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MEMS 411: Dog Mobility Aid

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The goal of this project was to create a mobility aid for Henry the dog, who has angular limb deformity. His deformity has gotten worse with age so his owner, Mason Dahl, wanted a device that would allow him to have better mobility. Various designs were proposed and several iterations of the device were constructed. The first prototype was made quickly out of every day objects to determine the desired shape and dimensions. The next iteration was 3D printed, but ended up too bulky and heavy. This led to the pursuit of a different material and smaller overall design. The third iteration had a c-shaped base made form wood veneer and wood glue, and had an arm piece made of moldable thermoplastic. Nylon straps were added as a way of securing Henry's arm in the device. This version of the device was too heavy and did not fit Henry well. This led to the construction of the final prototype which is lower profile, lighter weight, and better fitted to Henry. The base of the final prototype is much smaller, and made of a carbon fiber and epoxy composite instead of wood veneer and wood glue. The leg piece is made of schedule 40 pvc and functions similar to the leg of a crutch. The arm piece is still made of moldable thermoplastic, but was molded directly to Henry's arm so the fit is much better. Velcro straps were fastened into the arm piece so that padding could be attached and as a way to secure Henry's arm in the device. The final prototype was tested for three performance goals. These goals were to withstand at least 50 lbs of vertical load, Henry can move his arm in all degrees of freedom, and Henry can walk forward and turn at least 90 degrees. All performance goals were met. Henry is currently not comfortable walking in the prosthetic on his own, however we are hopeful over time he will become more comfortable and be able to walk in the device on his own. This report includes drawings and CAD models from the design process, as well as details about design decisions. Each step of the design process is included, as well as a detailed risk analysis. Previous iterations and design morphologies are included, as well as explanations for why certain design attributes were chosen. Finally, details regarding construction and testing of the final prototype can be found at the end of this report.

DOG MOBILITY AID

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1 Introduction

Mason Dahl and Grace Vinson's dog, Henry, suffers from an Angular Limb Deformity (ALD). This means that his radius and ulna, and metacarpal bones are deformed such that his paw twists outward from his body. Henry began developing ALD when he was six months old. Now nine years old, his paw is almost entirely backwards as seen in Fig.1 below.

The deformity will only worsen as Henry ages. His crooked paw affects his gait in a way that makes walking more difficult. He has to exert more energy to walk due to compensating with his other legs. Mason's top priority is to allow Henry to walk and run comfortably, for longer periods of time. He wants a device made of non-toxic material that will not irritate Henry's skin or joints and will not mold or rust.

Henry is a good candidate for either a wheelchair or prosthetic front legs. A wheelchair could help take all strain off of Henry's legs by supporting his torso. Prosthetics could allow Henry to utilize his functional upper arm with his natural range of motion, while also taking strain off Henry's carpal joints and preventing further deformation of his limbs.

Figure 1: Henry's Angular Limb Deformity

2 Problem Understanding

2.1 Existing Devices

The following section lists examples of existing devices with similar functions to our product. While these devices are similar to what we want to accomplish with our product, we haven't found anything exactly like what we are planning to design. Therefore, the following devices will help in our design process, but our end product will be unique.

2.1.1 Existing Device #1: Dog Able-Bodied Prosthetic for Deformities

Figure 2: Dog Able-Bodied Prosthetic for Deformities (Source: Animal Ortho Care)

Link: https://www.aocpet.com/products/dog-able-body-prosthetic-for-deformities
Description: The Dog Able-Bodied Prosthetic for Deformities is designed for dogs with limb deformities and no amputation. Animal Ortho Care sends the customer a casting kit, the customer sends back a mold of the dog's legs, then the company designs the casts for the dog. The dog's legs are strapped into the top of a c-shaped prosthetic. The prosthetic is said to prevent further deformation of the dog's limbs while still maintaining a proper gait.

2.1.2 Existing Device #2: Walkin' Wheels MEDIUM Front Wheel Attachment

Figure 3: Walkin' Wheels MEDIUM Front Wheel Attachment (Source: Walkin' Pets)

Link: https://www.handicappedpets.com/dog-wheelchair-medium-front-attachment-adjustable-whe
Description: Walkin' Wheels MEDIUM Front Wheel Attachment is a wheelchair device for dogs with weak front and back limbs. It attaches to a wheelchair with existing rear leg support. The full assembly includes large back wheels, smaller front caster wheels, a back harness, and a front chest support bar. The assembly is able to provide either partial support for dogs with weak limbs or full support for dogs with no leg strength.

2.1.3 Existing Device #3: Dog Leg Prosthetic - Full Limb

Figure 4: Dog Leg Prosthetic - Full Limb (Source: Animal Ortho Care)

Link: https://www.aocpet.com/collections/dog-prosthetics/products/dog-full-limb-prosthetic

Animal Ortho Care's Dog Leg Prosthetic - Fill Limb is a front leg prosthetic for dogs with amputated limbs. The customer receives a casting kit, sends the company a mold of the dog's residual limb, then the prosthetic is designed to fit the dog's body. The loop-shaped prosthetic is attached to a harness. It is designed to protect the functionality of existing joints by preventing deviations in the dog's gait.

2.2 Patents

2.2.1 Pet Dog Harness Wheelchair (CN104473735A)

This patent provides an example of the harness wheelchair we discussed. Two wheels and the wheelchair frame provide better mobility for the pet dog. It provides better support for the upper body weight on the chest using a harness support frame. It also includes a strap and hip protection pad for the lower body fixation and a tighter strap on the pet dog's body. The shoulder protection and front limb back strap provide a more comfortable position for the pet dog.

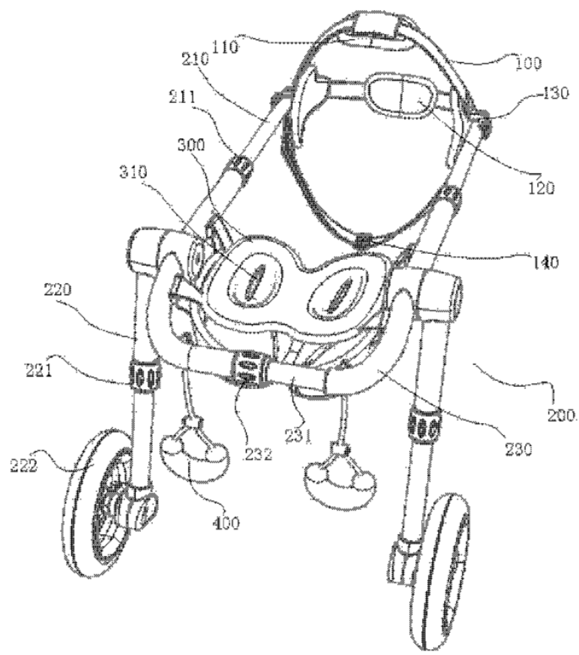


Figure 5: Patent Images for Harness Wheelchair

2.2.2 Pet Dog Orthopedic Brace (US9408738B2)

This design is the alternative possibility for the leg strap. Orthopedic braces and splints provide stability for movable joints and limbs for short or long-term support and fixation for pet limbs. It provides stability to the joint while assisting or restricting the range of motion. The orthopedic brace is adjustable and can be customized according to the pet's size. This orthopedic brace offers the possibility of correction on the limb bend.

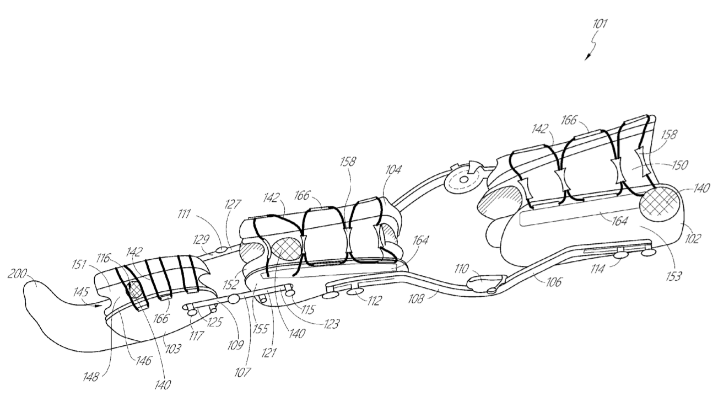


Figure 6: Patent Images for Orthopedic Brace

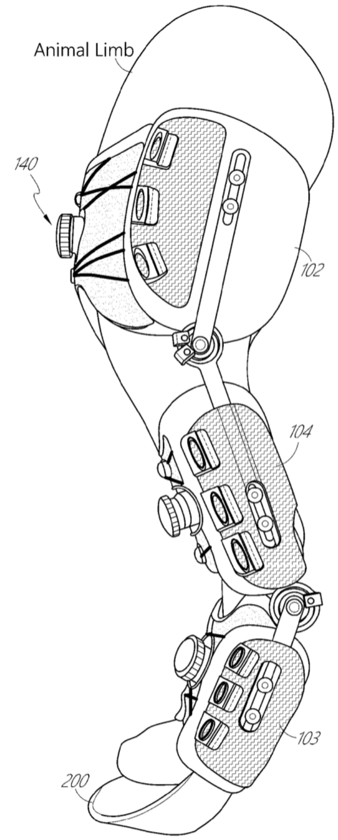


Figure 7: Patent Images for Orthopedic Brace on Pet Limb

2.3 Codes & Standards

2.3.1 Prosthetics – Structural testing of lower-limb prostheses – Requirements and test methods (ISO 10328:2016)

This standard discusses the testing of lower limb prosthesis. It talks about types of prosthetics this form of testing applies to, and those that it does not. The standard discusses the modes of testing that are to be used before prosthesis can be put on the market. This standard could apply to our project creating a prosthetic for Henry (the dog), because it could help us determine the best ways to test our device during the design process.

2.3.2 Prosthetics — Quantification of physical parameters of ankle foot devices and foot units (ISO/TS 16955:2016)

This standard pertains to ankle foot devices and foot units. It outlines qualitative testing methods for the prosthetics. While this is in reference to human anatomy, the summary shows a few definitions such as roll-over characteristics, torsional characteristic, and frontal plane characteristics which seem to be ideal parameters to keep in mind when designing the dog prosthetic.

2.4 User Needs

The following section includes notes from the customer interview and interpreted user needs. As a group, we interviewed Mason Dahl and took pictures and videos of Henry to get both static and dynamic views of his crooked paw and how it effects his motion.

2.4.1 Customer Interview

Interviewee: Mason Dahl and Henry the dog
Location: Schnuck's Pavillion, Washington University in St. Louis, Danforth Campus
Date: September 8^{th}, 2022
Setting: We asked Mason what his goals for Henry are, and what functions he would like device to have. We took pictures and videos of Henry's crooked paw while he was sitting, standing, walking, and running. The whole interview was conducted in by the tables out front of Schnuck's Pavilion, and took ∼45 min.

Interview Notes:
What are the typical uses of the device?

- Allow Henry to comfortably walk/run around on walks and at the park
- Walking for longer periods of time

What are the current likes and dislikes of the product?

- No device is currently available. Currently, Henry is walking on his crooked paw with no support. He likes the freedom for Henry to walk independently. However, Henry is unable to walk for long periods of time because he has little support from his front leg. His other front leg has begun to deform due to his gait. Over time, his limbs have gotten more deformed with use.

Further questions directly involved the user needs shown in the next section.

2.4.2 Interpreted User Needs

This section describes the user needs inferred from the initial interview. The costumer was asked to rate the importance of various functions of the product. The interpreted costumer needs as well as the importance of each function are given in Table 1 below.

Table 1: Interpreted Customer Needs

Need Number	Need	Importance
1	The device is comfortable for his joints	5
2	The device avoids skin irritation	4
3	The device allows walking and running for extended time periods	5
4	The device is made of non-toxic material	5
6	The device allows Henry to sit	2
7	The device allows Henry to lay down	1
8	The device will not degrade with use over time	1
9	The device will not succumb to environmental wear (rust, mold)	3
10	The device allows Henry to stop quickly (if wheelchair)	2
11	The device allows Henry to swim or float	1
12	The device is aesthetically appealing	1
13	The device gives Henry mobility on different terrains	1
14	The device is safe for Henry to wear around kids	4

The most important functions of our product are shown in the table above. The most important function is comfort for Henry. The goal of the product is to allow Henry to walk comfortably with less stress on his joints, and increase his stamina while walking and running. It is also very important that the prosthetic or wheelchair is made of a non-toxic material that causes minimal skin irritation. It is important that we consider environmental wear on the product, as it will be used outdoors and may get dirty and wet. Less important, but still desirable functions, include looks and mobility on different terrains.

2.5 Design Metrics

ISO 10328:2016 section 16.2: "Principal Static Test" and section 16.3: "Principal Cyclic Test" pertain to Need Number 3. Walking and running for extended periods of time requires that the device can withstand static loading as well as repeated/cyclic loading. The loading forces used in the test would be altered to better suit Henry's weight (approximately 35 lbs).

21 CFR 570 As dog wearing this wheelchair might bite or even accidentally swallow parts of the product. It is important for the product to meet the FDA requirements to be edible by pets. This standard shows the FDA-required tests for pet food additives and the requirements needed to be met to be eligible for pet food. If all the parts of the wheelchair are safe to meet the requirements of pet food, it should be fairly safe for accidents of swallowing pieces and won't hurt the dog.

ASTM F963-17 As this wheelchair is used for dogs and children might play with dogs a lot. It is crucial to find a standard that regulates children's toys or pet products so it is safe for the dog to wear this wheelchair around children. This standard covers requirements and contains test methods for toys intended for use by children under 14 years of age. Different age limits for various requirements will be found in this specification. These limits reflect the nature of the hazards and the expected mental or physical ability, or both, of a child to cope with the hazards.

Table 2: Target Specifications

Metric Number	Associated Needs	Metric	Units	Acceptable	Ideal
1	3	ISO 10328:2016 Section 16.2: Principal Static Test	binary	pass	pass
2	3	ISO 10328:2016 Section 16.3: Principal Cyclic Test	binary	pass	pass
3	3	21 CFR Part 570	binary	pass	pass
4	3	ASTM F963-17	binary	pass	pass

2.6 Project Management

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

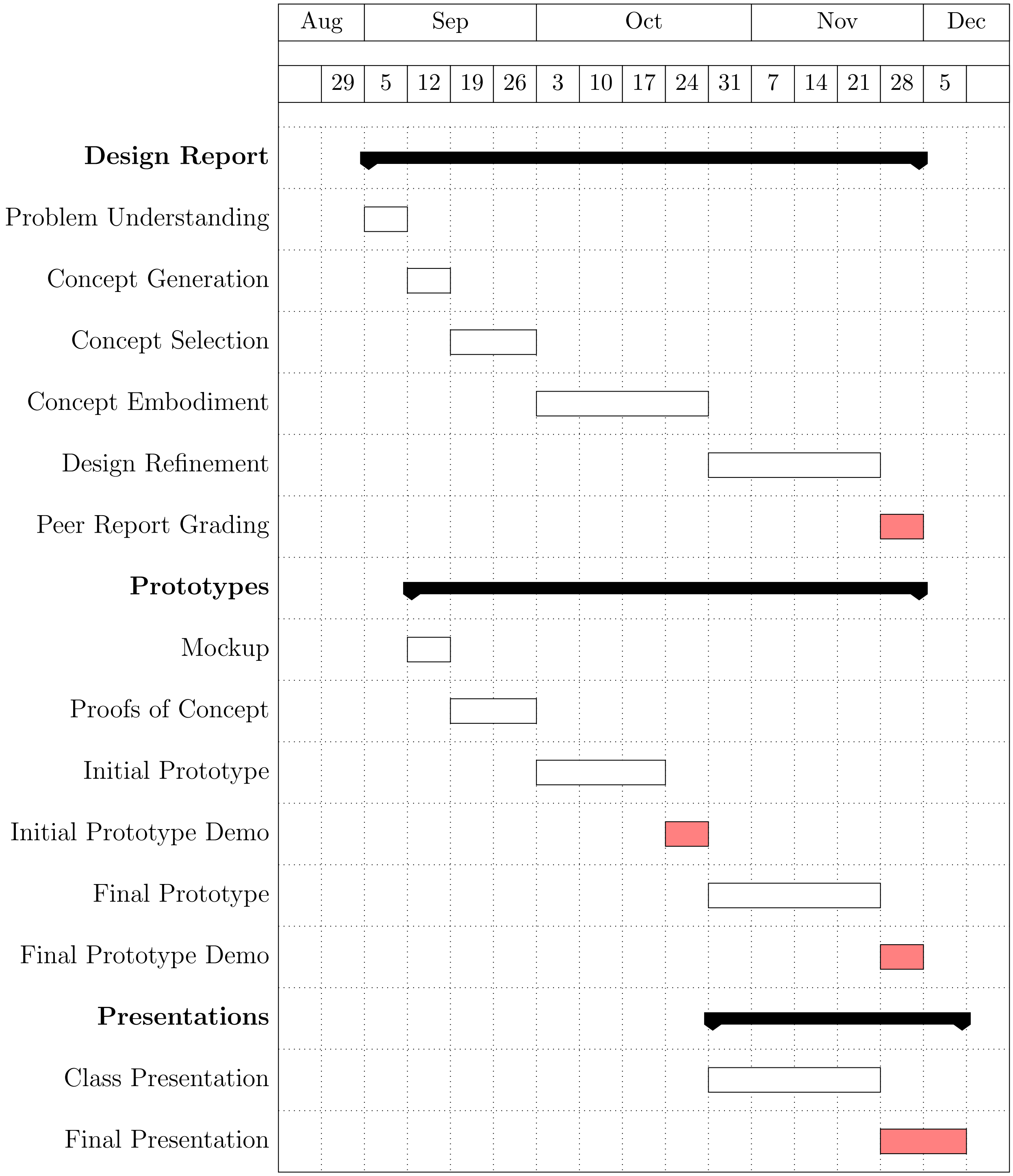


Figure 8: Gantt chart for design project

3 Concept Generation

3.1 Mockup Prototype

During the mockup prototype design, we discovered some key elements that would be useful for our design:

- The device will need added support around the steeply-curved part of the prosthetic.
- The material should be strong, but have some flexibility to absorb shock while he walks and runs.
- The device should support the back of his elbow in addition to the bottom of his arm.
- It will need one strap near the elbow and one strap near his wrist. The ideal design we found was a padded loop that went through the strap, so that the strap passed through the loop and secured (possibly with Velcro) on the side.
- The padding on the arm support should form to his arm shape, such as a moldable thermoplastic.
- The arm support should be slightly concave upward to help his arm stay in place.

Figure 9 shows a side and front view of the mock up of our device, as well as the strap that will be used to hold Henry's arm in place.

Figure 9: Dog Prosthetic Mock Up.

3.2 Functional Decomposition

This is the function tree with the most crucial functions that this design should have. These functions can enhance the performance of this walking device to help Henry increase his mobility.

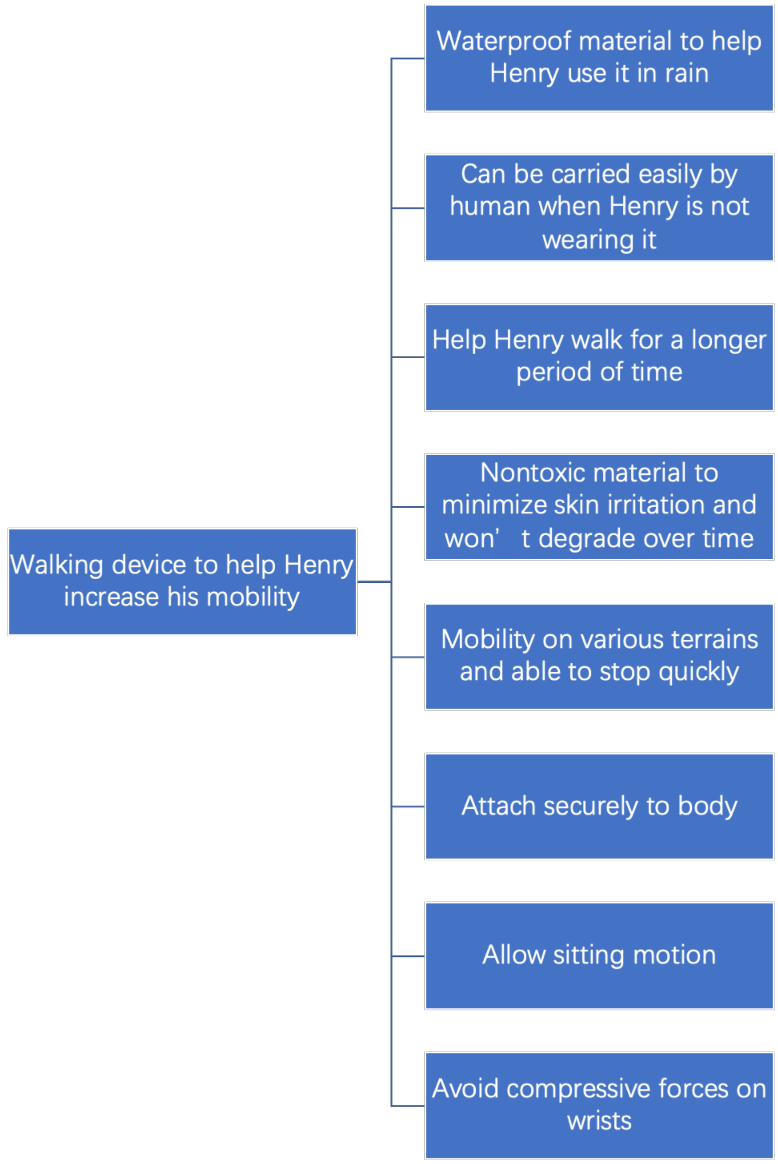


Figure 10: Function tree of the walking device for Henry

3.3 Morphological Chart

Below is the morphological chart containing morphologies for each function that we found crucial for the design.

Figure 11: Morphological Chart for the walking device

3.4 Alternative Design Concepts

3.4.1 Concept #1: C-Shape Prosthetic

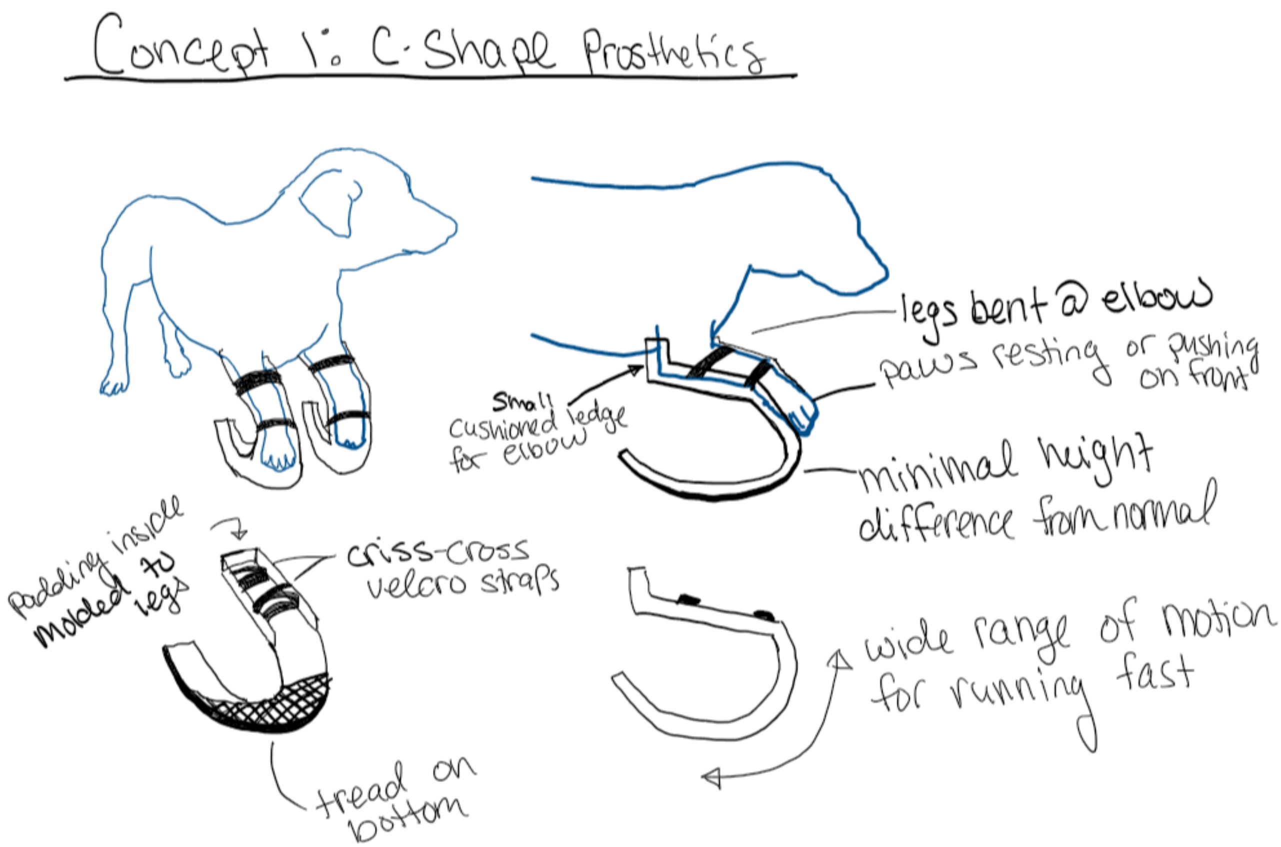


Figure 12: Sketches of C-Shape Prosthetic design

Description: Two c-shaped prosthetics attach to Henry's front legs with two straps. This design supports Henry's legs in a comfortable position, where his gait would be altered minimally from what he is used to. It would also allow him to utilize the normal range of motion for his shoulders, minimizing muscular decay. The bulk of the forces would be dispersed over the length of his arm on the padded part when standing. While walking, the force distribution would transfer slightly to his elbow, and the prosthetic would roll forward. This minimizes compressive forces on his crooked wrist. There is also a minimal height difference from his normal height, so there is no risk of injuring his lower spine. Finally, the bottom of the prosthetics would have a tread on the bottom so that he can use them on various terrains.

3.4.2 Concept #2: Another Concept

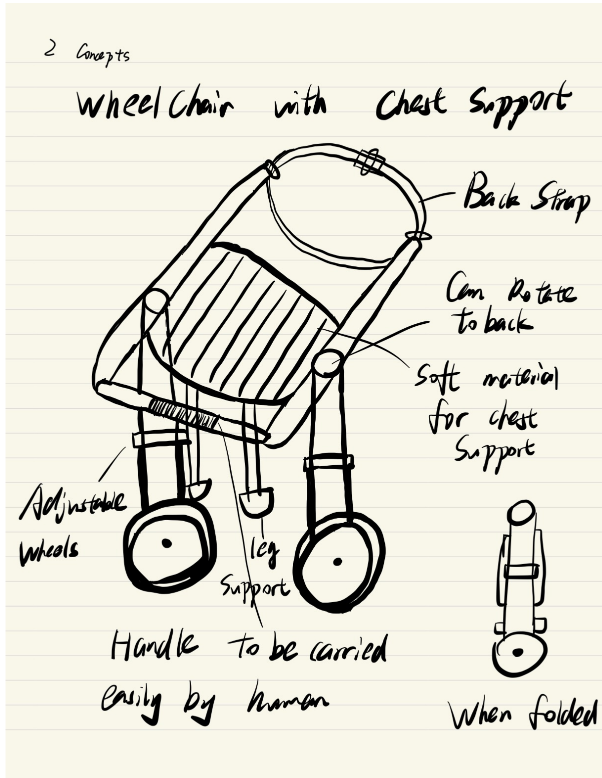


Figure 13: Pet Wheelchair With Chest Support

Description: This design is a wheelchair for Henry with chest support and back straps. With the large chest support, Henry is able to relieve his weight of the upper body and be more comfortable while wearing this wheelchair. There are also some back straps to fix this entire wheelchair securely on his body. There are two wheels to help Henry have more mobility. The wheels are flexible to adjust the height of the wheelchair. There are also two leg supports to fix Henry's front legs. When Henry is not wearing it, the wheels can be folded and there is a handle bar for humans to carry it around.

3.4.3 Concept #3: Tripod Wheelchair

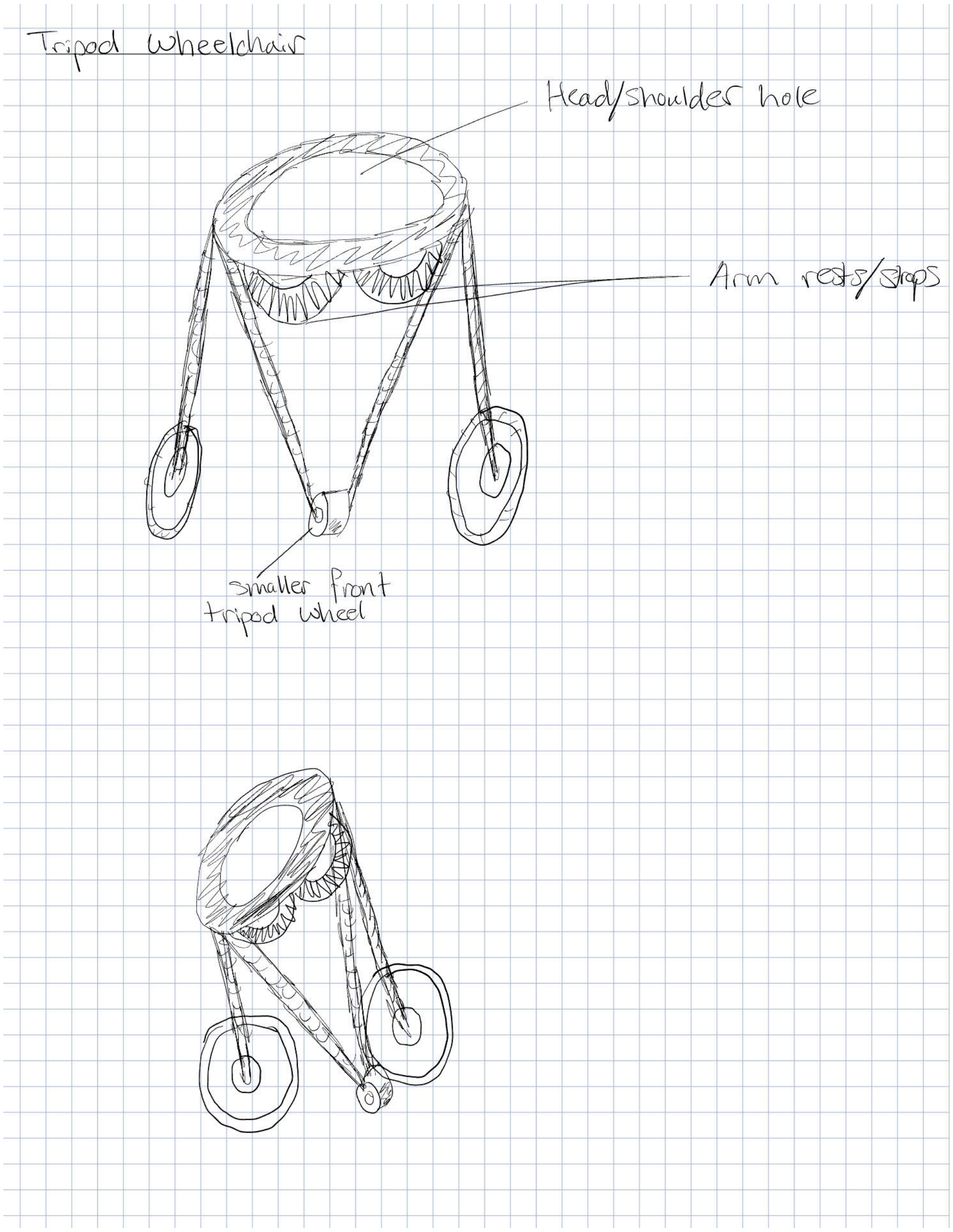


Figure 14: Tripod Wheelchair

Description: This design would support Henry's front legs and shoulders. There is a spot for his head and shoulders, made out of a comfortable fabric that would not irritate his skin. Below the head and shoulder hole, there are two straps where his front paws would rest. Thus, Henry's front end would be entirely supported by the wheelchair. This design would take the strain off of the front legs, which is where his deformity is the most prominent.

4 Concept Selection

4.1 Selection Criteria

The figure below gives various criteria we are using to design the prosthetic. Each criterion is weighted against the others to determine the most important aspects of the device. This process helps determine scoring matrix weights that will be used to determine which of the proposed designs will be the best fit for what we want to accomplish with our device.

	Wrists and back are not strained	**Device allows comfortable walking mechanics with no skin irritation**	**Design is resistant to environmental and mechanical wear**	**Henry is able to wear device while relaxing**	**Device attaches securely to body but is not cumbersome**		**Row Total**	**Weight Value**	**Weight (%)**
Wrists and back are not strained	**1.00**	3.00	9.00	5.00	3.00		21.00	0.38	38.35
Device allows comfortable walking mechanics with no skin irritation	0.33	**1.00**	9.00	7.00	1.00		18.33	0.33	33.48
Design is resistant to environmental and mechanical wear	0.11	0.11	**1.00**	1.00	0.20		2.42	0.04	4.42
Henry is able to wear device while relaxing	0.20	0.14	1.00	**1.00**	0.33		2.68	0.05	4.89
Device attaches securely to body but is not cumbersome	0.33	1.00	5.00	3.00	**1.00**		10.33	0.19	18.87
					Column Total:		**54.77**	**1.00**	**100.00**

Figure 15: Analytic Hierarchy Process (AHP) to determine scoring matrix weights

4.2 Concept Evaluation

The table below shows the three concepts we designed and the rated matrix for our selected criterion. Each device was rated on the five weighted criteria that we calculated from the criterion selection. The total score is then calculated and compared to decide which device is the most suitable for designing and meeting all the criteria that we wanted.

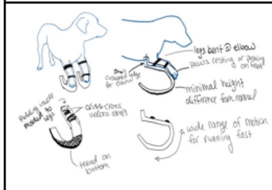
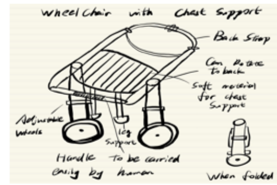
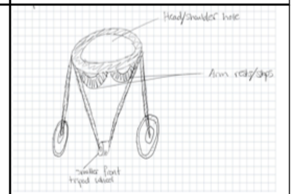
Alternative Design Concepts		C-Shape Prosthetic		Wheelchair Chest Support		Tripod Wheelchair	
							
Selection Criterion	**Weight (%)**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**
Wrists and back are not strained	38.35	4.5	1.73	3	1.15	3	1.15
Device allows comfortable walking mechanics with no skin irritation	33.48	5	1.67	4	1.34	4	1.34
Design is resistant to environmental and mechanical wear	4.42	4	0.18	3	0.13	3.5	0.15
Henry is able to wear device while relaxing	4.89	4	0.20	2	0.10	2	0.10
Device attaches securely to body but is not cumbersome	18.87	4.5	0.85	3.5	0.66	3.5	0.66
	Total score	**4.621**		**3.380**		**3.402**	
	Rank	**1**		**3**		**2**	

Figure 16: Weighted Scoring Matrix (WSM) for choosing between alternative concepts

4.3 Evaluation Results

Through use of the Analytic Hierarchy Process (AHP) and the Weighted Scoring Matrix (WSM), we were able to determine the importance of our design criteria as well as the best overall design concept proposed thus far. The Analytical Hierarchy Process revealed the most important design criterion is that Henry's wrists and back are not strain. The criterion with the second highest weight is that the device allows comfortable walking mechanics and no skin irritation. The three remaining criteria are still desirable, but not weighted as highly as the two previously mentioned criteria. Using the results of the AHP, our three concept designs were scored based on our selection criteria. The "C-Shape Prosthetic" was weighted the highest at 4.621, followed by the "Tripod Wheelchair" at 3.402, and the "Wheelchair Chest Support" at 3.380. Overall, the designs had fairly similar scores. The criterion with the highest difference in scores between the designs was "Henry is able to wear the device while relaxing". The "C-Shaped Prosthetic" scored a 4, the "Wheelchair Chest Support" scored a 2, and the "Tripod Wheelchair" also scored a 2. Henry would be able to sit while using the wheelchairs, however he would not be able to lay down. Through this evaluation of our design criteria and our three design concepts, we determined that the "C-Shaped Prosthetic" is the best design for our device.

4.4 Engineering Models/Relationships

Three of our engineering models and relationships are shown below.

4.4.1 Model #1

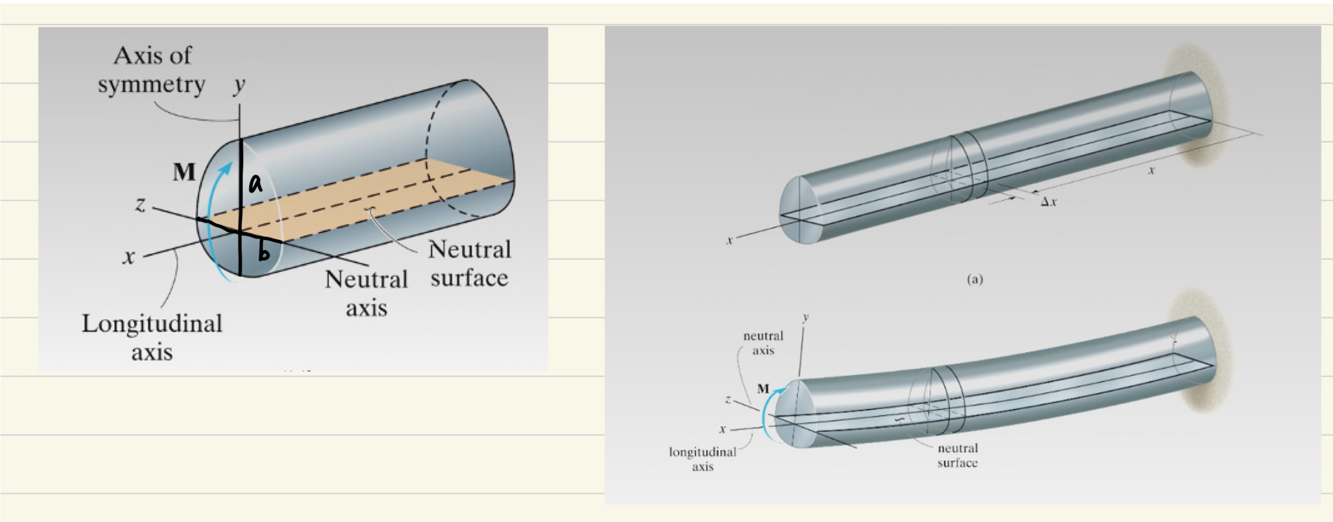


Figure 17: Engineering Models 1

Given: Moment M, horizontal length a, vertical length b.

Find: Shear stress and strain.

When we are determining the material for Henry's prosthetic, we need to calculate the shear stress and shear strain on the cross-sectional area of our design. After getting those, it is appropriate to decide the material that is able to resist such shear stress and strain with the appropriate safety factor considered.

4.4.2 Model #2

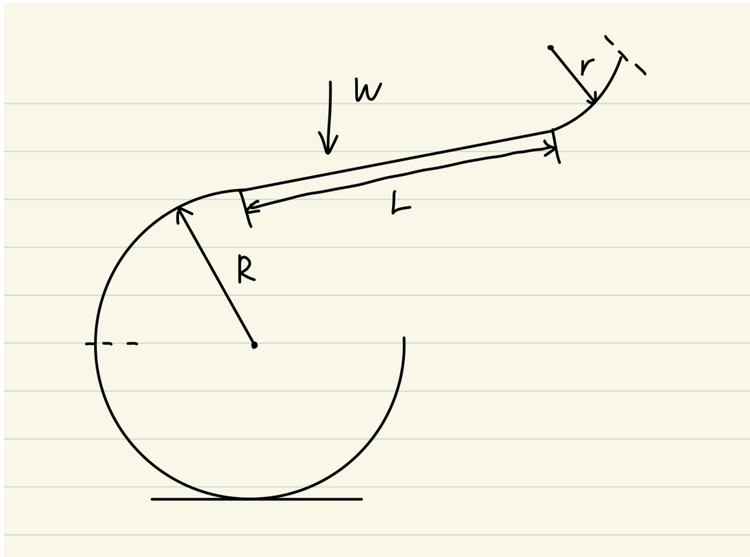


Figure 18: Engineering Models 2

Given: Width d, length L, radius R and r, weight W. Henry's front limb covers the part between the dashed lines.

Find: Pressure P = W/A

When designing the prosthetic, we need to consider the pressure that Henry is going to exert on the prosthetic. The pressure is used to determine whether it is comfortable and safe for Henry to use. Also, having that pressure will also assist us to find the appropriate material for this design as the metal should be able to resist such pressure.

4.4.3 Model #3

The variable dimensions for this model are the angle of the elbow (θ), thickness of the prosthetic (t), inner radius (r_i) and outer radius (r_o). The radii and elbow angle are dependent on each other, and both rely on the overall height of the prosthetic which is fixed to Henry's normal height. Not labeled is the wall thickness (t_w) which can also be varied along any part of the prosthetic.

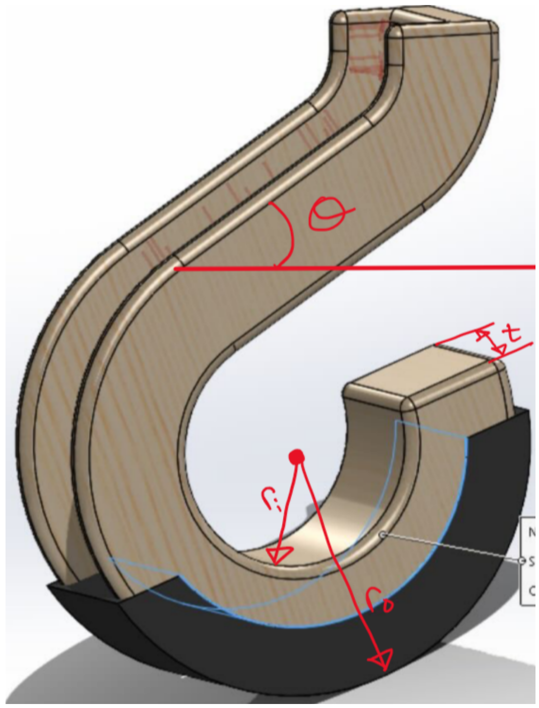


Figure 19: Model dimensions: elbow angle [θ], thickness [t], inner radius [r_i], and outer radius [r_o]

To decide on these parameters, we can preform a finite element analysis with Solidworks to see the stress concentrations on the model. Figures 20 and 21 include parameters necessary to model the stress analysis.

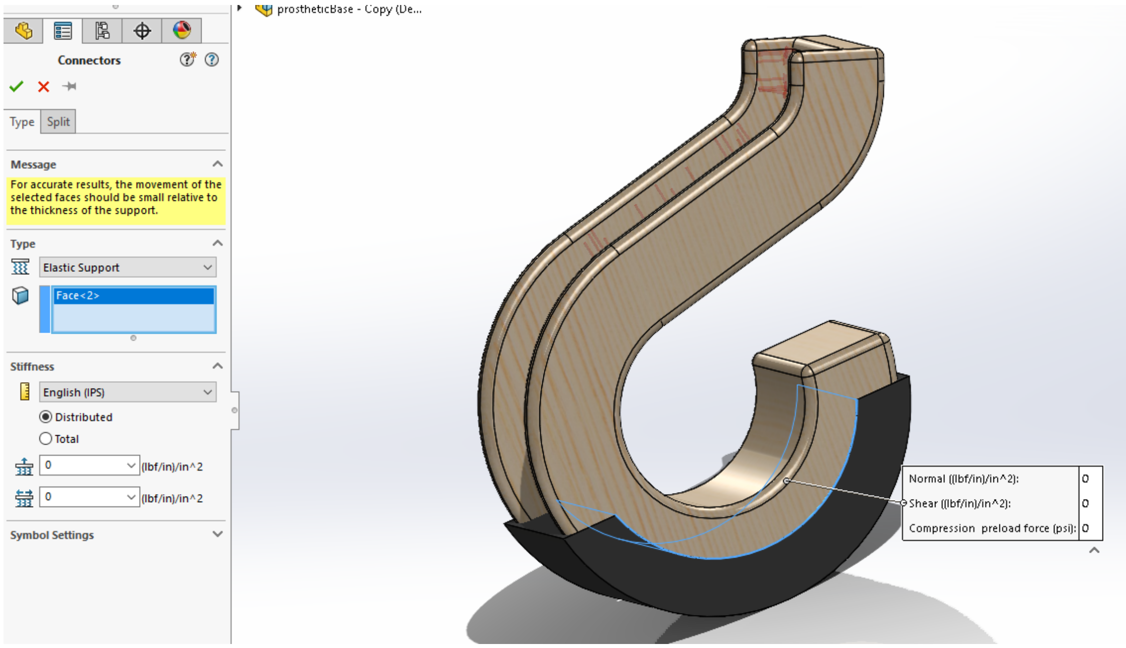


Figure 20: Elastic support parameters

The elastic support parameters pertain to the support given by the rubber tire. We can consider these as given variables, which can be found on the manufacturing details of the tires used.

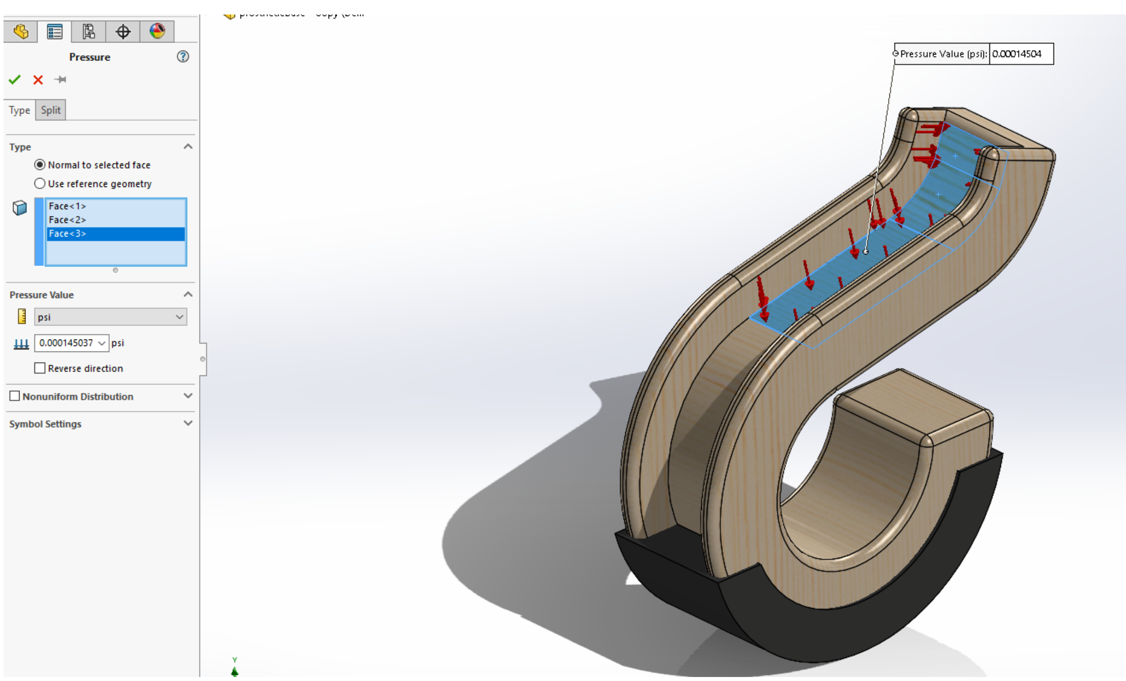


Figure 21: Pressure parameters

The pressure can also be considered a given, as we have Henry's weight and can evaluate the surface area which the weight will be distributed over, and pressure is force divided by area. With these given parameters, we can model the stress concentrations on the model and adjust the dimensions to minimize stress on the prosthetic frame.

5 Concept Embodiment

5.1 Initial Embodiment

The figures below show a drawing of the Initial Prototype assembly with top, right, and side views, and an unlabeled isometric view. Also, a large isometric view of the assembly, and an exploded view of the assembly with a Bill of Materials (BOM) and balloon callouts showing each item's BOM. This section will also detail the prototype performance goals.

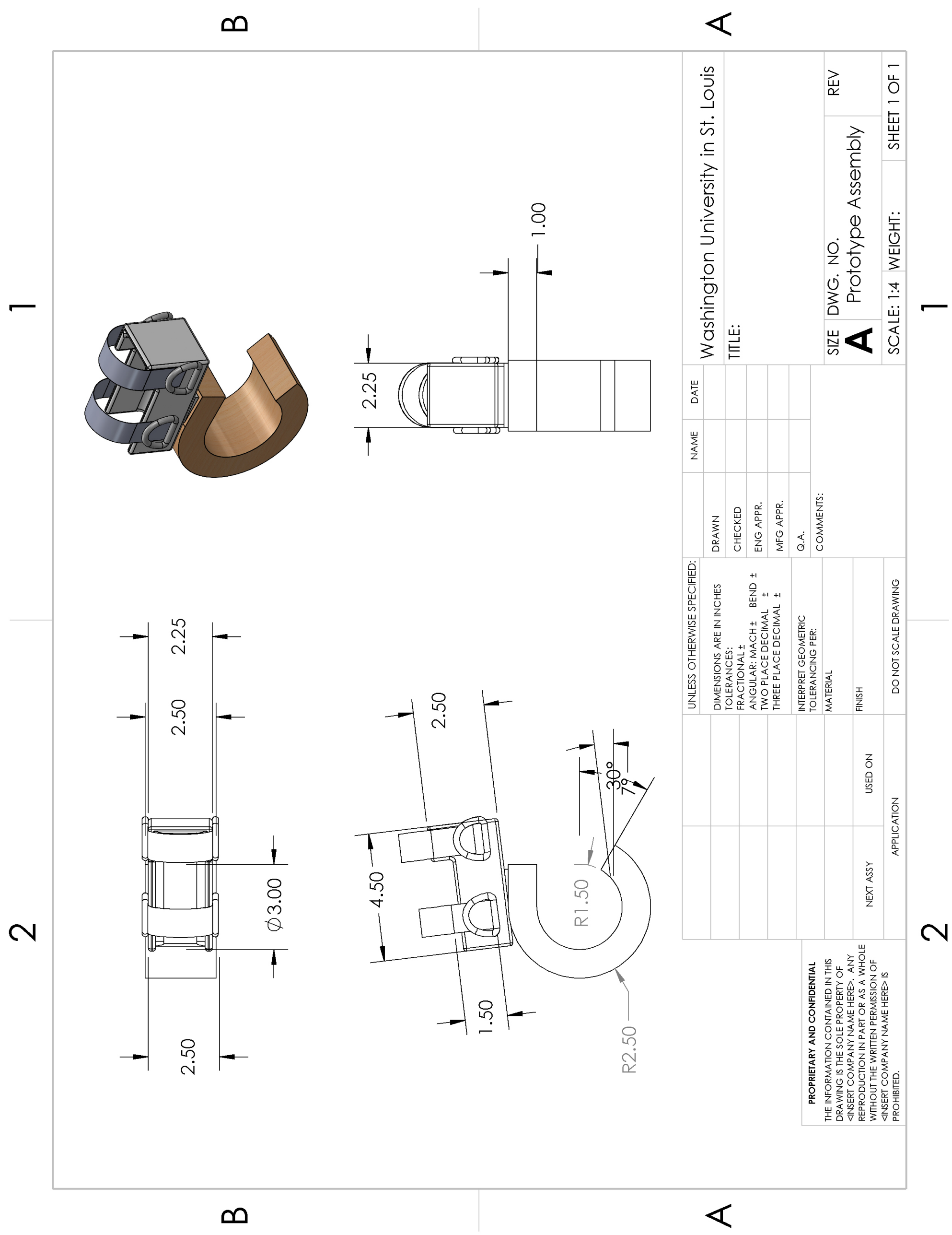


Figure 22: Assembled projected views with overall dimensions

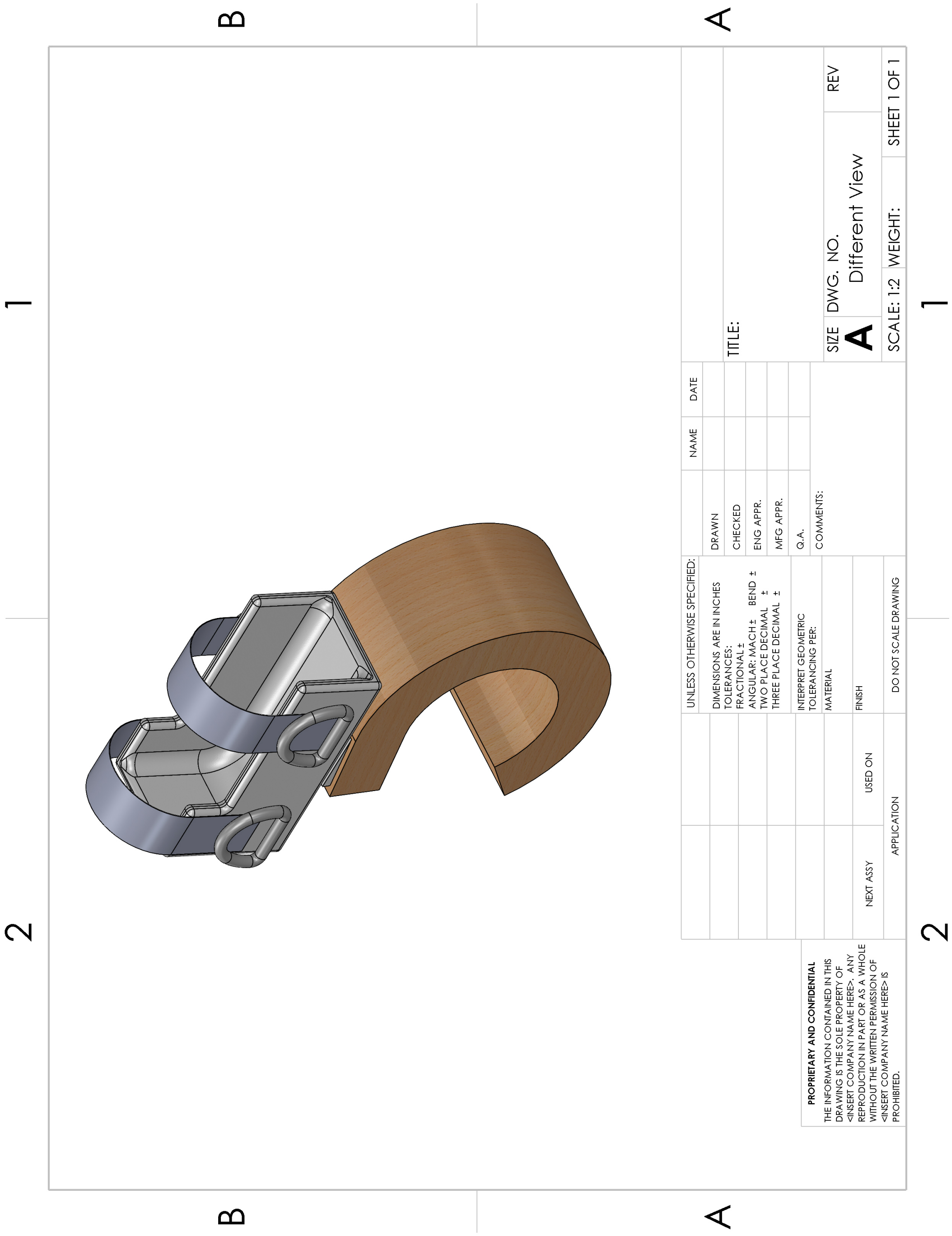


Figure 23: Assembled isometric view with bill of materials (BOM)

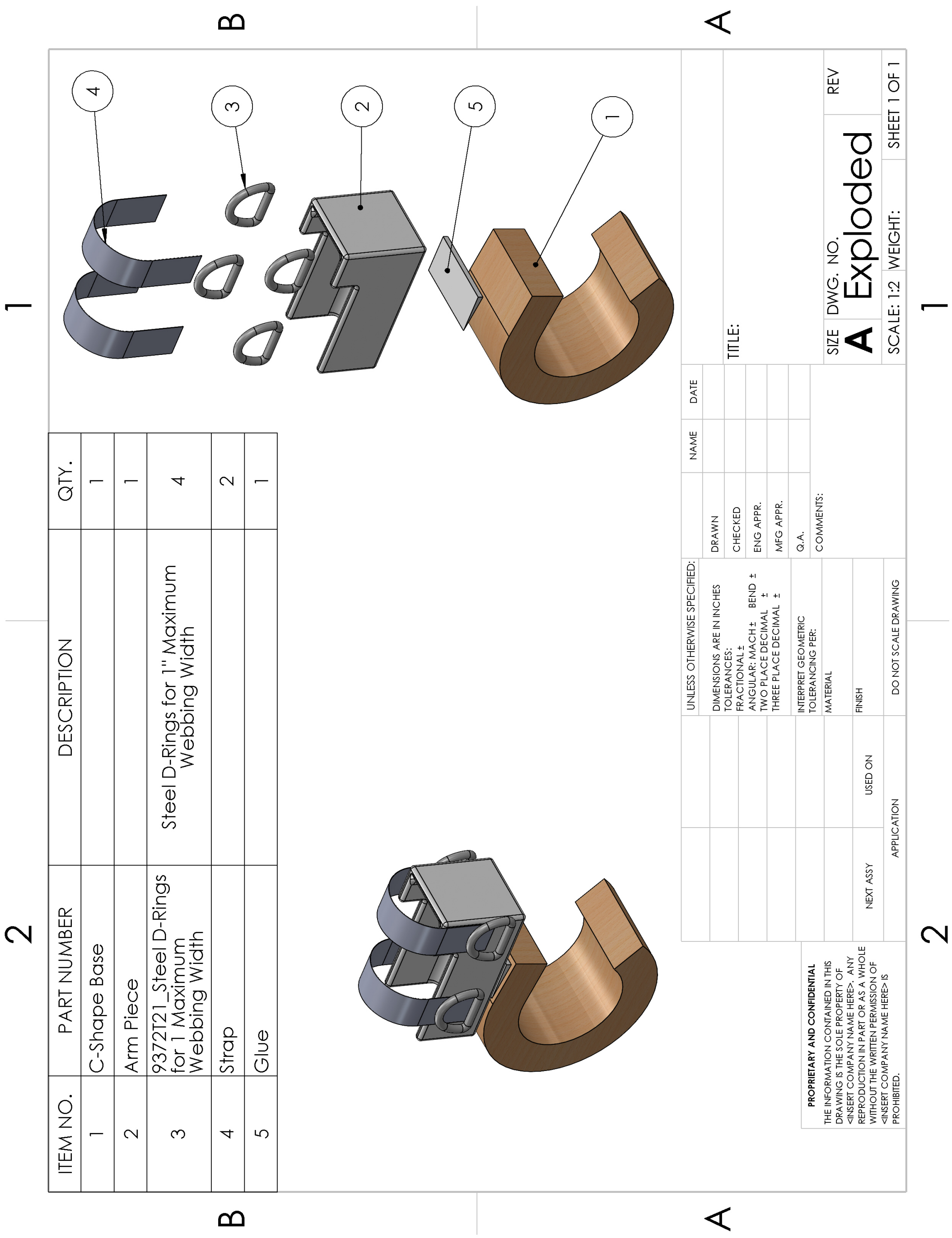


Figure 24: Exploded view with callout to BOM

The first performance goals for this prototype is that one prosthetic can support a vertical load of ≥ 50 lb without damage. The second performance goal is that Henry the dog can comfortably control motion of the prosthetics in all degrees of freedom. The third performance goal is that while wearing the prosthetics, Henry is able to stand, slowly walk forward, and turn (change his walking direction by ≥ 90 degrees).

5.2 Proofs-of-Concept

The first prototype of the prosthetic was the mock up shown in Figure 9. This gave us the initial idea for the shape of the device. For proof of concept, we created a SOLIDWORKS model of the body of the prosthetic and had that 3D printed. This proof of concept was much larger than we had envisioned, and ended up cracking after it was printed. This showed that we could significantly decrease the size of the device, and that we needed to find a different material to use for construction in order to decrease the weight. The proof of concept made it clear our initial design was much too heavy. We also tried to attach tire treads to the bottom of the device, in hopes or increasing traction, however the treads were difficult to attach to the 3D printed material and this idea did not work as planned. Testing of the proofs of concept led us to seek a different method for construction our initial prototype. Moving forward, we decreased the diameter of the c-shaped base of the device and decided to use wood for the construction to increase shock absorption and decrease weight. We also decided to use hot glue to create a tread, rather than attaching tire treads as we attempted in the proof of concept.

5.3 Design Changes

Overall, the initial prototype was very similar to the selected concept for the device. There were small changes between the chosen concept and the prototype. These changes include the straps and the diameter and shape of the c-shaped base. The overall shape was kept the same as the chosen concept, but the diameter ended up being much smaller than in the initial concept design. Additionally, the top of the c extends farther up than is shown in the original design. The type of straps shown in the concept design were velcro, however we ended up using buckles. Another change from the original design is the angle of the piece that supports the elbow. In the original design it was almost completely vertical, but in the prototype we increased that angle to improve comfort for Henry. Aside from small changes, the prototype is similar to the design concept on which it is based.

6 Design Refinement

6.1 Model-Based Design Decisions

After redesigning our overall shape to minimize weight and volume of the prosthetic, the models used for the design were reevaluated. The following models were used in order to ensure that our prosthetic's design is acceptable for use.

6.1.1 Model #1

To design the prosthetic, we needed to know how much pressure Henry would exert on the device. This is calculated by $P = W/A$. It was assumed that the majority of his weight would be distributed over the area highlighted in Fig. 25.

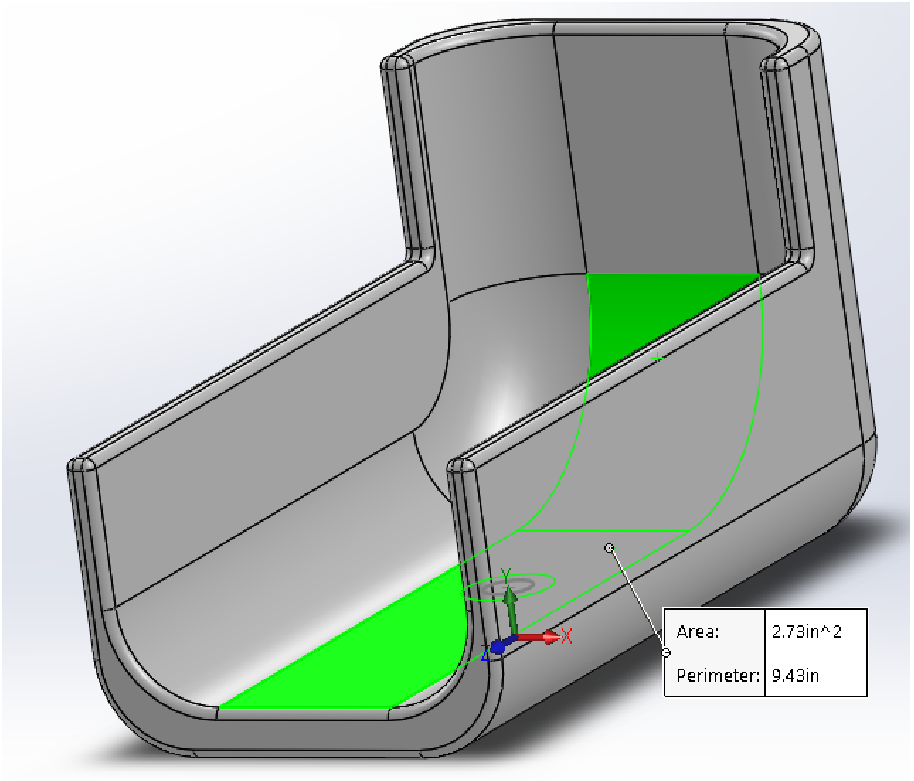


Figure 25: Surface Area of Distributed Force, A = 2.73 in^2

It is given that Henry weighs 35lbs. Thus, the pressure exerted on the prosthetic by Henry's weight is P = (35)/(2.73)=12.82psi. We can use this figure in subsequent models in order to simulate use of the prosthetic.

6.1.2 Model #2

Using the pressure calculated in Model #1, we ran a SOLIDWORKS simulation with the normal force of the pressure. The goal was to see stress and strain concentrations. Figures 26 and 27 show the two areas of highest stress concentrations.

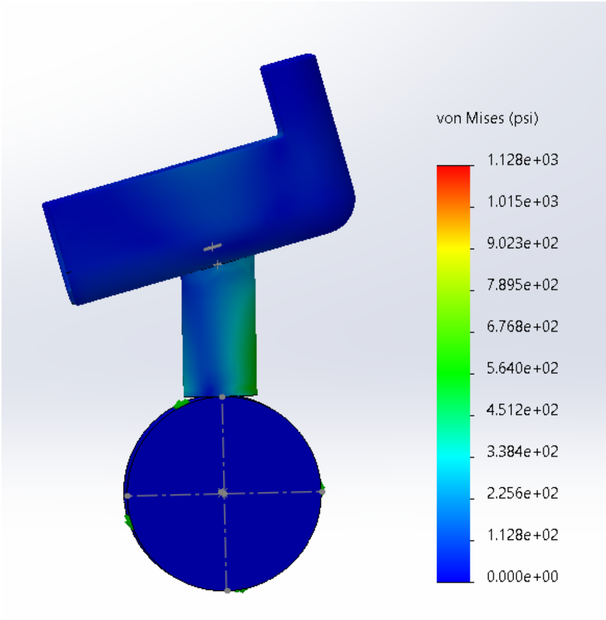


Figure 26: Stress Concentration on PVC Segment

There is an area of somewhat higher stress towards the back of the PVC segment. The stress is not extremely high, however, this could be minimized by moving the arm piece forward to balance the downward force more effectively.

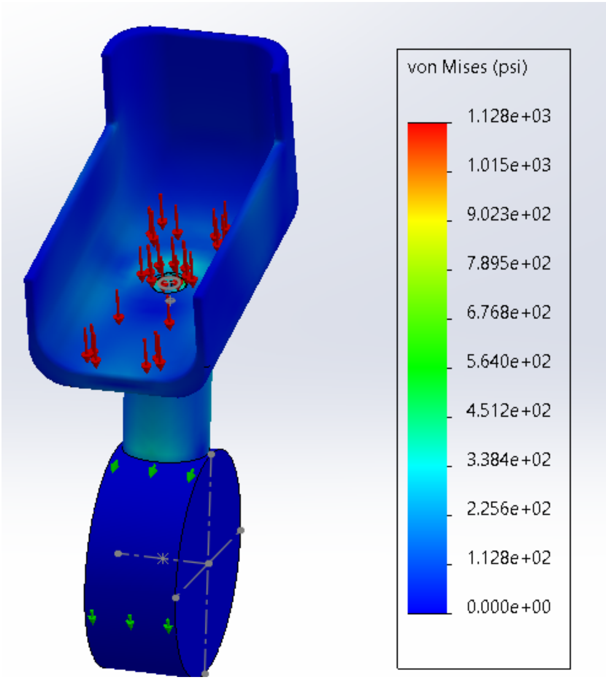


Figure 27: Stress Concentration on Arm Piece

There were also some small portions of higher stresses near the hole for the fastener. This is to be expected for any point with a fastener, so it is not a concern for our design.

Shown in Fig. 28, there was also a strain concentration on the back of the PVC segment.

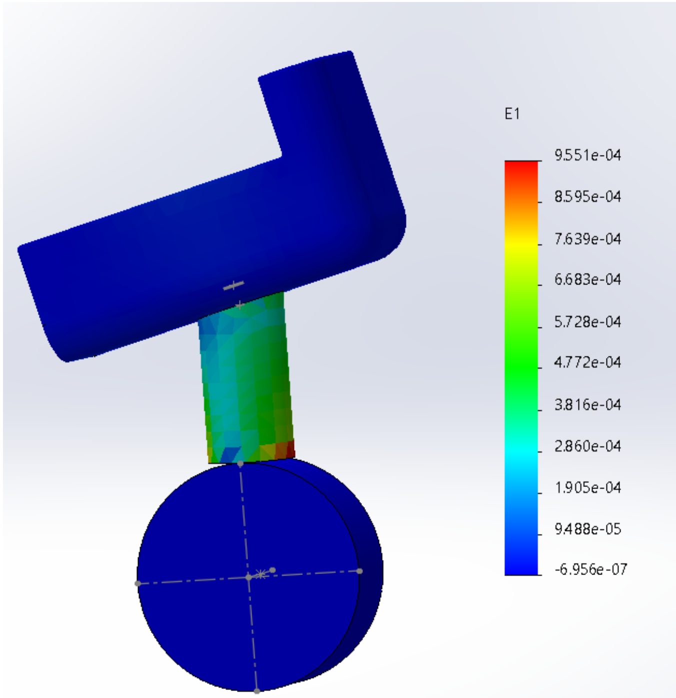


Figure 28: Strain Concentration on PVC

As with the stress concentration, we gathered that moving the arm piece would minimize this strain.

6.1.3 Model #3

From the SOLIDWORKS simulation, we were also able to find the displacement graph of the prosthetic, as shown in 29.

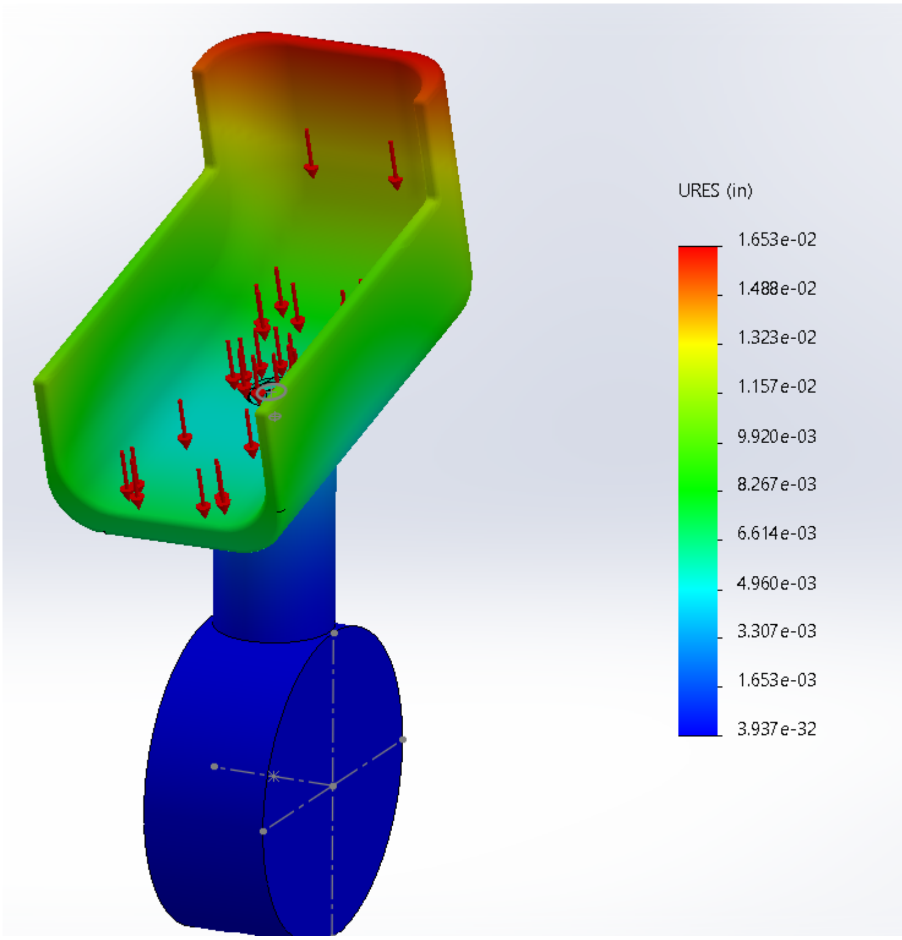


Figure 29: Displacement on Arm Piece

The arm piece showed a high displacement (0.016 in) at the top of the arm piece and no displacement on the bottom piece or PVC. This could be because of the positioning of the arm piece relative to the PVC and bottom base. The strain concentration in the PVC would allow the whole arm piece to tilt forward slightly, causing a high displacement on the top of the arm piece, a moderate displacement throughout the majority of the piece, and very little displacement on the fastener. We want to minimize this effect because repeated displacement of the prosthetic component under load could lead to cracking or breaking of the device. In our physical model, we will adjust the parameters accordingly and test with the simulation before assembling the device.

6.2 Design for Safety

6.2.1 Risk #1: Not Waterproof

Description: The frame of the prosthetic is not waterproof.
Severity: Negligible - This risk is negligible because it can easily be avoided with proper choice of material.

Probability: Frequent - If a waterproof material was not chosen, this risk would likely occur frequently. If the frame was not waterproof, the integrity of the device would be at risk.
Mitigating Steps: Utilize waterproof materials for frames of the prosthetic.

6.2.2 Risk #2: Toxic Material

Description: When the Henry bites or licks the prosthetic, he gets poisoned.
Severity: Catastrophic - If the material used were toxic, this would be very dangerous because it is hard to control what dogs bit/lick.
Probability: Likely - If the wrong material is used, it would be very likely that the dog could experience serious medical effects from ingesting the toxic material.
Mitigating Steps: Nonpoisonous materials and tests to ensure the material is pet safe.

6.2.3 Risk #3: Tip Over Instability

Description: With the current design, there is a hard edge on the side of the prosthetic. If Henry lost his balance or tripped, he could easily fall and injure his shoulder. This would likely cause shoulder strain, which we are trying to avoid.
Severity: Marginal - If Henry fell over while using the prosthetic, he may sustain some injuries but these likely wouldn't be too severe. However, we till want to avoid this risk.
Probability: Occasional - Tipping over is a possibility but not something that is likely to happen very often with our design. So this risk is only occasionally probable.
Mitigating Steps: To mitigate this risk we could alter the design to increase tip over stability. If we added more of a curved edge, this could allow for recovery after loosing balance, instead of automatically falling.

6.2.4 Risk #4: Wrist Injury

Description: Wrists handling too much impact load or prolonged load can cause injury or further deformation.
Severity: Critical - If Henry sustained a wrist injury from too much impact or load this would be critical. The deformity in his legs is the reason for building this product, so a wrist injury would be the opposite of what we are trying to accomplish with this device.
Probability: Occasional - While this risk is critical, it would not happen very often.
Mitigating Steps: Ensure that the prosthetic shape puts most of the load on his elbow and forearm.

6.2.5 Risk #5: Lower Back Strain

Description: Over time, there is a possibility of lower back strain due to overuse. Dogs with long bodies tend to have lower back issues, and the prosthetics will be putting his body in a slightly different position than he's used to. After prolonged use, there is a possibility of injury and strain to his lower back.
Severity: Marginal - Lower back strain would take a long time to occur, and with the current design it is not very probable. Therefore, the severity is marginal.
Probability: Occasional - This is an important risk to consider, however it would take a significant period of time to occur. Therefore, the probability is only occasional.

Mitigating Steps: To mitigate this risk we should make sure the prosthetics don't alter Henry's gait so much that it would make back issues more likely. We can make sure the height of the prosthetics are as close to the actual height of his legs as possible.

Severity of risk		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
	Catastrophic		Toxic material			
	Critical			Wrist injury		
	Marginal			Tip over instability Lower back strain		
	Negligible hazard presents a minimal threat to safety, health, and well-being of participants; trivial	Not waterproof frame				

Figure 30: Heat Map

Based on the heat map above, the most crucial risk that we have to address is that the material we are using for the design process should not be toxic. As Henry might bite his prosthetic from time to time, it is important for that to be food grade. Also, The next highest is to avoid wrist injury. We want Henry to wear the prosthetic for a long time and get used to it, so wrist injury should be avoided by decreasing the pressure on Henry's wrist. After that, the tip over instability, lower back strain, and water resistance of the frame should be addressed. These are not likely or extremely harmful to Henry, but if these problems are addressed, it will be very beneficial.

6.3 Design for Manufacturing

This design has five parts, excluding threaded fasteners. There are three threaded fasteners used in this design. The theoretically necessary components (TNC's) are the buckle straps and the d-rings. The straps need to be a separate piece because they need to be adjustable, so Henry's arm can be secured in the prosthetic. The d-rings are necessary because there needs to be some way to attach the straps to the device.

Hypothetically, this design could be modified so the body is all one piece and the only other parts needed would be the TNC's. The bottom piece, leg piece, and arm piece could all be made out of carbon fiber. A mold of the body of the prosthetic could be 3D printed so the body is one piece instead of three. The mold can be modeled in SOLIDWORKS and 3D printed in two parts which would allow us to use compression molding to shape carbon fiber into the desired shape. After the mold is 3D printed, carbon fiber flakes along with epoxy would be compressed inside the mold and allowed to sit for 24 hours (or as long as needed to cure). This would reduce the total number of parts (excluding threaded fasteners) to three instead of five. Another option for reducing number of parts would be to simply 3D print the body of the prosthetic as one piece. This would work in theory, however in practice would likely not be strong enough to withstand the stresses it would endure during use.

6.4 Design for Usability

1. Vision impairment (such as red-green color blindness or presbyopia) may influence the usability of your device. Henry is color blind, as he is a dog. The color of the prosthetic will not impact how Henry feels about the device. The color also will not impact the function of the device. Mason, Henry's owner, has stated that the color of the device does not matter to him. As this is a lower limb prosthetic, it will not affect Henry's vision at all.

2. Hearing impairment (such as presbycutia) may influence the usability of your device. Henry hears very well, so his hearing will not affect the use of this device. Henry's owner is not hard of hearing, so his hearing will also not affect the use of this device. The device does not require hearing to evaluate whether it is working or not. It also does not produce enough sound to affect Henry's or Mason's hearing.

3. Physical impairment (such as arthritis, muscle weakness, or limb immobilization) may influence the usability of your device. It is possible that the pet dog using the prosthetic is physically impaired with muscle weakness than immobilization. If the pet dog has weak muscles which cannot support its upper or lower body part, we will change our prosthetic to a wheelchair which supports the pet dog's upper or lower body.

4. Control impairment (such as those caused by distraction, excessive fatigue, intoxication, or medication side effects) may influence the usability of your device. There is a slight possibility that the pet dog has excessive fatigue or medication side effects. With such control impairment, our design of prosthetic might need to change to get a more stable frame for the pet dog. We would add some more auxiliary wheels on the sides or a more resistive material.

7 Final Prototype

7.1 Overview

The base of the final prototype is much smaller, and made of a carbon fiber and epoxy composite instead of wood veneer and wood glue. The leg piece is made of schedule 40 pvc and functions similar to the leg of a crutch. The arm piece is still made of moldable thermoplastic, but was molded directly to Henry's arm so the fit is much better. Velcro straps were fastened into the arm piece so that padding could be attached and as a way to secure Henry's arm in the device. The final prototype was tested for three performance goals. These goals were to withstand at least 50 lbs of vertical load, Henry can move his arm in all degrees of freedom, and Henry can walk forward and turn at least 90 degrees. All performance goals were met. Henry is currently not comfortable walking in the prosthetic on his own, however we are hopeful over time he will become more comfortable and be able to walk in the device on his own.

7.2 Documentation

The following images document the construction and testing of the final prototype.

Figure 31: Carbon fiber- epoxy composite base

Figure 32: Custom-molded thermoplastic arm

Figure 33: Velcro straps

Figure 34: Final Prototype

Videos of testing can be found here: https://wustl.box.com/s/x0s8gdmw4xye0lyg8p96t679c7weufsj

Figure 35: Performance goal 1: withstand at least 50 lbs of vertical load

Figure 36: Performance goal 2: Henry can move his arm in all degrees of freedom while wearing the device

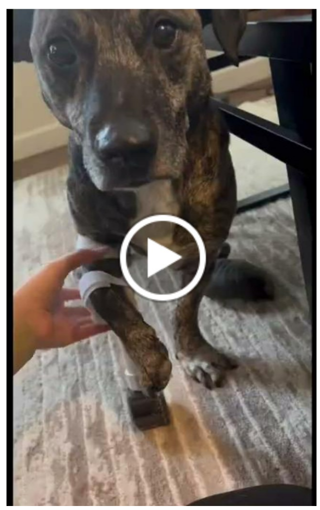


Figure 37: Performance goal 3: Henry can walk forward and turn at least 90 degrees

Figure 38: Henry standing in the prosthetic!