of the fiber gel composite based on the volume ratios. This will be useful as we can modify the volume of fibers to obtain a stiffness similar to that of brain tissue. This will eliminate a lot of guesswork in setting up models with too much or too little fiber volume.

3. Conceptual Model

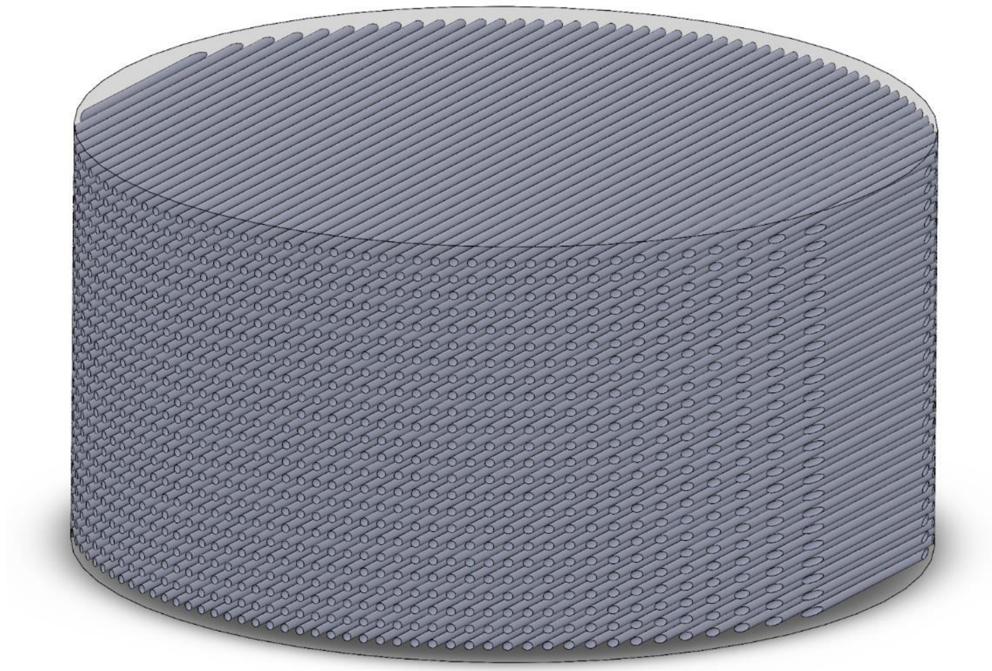


Figure 18: Conceptual model

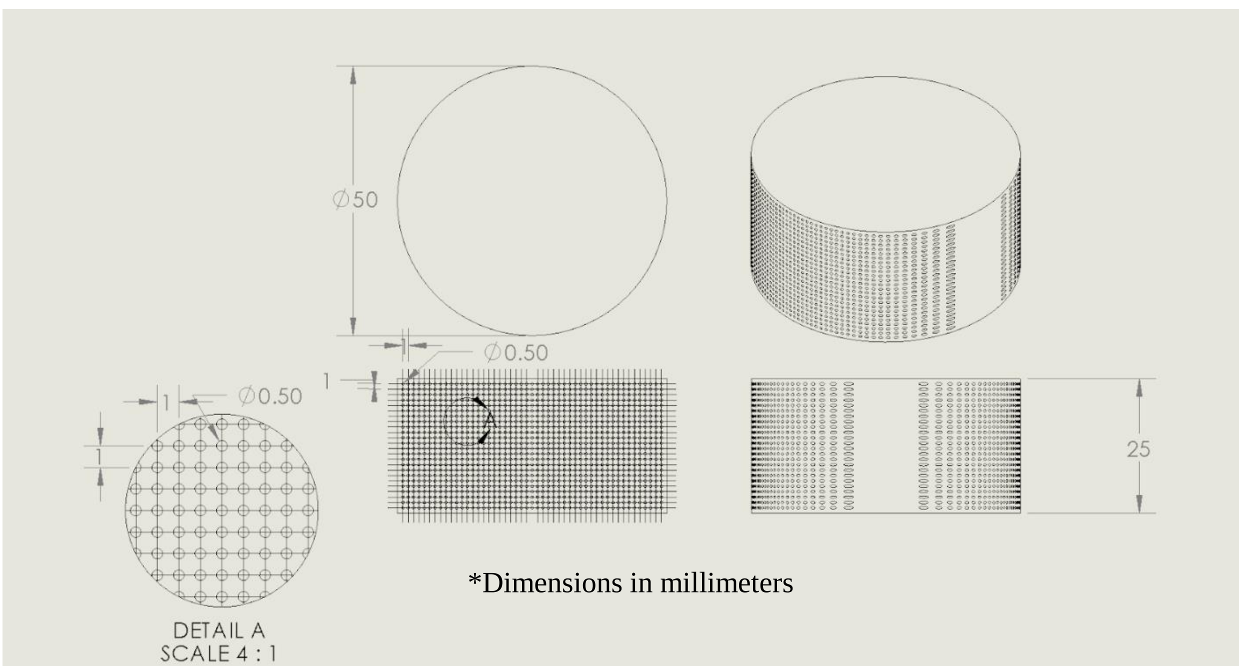


Figure 19: Dimensioned conceptual model

The above models serve as a roadmap for the ideal specimen our device will generate. It is difficult to convey exactly what fiber spacing and dimensions are needed to achieve the optimal anisotropic properties of the human brain, but this model facilitates this process. We are targeting a fiber spacing greater than 1 fiber per millimeter.

5 CONCEPT EMBODIMENT

5.1 INITIAL EMBODIMENT

The following section includes 3D models and drawings for the device made on Solidworks. The work introduces a concept designed to clamp down on various fibers, pull them over layers of disks, and provide a shape to fill with a liquid to harden and form an anisotropic tissue. The concept provides an efficient way to realize a process requiring hours at a time. Instead, this is done in minutes. A combination of parts, made and purchased, provide an optimal design with room for flexibility and quick debugging. This concept embodies a prototype capable of its function and testing.

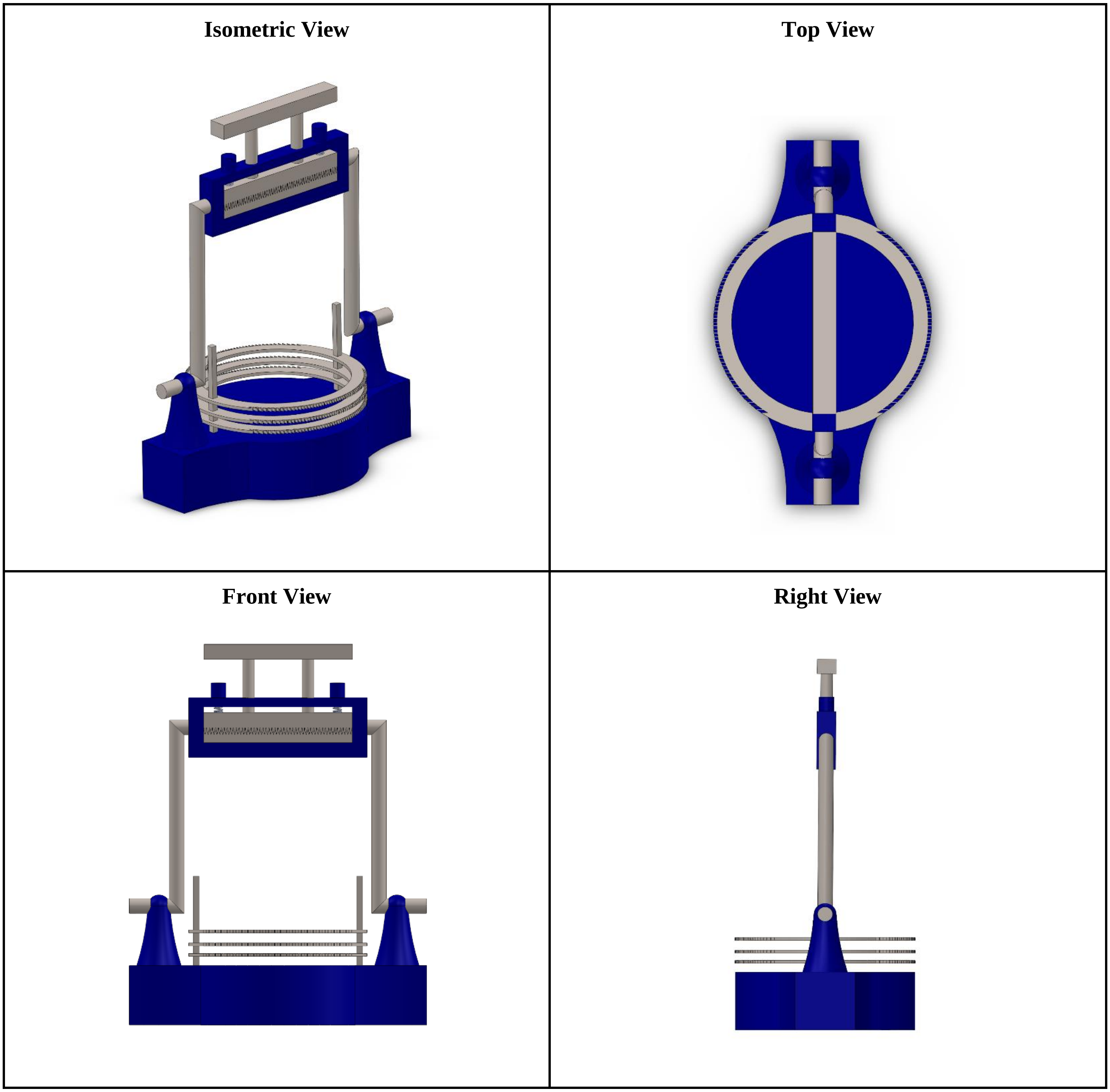
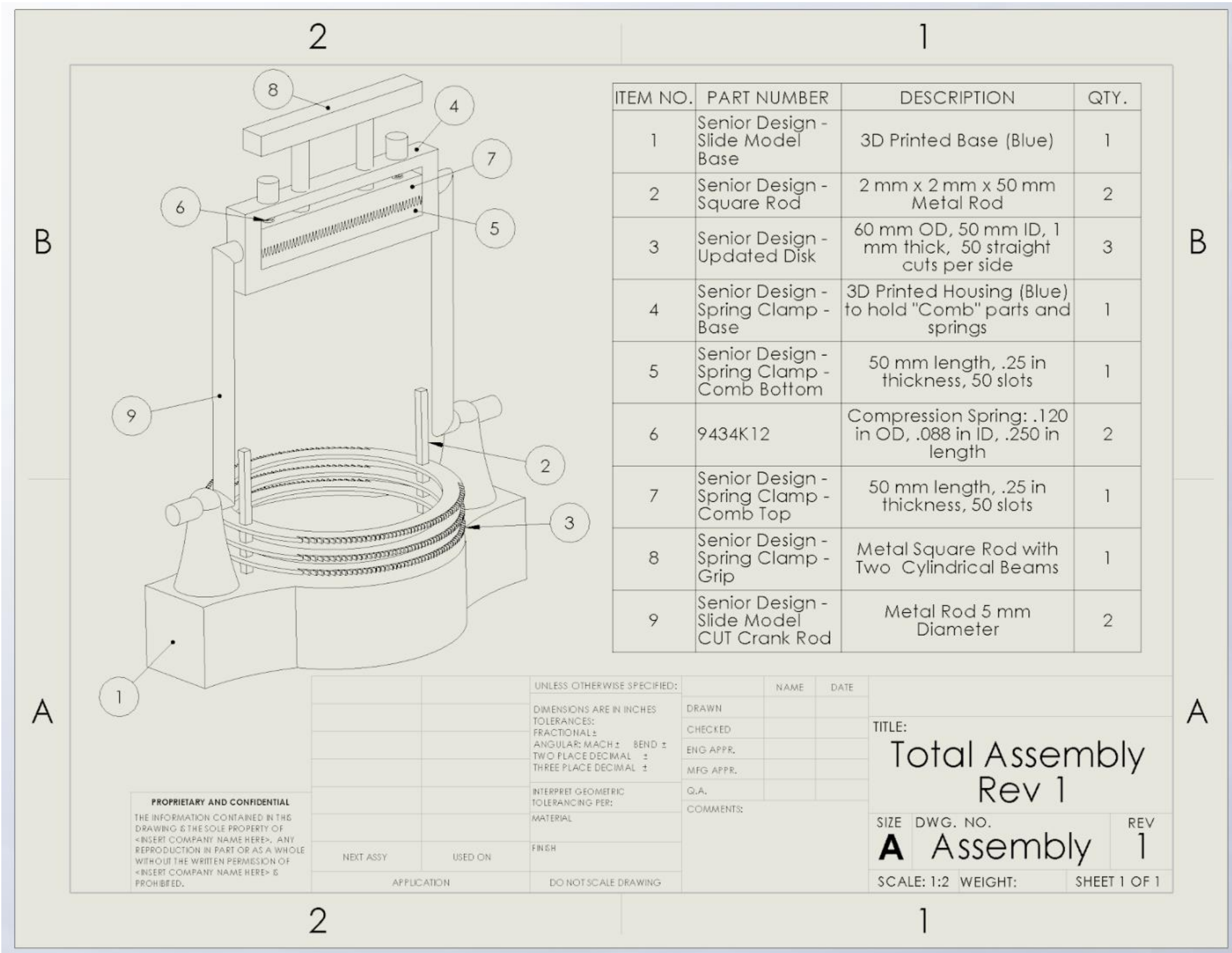


Figure 20: Four Solidworks Views of Model



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Senior Design - Slide Model Base	3D Printed Base (Blue)	1
2	Senior Design - Square Rod	2 mm x 2 mm x 50 mm Metal Rod	2
3	Senior Design - Updated Disk	60 mm OD, 50 mm ID, 1 mm thick, 50 straight cuts per side	3
4	Senior Design - Spring Clamp - Base	3D Printed Housing (Blue) to hold "Comb" parts and springs	1
5	Senior Design - Spring Clamp - Comb Bottom	50 mm length, .25 in thickness, 50 slots	1
6	9434K12	Compression Spring: .120 in OD, .088 in ID, .250 in length	2
7	Senior Design - Spring Clamp - Comb Top	50 mm length, .25 in thickness, 50 slots	1
8	Senior Design - Spring Clamp - Grip	Metal Square Rod with Two Cylindrical Beams	1
9	Senior Design - Slide Model CUT Crank Rod	Metal Rod 5 mm Diameter	2

Figure 21: Solidworks Assembly View Drawing with BOM

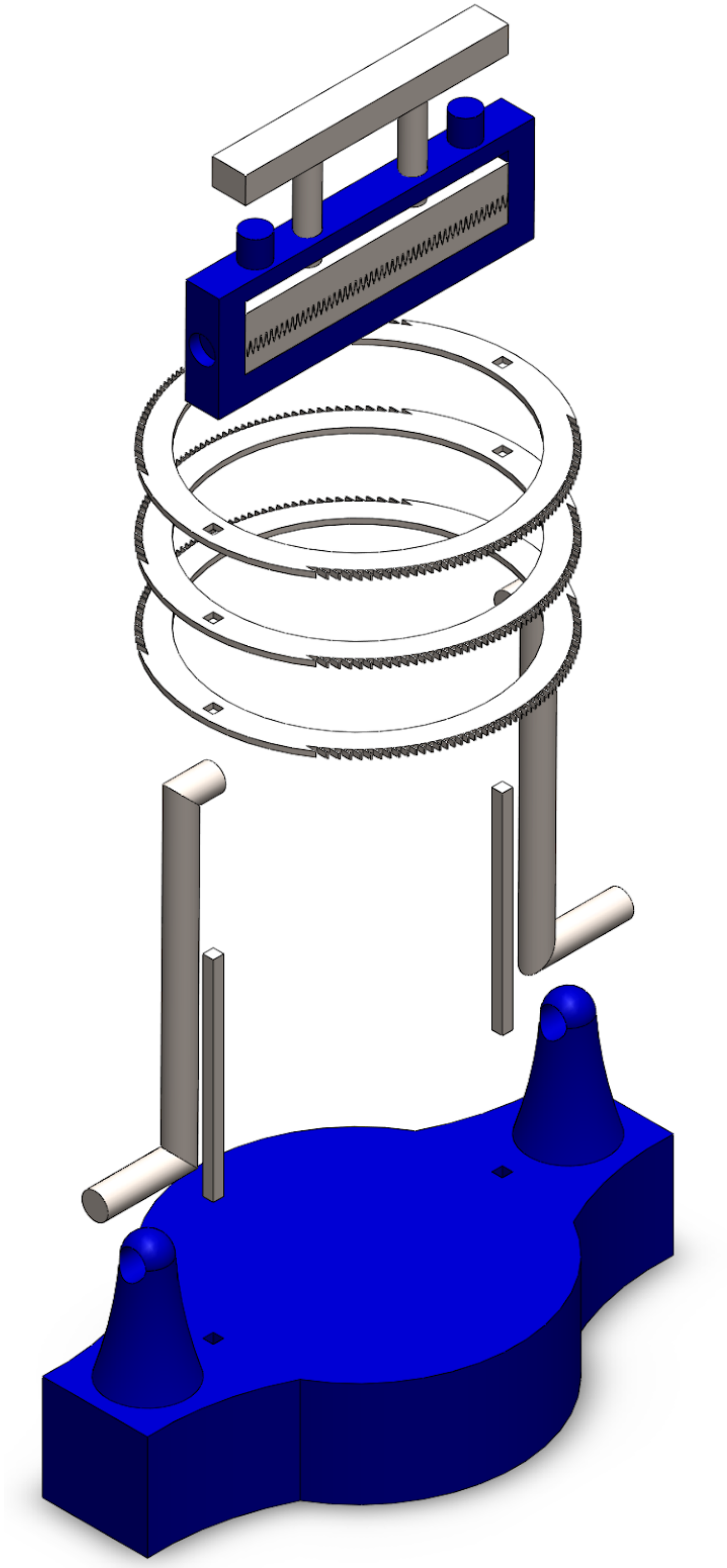
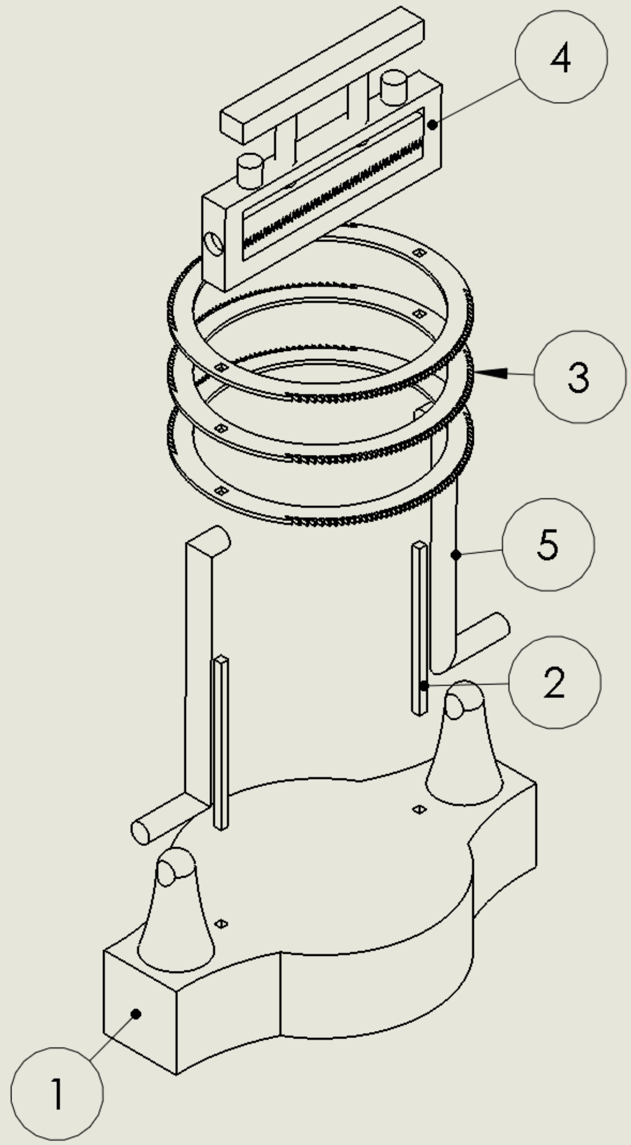
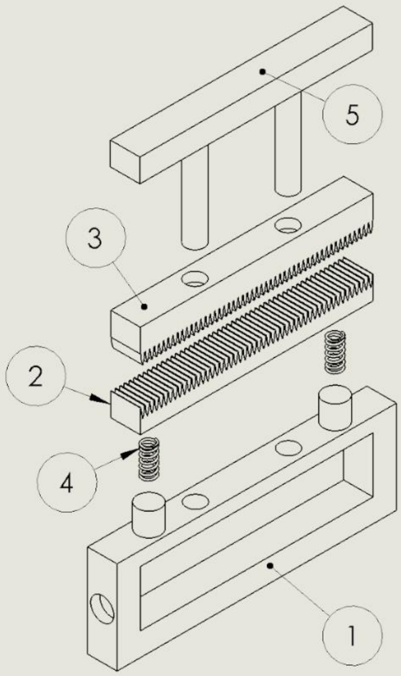


Figure 22: Exploded view of Solidworks Model



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Senior Design - Slide Model Base	3D Printed Base (Blue)	1
2	Senior Design - Square Rod	2 mm x 2 mm x 50 mm Metal Rod	2
3	Senior Design - Updated Disk	60 mm OD, 50 mm ID, 1 mm thick, 50 straight cuts per side	3
4	Senior Design - CLAMP ASSEMBLY		1
5	Senior Design - Slide Model CUT Crank Rod	Metal Rod 5 mm Diameter	2

Figure 23: Drawing Exploded View of Concept with Each Component



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Senior Design - Spring Clamp - Base	3D Printed Housing (Blue) to hold "Comb" parts and springs	1
2	Senior Design - Spring Clamp - Comb Bottom	50 mm length, .25 in thickness, 50 slots	1
3	Senior Design - Spring Clamp - Comb Top	50 mm length, .25 in thickness, 50 slots	1
4	9434K12	Compression Spring: .120 in OD, .088 in ID, .250 in length	2
5	Senior Design - Spring Clamp - Grip	Metal Square Rod with Two Cylindrical Beams	1

Figure 24: Drawing of Spring Clamp Section, Item 4 from Fig. 23

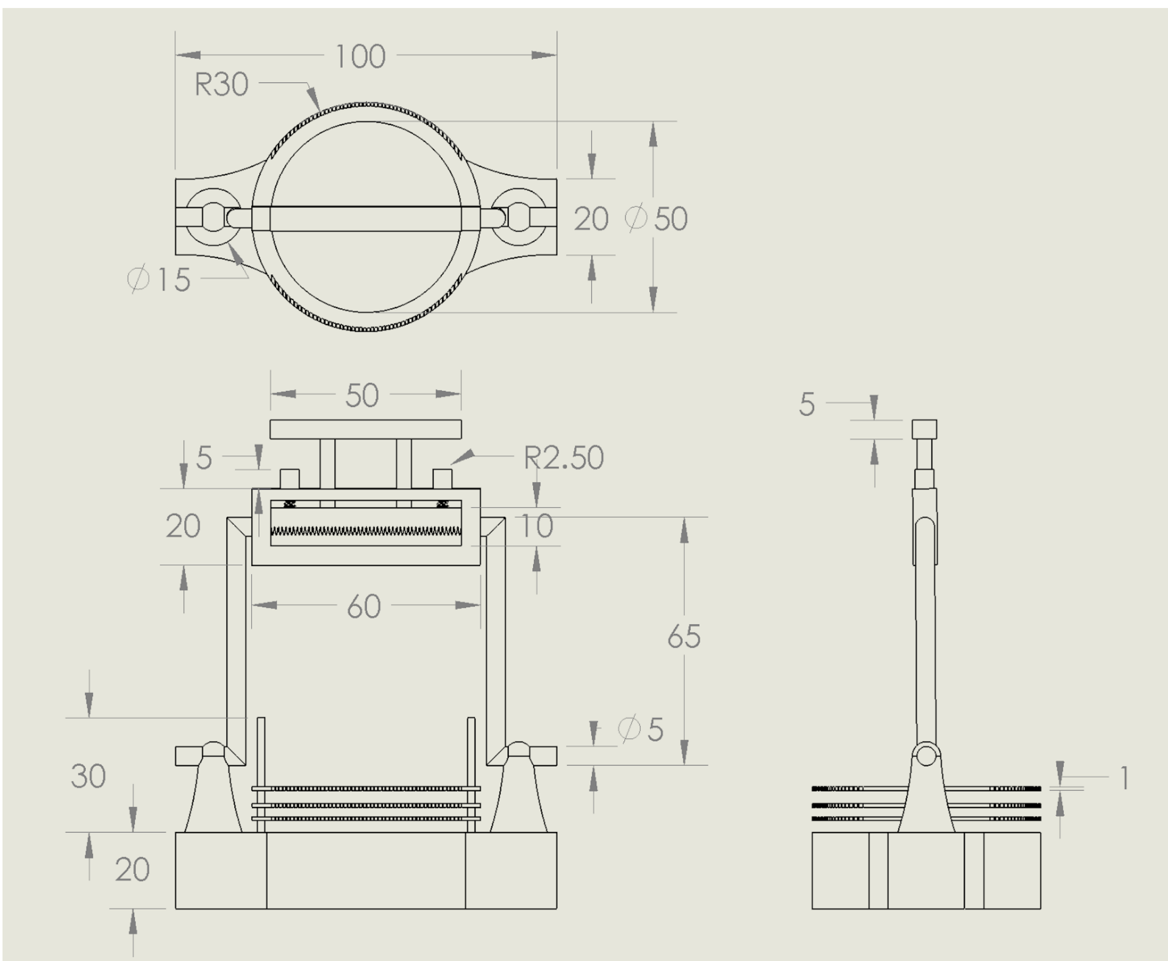


Figure 25: Drawing of Top, Front, and Side Views with Dimensions in Millimeters

Table 7: Initial Parts List of Prototype Components

	Part	Source Link	Supplier Part Number	Color, TPI, other part IDs	Unit price	Quantity	Total Price
1.	Metric Steel Machine Key Stock	McMaster	92288A710	2x2 mm 12' long	$1.93	1	$1.93
2.	Lycra	Provided by customer	N/A	N/A	N/A	N/A	N/A
3.	Music-Wire Steel Compression Springs	McMaster	9434K12	Zinc-Plated. 0.25" Long, 0.12" OD, 0.088" ID	$4.85 per 5 springs	1	$4.85
4.	Clear Acrylic Sheet	Lowe's	Item: 11230 Model: 11G0830A	OPTIX 0.08 x 28 x 20 in, Clear	$18.01	1	$18.01
5.	Pine Plywood	Lowe's	Item: 7701 Model: 199342	¼ in common pine, 2x2	$5.23	1	$5.23

5.2 PROOF-OF-CONCEPT

Prototype Performance Goals:

1. Once set up, device can thread 10 layers in less than 3 minutes and 20 seconds.
2. During testing, any debugging process will require less than 20 seconds.
3. When forming the Sylgard gel, the process will be able to pour and set completely without losing more than 10% volume outside of the mold cylinder.

Design Rationale for PoC Components:

Choosing the components of this proof of concept involved considering previously developed models and relationships in detail. The first, and most important, rationale was choosing a material like wood for our finer parts. As shown in section 4.4, the beam loading models cause potential deflections in a rod like that on which we will attach our fibers. Deflection in the beam would change the tension of the fibers set in the gel, which are expected to be taut. Wood has a high modulus of elasticity, E, and can withstand numerous iterations with minimal fatigue.

Our conceptual model provides further rationale for material and design choices. In order to space a large number of fibers in a 1mm by 1mm pattern, the fibers must first be inserted in a pattern and form. Using a comb/teeth-like clamp gives proper spacing while holding fibers in position. Wood has the benefit of being useable in a laser printer, giving way for precise, accurate spacing. This same reasoning is applied to disks, made of acrylic for its mutable, strong properties.

Sylgard is a two-part mix which can be adjusted to get a desired stiffness. Dr. Bayly lab already has a mixture ratio that closely resembles brain tissue stiffness (2-3 kPa). As previously mentioned, it is desired to take the current mixture of Sylgard and induced anisotropy by adding a fiber matrix. The current mixture is proven so it would be optimal to not alter. Adding fiber to the Sylgard matrix will make a composite with altered stiffness. Using composite stiffness equations, we can determine if adding the fiber matrix will greatly alter our composite stiffness to the point where the mixture ratio of the Sylgard would have to be modified. Stiffness can be measured in line with the fiber (E1) or perpendicular to the fiber (E2). The equations below show how to calculate the composite stiffness in the E1 and E2 direction using the volume fraction of the fiber:

$$E_1 = (1 - V_f)E_m + V_f E_f \quad (1)$$

$$E_2 = \frac{E_f E_m}{(1-V_f)E_f + (V_f E_m)} \quad (2)$$

Where V_f is the volume fraction of fiber, E_f is the elastic modulus of of the fiber, and E_m is the modulus of the matrix (Sylgard).

Results of Eq. 1-2 applied using various fiber materials are summarized below in the table to determine what fibers, if applicable, should be used in the design.

Table 8: Initial Parts List of Prototype Components

Fiber Material	Young's Modulus (kPa)	E1 (kPa)	E2 (kPa)
Sylgard (no fiber)	2	2.0000	2.0000
Nylon	2000000	316.1590	2.0003
Lycra	19	**2.0027**	**2.0003**
Rubber	100000	17.7076	2.0003
Flax	58000000	9112.6184	2.0003
PFTE	50000	9.8537	2.0003

The Table shows that to keep modulus values close to that of brain tissue, an extremely elastic fiber. Lycra was the only fiber option that kept the E1 term within the range of brain tissue stiffness. It is known that a 1 mm x 1 mm matrix of Lycra will give realistic brain tissue properties while creating anisotropy in the Sylgard matrix.

6 WORKING PROTOTYPE

6.1 OVERVIEW

Given the difficulty we had with manufacturing parts for our device, our proof of concept was demonstrating that we were capable of creating disks with the necessary geometry to create a network of fibers. We showed that we are capable of manufacturing disks that can guide up to 24 threads. We also presented the second iteration of the base that supports the entire assembly. For the final working prototype, we improved the base over a few iterations to have accurate tolerancing and spacing between components to facilitate the weaving process. In addition, we created the clamping device that guides the threads from one end of the disk to the other. This device was strategically manufactured to allow the exchanging of combs, or the parts in direct contact with the threads. This way the fiber density could be easily manipulated. Also, the clamping device was designed with the ability to releases tension in the threads. As passes are made over plates, there is a significant tension buildup that can damage the disks or break the threads. Lastly, atypical spools were designed for the device. Unlike typical spools purchased in a store, these spools have very small geometries relative to the amount of thread that they can contain. Additive manufacturing, or 3D printing, was essential to the success of our final working prototype. Improvements will continue to be made to the device as more accurate manufacturing methods, especially laser cutting, become more available to us.

6.2 DEMONSTRATION DOCUMENTATION

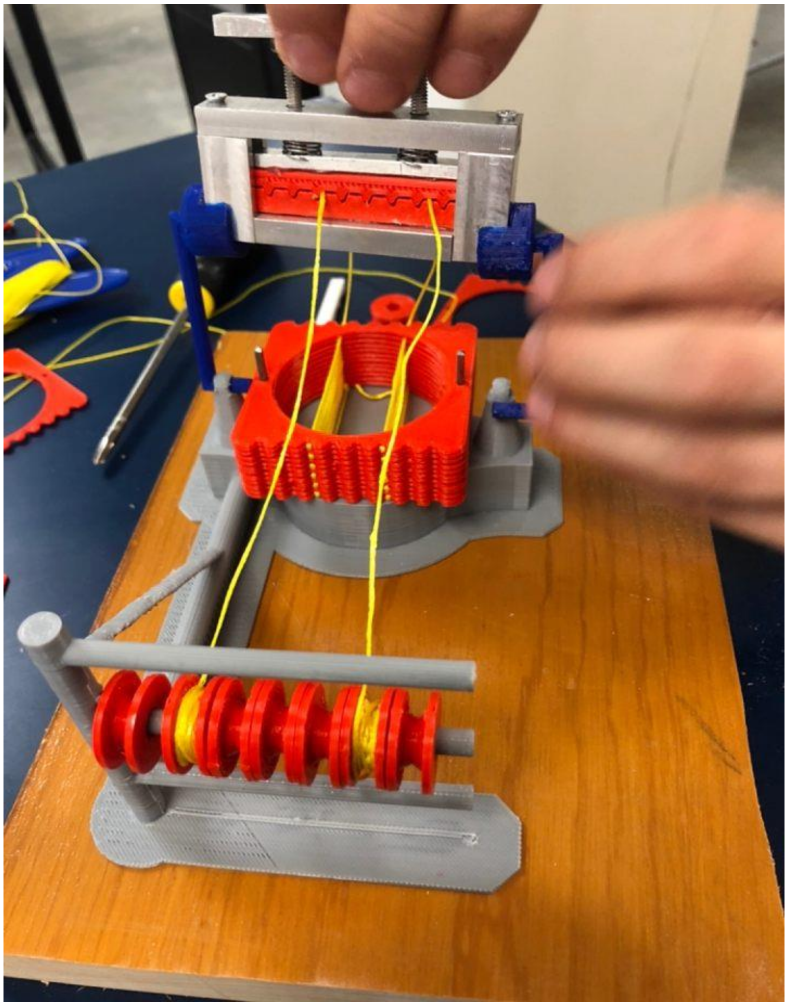


Figure 26: Front view of final working prototype

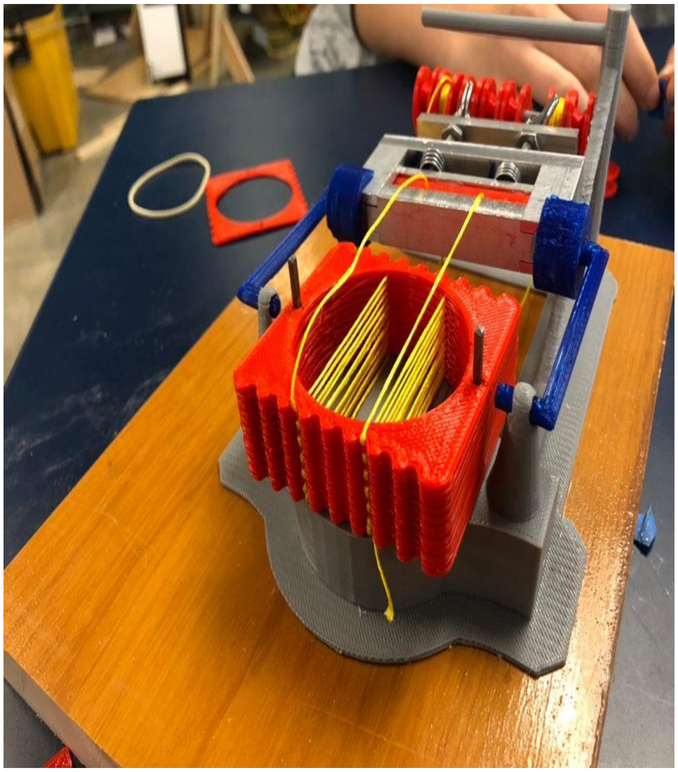


Figure 27: Isometric view of final working prototype

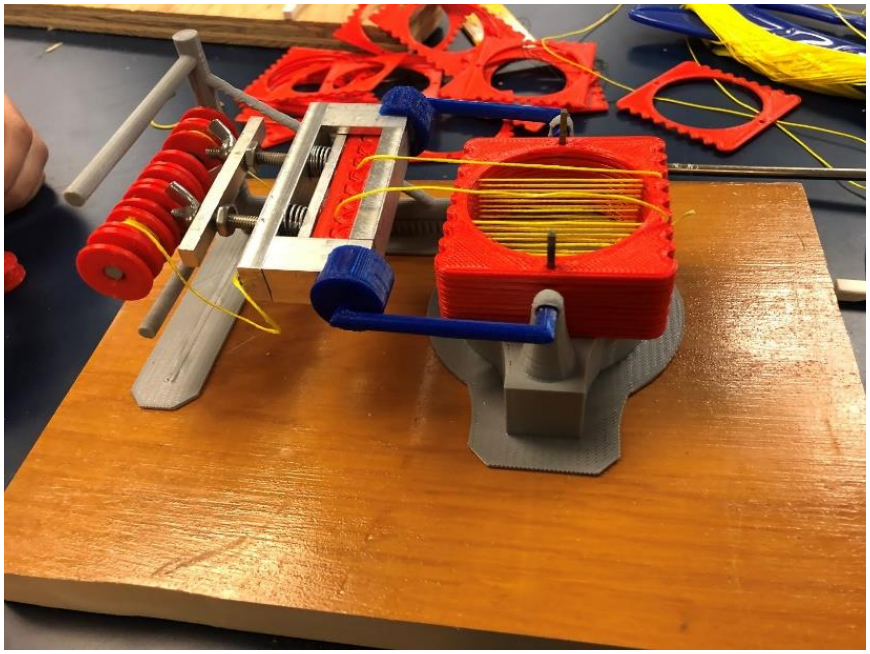


Figure 28: Side view of final working prototype

6.3 EXPERIMENTAL RESULTS

The first performance goal was to weave 10 layers of fiber in under 3 minutes and 20 seconds (200 seconds). This goal was accomplished; our design successfully threaded 10 discs (layers) with an actual time of 1 minute and 50 seconds (110 seconds). The process of adding discs prove to be quick and simple. Manipulating the clamp to relieve and apply tension was fluid after a few cycles of use to gain familiarity. The 3D printed arms limited the speed with which the device could be cycled as they were prone to bending. When the arms flexed, they slid out of their housing, preventing a smooth rotation.

The second performance goal was to weave the required 10 layers of thread with less than 20 seconds of debugging time. Our prototype met this goal with very little debugging time required. When evaluating our prototype, less than 5 seconds of debugging time was required. The disc and clamp design was very effective in guiding the strings to their respective slots. Debugging was only required when the clamp provided to much slack and the strings were free to shift to a different slot. Correcting this issue, which only happened once, took under 5 seconds. During most trials this issue did not occur, meaning no debugging time was required at all.

The final performance goal was to pour and set our matrix material, Sylgard 527, without leaking more than 10% of the original volume. This goal was accomplished by removing the woven fiber matrix from the design and placing it in a remote container. Initially, pouring and setting Sylgard was going to take place on the design, allowing the gel to leak through the plates. This would prevent the device from making more samples as the first is setting as well as get Sylgard all over the device. By placing the completed sample in a remote container, no Sylgard will leak and the device can be used to make more samples while the Sylgard cures, thus satisfying our final performance goal.

7 DESIGN REFINEMENT

7.1 FEM STRESS/DEFLECTION ANALYSIS

For this analysis, ABS was assigned as a material because it is a commonly used 3D printing material. Forces are applied on the rods intended to hold spools because they are representing the tension from pulling the strings. A horizontal force towards the base of a total 10 lbf is used to represent a potential human input on the device. The rods coming off of the base of the structure are not fixed, but the base is fixed. This is representative of the actual system because the base will be supported by hand, a clamp, or secured to a surface unlike the beam that comes off the base.

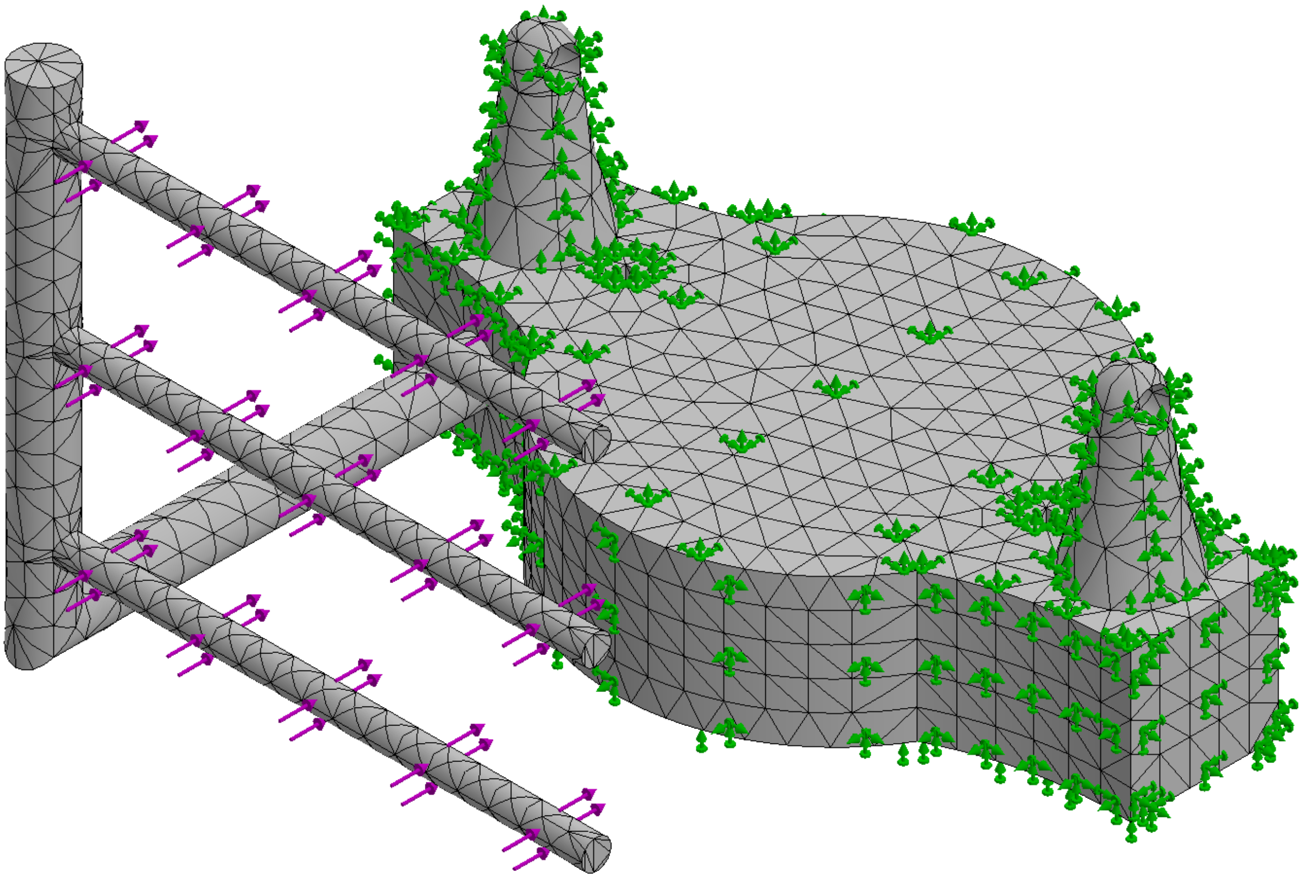


Figure 29: Unloaded Model with Mesh, Loads, and Boundary Conditions

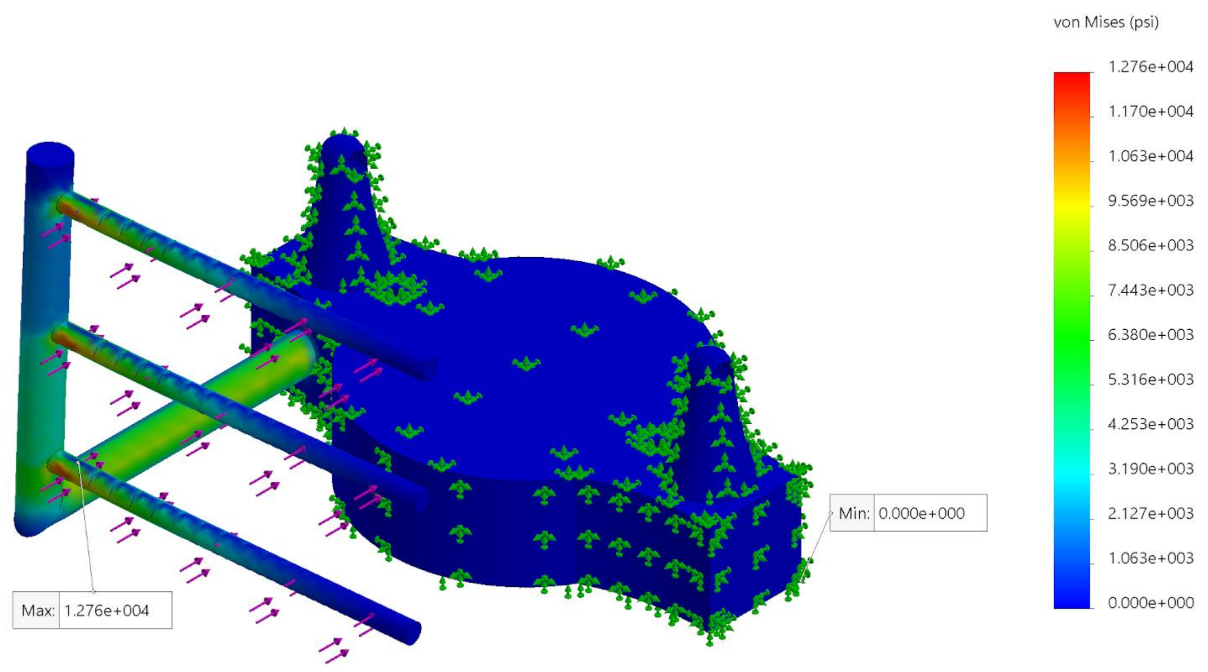


Figure 30: Unloaded Model with Color-coded Stress/Deflection and Legend

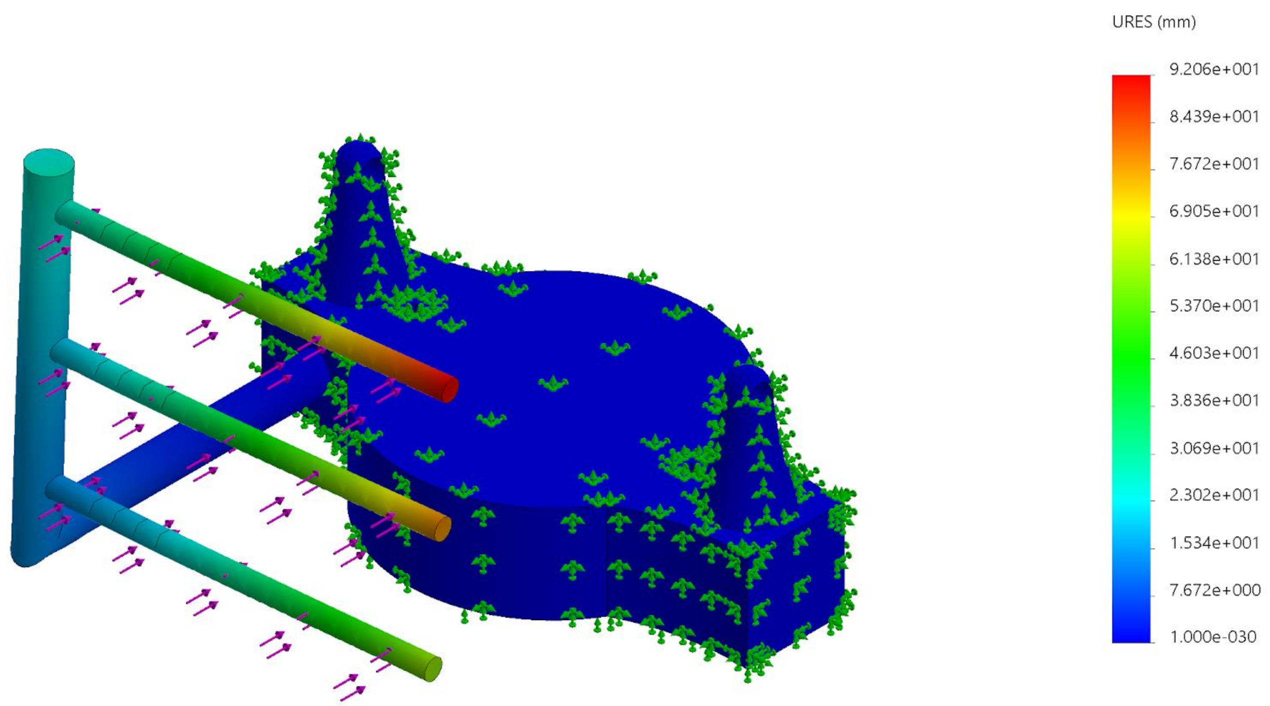


Figure 31: Loaded Model with Color-coded Stress/Deflection and Legend

Looking at the deflection, a large enough force could seriously displace the position of the rods, which would impact the alignment of the strings. However, the deflection being shown as a result of a reasonable human force does not seem to cause major deflection.

7.2 DESIGN FOR SAFETY

Risk Name: Rotating Crank
Description: When the user rotates the crank, their fingers may get caught and pinched in moving components.
Impact: 2, A pinch from the device would cause some pain but would not draw blood or seriously injure the user
Likelihood: 3, this risk is likely since the operation of the device is reliant on rotation and it would not be difficult for the user to misplace their finger under the crank.

Risk Name: Handling Discs
Description: When the user handles discs sharp edges could cut their fingers
Impact: 4, A sharp disc could easily cut the user possibly causing infection
Likelihood: 2, This risk likelihood is possible but low given that the discs will be 3D printed, making edges smooth.

Risk Name: Moving Strings
Description: If the user has to move a misaligned string they could get caught in the threat matrix, causing abrasions to fingers/hand
Impact: 1, Getting caught in the string matrix may be inconvenient but will not cause any serious injury to the user.
Likelihood: 1, The user should not have to adjust the string matrix, and the likelihood of getting a finger caught in 24 strings is very low given the discs dense spacing.

Risk Name: Placing Discs
Description: When the user places the discs on the guide pins there is risk of hand/finger impalement. If the fit between the disc's holes and the guide-pins is tight this becomes more likely as the user must apply more force to fit the disc.
Impact: 4, If the user impales themselves with the guide-pin it will cause bleeding and possibly infection. This will not kill the user, but it is significant.
Likelihood: 1, The force required to cause this type of injury is great and would require the user to be very careless, meaning this event has a low likelihood of occurring.

Risk Name: Weaving Strings
Description: As the strings are spread over the disc tension could build, causing the string to snap and hit the user.
Impact: 1, the tension generated in the device will be minimal and if a string breaks the force associated will be very small, making the resulting injury almost non-existent
Likelihood: 2, The string has a low chance of getting caught on the device, making the chance of it getting enough tension to snap low.

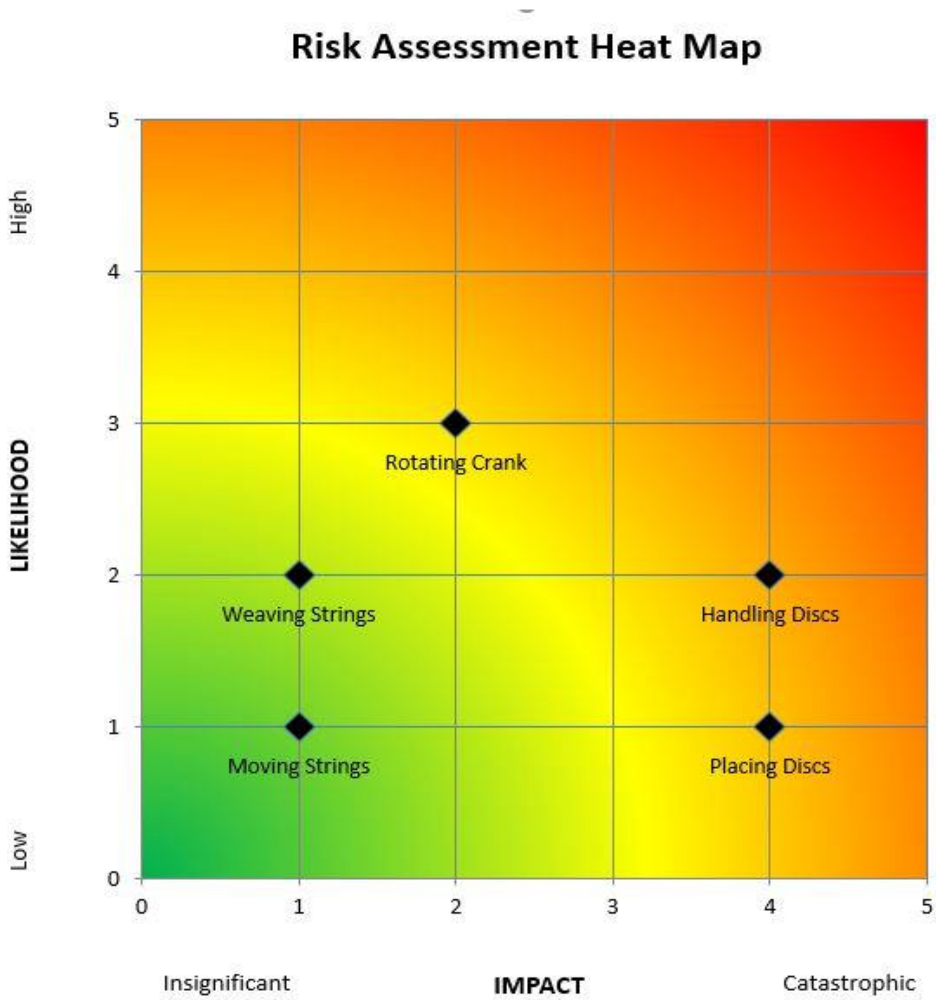


Figure 32: Risk Assessment Heat Map

Weighing the Impact and Likelihood score, a combined risk score can be gained for each risk. Ordering these scores from highest to lowest provides a good indication of where to prioritize risk mitigation. From the Heat Map we can see that Handling Discs should be our greatest priority as it is closest to the red-zone with a risk score of 8. Following that we should prioritize Placing Discs. Placing Discs still falls close to the red-zone of the Heat map but has a risk score of 6. Rotating Crank is the next most critical issue, with a risk score of 4. Mild risks Include Weaving strings and Moving Strings, with a risk score of 2 and 1 respectively. These risks are small and should be of minimal priority.

7.3 DESIGN FOR MANUFACTURING

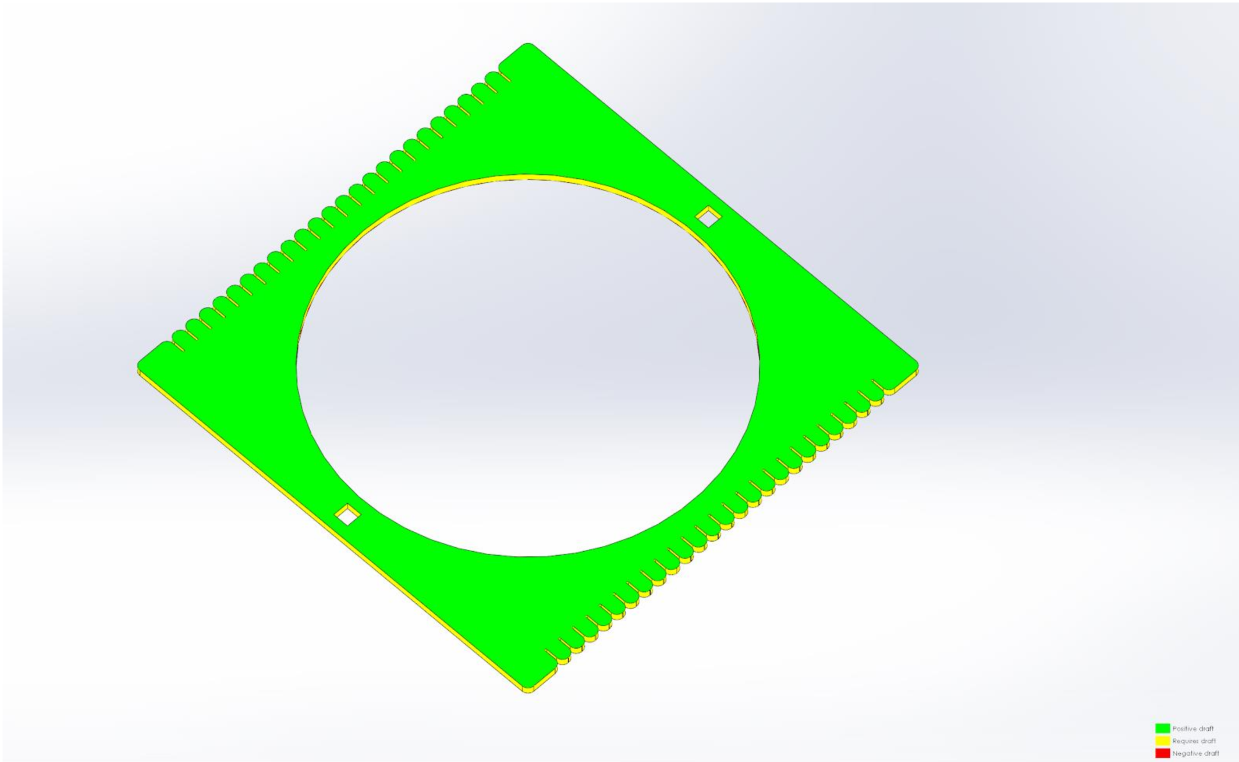


Figure 33: Disk Design Draft Analysis Before Modification

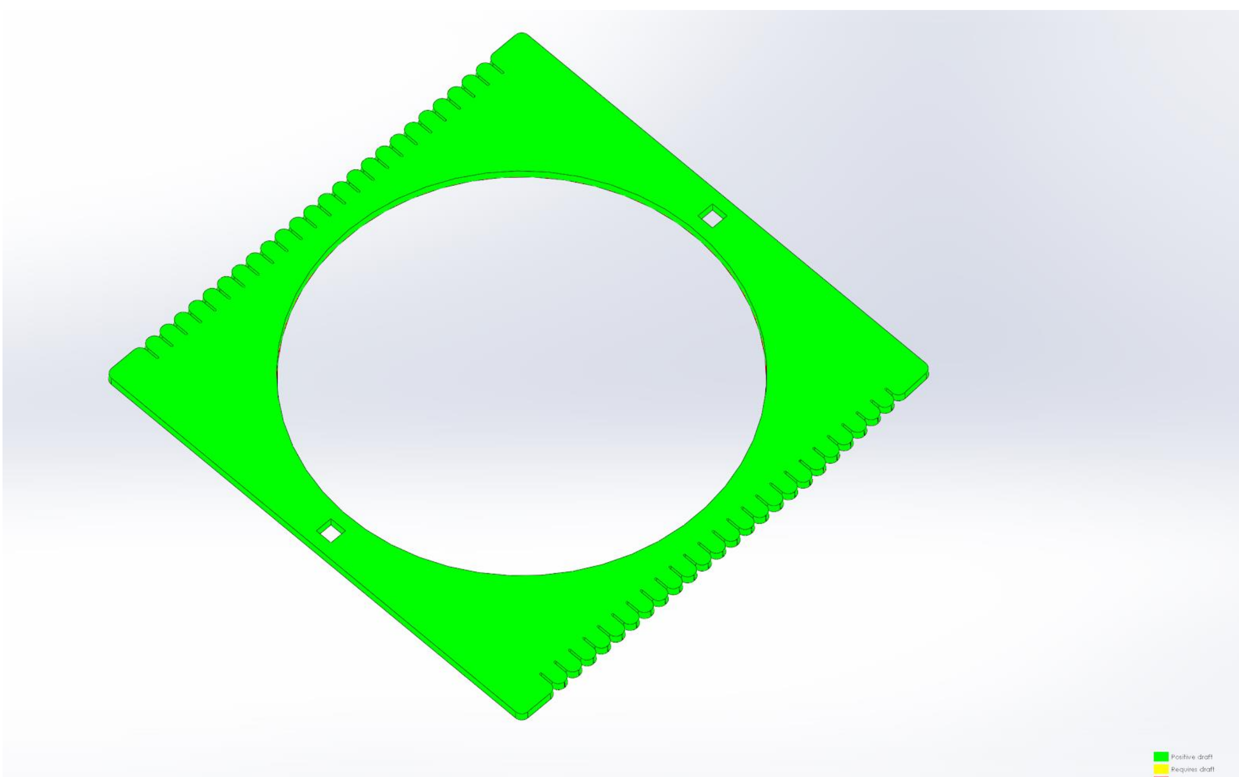


Figure 34: Disk Design Draft Analysis After Modification

To satisfy the draft analysis, the draft tool was used on the part. The top face was selected as the "direction of pull" and the vertical yellow faces that required a draft were selected to be pulled in that direction. As a result, the faces that required a draft now have a 3-degree draft, thus satisfying the analysis.

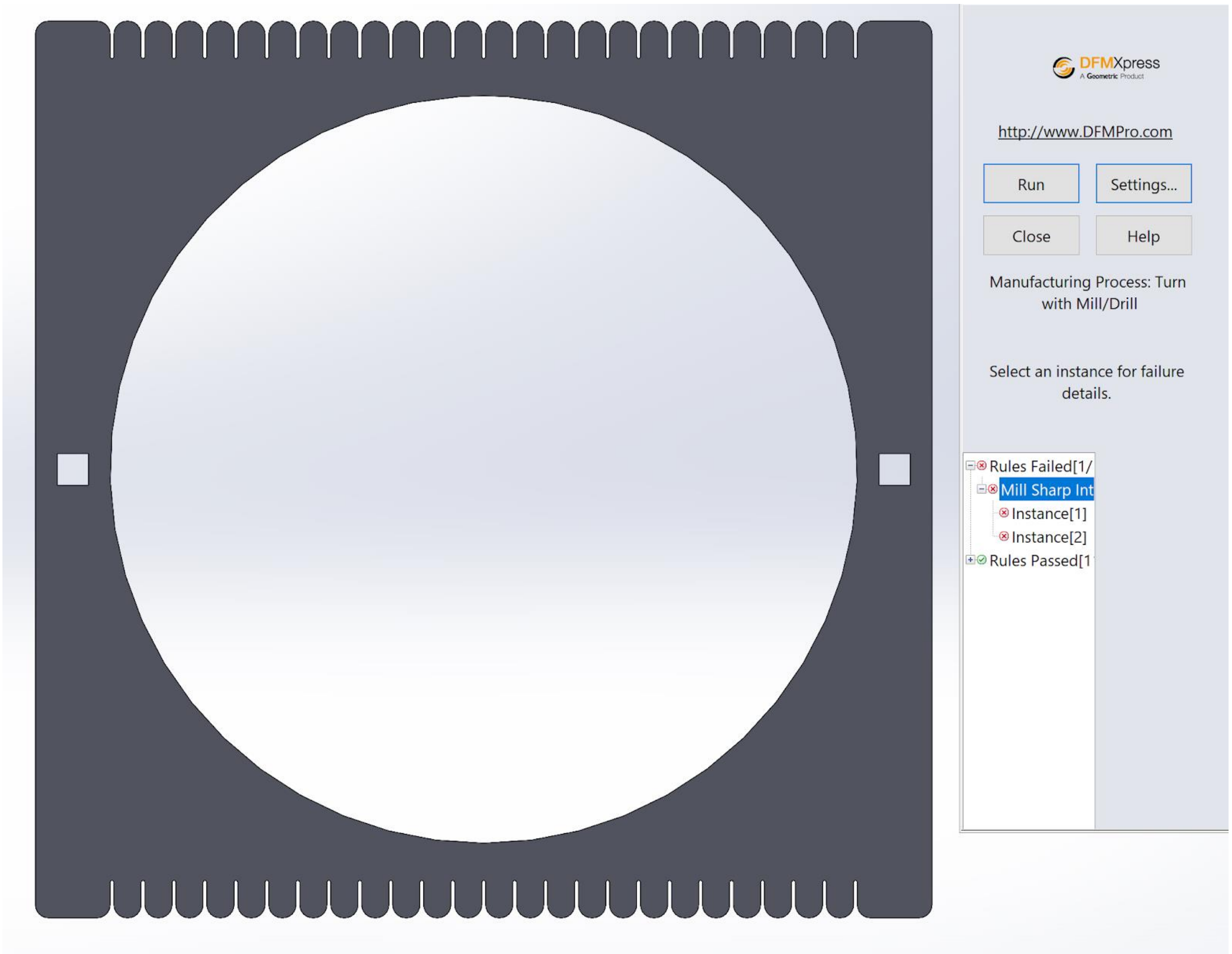


Figure 35: Analysis of Manufacturing Process: Turn with Mill/Drill

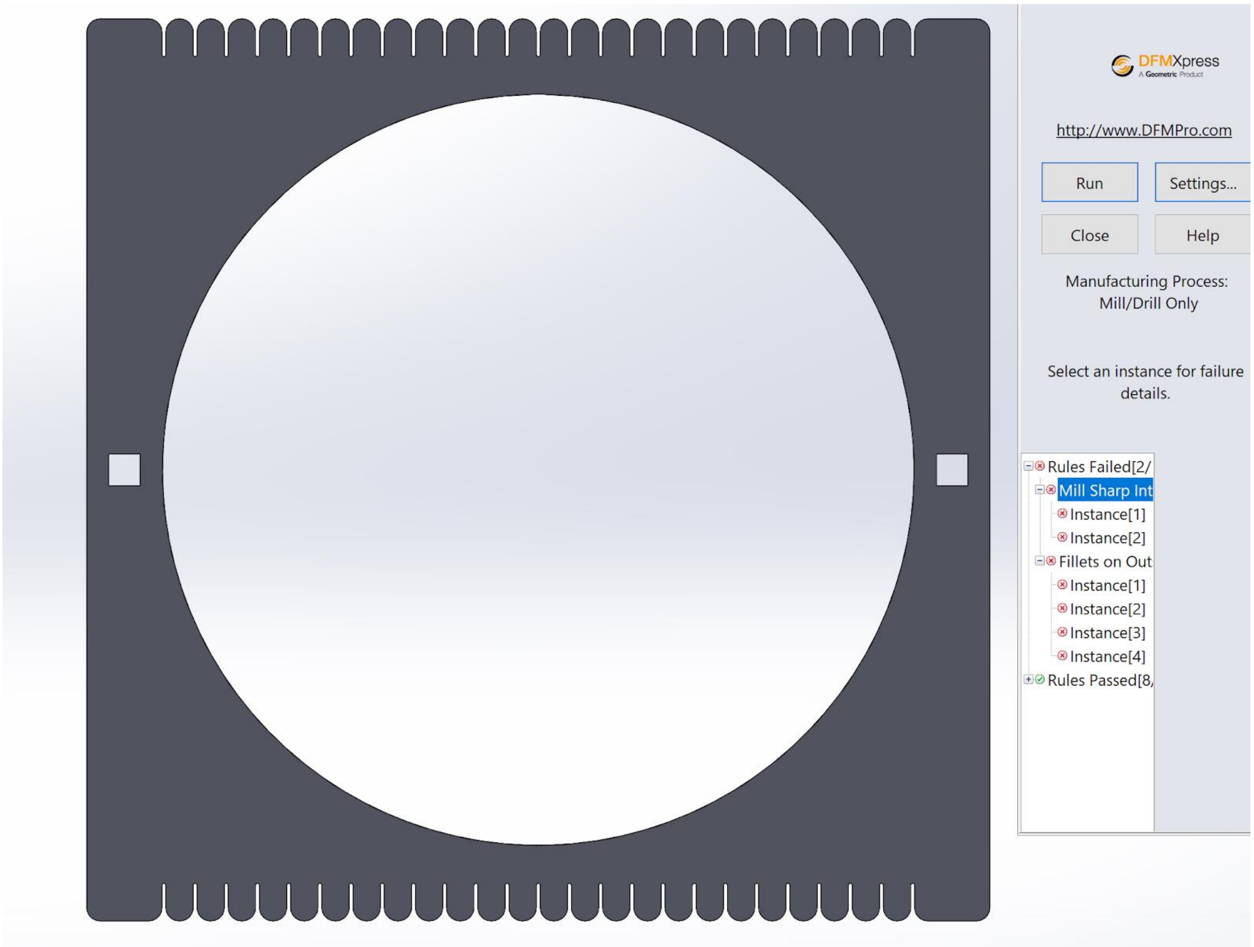


Figure 36: Analysis of Manufacturing Process: Mill/Drill Only

From the DFM Analysis, errors are expected to arise relating to milling/drilling with the part. These errors are mostly due to the small geometries of the part. A laser cutter is the optimal machining method for the part. Due to unexpected circumstances, 3D printing is being explored as an alternative. For reference, the diameter of the circular hole is 50 mm.

7.4 DESIGN FOR USABILITY

1. Vision impairment: Red-green color blindness should not be an issue because our design is all 3-D printed in the same orange color. If you had near-sightedness or far sightedness you could have trouble using the device because the thread, we are using is very small and thin. This could become a problem when setting up the spools and making sure all the threads are staying in the cutouts.

2. Hearing impairment: Hearing impairment will not be a big problem with our device. Our parts, including the lever arm, do not make any important or concerning noises. The only potential problem we see is that hearing the very minor sounds of pieces stacking on each successfully and the thread being placed in the cutouts help the operator know that everything is working without looking closely. To fix this the operator would need to make sure to visually check that everything is in the right spot.

3. Physical impairment: Having physical issues especially with your hands/arms could become an issue when using this device. It is essential to be able to move the lever back forth to thread the pieces. This act does not require a lot of strength but could be hard for a person to repeat over and over with arthritis in his or her hand.

4. Language impairment: Language issues should not present themselves as problems with this project because the instructions we make for the user will be primarily composed of diagrams and pictures with some words to support the diagrams. Basic reading skills would be an additional benefit for understanding, as well as an understanding of technical vocabulary. For the intended users, lab technicians, this should be of minimal concern unless the technology is deployed elsewhere.

5. Control impairment: Problems with control could be a potential issue because moving the lever arm back and forth requires a steady hand. If not, the threads will not be pulled tight and may not be placed in the right spots. Another issue with control could occur when setting up the device. The dimensions are very small and tight so, when setting up the spools on the supports, a person needs to have a decently steady hand.

8 DISCUSSION

8.1 PROJECT DEVELOPMENT AND EVOLUTION

8.1.1 Does the final project result align with its initial project description?

The overarching concept of the final design is in alignment with the initial project description. Aspects of the design have changed due to material and manufacturing limitations. The absence of laser cutting prevented the goal of a dense fiber spacing from being achieved. 3D printing has allowed for the implementation of the initial concept at a lower resolution. Testing 3D printed prototype components, we shifted some design criteria to match our capabilities. Despite this, the method of weaving has evolved and an improved method to handle threads have been generated. The robust manufacturing process that can generate reliable, consistent samples has been achieved.

8.1.2 Was the project more or less difficult than expected?

The project proved to be more difficult than anticipated. As a team we did not expect achieving a dense mesh of fibers to be too difficult. Our initial ideas involving laser cutting were not possible as the laser cutter we had access to in the art school suffered an unexpected accident. 3D printing was the only in-budget option and was not have a high enough resolution to allow for an optimal fiber density. Additionally, tolerancing proved to be problematic as 3D printing does not reflect the exact geometry of the 3D model. Also, tolerancing using 3D printing can have different results between prints even when using the same model. This inconsistency did not allow our clamp to apply even pressure across all strings. Overall, getting everything to work was far more challenging and time-consuming than expected.

8.1.3 On which part(s) of the design process should your group have spent more time? Which parts required less time?

Our group should have spent more time on the early stages of design; more specifically, the mockup prototype phase. The initial mockup we developed was not completely thought out. Considerations for fiber loading and matrix gel insertion were not considered. We essentially pivoted to a new design approximately halfway into the semester. Had more time been spent making a very deliberate mockup, time spent later in the design could have been saved. This would foster a more functional final design in a shorter time. Design refinement took the least amount of time. The group tackled this task together over the course of a week. In reality, this could have been executed in a few days.

8.1.4 Was there a component of the prototype that was significantly easier or harder to make/assemble than expected?

Our groups should have spent more time developing the clamp mechanism and its corresponding jaws. A lot of time was spent working with various disk designs and when time came to make the clamp, a functioning design was not prepared. We initially planned to use laser cutting to cut the majority of the clamping assembly, jaws included. When the laser cutter was taken offline our group had to adjust and machine the clamp. Many hours were spent in the machine shop milling the components of the clamp, drilling and tapping holes. Many more hours were spent 3D printing jaws that are compatible with the remaining clamp assembly. It took trial and error to find jaw dimensions that fit within the clamp channels considering the variation between SolidWorks and actual 3D printed geometry. By the time the clamp housing was machined the prototype needed to be finished within a week; this did not allow us to refine the clamp assembly. Components like the clamp arm did not take nearly as much time as anticipated. Initially, the arms were going to be bent from stainless steel rods. This concept was abandoned and replaced by 3D printed components. The parts only took minutes to print and could easily be adjusted and re-printed.

8.1.5 In hindsight, was there another design concept that might have been more successful than the chosen concept?

Looking over our other design concepts, the design we selected would have been the most successful. Other concepts shared a similar idea but using the crank and stack method is the fastest, simplest, and most reliable method of the lot. Methods using DC motors and programmed movements would add more complexity and cost. Using human power paired with the crank and stack design is also far more intuitive to users. A more complex design would take too much time to create and prototype. Also, a limited budget would make it difficult to purchase motors and corresponding hardware. Given our constraints, the design we selected is the optimal choice.

8.2 DESIGN RESOURCES

8.2.1 How did your group decide which codes and standards were most relevant? Did they influence your design concepts?

The two standards chosen were the ISO standard for atmospheres for conditioning and/or testing as well as the banned hazardous substances code from the Electronic Code of Federal Regulations. When choosing standards/codes to use, consideration was given to the fact that our device had medical applications. Because it was not to be used directly on patients, we instead focused on the safety of the lab user. For this reason, the banned hazardous substances code provided insight as to what materials we would use. Similarly, the design concepts were inspired by the necessity to undergo multiple trials of our product process. Having a standard atmosphere code allowed for creating a consistent environment and developing a product that could withstand multiple locations.

8.2.2 Was your group missing any critical information when it generated and evaluated concepts?

During initial concept generation information relating to the materials and equipment was missing. The initial design called for a 1 mm x 1 mm density of Lycra. The diameter and material behavior of Lycra were unknown during initial concept generation. Cost and availability of machinery that is capable of creating a disk with this thread spacing was also unknown. If we knew we would not have access to laser cutting services we would have taken a different initial approach regarding thread type and density. The diameter of Lycra is simply too small to be passed through and clamped in 3D printed grooves.

8.2.3 Were there additional engineering analyses that could have helped guide your design?

Conducting a motion study in SolidWorks and checking for interference would have proven useful. Our early prototypes encountered interference when rotating from one side of the device to the other. The top of the clamp was also initially too close to the spools for the user to fully rotate the device. Performing an interference analysis would have saved us hours assembling and testing prototypes that do not function. Additional finite element analysis would have been useful on the disks. The deflection on the disk is sizeable when the strings pull up on the disk. FEA would show this deflection, allowing us to modify the thickness or material to mitigate the large deflection.

8.2.4 If you were able to redo the course, what would you have done differently the second time around?

If we were to redo the course, we would spend more time working on the project earlier in the semester. The initial pace of the project was fairly slow. By the time performance goals needed to be complete our prototype was in its infancy. Spending more time in the earlier part of the year working on mockups and prototype models would allow more time to improve the design. Had we started earlier we may have been able to cut parts before the laser cutter was decommissioned. Essentially, working at a quicker pace would have allowed us to achieve more, avoid pitfalls, and create a better end product.

8.2.5 Given more time and money, what upgrades could be made to the working prototype?

The key issue our group encountered was achieving an extremely dense fiber network. Ideally, we would have a 0.1 mm diameter thread of fiber 1 mm away from the next. To accomplish this extremely precise micromachining is required. If our budget was increased, we would pay a local micromachining company to fabricate plates with a 1 mm density and a corresponding clamp assembly. All 3D printed parts would be machined for higher precision and strength. Given more time, methods of securing the fiber to the base would be explored. The 3D printed clamp would be modified to include a rubber upper jaw. This would hopefully allow a tight interference fit, preventing fibers from slipping out.

8.3 TEAM ORGANIZTION

8.3.1 Were team members' skills complementary? Are there additional skills that would have benefitted this project?

Our team was very well rounded, all members were versed in the practice of generating concept sketches. Some members had CAD experience and provided the majority of 3D modelling and finite element analysis. Other members were skilled in the machining and assembling components. These group members did the majority of the fabrication and assembly. All members have taken courses like composites, providing helpful knowledge in generating engineering models. These models were used when making design considerations, especially regarding fiber spacing and material selection. Nobody on the team was familiar with welding, this skill could have aided the design process when generating clamp arms.

8.3.2 Does this design experience inspire your group to attempt other design projects? If so, what type of projects?

Completing senior design has made many of us realize what we are capable of designing and building. Going through the design process creates a sense of pride and accomplishment. For some of us, this translates into motivation for other design projects. Jake will continue to improve this design for his research with Dr. Bayly. Some of the group is also involved various startups in the area. Concepts and advice from the course will undoubtedly be beneficial and contribute to the success of those endeavors.

APPENDIX A – COST ACCOUNTING WORKSHEET

Table 9: Cost Sheet

	Part	Source Link	Supplier Part Number	Color, TPI, other part IDs	Unit price	Quantity	Total price
1	Pine Plywood	Lowe's	Model: 199342	Item: 7701 Pine 2x2	$5.23	1	$5.23
2	Acrylic Sheet	Lowe's	Model: 11G0830A	Item: 11230 Clear OPTIX 0.08in x 28in x 30in	$18.01	1	$18.01
3	Springs	McMaster-Carr	9434K12	Steel, 5 pack 0.25" Long, 0.12" OD, 0.088" ID	$4.85	1	$4.85
4	Machine Key	McMaster-Carr	92288A710	Steel, 2x2mm, 12" Long	$1.93	1	$1.93
5	Stainless Steel Screw	McMaster-Carr	91771A110	18-8 Strainless Steel Phillips Flat Head	$4.61	1	$4.61
Total:							$34.63

APPENDIX B – FINAL DESIGN DOCUMENTATION

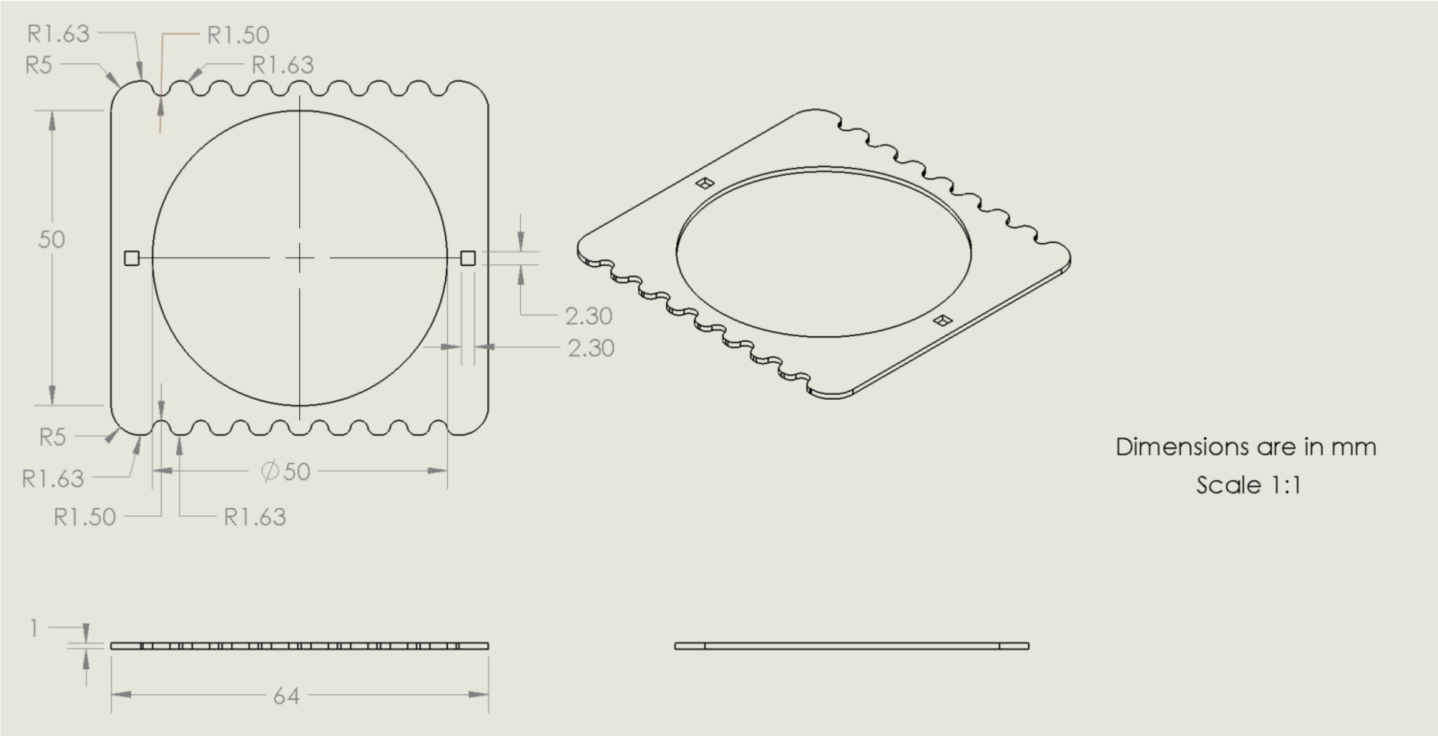


Figure 37: Pronged Filleted Square Disk

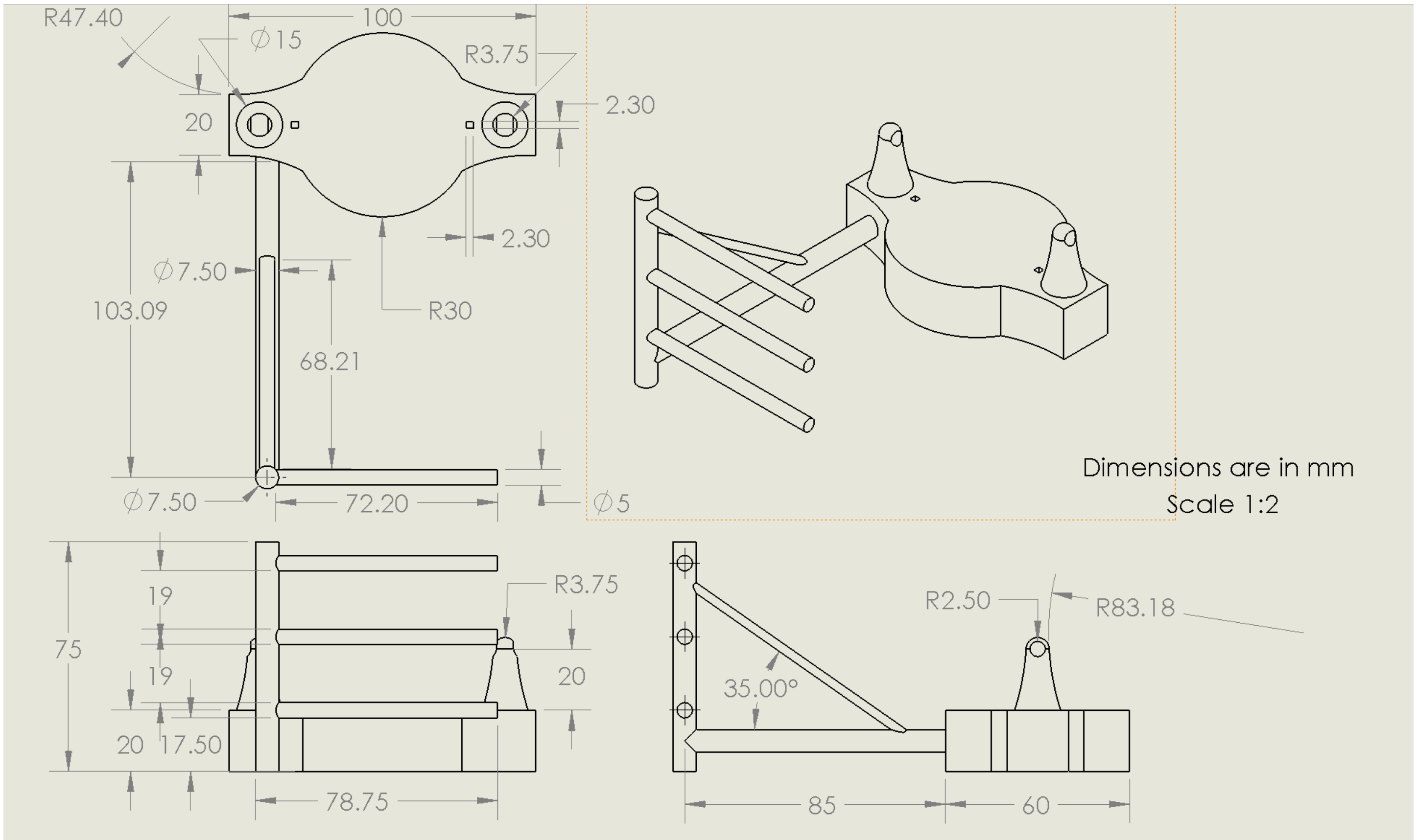


Figure 38: Base and spool rack

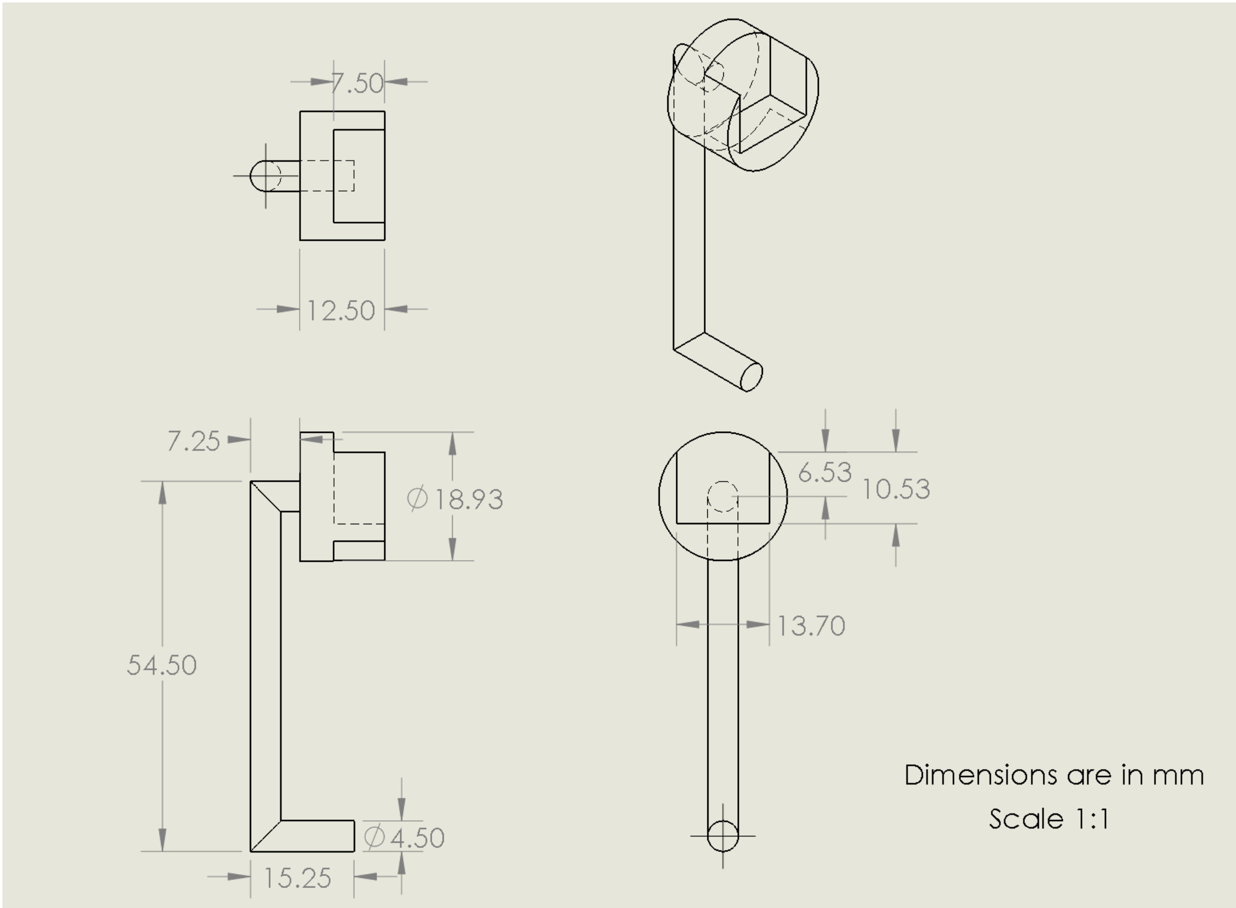


Figure 39: Clamp arm

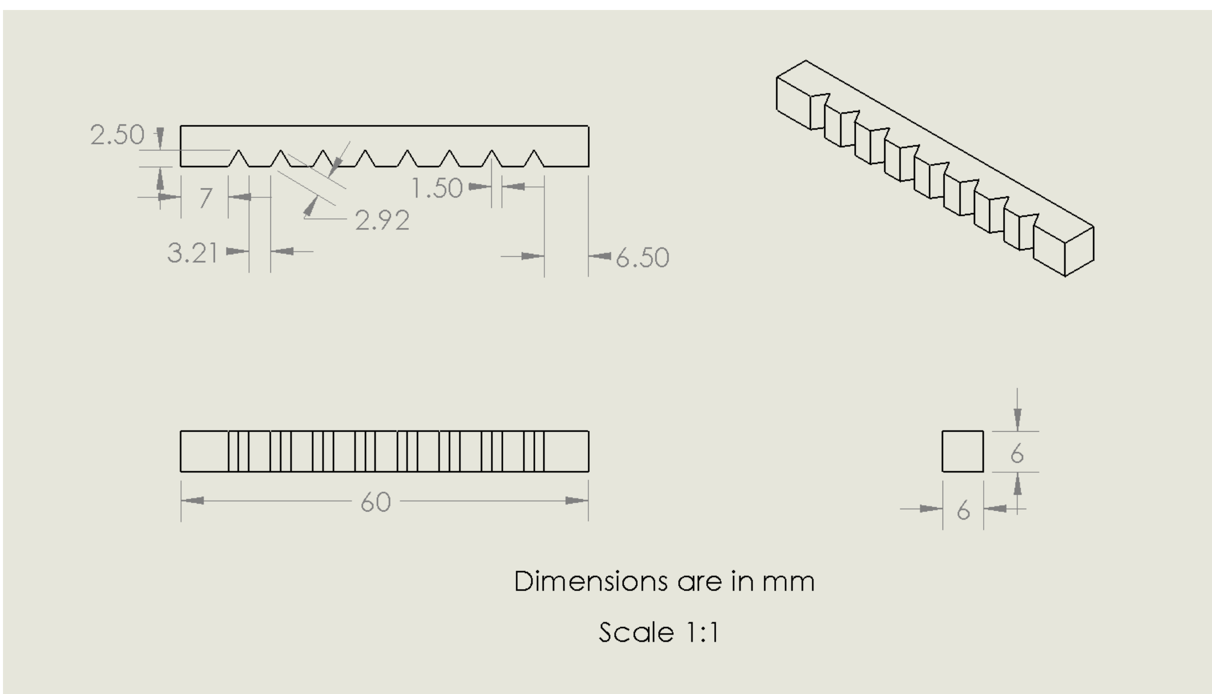


Figure 40: Comb

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