Fall 2022

MEMS 411 - Prosthetic Arm Group W

Spencer Gladstone
Washington University in St. Louis

Lila Dickstein
Washington University in St. Louis

Nate Bloedorn
Washington University in St. Louis

Matthew Riak
Washington University in St. Louis

Washington University in St. Louis
James McKelvey School of Engineering

Mechanical Engineering Design Project
MEMS 411, Fall 2022

Prosthetic Arm Project

The customer, Ilana, sought to find a prosthetic arm to replace her current static prosthetic. She has gotten used to using a prosthetic with no variable grips and a somewhat heavy weight that can be a burden when dealing with her child or day to day tasks. The design described in this report is an electronically powered prosthetic that used a button to change between open and closed grips.
When creating this new prosthetic arm, three goals were kept in mind: be able to support a water bottle, hold a moment about Ilana's elbow while also weighing approximately less than her current prosthetic , and lift a 5 pound weight. A servo and Arduino embedded in the device serve to accomplish the two goals that were tasks while also keeping the weight low with a hollow 3d printed shell.
The design made major changes from protoype to final product. The initial design was completely mechanical with no electronic components and the final used only mechanical components to reduce the chance of individual parts breaking and the arm failing structurally. Certain changes in the design along the way made major steps towards reducing weight and having set grips, but others led to complications and unforeseen failures in the electrical components. Overall, the report below shows the progression of our design and the logic behind major design decisions made along the way.

Riak, Matthew
Bloedorn, Nate
Dickstein, Lila
Gladstone, Spencer

Contents

List of Figures **1**

List of Tables **2**

1 Introduction **3**

2 Problem Understanding **3**
- 2.1 Existing Devices . . . 3
- 2.2 Patents . . . 7
- 2.3 Codes & Standards . . . 10
- 2.4 User Needs . . . 11
- 2.5 Design Metrics . . . 12
- 2.6 Project Management . . . 12

3 Concept Generation **14**
- 3.1 Mockup Prototype . . . 14
- 3.2 Functional Decomposition . . . 16
- 3.3 Morphological Chart . . . 18
- 3.4 Alternative Design Concepts . . . 19

4 Concept Selection **23**
- 4.1 Selection Criteria . . . 23
- 4.2 Concept Evaluation . . . 23
- 4.3 Evaluation Results . . . 23
- 4.4 Engineering Models/Relationships . . . 24

5 Concept Embodiment **27**
- 5.1 Initial Embodiment . . . 27
- 5.2 Proofs-of-Concept . . . 31
- 5.3 Design Changes . . . 31

6 Design Refinement **31**
- 6.1 Model-Based Design Decisions . . . 31
- 6.2 Design for Saftey . . . 31
- 6.3 Design for Manufacturing . . . 33
- 6.4 Design for Usability . . . 35

7 Final Prototype **35**
- 7.1 Overview . . . 36
- 7.2 Overview . . . 37

List of Figures

1 The Hero Arm (Source: Hero Arm Website) . . . 4

2 Unger Professional (Source: Amazon) 5
3 Hydraulic Arm Kit 6
4 Patent Image for Mechanical Prosthetic Hand 7
5 Patent Images for expansible shaft 8
6 Patent Image for Moveable and Adjustable Prosthetic Fingers 9
7 Patent Image for Lockable Prosthetic Fingers 10
8 Gantt chart for design project 13
9 Mockup Prototype 14
10 Mockup Prototype connection mechanism 15
11 Mockup Prototype with string controlled fingers in a closed grip 16
12 Function tree for Useless Box, hand-drawn and scanned 17
13 Morphological Chart for Useless Box 18
14 Lila's Sketches of Robotic Arm concept for Manual Grip Arm Design 19
15 Matthew's Sketches of Robotic Arm concept for hydraulic design 20
16 Spencer's Sketches of Robotic Arm concept for Rope Motor Design 21
17 Nate's sketches of a prosthetic arm concept that has manually adjustable fingers . . 22
18 Analytic Hierarchy Process (AHP) to determine scoring matrix weights 23
19 Weighted Scoring Matrix (WSM) for choosing between alternative concepts 23
20 Engineering model for hand operated by ropes and a motor 25
21 Engineering model based on frictional force 26
22 Engineering model based on gear ratios 27
23 Assembled projected views with overall dimensions 28
24 Assembled isometric view 29
25 Exploded view with callout to BOM 30
26 Heat Map for risks 33
27 Theoretically Necessary Part Analysis 34
28 Final Prototype 36
29 Inside of Final Prototype 37

List of Tables

1 Interpreted Customer Needs 12
2 Target Specifications 12

1 Introduction

This paper describes the design process for a prosthetic arm. It explains the initial concept based upon user needs and target specifications that were identified through a customer interview and research of existing standards and products. It will then walk through the concept development process, starting with concept brainstorming and prototyping, to concept selection, through concept embodiment. Then it will explain the refinement of this product, ultimately landing on the final prototype of the prosthetic arm.

This prosthetic arm is being built for a customer, Ilana, who is a mother of two young children and a teacher. She was born with a limb deficiency, and has lived her whole life with a passive prosthetic for one of her forearms. Since this provides limited functionality, her other hand experiences extra stress since it's compensating for the lack of movement in the other arm. This prosthetic arm was designed with finger and wrist movement so that it can perform key everyday functions, with the goal of alleviating some of that stress in Ilana's other hand.

2 Problem Understanding

2.1 Existing Devices

Provided below are existing prosthetics that have similar specifications to that of our desired product, except are not personalized to our customer. Their various differences and scopes will be helpful in narrowing down the focus of our individual product.

2.1.1 Existing Device #1: The Hero Arm

Figure 1: The Hero Arm (Source: Hero Arm Website)

Link: https://openbionics.com/hero-arm/
Description: The Hero Arm as an innovative and affordable multi-grip prosthetic arm. Its custom lightweight material combined with wide range of grip settings aims to support and empower those with limb deficiencies. The company uses a 3D scan of the customer's stump and (if available) their other arm in order to create a personalized product. The arms have an intentionally futuristic look as seen in the figure above.

2.1.2 Existing Device #2: Unger Professional 36" Nifty Nabber Reacher Grabber Tool and Trash Picker

Figure 2: Unger Professional (Source: Amazon)

Link: https://www.amazon.com/Unger-Professional-Nifty-Nabber-36/dp/B0000V0AGS/ref=asc_df_B0000V0AGS/?tag=hyprod-20&linkCode=df0&hvadid=198069016725&hvpos=&hvnetw=g&hvrand=14705277857551132581&hvpone=&hvptwo=&hvqmt=&hvdev=c&hvdvcmdl=&hvlocint=&hvlocphy=9022860&hvtargid=pla-338189049106&th=1.

Description: This grabber from Amazon consists of a 36 inch aluminum pole with a lever mechanism on the handle end and a grabbing mechanism on the opposite end. The lever contraction prompts the jaws of the grabber to close. The jaws are lined with a rubber coat for better grip and contain a magnet for picking up small metal items.

2.1.3 Existing Device #3: Hydraulic Arm kit

The following shows a hydraulic arm kit which uses water and pistons to push water through tubes and make the fingers curl and expand. This could be very useful when designing the mechanism for how to grip something, but needs to be altered so it can be attached to a human.

2.1.4 Existing Device #3: Hydraulic Arm

Figure 3: Hydraulic Arm Kit

Link: https://patents.google.com/patent/US20170266020A1/en

2.2 Patents

2.2.1 Mechanical Prosthetic Hand (US20170266020A1)

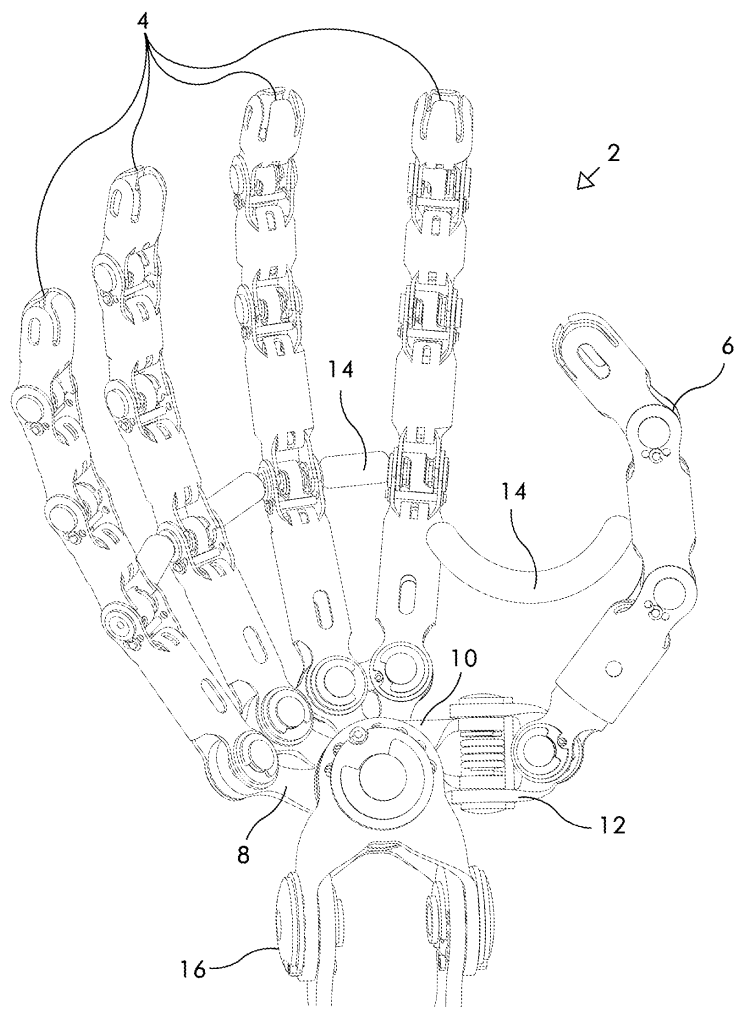


Figure 4: Patent Image for Mechanical Prosthetic Hand

This patent is an intricate body-powered prosthetic hand. The sizing of each feature is adjustable meaning it can be properly proportioned based on the user. Almost every feature of this creation is thought out because of the various obstacles it faces. It is crushable due to its flexibility, it has hollow components to reduce its weight, and has fingers that are controlled with cabled mechanisms with voluntary open or voluntary closed modes. This serves as an advanced example of the goals our customer's future prosthetic arm's hand.

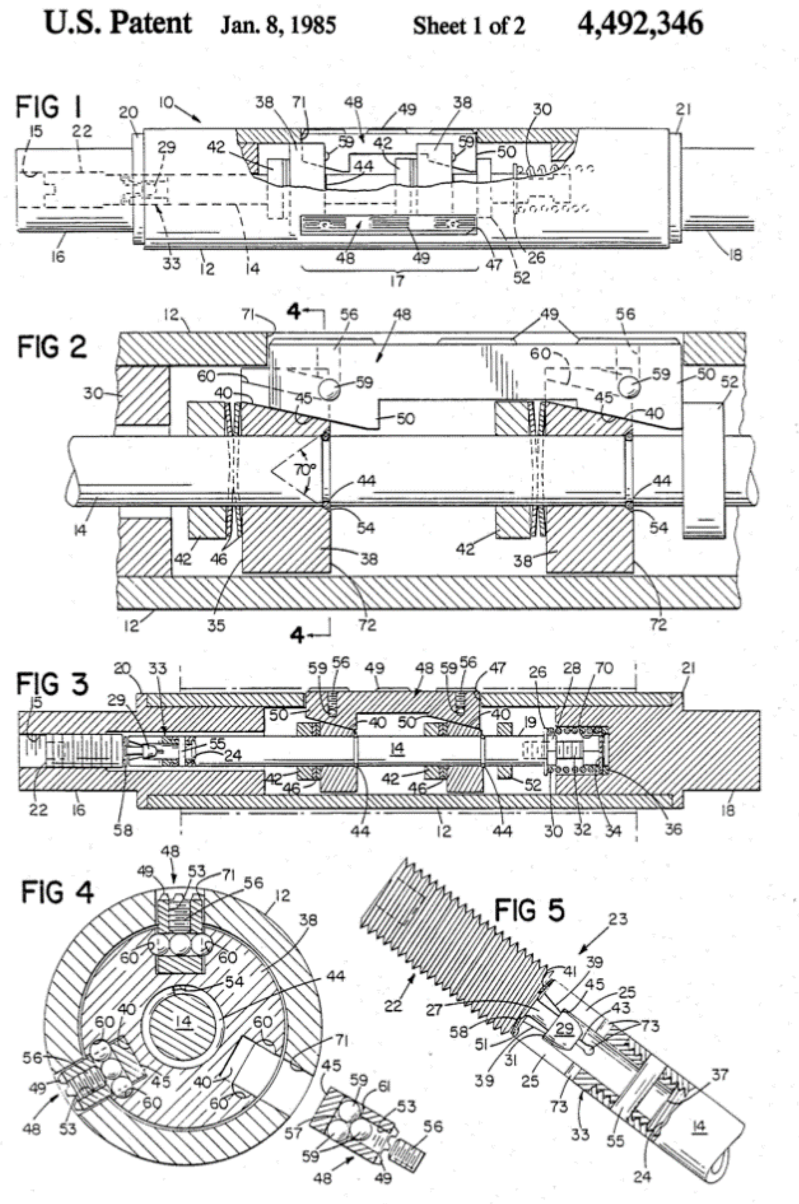


Figure 5: Patent Images for expansible shaft

2.2.2 Patent 2

2.2.3 Lockable Finger System and Related Methods (US11246721B2)

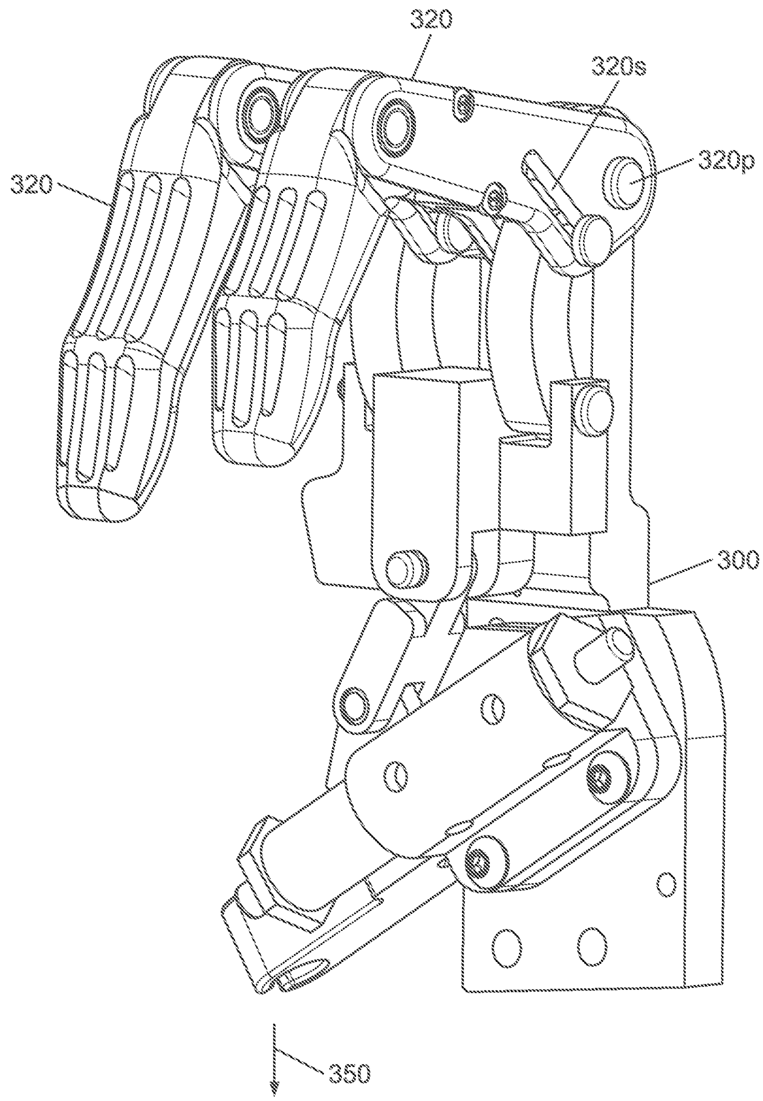


Figure 6: Patent Image for Moveable and Adjustable Prosthetic Fingers

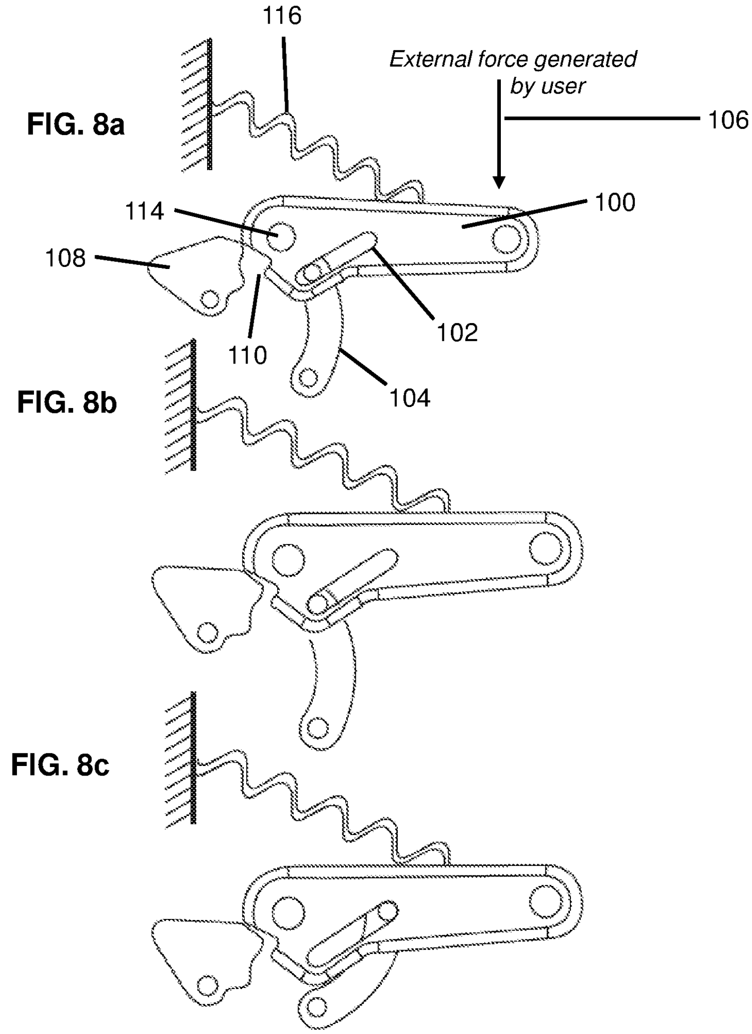


Figure 7: Patent Image for Lockable Prosthetic Fingers

This patent focuses on the locking mechanism for prosthetic fingers. The locking mechanism consists of a linkage that can be positioned through the phalanges to suppress movement. In our design, the most important aspect is manipulating the hand and fingers into the positions that the customer wants. This goes hand in hand with also being able to lock the fingers in that position while the customer performs tasks.

2.3 Codes & Standards

2.3.1 Standard for Prosthetics and Orthotics (ISO 13405-03)

This standard for prosthetics and orthotics classifies and describes upper limb prosthetic components. This standard was created with the purpose of "systematically describing each component which is incorporated in a finished prosthetic". As we plan to make an arm (upper body) that has moving fingers/knuckles, this is a fitting standard for our purposes.

2.3.2 External limb prostheses and external orthoses — Requirements and test methods (ISO 22523:2006)

This standard covers the general principles of prosthetics. It defines the industry standard terms and definitions. The most important aspects of this standard as it pertains to our design is the restrictions on materials in regards to both strength and flammability/toxicity. It provides standards on what adhesives and methods of connecting pieces are safe to use and will influence what materials are used and how they are connected in our design.

2.4 User Needs

The following section depicts the user needs for Ilana based on an interview we conducted. Detailed tables are shown with needs.

2.4.1 Customer Interview

Interviewee: Ilana
Location: Zoom.us
Date: September 9^{th}, 2022
Setting: The interview was conducted on zoom. Students were able to ask Ilana questions about the project, along with her experiences. The interview was about 30 minutes.

Interview Notes:
Will you be wearing the arm all day?

- Takes arm off at night, does not wear during shower.

Does the weight matter?

- Yes, I tried a robotic prosthetic arm that was 4-5 pounds, and found it to be too heavy. 2-3 pounds is much better.

Do you like how your arm attaches to the sleeve right now?

- Yes, if it could attach the same way, it be nice.

Do you care about the appearance of the arm?

- Yes, I would prefer if it looks like a real arm. This can be done by having a glove fitted over the prosthetic that looks more like skin and matches my skin color.

Can you provide examples of actions that you would like the prosthetic to be able to perform?

- Everyday actions that are involved with being a parent and teacher. For example: pushing a stroller, grasping a water bottle, and unbuckling a child's car seat.

2.4.2 Interpreted User Needs

The following section includes the necessary attributes of the prosthetic arm based on the interview we conducted with Ilana.

Table 1: Interpreted Customer Needs

Need Number	Need	Importance
1	The prosthetic arm is lightweight	5
2	The prosthetic arm looks like a real arm	4
3	The prosthetic arm has easily implemented grasping/pushing abilities	5
4	The prosthetic arm is easy to clean	2
5	The prosthetic arm is compatible with the current sleeve attachment mechanism	3
6	The prosthetic arm is easy to attach and detach from the sleeve	4

Based on the interview conducted with Ilana, we concluded that the two most important needs for the prosthetic arm are the weight of the arm and its functionality for performing simple tasks such as pushing a stroller, unlocking a car seat, and holding a water bottle.

2.5 Design Metrics

The following section describes a more specific table of needs with target specifications. Each need has associated an associated ideal value, along with units. Note that some of the metrics are not left as N/A because we need to measure the arm she is sending in.

Table 2: Target Specifications

Metric Number	Associated Needs	Metric	Units	Acceptable	Ideal
1	1	Total weight	lb	3	2-3
2	5	Wrist diameter	in^3	TBD	TBD
3	5	Base Diameter	mm	TBD	TBD
4	3	Number of settings	N/A	3	∞
5	3	Grasp diameter range	in	1-3	0.25-4
6	3	Grasp strength	lb	2	3
7	6	Ease to remove device	integer scale	3-4	5
8	4	Ease to clean device	clean time (min)	7-10	2-5

2.6 Project Management

The Gantt chart in Figure 8 gives an overview of the project schedule.

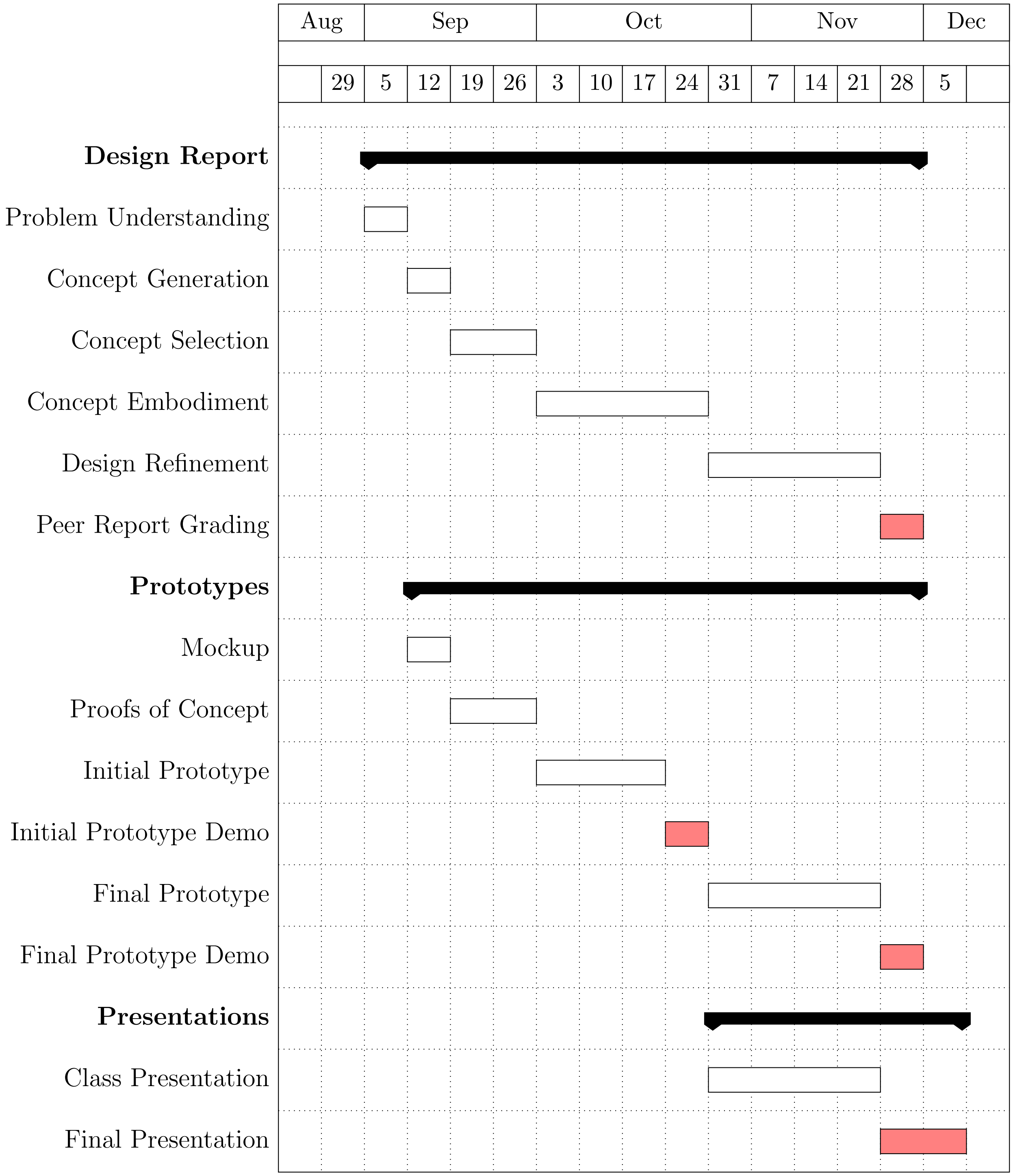


Figure 8: Gantt chart for design project

3 Concept Generation

3.1 Mockup Prototype

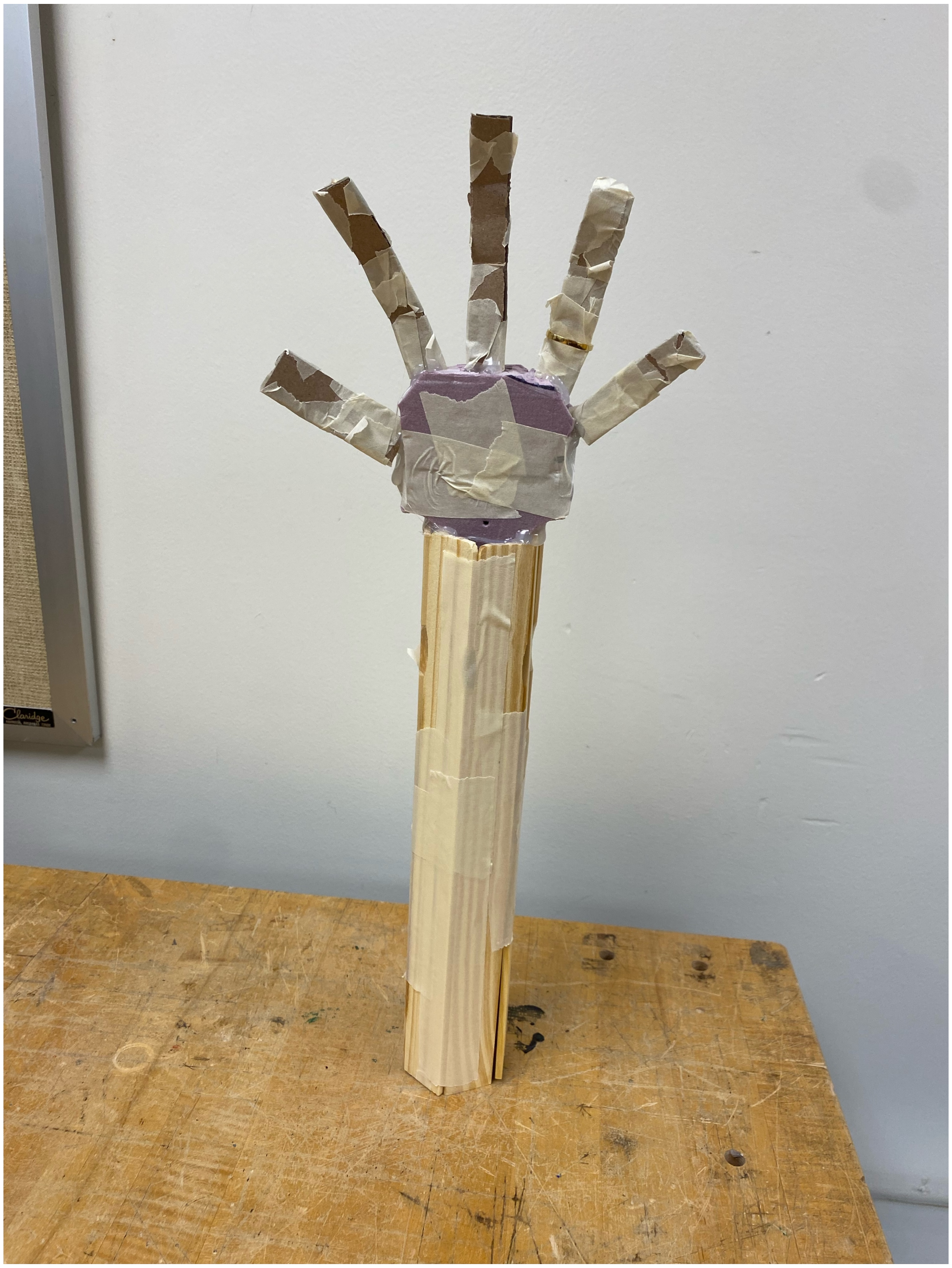


Figure 9: Mockup Prototype

Figure 10: Mockup Prototype connection mechanism

Figure 11: Mockup Prototype with string controlled fingers in a closed grip

When designing our mockup prototype we began with getting a generic arm shape by connecting paint stir sticks in a hollow rough circle. We found that the hollow design works well to help reduce weight while still providing the structure and support we are looking for. The hollow arm also allows for room inside the prosthetic to conceal any added mechanisms. The connection to the customer's existing arm sleeve can be seen in figure 10. The pin will slide and hook into the small hole that can be seen. While constructing the fingers, we found that multiple joints allow for more natural grasping movements and make the hand more aesthetically pleasing which is important to the customer. Figure 11 shows the mechanism we implemented to close the fingers by using strings run along the forearm connected to the fingertips. After constructing this mockup, we found it would be best to start the hand in a closed position and run the strings along the backside of the fingers so they can stay flush to the arm. We found the string mechanism to work well and in the future will add tension in the fingers to start them in a closed position and run the strings along the top side of the arm.

3.2 Functional Decomposition

The function tree address the products overall function by sub-dividing it into sub-functions. These sub-functions are determined mainly by using the user needs and building upon each previous one. The graphics give a visual of what each sub-function contributes to the prosthetic.

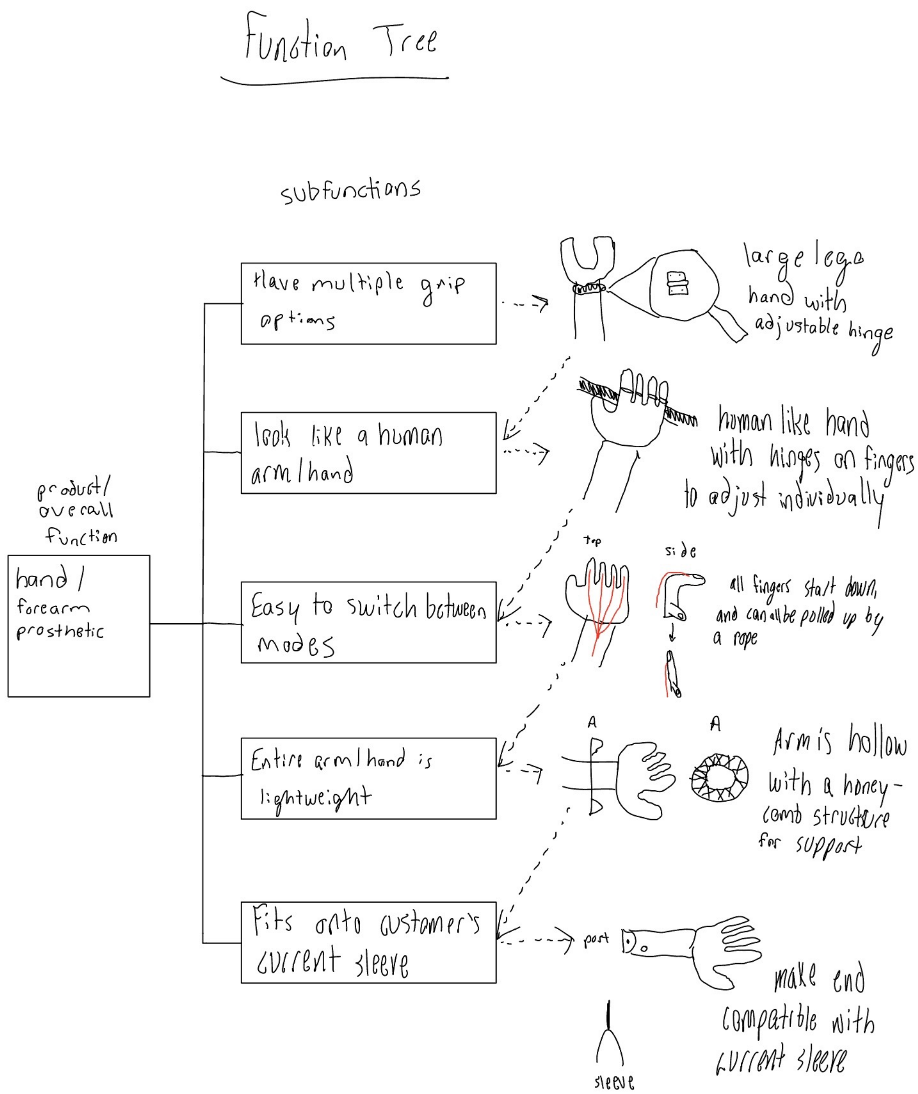


Figure 12: Function tree for Useless Box, hand-drawn and scanned

3.3 Morphological Chart

The morph chart below shows subfunctions from the function tree with pictures demonstrating each.

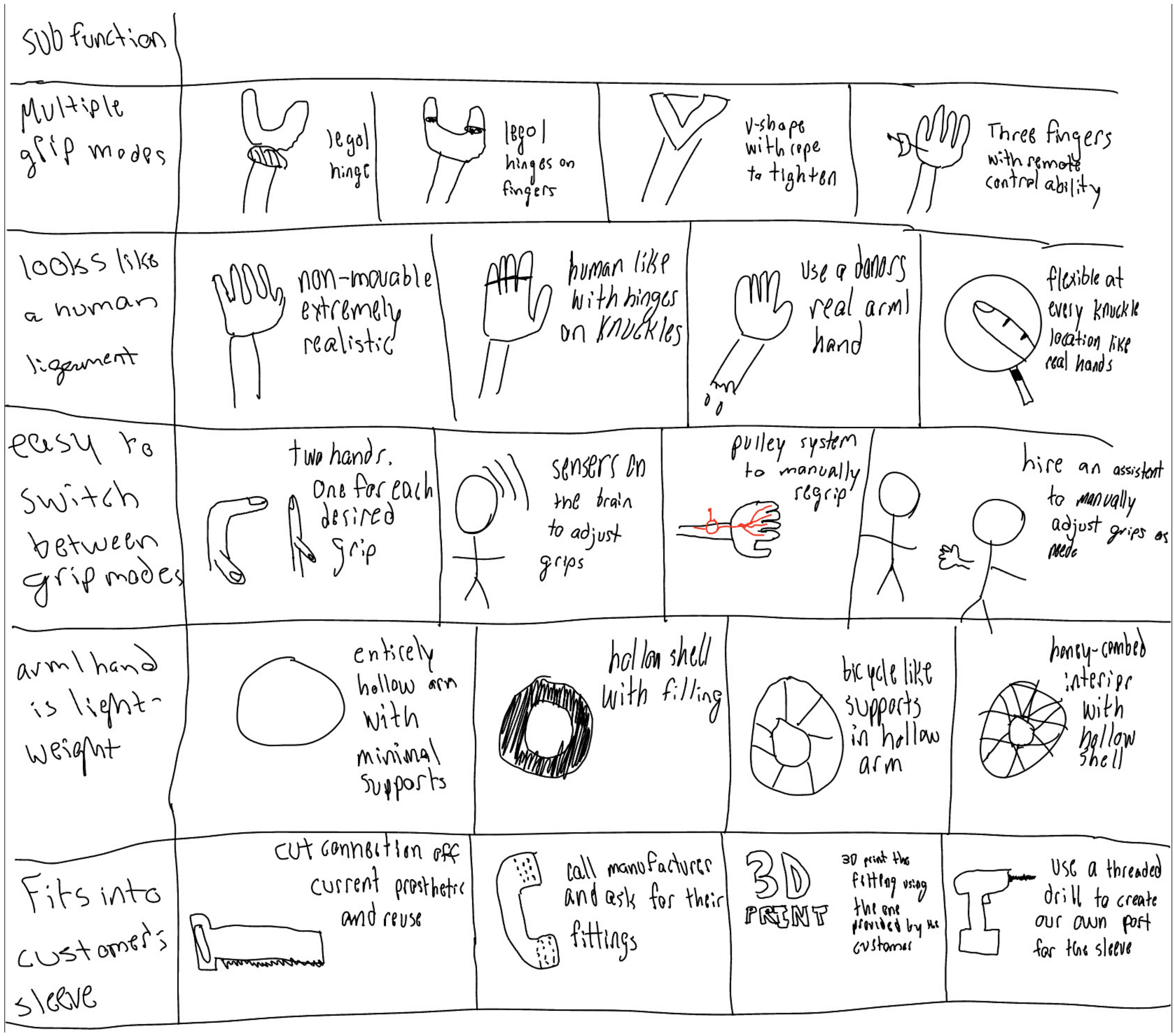


Figure 13: Morphological Chart for Useless Box

3.4 Alternative Design Concepts

3.4.1 Concept #1: Manual Grip Arm

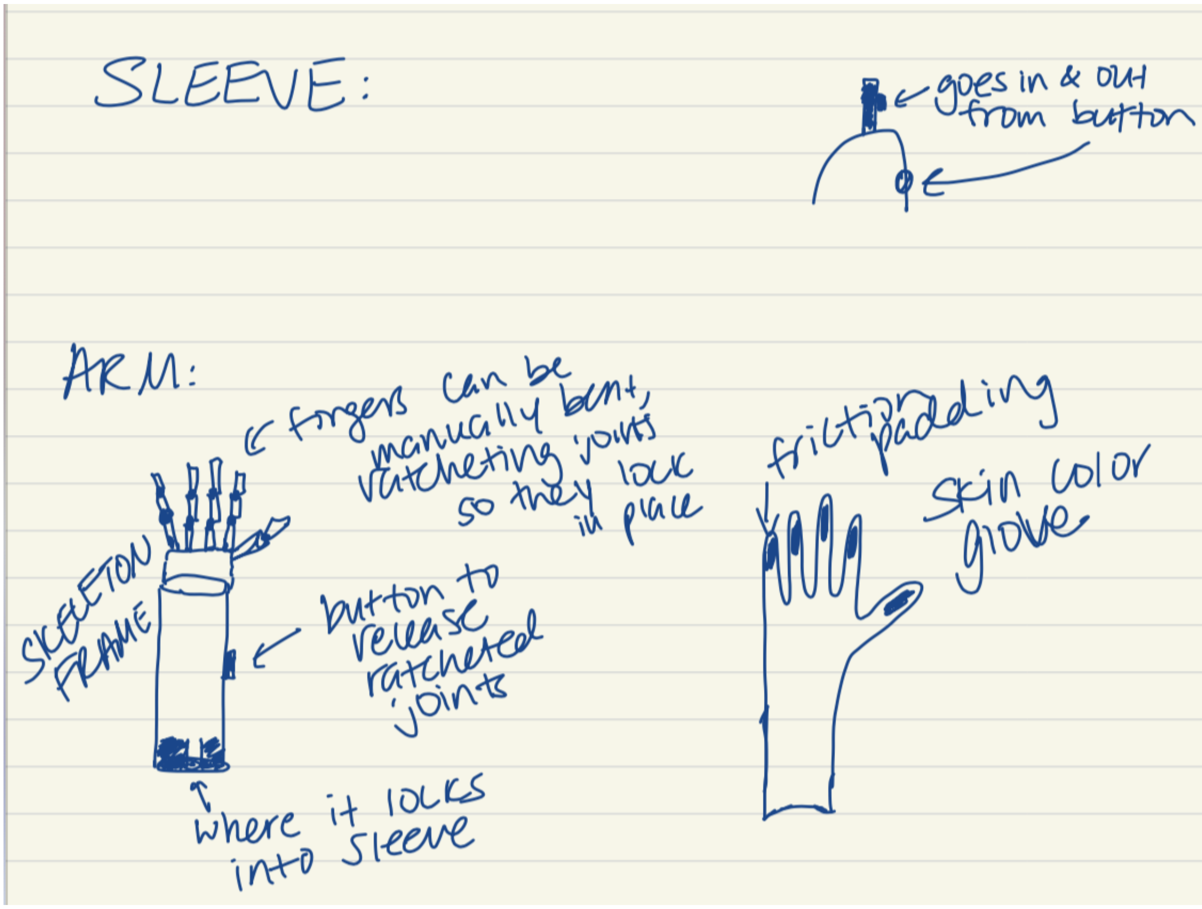


Figure 14: Lila's Sketches of Robotic Arm concept for Manual Grip Arm Design

Description: This design uses a stiff skeleton frame that provides support and movement for the arm, with a glove over it. This is to make the arm as lightweight as possible, while also providing a realistic appearance, given that the glove is made of a skin-like material. The arm has a hole in the bottom that matches the small extrusion from the sleeve, so that it can lock into place. The fingers have ratcheting joints to that they can be manually moved to the desired positions, and there is a button near the wrist to release them. The glove has a high-friction surface on the pads of the fingers so that the hand can grip items.

3.4.2 Concept #2: Hydraulic Arm

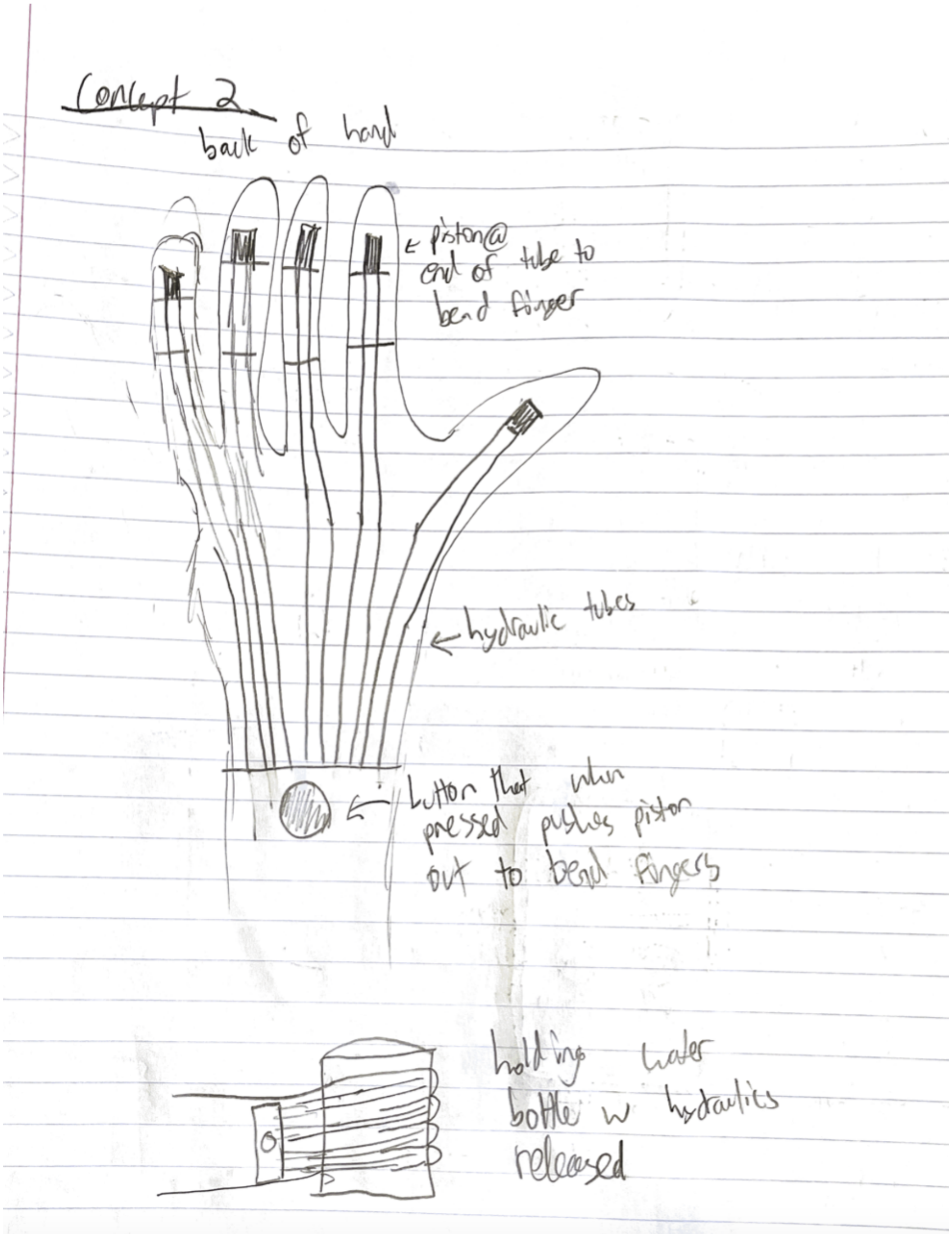


Figure 15: Matthew's Sketches of Robotic Arm concept for hydraulic design

Description: This design utilizes hydraulic tubes with water in them. After a button on the forearm is pressed, pistons shoot water down the tubes which will make the fingers bend. There will be two positions that the hand can be in: extended fingers and closed fingers (so that they can close around an object).

3.4.3 Concept #3: Rope Arm

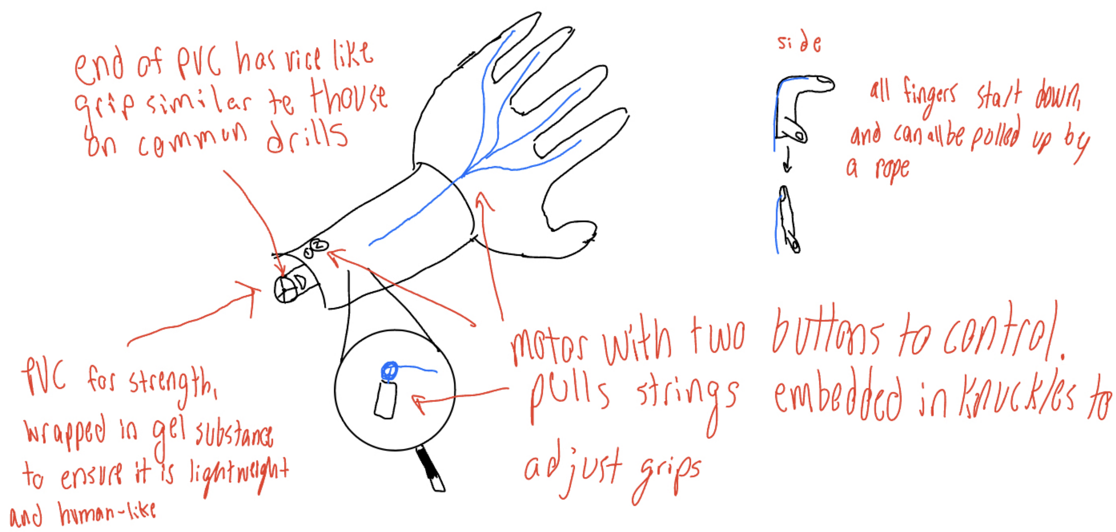


Figure 16: Spencer's Sketches of Robotic Arm concept for Rope Motor Design

<u>Description</u>: The Rope Arm design utilizes a pipe like structure inside the arm serving the same purpose human bones do, structural support. This is wrapped in ballistic gel to ensure a realistic feel and look for the arm and forearm prosthetic. The ropes are motorized to be pulled back and create tension to form an open position. These ropes will have to be strong enough to hold the fingers upright while also withstand some load of the tasks at hand.

3.4.4 Concept #4:

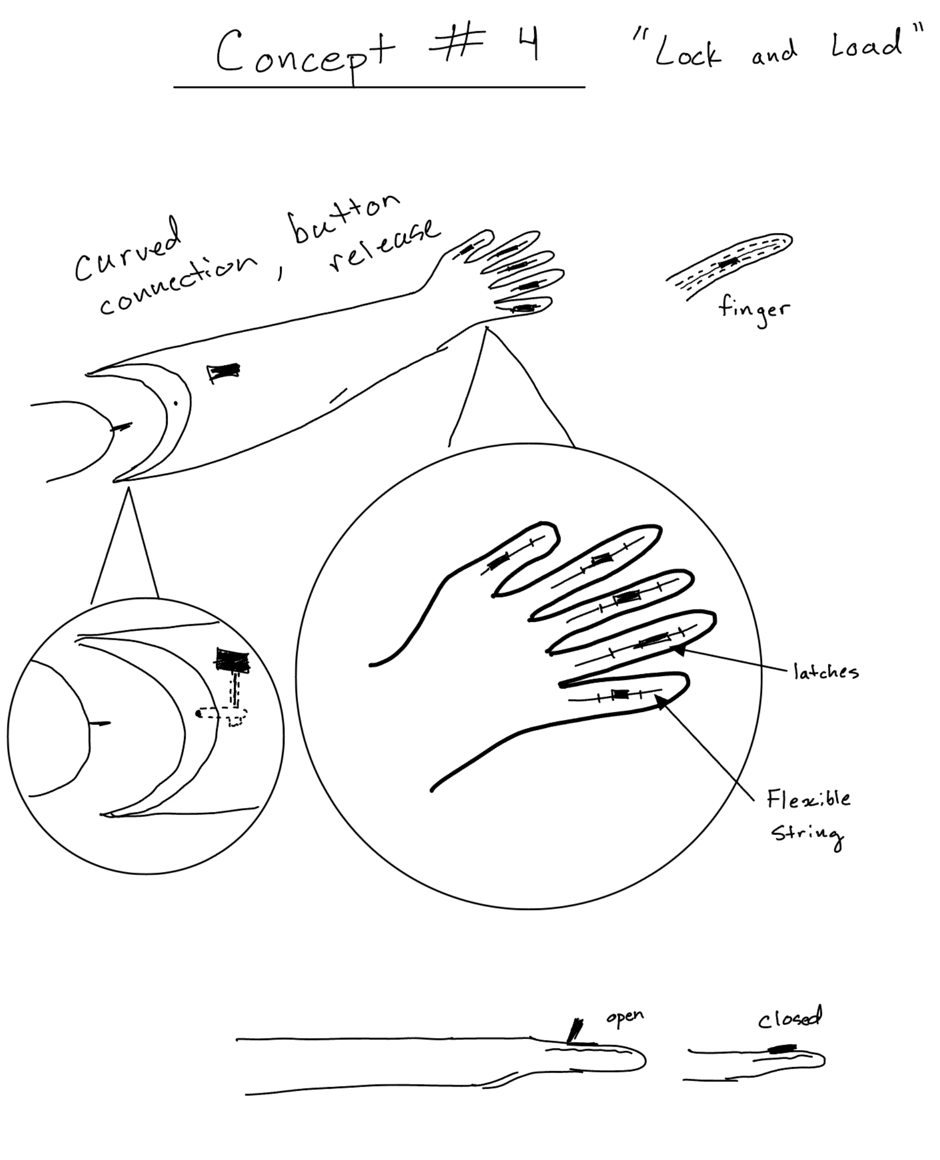


Figure 17: Nate's sketches of a prosthetic arm concept that has manually adjustable fingers

Description: The Lock and Load design consists of a hollow arm with a small hold near the elbow for the prosthetic to lock onto the existing arm sleeve. There is a button release mechanism to release the prosthetic arm from the connection. A flexible string is ran through each finger with bendable joints at the normal spots that fingers bend. On top of each finger is a lever that when closed tightens the string in the fingers and locks them into their current position. To change finger positions the customer must use their other hand the adjust and lock all fingers individually into the desired position.

4 Concept Selection

4.1 Selection Criteria

The following table was used to determine percentages on the weighted scoring matrix.

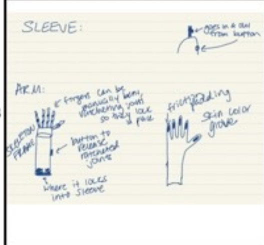
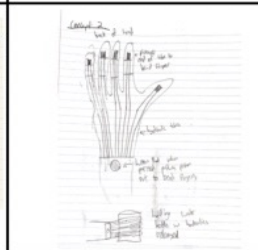
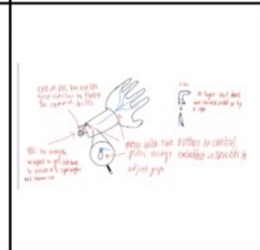
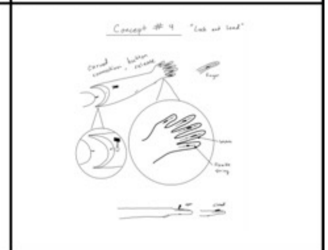
Alternative Design Concepts		Concept #1		Concept #2		Concept #3		Concept #4	
									
Selection Criterion	Weight (%)	Rating	Weighted	Rating	Weighted	Rating	Weighted	Rating	Weighted
lightweight	30.14	2	0.60	1	0.30	2	0.60	4	1.21
looks realistic	22.41	4	0.90	3	0.67	3	0.67	5	1.12
independent finger movement	4.17	5	0.21	1	0.04	1	0.04	4	0.17
3 different hand positions	25.50	5	1.28	5	1.28	5	1.28	5	1.28
easy to use	17.77	3	0.53	5	0.89	4	0.71	2	0.36
	Total score	**3.516**		**3.179**		**3.303**		**4.123**	
	Rank	**2**		**4**		**3**		**1**	

Figure 18: Analytic Hierarchy Process (AHP) to determine scoring matrix weights

4.2 Concept Evaluation

The following scoring matrix was created to show our designs.

	lightweight	looks realistic	independent finger movement	3 different hand positions	easy to clean		Row Total	Weight Value	Weight (%)
lightweight	1.00	3.00	5.00	1.00	3.00		13.00	0.30	30.14
looks realistic	0.33	1.00	5.00	0.33	3.00		9.67	0.22	22.41
independent finger movement	0.20	0.20	1.00	0.20	0.20		1.80	0.04	4.17
3 different hand positions	1.00	3.00	5.00	1.00	1.00		11.00	0.26	25.50
easy to use	0.33	0.33	5.00	1.00	1.00		7.67	0.18	17.77
						Column Total:	**43.13**	**1.00**	**100.00**

Figure 19: Weighted Scoring Matrix (WSM) for choosing between alternative concepts

4.3 Evaluation Results

Through the use of an analytic hierarchy process, we determined that our top weighted criteria were lightweight, different hand positions and realistic looking. The customer expressed to us specifically that a heavy arm would not work. The customer's current arm is lightweight and appears realistic but has no mechanical function. Therefore, it makes sense that these criteria are the most important. Our design must meet the requirements of the previous arm by being lightweight and realistic, while providing a new functionality by being able to change hand positions. Based on these results, concept 4 "Lock and Load" was our highest rated concept. In theory, this concept seems great but from proof of concepts we learned that "Lock and Load" will not meet our needs. The customer wears a realistic silicone sleeve over her prosthetics that would interfere with being able to adjust the fingers. In addition, to appear realistic the fingers do not have enough space for a locking mechanism on the outside of the fingers. Our proof of concept showed us that mechanisms where the components are hidden inside of the hollow arm and hand, work best. Concept 3 will work the best as the strings and motors are kept inside of the prosthetic.

4.4 Engineering Models/Relationships

The three following models will be useful for understanding physical relationships that are relevant for this use case. They will be necessary for determining certain design constraints.

4.4.1 Rope/Motor Hand

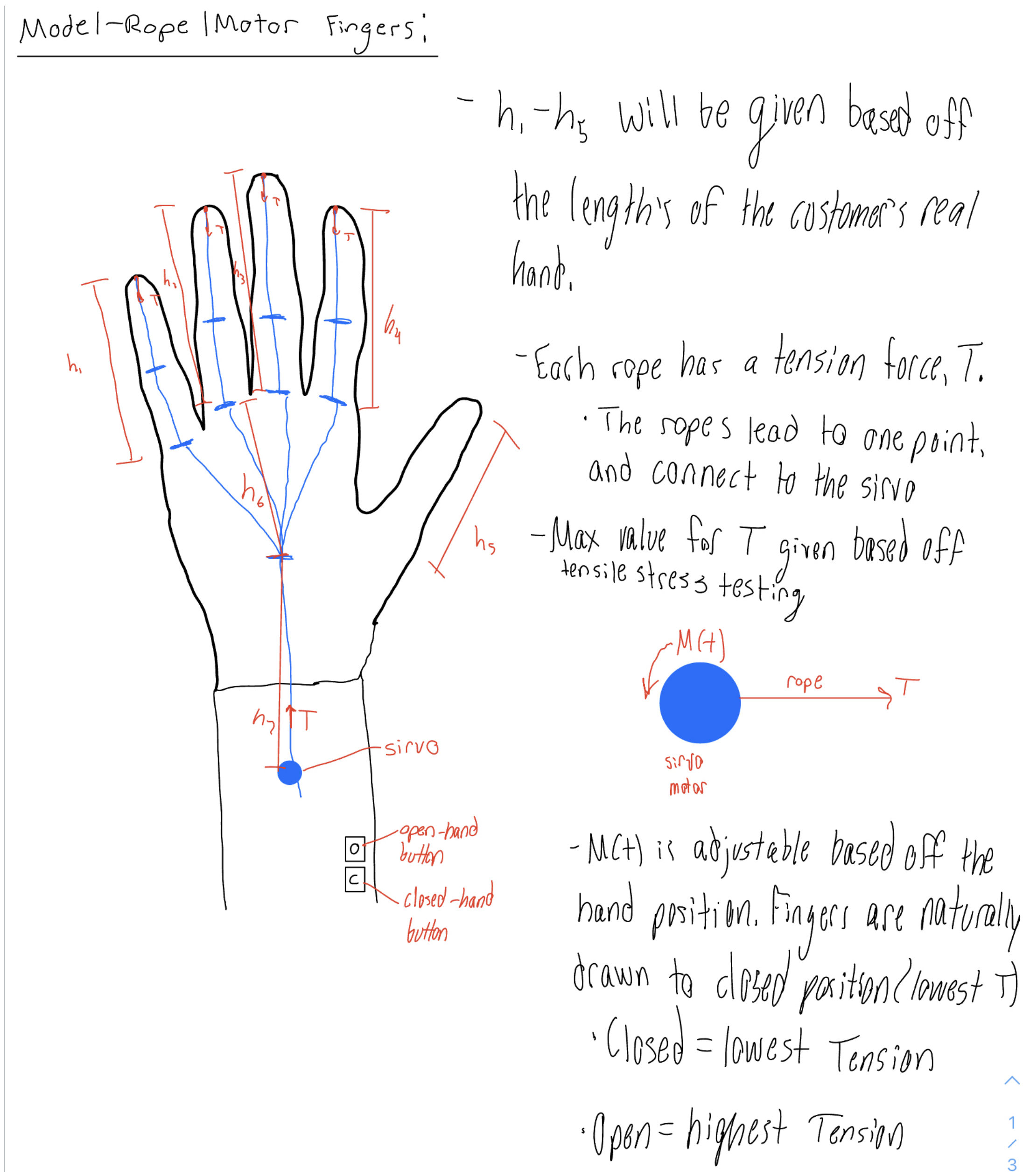


Figure 20: Engineering model for hand operated by ropes and a motor

Figure 20 shows an arm with fingers operated by strings connected to a motor. The motor applies a specified torque, M(t), provided by the servo. This then increasing the tension, T, in the rope which connects to all the fingers at a distance h_7 away from the motor. Each finger has a finger length of h_1 to h_5 from pinky to thumb respectively. With this model, a maximum tension (max load that the hand can take) must be provided to the user to they have a relative estimate of their prosthetic capabilities.

4.4.2 Friction Model

The following model demonstrates the importance of the frictional force the hand may need to apply to an object to keep it in place. Because F = μ*N, where μ is the coefficient of friction and N is the normal force, we need to decide the correct force that must be applied, along with a material that has a high enough friction coefficient.

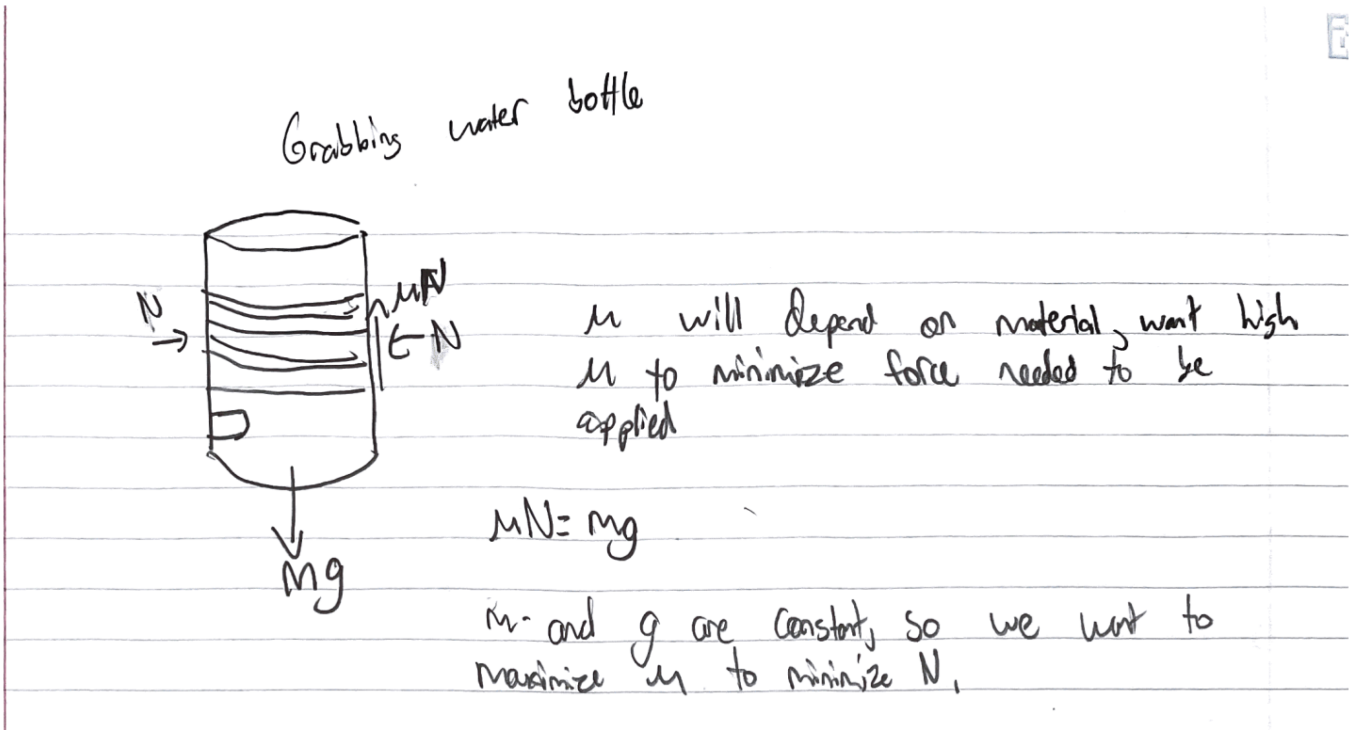


Figure 21: Engineering model based on frictional force

4.4.3 Gear Model

This model explains the relationship between torque and gear ratio when coupling two gears together. This is relevant because we might use gears to translate torque from a servo or stepper motor to the fingers, since there is more space for a motor higher up in the forearm. One can calculate the output torque by multiplying the input torque by the ratio of the gear radii. We should work backwards, starting from desired output, to pick the correct gear sizes and motor.

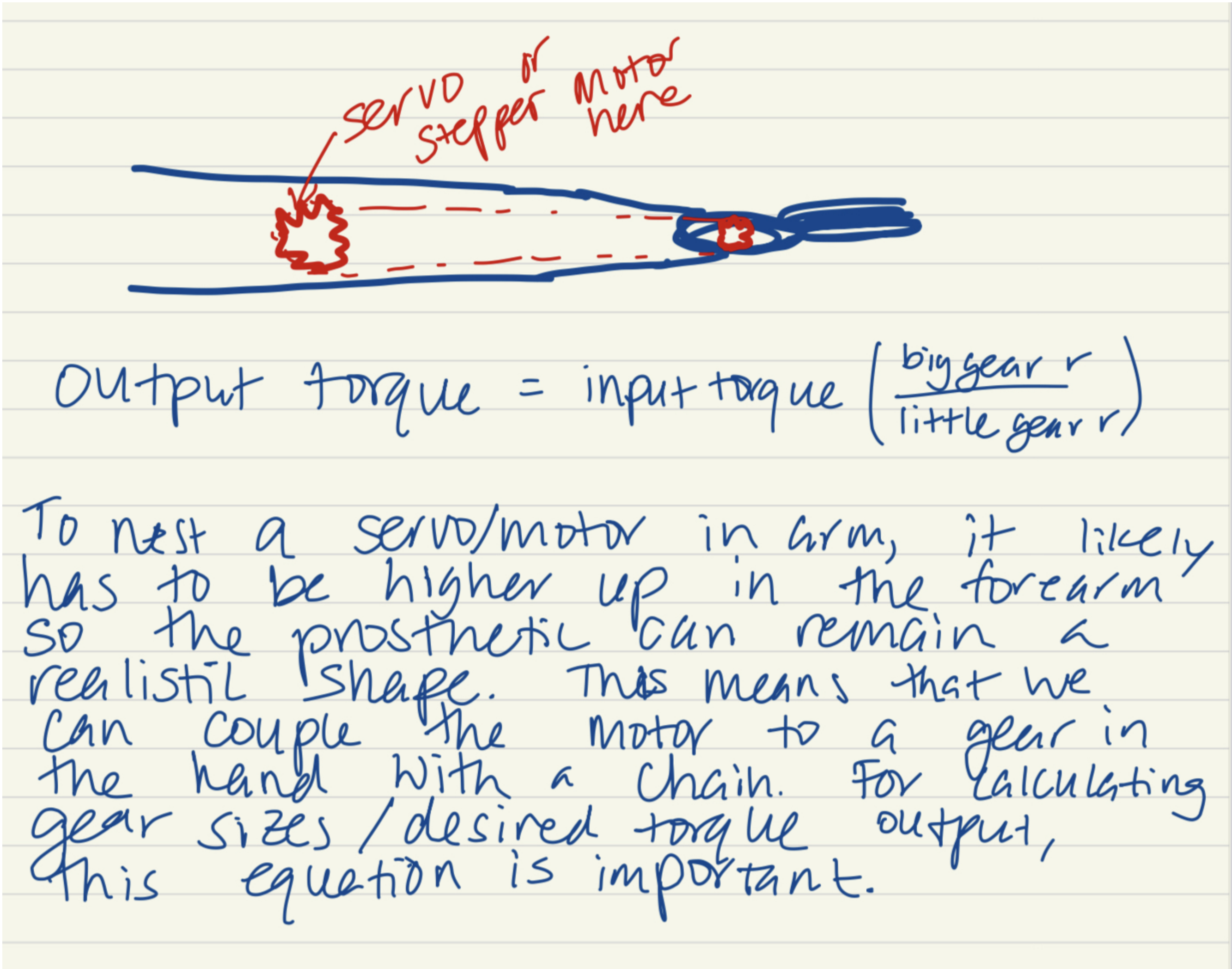
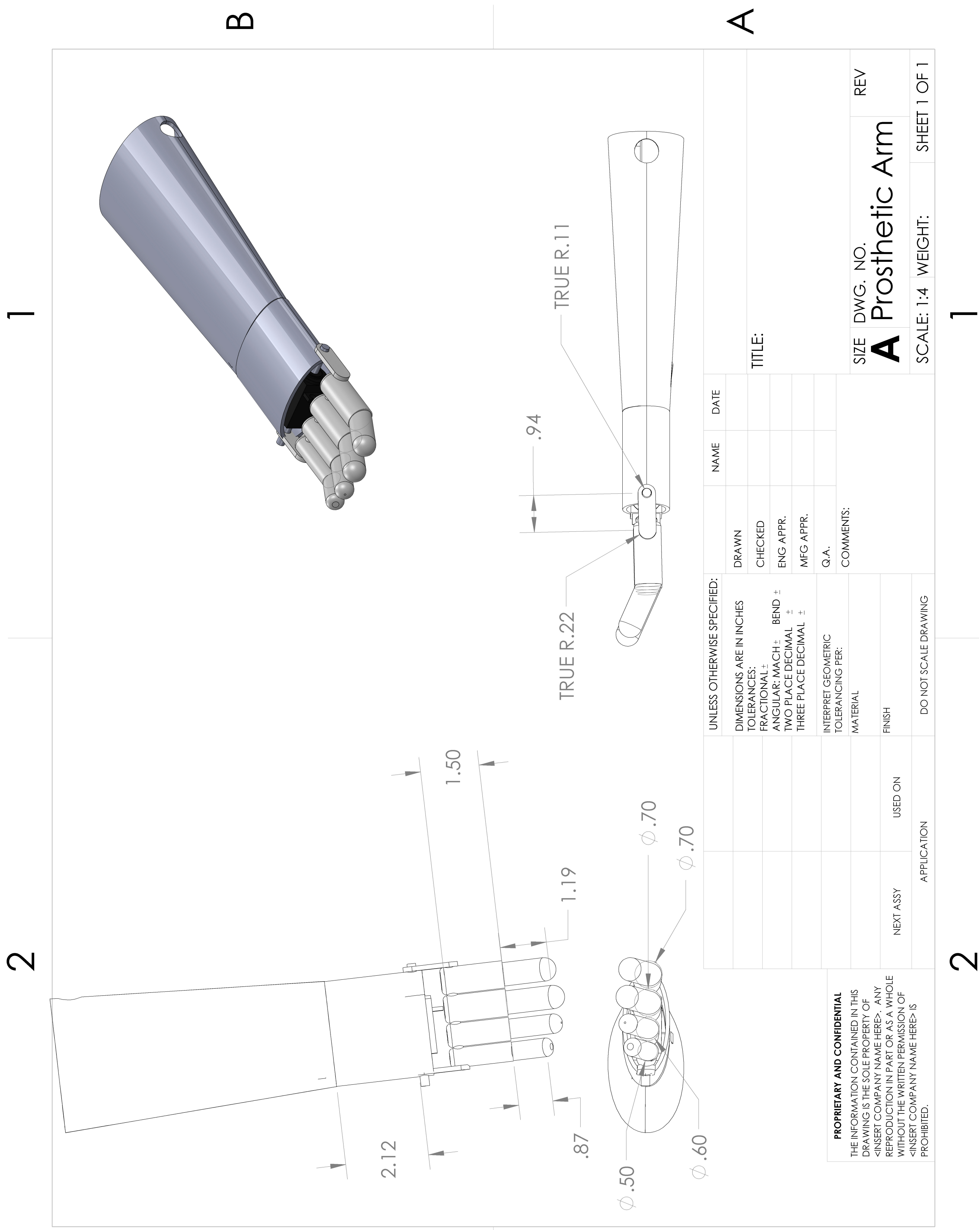


Figure 22: Engineering model based on gear ratios

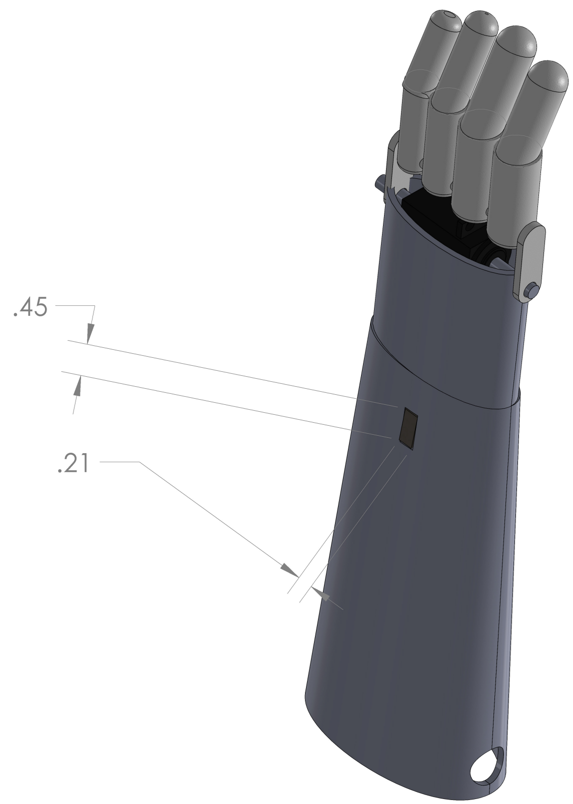
5 Concept Embodiment

5.1 Initial Embodiment

The following three figures show our initial embodiment. The figures include an assembled projected view with overall dimensions, an assembled isometric view, and an exploded view with callouts to bill of materials. One of the main components of the initial embodiment is the forearm/palm which house the servo, arduino, breadboard, battery, button and dowel. The forearm and palm is split in half to make accessing the inner components easier. The other main component is the fingers which attach to the top of the palm through the use of the dowel. Our first prototype performance goals is to stabilize a water bottle and support it as its filled. The second goal is that the prosthetic arm does not produce a moment about the elbow greater than the customers current arm. The third goal is that the prosthetic arm can complete at least 10 curls holding a 5 lb weight.



Prosthetic Arm
TITLE:
SIZE
A
DWG. NO.
REV
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.
TRUE R.11
TRUE R.22
.94
1.50
1.19
2.12
.87
⌀.70
⌀.70
⌀.50
⌀.60



PROPRIETARY AND CONFIDENTIAL

THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

SIZE	DWG. NO.	REV
A	Iso View	

SCALE: 1:4 WEIGHT: SHEET 1 OF 1

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	fingers		1
2	forearm/palm Top		1
3	forear/palm Bottom		1
4	dowel	one coupled to servo, one not coupled	2
5	button		1
6	battery		1
7	breadboard		1
8	arduino		1
9	servo		1

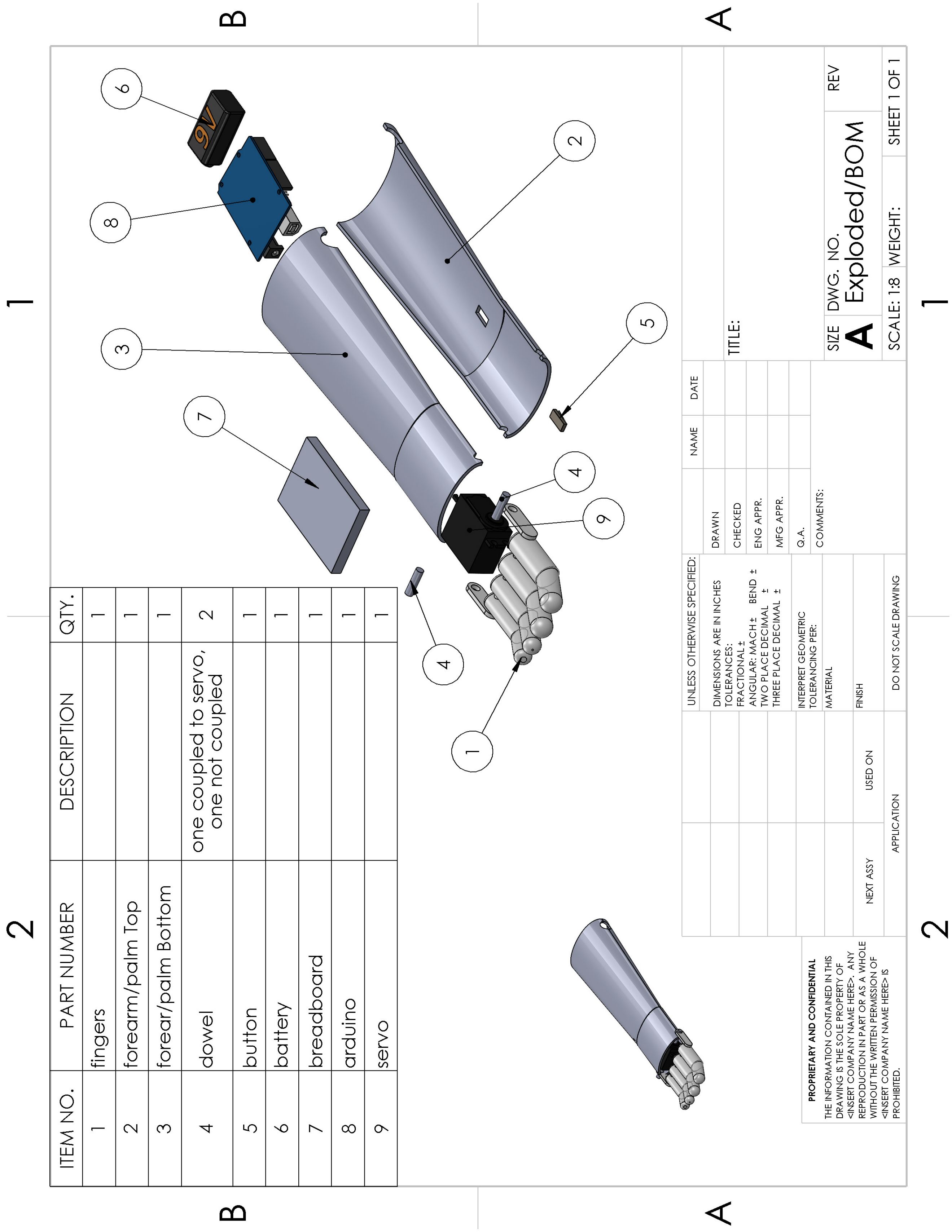


Figure 25: Exploded view with callout to BOM

5.2 Proofs-of-Concept

Our initial proof of concept cleared up some of the questions we had about whether or not our design would work. We used a hinge to simulate how the fingers would bend. Our prototype helped us understand that the sizing of some of the components would need to change. For example, our internal electronics need to fit inside of the wrist, so we now have to make the forearm slightly larger.

5.3 Design Changes

Based on our scoring matrix, design 4 was the design we chose. After testing and creating a prototype, we realized some of the issues with the design. We decided that instead of latches and string to hold the fingers in place, we were going to use a servo and axle to rotate the fingers to a set position. This was a large change from our initial concept idea, as we didn't plan to use any electronics, and now have a few different internal electronic components. We also planned to have each finger adjust, while in our initial prototype, we have the fingers move together.

6 Design Refinement

6.1 Model-Based Design Decisions

The following are design decisions that were tested in the initial prototype.

6.1.1 Switch Operated Servo

Movement in the fingers is caused from a servo motor located inside the palm of the prosthetic. An arduino and breadboard are used to connect the servo to a switch that moves it approximately 60 degrees back and forth each time the switch is triggered. Based on our prototype the system works as intended and the switch is easily accessible and user friendly.

6.1.2 Finger Rotation Around Central Rod

In the initial prototype, the axis which the fingers rotate about is a single rod connected to the servo motor at the base of the fingers. From testing the prototype, it was determined that the design chosen can support the weight of 5 pounds needed. There were initial concerns that the axis of rotation was too far from the loading area and the motor would not be able to turn properly.

6.1.3 Hollow Forearm

A hollow forearm was used in the initial prototype to be able to conceal all equipment used while staying as lightweight as possible. The thickness and oval shape of the hollow forearm is able to easily support the weight required and more. The design is able to withstand the required loading as well as any unexpected weight that may be applied while operating the prosthetic.

6.2 Design for Saftey

The following are five risks associated with our device. Each risk has an description, severity level, probability and mitigating steps section.

6.2.1 Risk #1: Battery overheat

Description: The battery has the chance to become overheated if it is working too hard. This could potentially burn Ilana. If there is too much weight on the fingers, the servo might have to work extra hard by drawing extra power from the battery.
Severity: This risk is a critical risk because of safety.
Probability: Seldom
Mitigating Steps: We can ensure that the battery is not near the outside of the arm so that Ilana would burn herself. We can also thoroughly test the design to ensure it does not overheat.

6.2.2 Risk #2: Fingers break

Description: If too much weight is added to the fingers, the servo link or fingers could possibly snap off. There aren't really environmental issues that would impact this.
Severity: Negligible
Probability: Occasional
Mitigating Steps: During our final creation, we will make sure the materials are strong enough to hold onto the weights. We will thoroughly test the design before using it.

6.2.3 Risk #3: Battery runs out of power

Description: The battery could run out of power when she is using it. There aren't really environmental issues that would impact this.
Severity: Marginal
Probability: Occasional.
Mitigating Steps: We will always ensure the battery is charged before using it. She can charge the battery overnight when she is not using the arm.

6.2.4 Risk #4: Hand is much lighter than old hand and can't judge weight

Description: Because one of our goals is to make the moment much smaller, she might not be able to judge the weight of it and hurt herself.
Severity: Negligible
Probability: Unlikely.
Mitigating Steps: We will ensure she is clearly aware of the weight before using the arm. Hopefully she will be able to get used to the weight of the arm.

6.2.5 Risk #5: Servo moves to incorrect position

Description: The servo is coded so that it only moves about 60 degrees at a time, but something could go wrong where it goes too far in one direction.
Severity: Negligible.
Probability: Unlikely.
Mitigating Steps: We will thoroughly test the design to ensure it only goes to the desired angle. Ilana will not use this device without thorough testing.

6.2.6 Heat map

The following shows the heat map for all of the risks associated with our design

		Probability that something will go wrong				
	Category	**Frequent** Likely to occur immediately or in a short period of time; expected to occur frequently	**Likely** Quite likely to occur in time	**Occasional** May occur in time	**Seldom** Not likely to occur but possible	**Unlikely** Unlikely to occur
Severity of risk	**Catastrophic**					
	Critical				Battery overheat	
	Marginal			Battery runs out of power		
	Negligible hazard presents a minimal threat to safety, health, and well-being of participants; trivial			Fingers break		Hand is much lighter than old hand and can't judge weight Servo moves to incorrect position

Figure 26: Heat Map for risks

6.2.7 Prioritization of different risks

Based on our heat map, the highest prioritization should be that the battery could overheat. This poses the biggest safety issue toward our client. The next highest issue is that the battery could run out of power when she is using the device. She might be doing an important task where she needs to have battery and if it dies it could be a large problem for her. Our third priority is that the fingers could snap off when she is carrying something. Our fourth and fifth priorities are that the hand is much lighter than her previous hand so she could hurt herself, and that the servo could move to an incorrect position.

6.3 Design for Manufacturing

When focusing on design for manufacturing with our prosthetic arm, we check to see which parts are necessary and which can be theoretically eliminated.

6.3.1 Parts and Fasteners

Figure 25 shows the exploded view of the part, there are approximately 9 parts with no specific fasteners. The rest of the arm is glued together with parts being permanently attached.

6.3.2 Theoretically Necessary Components

The **Arduino** is a TNC as it has to be repaired separate from the rest of the apparatus. The **button**, **bread board** and **battery** must be a separate piece from the rest of the arm because they is embedded into the forearm, but can break due to usage and may need to be repaired separately as well.

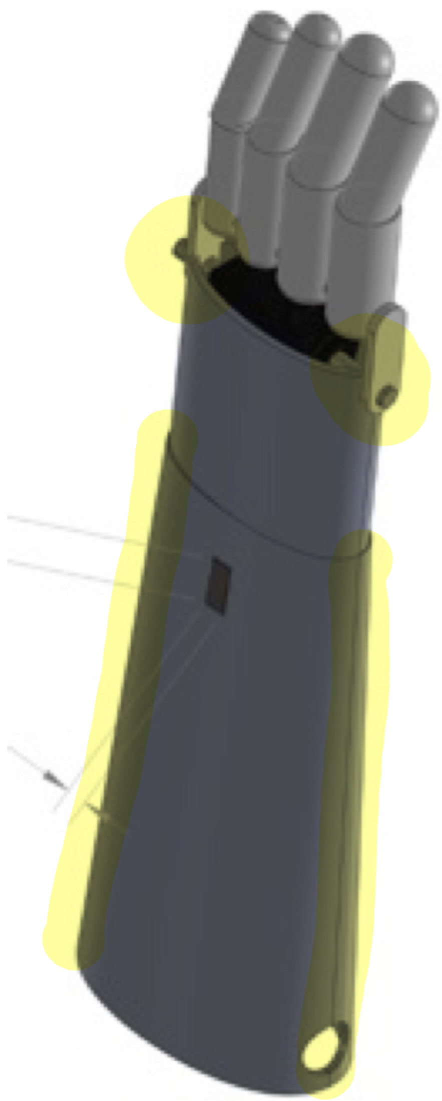


Figure 27: Theoretically Necessary Part Analysis

The design has a lot of parts the need to be attached and glued together in order to create a final product. In order to reduce the amount of parts from 9 closer to 5 (the number of TNCs) the individual parts can be reduced by attaching the fingers directly to the servo and removing the dowel. Figure 27 shows the locations where the arm can be attached or where a part can be removed in order to decrease the total number of parts. In a real manufacturing process this can be achieved, but in our case we need to be able to make constant changes within the arm, so these piece must be separate.

6.4 Design for Usability

The following subsections explain how various impairments might influence the usability of the prosthetic arm.

6.4.1 Vision Impairment

A vision impairment, such as red-green color blindness or presbyopia, should not impact the typical usage of the prosthetic arm. It may become an issue if the user has to troubleshoot the arm for some reason, and is looking at the wiring. It may be difficult to keep track of the jumper wires if vision impaired. This can also come into play if someone were reliant on feeling something to distinguish it due to a vision impairment. However, this would be the case for most prosthetic arms.

6.4.2 Hearing Impairment

Use of this prosthetic arm requires no hearing capabilities, so a hearing impairment will not influence its usability. There is a slight chance that if the prosthetic were to malfunction, there might be some sort of audible indication that the user might miss if they have some sort of hearing impairment.

6.4.3 Physical Impairment

This device is designed to help with a physical impairment! It requires the use of another functioning hand to put on and remove the arm, as well as press the button to move the fingers. If the user's other hand became impaired, likely a more autonomous prosthetic would be required.

6.4.4 Control Impairment

Once the user learns to incorporate this prosthetic into their daily practices, control impairments should not pose an issue. The arm has limited movement (small range of motion in four fingers) so it would be hard to accidentally hurt oneself with the arm. They may have more trouble using the arm if dizzy or intoxicated, but just in the way that all motor functions become limited and more difficult.

7 Final Prototype

7.1 Overview

Figure 28: Final Prototype

7.2 Overview

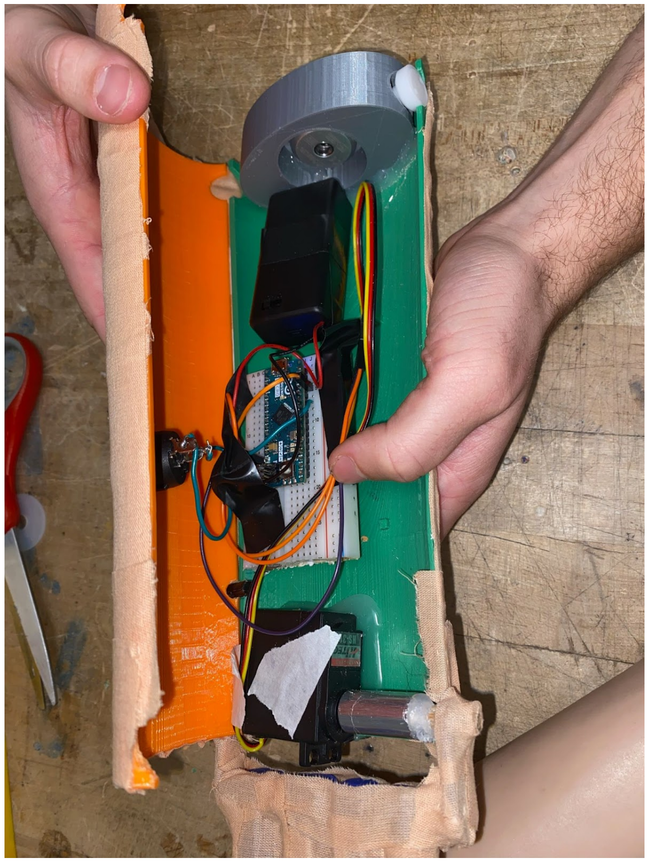


Figure 29: Inside of Final Prototype

Fig. 28 shows the final prototype for our prosthetic arm. It is wrapped in tape to emulate skin like color and has a button that is easy to access for the user to change grip modes. Overall the design made great leaps from the original prototype till now. This product has individual components that can be switched out in order to make it function better like the servo and fingers. Fig. 29 shows the inside of the hollow 3d printed forearm with all of the electronic components.The goals were completed except for the curling five pounds because of the servo not being able to support enough weight. In the future a different servo would be used to account for this shortcoming.