

# Design of a Prosthesis for Canines with Front Limb Deformities

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# Abstract

The current canine prosthesis market is catered towards dogs with amputations. Due to the variations in limb deformities, there is yet to be a customizable solution. Instead, the production of prostheses for deformities occurs on a 'case-by-case' basis and the products are tailored to a specific user. The goal of this project was to design and fabricate a low cost device that would increase mobility and stabilize the gait of the canine user. Our project focused on a dachshund with a front limb deformity to produce a device that can be customized to other canines with similar deformities. The final device was a 3D printed custom fit prosthesis.

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# Chapter 1: Introduction

As society continues to evolve and technology advances, animal prosthetics have become more prevalent and accessible in today's society. Prosthetics are used to improve the quality of life, not only for people, but canines as well. The market of canine prosthetics is growing as more people acquire dogs as pets. According to the 2015-2016 APPA National Pet Owners Survey statistics, approximately 65% of U.S. households have a pet. Among this percentage more than 68%, about 54.4 million U.S. households, own at least one canine companion [1]. The U.S. pet industry expense is estimated to be 60.28 billion dollars in the year 2016 alone [1].

The market for prosthetics in this population is relatively new. There are a variety of prosthetics currently available to compensate for the absence of a limb. This industry is currently limited to creating prosthetics that are designed and are customized for the patient. Due to the fact that canine prosthetics have to be customized to the specific needs of the dog, there is no "official gold standard" prosthetic for canines. In addition, because canine prosthetics are a custom market, these prosthetics are expensive at an individual cost upwards of \$1000 [2]. Many factors are involved in the designing and fabricating of a functioning prosthetic that fully meets the needs of a client. Types of prosthetics range in complexity, from body-powered prosthetics to externally powered prosthetics, and the final design depends on the application and the recipient's condition. However, there is very little in the current market that targets dogs with abnormally shaped limbs. This is because the current gold standard treatment is typically to amputate a maimed/deformed limb (Appendix A). That being said, it is a common occurrence for dogs with a partial or deformed limb to go without prosthetics due to the belief that they can compensate well with on three limbs. Despite this long standing belief, there is a sizeable pool of amputee dogs that are fitted for prosthetics and thrive as a result [3]. There is still a gap in the market for prosthetics that target dogs that have not undergone amputation.

Our project team was tasked with creating an affordable prosthetic device for a Dachshund breed dog with a front limb deformity, named Baxter, who has not undergone amputation. Baxter's front left limb is significantly shorter than the right counterpart. After physical inspection and measurements the deformity appears to be in his left forefoot, while the upper arm and forearm appear to be of a normal length in comparison to the right limb.



**Figure 1: Comparative image of Baxter's two front limbs. As seen from this image, Baxter's deformed limb is shorter than the healthy limb (Left). Shows Baxter's deformed limb is missing digits as well as other anatomical parts of a normal paw (Right).**

His left deformed paw is only one centimeter in length and physically appears to be missing crucial anatomical landmarks (Figure 1). This deformity can possibly be related to a genetic disease called chondrodysplasia. This disease is found in canine and is characterized by crippling deformities and abnormally shaped limbs. The severity of this disease ranges from mild to extremely severe. In mildest cases, dogs would appear normal, however, with front leg deformity. In extreme cases, dogs would be completely crippled due to severely deformed limbs [4].

While it is true that some dog breeds can function well as a tripods, this is not the case for all dogs. In the case of small dogs amputation would not be the optimal treatment. In addition, one of the user needs as stated by our client, Baxter's owner, was not to pursue amputation as a viable option. As a result, an objective of this project was to design and create a device that, without amputation, would increase mobility. The device we aim to create should also assist in stabilizing the gait of small dogs with front limb deformities. This device was not created to only apply to Baxter but the process aims to be applicable to other small dogs with similar front limb deformities as well.

In order to test the prosthesis and verify it against the project objectives, a set of tests were designed to be completed by Baxter with and without the prosthesis. The client's healthy dachshund was tested in addition to Baxter to provide a reference point or a "control" to compare test values obtained from all of the tests in the set. The tests without the prosthesis were completed

before designing the device to enable the project team to identify the main areas that needed improvement.

The team performed various tests to ensure the success of the prosthesis. These tests focused on numerically improving the dog's static gait as well as the kinetics of the dog's walking gait. Four tests were done to quantify the results. Initial testing was done to understand the dog's weight distribution during standing, or static, gait. For this test, two of the dog's limbs were placed on a force plate at a time. The percentage of overall body weight on the front and back limbs was separately recorded.

Three separate joint angles relative to the medial plane were found during walking gait. The three regions selected were the shoulder, elbow, and carpal angles pre and post prosthesis. The team chose these regions for analysis due to observations made when comparing the case dog's normal walking gait with the client's healthy dachshund. It was noted that his shoulder inverted, due to compensation for the deformed limb, causing his healthy forelimb to go towards the center of his body. It was also noted that his elbow and carpal angles did not have as large of a range of motion as the control. These joint angles were calculated by placing small fiducial markers at the appropriate anatomical landmarks and using video analysis to locate the coordinates of the markers at various positions. The coordinates obtained from this testing were used to calculate the joint angles during standing and walking gait. After successfully manufacturing the device and validating its functionality with the dog, the team created a website and published the process of creating the final prototype. This process includes a guide for recreation of the prosthesis as well as modifiable CAD files of the final design.

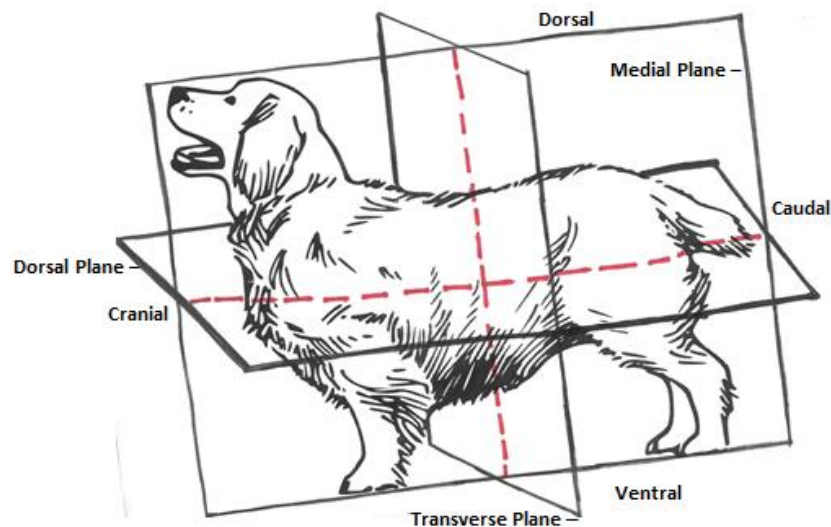
The following chapters will provide greater detail on the methods used to produce the final product. The literature review will delve further into canine anatomy, the gait cycles of canines, prosthetics, manufacturing processes, and further topics. The project strategy chapter outlines in greater detail the approach for this project. Our initial client statement is presented, followed by our objectives and constraints. This leads to the revised client statement. The design alternatives chapter gives more insight to designs that were considered but not chosen due to the constraints and design criteria. The final design validation chapter provides data from our testing and proves that the final design accomplishes the goals the group set out to accomplish. The conclusions and recommendations chapter is a summary of the team's work and suggestions for future works.

## Chapter 2: Literature Review

The purpose of this chapter is to provide information on canine anatomy, front limb deformities, canine amputation, prosthesis design and fabrication, the quadruped gait cycle, prosthetics available to canine amputees in the existing market and rehabilitation therapy. These topics helped give the team a reference point in the design, fabrication and implementation of the final device.

### 2.1 Canine Anatomy

There are three anatomical planes in the canine body; the median, dorsal, and transverse plane. The median plane divides the canine at the snout lengthwise through the body into left and right halves. The dorsal plane separates the upper and lower halves of the canine. Lastly, the transverse plane intersects the midline of the canine torso separating the fore and hind limbs. These planes, seen in Figure 2, will be used from this point forward when referring to different anatomical segments.



**Figure 2: Canine anatomical planes**

In addition, the veterinary community uses the terms cranial/caudal and dorsal/ventral to describe the relative location of canine anatomical features. Cranial indicates the feature is towards the head while caudal indicates towards the tail. The term dorsal is used when describing features that are on the upper half of the body, while ventral is used for features that occupy the lower half



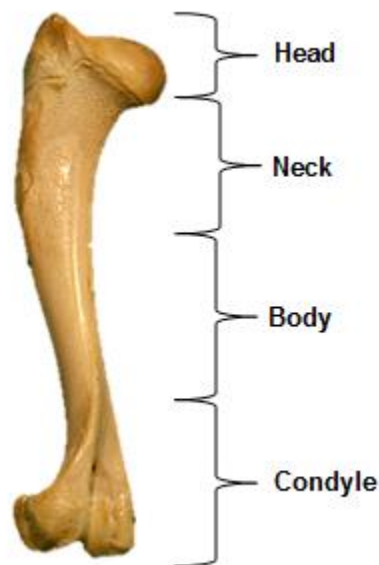
(Figure 2). Overall, the canine limb anatomy is fairly homologous to humans. Many of the same bones found in canines are reflected in the human skeletal structure.

### 2.1.1 Forelimb Structure

The limb of focus in this report is the forelimb. Each healthy canine has two forelimbs at the cranial end of its body. It can be noted that the hindlimb has a similar overall structure as the forelimb. For the purpose of this report many of the anatomical descriptions are simplified and the muscle insertion/origin locations are generalized.

#### 2.1.1.1 Skeletal

The bones of the forelimb can be broken into three groups; the upper limb, lower limb and paw. The upper limb consists of the humerus. The humerus connects with the scapula proximally to form the shoulder joint and connects with the radius and ulna distally to form the elbow. It is broken into 4 parts, the head, neck, body, and condyle. The head and neck are located on the proximal end of the bone while the condyle is located on the distal end. These structures are separated by the body of the humerus. These anatomical structures can be located in Figure 3.



**Figure 3: The anatomical structure of a canine's humerus [5].**

These portions of the bone are responsible for joint interactions and are fairly standard across breeds. In contrast the body of the humerus varies greatly in shape and size based on breed [6]. The lower limb is comprised of the radius and ulna (Figure 4). These bones run parallel with

each other. The ulna is the longer of the two bones and is the longest bone in the canine body. The radius is the shorter of the two bones and is the main weight-supporting bone of the forelimb [6].



Figure 4: Images of the A) Radius and B) Ulna in a dog's forearm [7].

The paw is further broken into the carpus (wrist), metacarpus, and phalanges. The carpus is composed of seven bones arranged in two transverse rows [6]. Distal from the carpus are the five metacarpal bones in a single row (Figure 5).

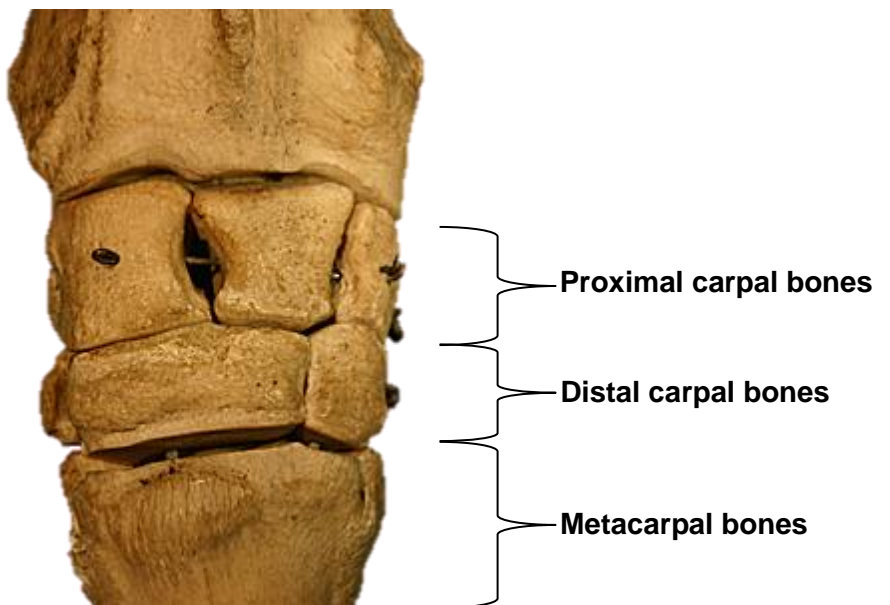


Figure 5: Carpal bones in the wrist or knee of a dog [8].

Lastly, each metacarpal bone connects distally to the phalanges or toes. There are four fully developed and one rudimentary phalanges (Figure 6). Each of the fully developed phalanges consists of a proximal, middle phalanx, and distal phalanx.

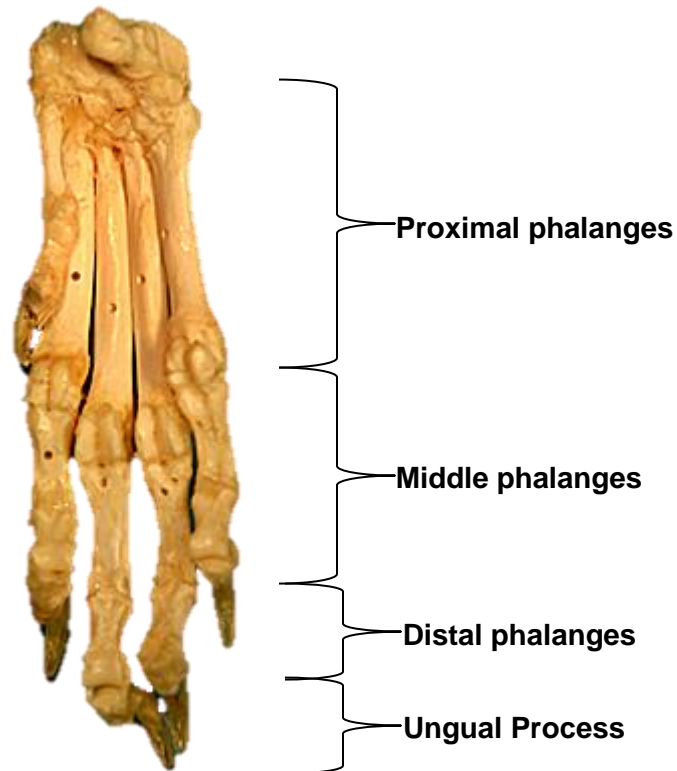


Figure 6: Phalanges attached to each metacarpal bone [9].

## 2.2 Front Limb Deformities

There are several developmental bone disorders that cause limb deformities in dogs. Some are congenital, genetic, and or due to nutritional deficiency. Trauma is one of the most common causes, which can lead to an interference with cartilage production hindering bone development [10]. Some of the most common diseases that cause one front limb to be shorter than the other include Angular Limb Deformity (ALD), Antebrachial Growth Deformity (AGD), and Chondrodysplasia [10].

### 2.2.1 Angular Limb Deformities (ALD)

One of the most common front limb deformities is angular limb deformities, which is an abnormal development of the foreleg bones due to growth plate injury. This could cause one limb

to be shorter than the other. It can also cause partial displacement of the elbow joint and or twisting of the carpus. This disease mainly affects small dogs such as dachshund and basset hounds. This disease can occur due to a variety of reasons such as genetics, injury in the growth plate before fully developing, and damage of the blood supplies [10]. There are no known treatments for this disease, other than surgery, and it can be diagnosed by the doctors using X-rays [11].

### 2.2.2 Antebrachial Growth Deformity (AGD)

Another common deformity is the Antebrachial Growth Deformity (AGD), which occurs when one leg continues to grow after the other one has fully grown [12]. As a result, one of the limbs will be irregularly shaped, which leads to misalignments between the front limbs. This deformity usually occurs due to an early closure of one of the growth plates [10]. This deformity can be diagnosed the same way as ALD using X-rays, and can occasionally be treated through corrective surgeries or by using internal or external braces [10].

### 2.2.3 Chondrodysplasia

Chondrodysplasia is a genetically transmitted disorder that results in shortened front limbs in many breeds of dogs. This disorder is a type of osteochondrodysplasia where it affects the development of the bones and cartilages of long bones. In order for a dog to have this disorder, both of its parents must carry this gene [13]. The severity of Chondrodysplasia can vary significantly from one case to another. It can cause crippling effects in one or more of the limbs. In mild cases, dogs can have a fully healthy life and are able to perform all of their daily activities. In severe cases, dogs will have four deformed limbs and are unable to survive on their own. In these severe cases, most dogs are usually euthanized [13]. This disorder is genetic, and therefore there is currently no treatment available.

## 2.3 Understanding Amputation in Canines

A difficult decision for a dog owner to make is amputation, but sometimes it is needed to minimize pain and potential future complications. Amputation is used when canines undergo severe trauma, develop cancer, or have a birth defect. The dog's age, weight and disease severity could affect the need for amputation. However in some cases, amputation is not the answer to the problem [3].

### 2.3.1 Limitations

Tripods, or 3-legged dogs, can experience challenges due to change in gait. Canines can compensate in different ways to make up for the absence of a limb. Hind Limb amputations often have the least impact as the canine is more easily able to shift the hindlimb to the center of the body. In contrast, forelimb amputations are more difficult to compensate for as the canine supports more of its body weight on its forelimbs.

Some physical limitations with forelimb amputations include, but are not limited to difficulty with walking/running, climbing inclines such as stairs, difficulty with urinating and defecating. In addition, an accumulation of fluid at the surgical site, called a seroma, can follow amputation. Seromas can cause the surrounding tissues to become infected and, in severe cases, cause tissue necrosis. The seromas could prevent proper healing from occurring thus causing the need to perform another surgery. Tripod's can also experience phantom limb pain, which is when a nerve is trying to control a limb that is no longer attached. This is a pain that is felt in the region where the limb is missing. Phantom limb pain is not a pain associated with mechanical stresses, but with the misinterpretation of generated impulses from the residual limb by the central nervous system. Over time, sometimes phantom limb pain can go away [14]. According to some rehabilitation experts there are consequences, both long and short term, that prevent dogs from being able to function properly on 3-legs. Some of those consequences include the residual limb experiencing degenerative joint problems and breakdown in the tissues [3].

### 2.3.2 Advantages

Amputation does have benefits as well as drawbacks in certain cases. Those cases include diseases, tumors, and other physiological abnormalities that the dog may undergo. In some cases, amputation is the only option to save a dog's life. When a dog gets bone tumors, that potentially cancerous invasive tumor will spread throughout the body killing the living cells and simple excisions are not enough to remove it. Therefore, the best way to cure the disease at the specific location of the limb is to remove the limb entirely. In addition to the removal of bone tumors, amputation of the limb may be favorable when severe trauma occurs to the tendons and ligaments as well as the occurrence of multiple fractures. Amputation may also be a more cost effective way of resolving the situations that involved more complicated medical problems that require more

extensive surgery. As a result of negative perception towards amputation, pet owners are becoming more in favor of salvaging the limb [3].

## 2.4 Prosthetics Overview

Prosthetic limbs are artificial replacements for missing limbs due to a deformity, injury, or amputation. In most cases, these replacements are intended to replace the functionality of the missing limbs; however, in some instances, they are made for cosmetic purposes. Prosthetists, trained professionals in creating prosthetics, are an integral resource in the process of fabricating prosthetics for specific individuals.

With the new developing technologies, the field of prosthetics has been developing incredibly quickly. Many different techniques and technologies have been employed on both the functionality and aesthetics of the prosthetics, such as 3D printing and biometrics. Current prosthetics provide more than the basic need of the functionality; rather they endow a sense of wholeness to the patients as they provide similar gaits to the original limbs, high level of mobility, and controllability. The advancements in technologies have moved beyond providing solutions to human needs. Prosthetics are now being used to improve animal lives. In the past, animals born with defects or facing serious injuries are euthanized, simply because they are unable to survive on their own. Now things are changed and many animals, such as birds, dogs, cats, elephants and turtles, are being helped to obtain their ability to move and perform their daily activities with the use of prosthetics.

Prosthetics exist in various complexity levels and are diverse in mechanisms, functions, materials and designs. Currently, there are many types of prosthetics available that range from passive to hybrid prosthetics. Passive, also known as cosmetic, prosthetics are used for visual replacement purposes only and provide no mechanical stability and functionality. The second type of prosthetics is the body powered prosthetics, which uses the body's natural movement such as glenohumeral flexion, scapular protraction or abduction, shoulder elevation or depression, and chest expansion to generate a mechanism for controlling their movement, which may require some adjustments and training. Body-powered prosthetics are the most common type of prosthetic used with canines due to their simplicity, efficiency and cost effectiveness. A more advanced type of prosthetic is a myoelectric prosthetic, which involves the use of the residual limb and an electric motor. An electromyogram is used to convert the muscles action potential to electric power. This

electrical power gets amplified and is used to control the prosthetic. These advanced myoelectric prosthetics can be combined with body powered prosthetics to form hybrids [15]. Another uncommon type of prosthetics that is used in canine is the stump socket prostheses (SSP), which are applied when only a stump remains in a dog. This mechanism of this prosthetic relies on the interaction and transmission of forces between the load bearing residual limb and soft tissues and the prosthesis. In addition to its frequent adjustments requirement and difficulty to maintain, SSP can cause irritation or infection in the skin as well as tissue necrosis [16].

#### 2.4.1 Factors and Considerations in Designing a Prosthesis

Each patient and their physical limitations is unique and requires a custom-fit prosthetic. When designing the prosthetic, many factors need to be considered. Factors that need to be considered are the forces that transmit from the device and the residual limb, the pressures distributed amongst the interface between the device and residual limb, and the material properties and structure of the prosthetic device [17]. Ultimately, the goal of a prosthetic is to restore walking capabilities and thus the prosthesis needs to be able to support the user's body weight in a comfortable manner while distributing mechanical stresses properly throughout the prosthetic and residual limb.

When designing a prosthetic, it is important to understand how deviations occur in the patient's gait and pressure distributions. A prosthetic changes the way forces interact with the residual limb. Using the equation  $\text{pressure} = \text{force}/\text{area}$  a prosthetic socket applies a force that is distributed amongst a specific area creating an applied pressure to the residual limb. Using the same equation, increasing the surface area of the prosthetic reduces the pressure applied to the residual limb. Therefore, reducing the applied pressure by increasing the contact area underneath the foot can lead to a decrease in pain the user of the prosthetic experiences.

In addition to size, positioning of the prosthetic on the residual limb is important. Aligning the prosthetic alters the joints of the artificial limb and position of the residual's lower limb extremity in relation to the ground reaction force. This will affect the gait of the user. With an amputee, the missing limbs will not be able to counteract the ground reaction force because the necessary muscles and joints are not present. A prosthetic will be able to act as the artificial limb to counteract the ground reaction force. The prosthesis should be able to withstand axial loading; the transmission of vertical forces through the longitudinal axis of the body. Thus the prosthetic has to

be able to exert an equal and opposite force on the patient's body weight acting downwards. Ultimately, when designing a prosthesis many factors are involved to fabricate the most mechanically optimal prosthetic specific to the patient's needs [18].

#### 2.4.2 Materials in Prosthetic Design

For the prosthetic to function optimally, the device needs to be lightweight and strong. One of the most common materials used in prosthetics today are thermoplastics. Thermoplastics are ideal for prosthetic applications because of their moldability and mechanical properties. Thermoplastics can be used as both the structural components of the prosthetic as well as for the socket interface. Two of the most basic thermoplastics are polypropylene and polyethylene. Polypropylene, due to its rigid structure, is typically used as the supporting structure of the prosthetic interface [19]. Polyethylene is softer and more flexible than polypropylene and is often used as the socket component of the prosthetic. Both polypropylene and polyethylene can be heated and reshaped to provide an optimal fit. Since prosthetics are made to be lightweight, they are typically fabricated with plastics or lightweight metal. Another material used in the socket of prosthetics is silicone. Silicone is used to cushion the limb and reduce friction within the socket.

The prosthetic shin portion of the limb is known as a pylon, usually they are made from aluminum and titanium due to their light weight and mechanical properties. Titanium is lighter than aluminum but it is also more expensive. Stainless steel is both heavier and stronger than both titanium and aluminum. Due to its weight, stainless steel is only used for small components within the prosthetic that may require a higher strength. However, new developments have made in using alloys of the materials to achieve better properties. Carbon fiber has also been explored as an option for fabricating a pylon that is lightweight. The aforementioned materials are summarized in Table 1.



**Table 1: Possible materials and properties to fit device function [20] [21]**

<b>Function</b>	<b>Material</b>	<b>Properties</b>
Internal Structure	Titanium Alloys	<ul style="list-style-type: none"> <li>- Light weight</li> <li>- Expensive</li> </ul>
	Aluminum Alloys	<ul style="list-style-type: none"> <li>- Strong</li> </ul>
	Stainless Steel	<ul style="list-style-type: none"> <li>- Heavier &amp; stronger</li> <li>- Usually used for small components</li> <li>- Cheap</li> </ul>
	Carbon Fiber	<ul style="list-style-type: none"> <li>- Light Weight</li> </ul>
Socket	Polypropylene (PP)	<ul style="list-style-type: none"> <li>- Rigid structure</li> <li>- Soft &amp; Flexible</li> </ul>
	Polyethylene	<ul style="list-style-type: none"> <li>- Thermoplastic: can be reshaped</li> <li>- Softer &amp; more flexible than PP</li> </ul>
	Silicone	<ul style="list-style-type: none"> <li>- Reduces friction</li> </ul>
Feet	Urethane Foam w/ Wood interior	
Physical Appearance	Polyurethane Foam	<ul style="list-style-type: none"> <li>- Soft</li> <li>- Can be painted to look like skin</li> </ul>

### 2.4.3 Manufacturing Prosthetics

Prosthetics can be made through various manufacturing processes and steps. Parts of the prosthetic, such as the pylon and ground interface, can be mass-produced for purchasing. The

socket portion of the prosthetic however needs to be custom- made to the user and cannot be mass-produced. Before manufacturing occurs, proper and accurate dimensions need to be taken of the residual limb. An impression mold is taken of the residual limb and creates a cast to be used to make a replica of the residual limb.

There are two main parts of the prosthetic that require manufacturing, the socket and the artificial limb. The socket can be made by vacuum forming a heated thermoplastic around the cast/mold that was made of the residual limb. Vacuum forming is when the air that sits between the mold and thermoplastic sheet is sucked out of the chamber cast causing the sheet to collapse around the mold of the residual limb. Before permanently setting the fabrication of the final socket into its final shape, this thermoplastic test socket is tested on the user and the user's gait is analyzed with the test socket attached. If it is required, the test socket can be adjusted accordingly by reheating the thermoplastic and adjusting the shape. Once final shape is ensured, the test thermoplastic socket is left to permanently set. When ready, a plastic, usually polypropylene, is used to make the final socket through vacuum forming like the test thermoplastic socket was made [20].

Manufacturing the prosthetic limb can be done in various ways. If using plastic pieces, they can be made through injection molding, vacuum-forming, and extrusion. Injection molding is when plastic is melted and forced into a mold and left to cool. The process of vacuum forming is explained above in the fabrication of the socket. Extrusion is the process of pushing material through a set shaped die to produce a product of continuous shape. The pylons can be made from metals, such as aluminum and titanium and be fabricated using die- casting, which involves melting the metal into a liquid and forcing that liquid to form the proper shape in a steel die. Once the components are made, they can be assembled through adhesives, screws and bolts, and lamination. Lamination is a technique that builds layers to improve the strength and stability and can be done through welding, heat, pressure, and or adhesives. Using tools such as screwdrivers and wrenches can be used to attach all the parts together [15].

Some other prosthetic options, such as machining the parts, can be costly. Advanced three-dimensional (3D) printing and computer aided design (CAD) software programs have made designing and manufacturing a low cost prosthetic an option. 3D printing is an additive process that involves material being added layer by layer to form the final product. Mechanical devices, such as body powered prosthetics, and myoelectric prosthetics are costly to maintain. Due

to CAD, open source image editing software, and additive manufacturing a low-cost, easily customizable, and easily maintained prosthetic device can be made [22].

## 2.5 Quadruped Gait Cycle

Normal gait is a series of rhythmic alternating movements of the limbs that enable forward movement through the change in center of gravity (COG) [23]. Gait analysis is done by using kinematics and kinetics [24]. Kinematics is used to obtain information such as displacements, change in joint angles, velocities and acceleration of the moving body segments. Kinetic analysis uses ground reaction forces that are measured to determine the forces in the joints of the subject. The natural gaits of quadrupeds include walking, trotting, cantering, and galloping. These specific types of gait can be considered symmetric or asymmetric. Galloping is considered asymmetric because the limbs on opposite sides do not repeat the same motion [25].

A gait cycle follows the movement of a single limb and ends when that limb has gone through its full range of motion completing a single stride. There are two phases within the gait cycle; stance and swing. The stance phase consists of the movements of the reference paw while it's on the ground. During the stance this phase, the reference paw goes through the initial paw strike, braking, propulsion, and toe-off. When the reference limb is completely off the ground, this is called the swing phase [25]. In humans, the stance phase lasts for about 60% of the gait cycle, while the swing phase lasts for 40% of the gait cycle. The timing of the gait cycle for dogs is similar to a humans' during the symmetric gait types [25].

### 2.5.1 Walking -Symmetric Gait

During canine walking gait, the dog will have at least two, and at times three, limbs on the ground [25]. In fact, the walking gait is the only gait type in which the animal will have three limbs touching the ground (Figure 10) [26]. Due to the support the canine has during this type of gait, walking is the least tiring and most efficient type of motion. In dogs with normal walking gait, the velocity they travel at is usually between 3-5 ft. /s. Dogs naturally hold about 60% of their weight with their front legs during the walking stance phase. In addition to being weight bearing, the front limbs are used for shock absorbance and slowing the animal down [25]. The hindlimbs of the dogs are mainly used to keep momentum and propel the dog forward [27]. Due to the shock

absorbance features of the front limbs, the force exerted on them is about 1.1 times the body weight. While the rear limbs experience about 0.8 times the body weight [25].

The force of the impact of a step is first absorbed through metacarpal pads to the digital pads and up the forearm in the proximal direction. The force is ultimately absorbed by the syssarcosis, which is the connection of the thoracic limb to the trunk of the animal through the muscles in the shoulder [27]. For each impact of the forelimbs, there is an associated downward movement of the head and neck [25]. In the hindlimbs, the force is directed to the acetabulum; the hip socket [27]. A sign of forelimb lameness is a shift of weight forward during walking. Through visual observation, the shift can be seen when the dog's head lowers more than usual when the good limb strikes the ground. This head movement can increase weight in the front by about 10-15% [26].

### 2.5.2 Trotting - Symmetric

Trotting is a type of symmetric gait and is unique in that diagonally paired limbs are in contact with the ground at all times. To propel the animal forward the diagonal pairs alternate contact with the ground. To allow the forelimbs to clear the ground, they are not in contact with the ground for as long as the hindlimbs. This gait is considered medium speed and is often the preferred choice to do gait analysis with due to the front and rear legs supporting the body with no additional support from the opposite limbs [27]. The forces exerted on the forelimbs and hindlimbs are about 2 times greater than they would be while walking [26].

### 2.5.3 Pace - Symmetric

This symmetric gait occurs when ipsilateral, same side, paired limbs are in contact with the ground [27]. The pace gait is inefficient due to unnecessary expenditure of energy that is needed to constantly shift the COG from one side of the body to the other. As a result of this, an animal that is pacing cannot quickly react to a necessary change in speed [26]. This gait is seen in dogs with longer legs due to the legs' ability to dampen the rolling action of the body. Breeds that this can be seen in include Great Danes and German shepherds [27]. With that being said, this gait is often considered abnormal. It is associated with fatigued and overweight animals, or those that have orthopedic issues [25].

## 2.5.4 Galloping - Asymmetric

Galloping is used for faster mobility; it is the only type of asymmetric gait. Galloping can be broken into two types, transverse gallop and the rotary gallop. While there are two types of galloping, dogs favor rotary galloping over transverse galloping. During the galloping gait cycle, the stance phase decreases while swing increases. Unlike the symmetrical gaits, during the gallop, the animal will only have 1-2 support limbs while at times having none.

The relationship between speed and stride frequency do not increase linearly as they would do when the animal is walking or trotting. While a canine is galloping, the stride length and speed of the gait increase. Therefore, as the animal speeds up, instead of increasing stride frequency, the stride length increases to compensate. To achieve this high speed, muscles within the limbs as well as muscles in the trunk are used. These muscles are not only contracting but are contributing to the creation and storage of elastic energy which gives the system a higher overall efficiency than if simple muscle contraction was occurring. Elastic energy is generated and stored by muscles lengthening and shortening. This muscular process increases as velocity of the dog's movement increases [25].

## 2.5.5 Methods of Gait Analysis

Gait analysis is done through using kinematic, kinetic, and electromyography methods. Kinematic analysis is used to determine the velocity, acceleration, and joint angles of the given subject. Video analysis can be used for this type of analysis. Markers are put on the animal subject where the specific joints in question are. This allows the joint angles to be calculated using the dot product. Often to facilitate these calculations, electrogoniometry was developed. Electrogoniometers are used to electronically measurement of joint angles. This device is a small flexible sensor that is placed moves with the joint during dynamic movement. An electrogoniometer is made of a strain gauge that runs the length of the device. While very accurate, this device is difficult to properly place. Another method that has been used for research of animal gait in the past involves invasive placement of instrumented linkages to the desired locations. This method is cannot be used in clinical patients and can affect the baseline gait of animals. Due to these reasons, the noninvasive video analysis of kinematic gait is the method that is most commonly used.

Kinetic analysis is uses ground reaction forces to determine the forces in the joints of the subject. A ground force reaction (GFR) determines the force going through the leg but not the specific joints. Performing kinetic analysis for dogs is due to the variance in gait between large and small dogs, they should not be compared to each other. To complete this analysis, force plates are set up concurrently so that the dog can simply walk straight. The force plates are placed so that one limb will placed on it at a time. There are many factors that can cause variance when performing the force plate analysis [25].

## 2.6 Existing Market

The team interviewed various prosthetic companies. The companies that were interviewed were Orthopets, Animal Ortho Care, K-9 Prosthetics, and My Pet’s Brace. From these interviews, we learned about 3- point corrective prosthetics, rocker prosthetics, and bottom sole prosthetics. The information from the company interviews can be found in Appendix B to Appendix E. Table 2 synthesizes the various prosthetics found in use by the interviewed companies.

**Table 2: Existing market of canine prosthetics implemented by interviewed companies**

Type of Prosthetic	Advantages	Disadvantages	Suppliers
3-point corrective	Marketed to last lifetime	Heavy/bulky Expensive	Orthopets
Rocker	Easily customizable, susceptible to wear	Heavy Expensive	Animal Ortho Care
Partial paw	Gel lining for comfort/protection For congenital deformity or traumatic injury	Expensive	K-9 Prosthetics
Bottom sole	Not bulky User friendly	Does not work well for amputations above elbow or knee Expensive	My Pet’s Brace

Orthopets is a company that designs and manufactures custom-made orthotics and prosthetics. The main type of prosthetic they make is the three point corrective prosthetic. The three point pressure distribution allows for mechanical stability of the canine’s limb. Figure 7 displays the three point corrective prosthetic.



Figure 7: Orthopets' three point corrective prosthetic [28]

Animal Ortho Care features prosthetics that involve a plastic limb socket attached to a rocker bottom foot as seen in Figure 8 below. This type of prosthetic is easily customizable to meet the needs of the patient. However the rubber rocker bottom is most likely susceptible to wear and may need replacement over time to ensure optimal function. In addition the rocker bottom is made of metal which makes this design fairly heavy.



Figure 8: Animal Ortho Care's rocker prosthetic [29]

K-9 Prosthetics Inc., provide different prosthetic products such as carpal prosthetics, partial paw prosthetics, tarsal prosthetic and metatarsal prosthetics. Each of these products is designed for different amputation and deformity levels. There are many limitations in today's canine prosthetic market. The primary limitation is limb length. If the residual limb is too short, the candidate is not qualified to receive a prosthetic. Carpal prosthetics are for amputations at the carpal level where the medial and lateral processes are not amputated. Partial Paw prosthetics are for patients with congenital deformities or traumatic injuries that affect the paw. Tarsal prosthetics are designed for

tarsal level amputation to assist with the ambulatory movement of the canine. In terms of materials, their prosthetics are made using thermosetting laminate plastic and closed cell thermoplastic foams, which provides optimal functionality and comfort. The paws of these prosthetics have rocker bottoms and rubber grips that allow smoother gait and high traction on slippery surfaces. Additionally, they have different colors and cosmetic designs available.

My Pet's Brace most common prosthetic is those with bottom soles. The advantage of prosthetics made by My Pet's Brace is the simplicity of the design, simply just a brace and insoles to make up for the missing length. The limitations of the prosthetics created by My 'Brace are two fold; prosthetics are not provided for complete amputations, and they do not provide prosthetics for front limb deformities.

### 2.6.1 Intraosseous Transcutaneous Amputation Prosthesis (ITAP)

To address the limitations in stump socket prostheses, a new approach involving a portion of the prosthesis that is implanted inside the limb, called the endoprosthesis, and an external portion called the exoprosthesis. The endoprosthesis, which is an intraosseous prosthesis, is comprised of an inert material which is inserted into the bone of the residual limb. This part of the prosthetic involves a technique known as osseointegration. Essentially it is where a connection occurs between the bone and the implant, causing the surgical attachment of the prosthetic to the bone [16]. In ITAP, the intraosseous refers to inside the bone, the transcutaneous refers to across the skin, and the amputation refers to removing a limb or part of one and replacing it with an artificial limb. The exoprosthesis, known as transcutaneous prosthesis, is attached to a part of the intraosseous prosthesis that is not immersed into the bone. This intraosseous and transcutaneous prosthesis relationship transfers the mechanical load from the bone to the prosthetic limb unlike the stump socket prosthetic. This prosthetic can be quite expensive due to the complexity and use of many resources and manpower. It is very easy to fracture the distal part of the bone if the implant is not inserted correctly. The load transfer from the weight bearing implant to bone needs to be studied more during in vitro studies to get a complete understanding of how to minimize the load stress and optimize force dissipation parameters [22]. Figure 9 and 10 show the different ITAP designs.



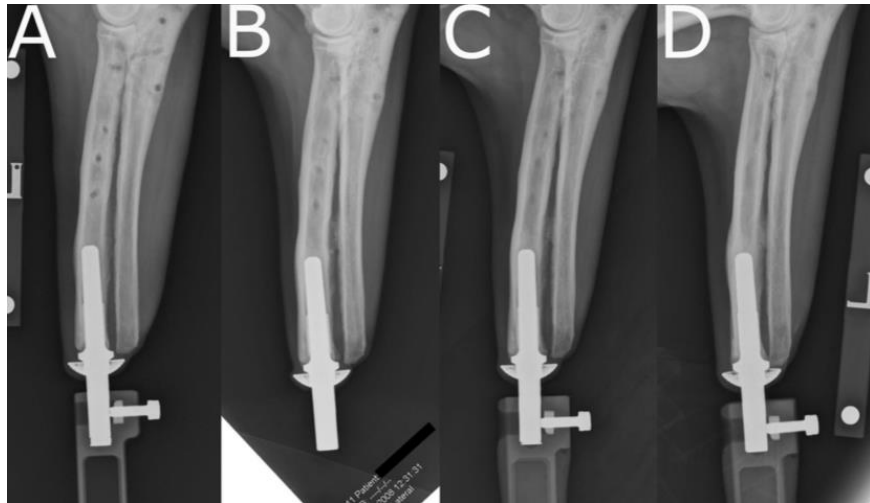


Figure 9: Images of a dog's limb showing osseous remodeling around the intrasosseous part of the ITAP implant at (A) 6 weeks; (B) 3 months; (C) 5 months; (D) 7 month [30]



Figure 10: Images showing some different types of designs and materials used for transcutaneous parts of the ITAP implant. (A) Blade design made from carbon fiber; (B) metal concentric cylinders with a rubber insert; (C) rocker made from Derlin TM; (D) foam beds that are shock absorbing inserted in rubber that has Kevlar attached; (E) a deformable polymer design that is one-piece; (F) a multidirectional foot piece made with a Derlin TM shaft [31]

## 2.6.2 Previous Patents

Canine prosthetics, and at a greater scale animal prosthetics, is a relatively new and advancing field that hasn't reached full acknowledgement by the scientific community. Companies that provide reliable assistive devices to clients have been in business for less than 15 years, while prosthetic companies for people have been in business for more than 20 years. OrthoPets, a

credible company that has been in business since 2003, is one of the oldest animal prosthetic companies in the field. K-9 Orthotics and Prosthetics Inc. has been in business since 2010. The team conducted a patent search as well as consulted with two Research and Instruction Librarians and did not find any relevant patents. This result supports the fact that the field is still a new technology that has not been fully implemented in society. However, since the prosthetic technology was first introduced to humans there are numerous patents of limb prosthetics for people.

## 2.7 Rehabilitation Therapy

Canine rehabilitation therapy is similar to physical therapy in people; however there are differences in the methods used. This difference is due to the dissimilar anatomy and the variance in the loads applied to the joints and muscles. The goal of rehabilitation therapy is the reduction of pain, improvement of muscle strength and tone in order to reduce muscle mass atrophy, increase in range of motion, and an improvement in quality of life [32] [33]. In the case of dogs with prosthetics, rehabilitation therapy is important to ensure that the bone, muscles, joints and ligaments are able to build enough strength in order to prevent injury. In this section, the topics that will be discussed will include a definition of quality of life, how the parameter is measured in the canine population, how pain is currently measured, and the methods used to rehabilitate a dog following the attachment of a prosthetic.

### 2.7.1 Defining Quality of Life

Quality of life (QoL) is an important marker used to define the health of an individual in broad terms. In humans it is usually defined as “one’s general enjoyment of life”, and as a result is measured subjectively by evaluations [34]. The human QoL definition is not appropriate for use in domestic animals [35]. As a result, understanding the QoL measurements for canines would provide a marker for the team to compare the benefits and deficits of the use of a prosthetic.

In a study that reviewed QoL assessments in pet dogs, four main concepts were identified: satisfaction and predictability of basic needs, a high degree of biological functioning, a satisfaction of core essence (telos) needs, and opportunities for pleasure and minimal distress [34]. Since quality of life is very individualized, based on each animal’s specific needs, and scored through varying evaluations with a range of contributing factors, it is a parameter that is very difficult to

quantify [36]. So, while it is useful to determine the QoL of an animal, especially in regards to pre and post evaluations of the effects of a prosthetic placement, it is not a highly accurate or a precise measurement. Two QoL scales were examined and common denominators between them include, pain/hurt, hunger/appetite, hydration, hygiene, happiness/mental status, mobility/activity, and general behavior patterns [37] [38]. Appendix F displays a QoL scale that the team will be able use in their analysis of Baxter pre and post prosthetic placement. This scale will allow the team to quantitatively determine whether or not the prosthetic is a promoter of the dog's QoL.

### 2.7.2 Pain Monitoring

Pain monitoring is an essential part of both the QoL scale and analyzing the comfort of a prosthetic device. There are two different categories of pain, adaptive and maladaptive pain [33]. Adaptive pain inhibits activity by protecting the organism from injury or promoting healing when an injury has occurred [39]. Maladaptive pain, in contrast, is an expression of the pathological operation of the nervous system [39]. That is to say that the pain doesn't serve a physical purpose. Pain detection and management should be evaluated in dogs that have prosthetics in order to understand how comfortable the device is.

There are various parameters checked to measure pain in dogs. While dogs cannot verbally express when they are in pain, there are certain behavior categories that veterinarians have identified as important parameters: demeanor and response to people, posture, mobility, activity, response to touch, and, last but not least, vocalization [40]. Appendix G displays a scale created by the Colorado State University School of Veterinary Medicine includes these parameters and can be used to assess the pain scale in dogs [41]. This scale, while not validated, can be used in quantitatively assessing the comfort of the prosthetic and provide the team with insight on how to improve or modify the design as needed.

### 2.7.3 Rehabilitation Methods

As mentioned earlier, rehabilitation therapy for dogs is similar to physical therapy for people. That being said, similar to humans, there are two different aspects of rehabilitation therapy for dogs. The first is nutritional therapy. For instance, obesity contributes to a multitude of joint and gait problems. Therefore ensuring a proper diet and body weight is essential [39]. The second aspect of therapy is physical rehabilitation, which is important for building strength and improving

the function of a limb that has had little to no loading or force applied. This type of therapy is done to minimize the chances of injury and discomfort. There are two different types of rehabilitation methods. The first is termed modalities, or therapeutic methods, and the second is manual therapy.

#### 2.7.3.1 Modalities

Modalities, as stated previously, are methods or agents of physical therapy. The methods that will be discussed in this section are thermotherapy, cryotherapy, and contrast therapy. While therapeutic ultrasounds, laser therapy, and shockwave therapy are also modalities, they will not be discussed at length due to the relevance of the scope of our project.

Thermotherapy is when heat is applied through conduction, convection, radiation, evaporation and conversion. The most common method of thermotherapy uses heat packs. One benefit of thermotherapy includes reabsorption of edema, which is useful since edema is a known problem in those who use prosthetics [33]. In contrast to thermotherapy, cryotherapy uses applies cold temperatures to the desired site. This causes vasoconstriction, decreased blood flow, slowed edema formation, and an inability to feel pain (analgesia) [33]. The common applications of cryotherapy are cold packs, cold immersion, or ice massage. Contrast therapy is the use of both thermotherapy and cryotherapy.

These modalities would be useful in treating pain caused by the use of a new prosthetic. By applying these modalities in conjunction with the knowledge and insight given by the pain scale, the team was able to create a regime that provided maximum comfort during the acclimation period of the dog to the prosthesis.

#### 2.7.3.2 Manual Therapy

In addition to modalities manual therapy and exercise is another method by which rehabilitation is done. Exercising the affected limb enhances the range of motion, balance, posture, motor control, and gait. The types of exercise done include; gait training on flat surfaces as well as inclines and declines, aquatic therapy, muscle strengthening, and balance exercises using balls or peanuts. Stretch therapy, a type of exercise therapy, can be performed by encouraging the dog to go up and down the stairs or walking the dog on a leash. Another method of manual therapy is massaging. Different types of massages, for example stroking, effleurage, compression, friction and percussion, have different and varying effects and can be used as needed [33]. These types of

exercises are important with the application of prosthetics because dogs missing a limb have a change in proprioception, as the position of that limb in space has been changed or altered as a result of the addition of a prosthetic. Therefore the proprioceptive capability of the dog has to be trained to acclimate to this change.

Understanding and designing a way to implement the different aspects of rehabilitation therapy such as QoL, the pain scale, pain monitoring, as well as rehabilitation methods was important information for the team to know in the validation of the prosthetic design. Using this information the team adequately ensured that the transition into wearing the prosthetic is comfortable and easy, thereby increasing the chances of success in the dog's willingness to wear and use the device.

# Chapter 3: Project Strategy

## 3.1 Initial Client Statement

There are various styles of custom veterinary prosthetics for canines on the market; however the majority of these are designed to attach to an amputated limb. While most canines are believed to be able to function well with only 3 limbs due to their ability to compensate well with an injured or missing limb, there are potential negative effects on the joints that can lead to less desirable gait patterns. Our client is the owner of a Dachshund dog that has a congenital birth defect manifested by the lack of total development in his right forelimb. Our team was given an initial client statement:

*Provide a prosthetic that will allow Baxter, a Dachshund dog, to have a more normal life, allow the client to be able to take him on long walks in the woods with their other dogs, and reduce any future joint issues that he may have as a result of his birth defect.*

## 3.2 Technical Design Requirements

With the client's initial client statement and the background research the team had enough information to create objectives for the remainder of the project. These objectives and their connection to the main project aim will be discussed in this section.

### 3.2.1 Objectives

To ensure that we complete our goals for this project, the team determined objectives that are applicable to our project. Table 3 summarizes the objectives and what they mean in the context of this project.

**Table 3: This table displays the team’s project objectives and their specific descriptions**

<b>Primary Objectives</b>	
<b>Objectives</b>	<b>Description</b>
Value	<ul style="list-style-type: none"> <li>• Less than \$ 300 per annum</li> </ul>
Comfort	<ul style="list-style-type: none"> <li>• Device should not cause pressure sores or chafing</li> <li>• Device should be simple to place on and remove</li> <li>• Device should be easily cleaned and stored when not in use</li> <li>• Breathability of device to prevent discomfort from overheating if worn long term</li> </ul>
Adjustability	<ul style="list-style-type: none"> <li>• Device should allow for flexibility and attachment tightness</li> </ul>
Mechanical Stability	<ul style="list-style-type: none"> <li>• Solution shall not introduce new complications and experience significant wear</li> </ul>
Durability	<ul style="list-style-type: none"> <li>• Solution shall have a life cycle of 1 year minimum before minor replacement parts are needed</li> </ul>
Marketable	<ul style="list-style-type: none"> <li>• Competitive solution compared to current market products</li> </ul>
Adjustable	<ul style="list-style-type: none"> <li>• Material will not make the dog sick if chewed or cause skin irritation</li> </ul>

After establishing the project objectives, a pairwise comparison chart, in Table 4, was created by the team to help rank the objectives. A pairwise comparison chart is a method of comparing each objective to every other objective. In doing so, each objective has a final score, which reflects its importance. The pairwise comparison helped the team split the objectives into two categories: primary and secondary objectives.

**Table 4: Pairwise comparison chart of project objectives**

	Low Cost	Durable	Comfortable	Mechanically Stable	User Friendly	Non Toxic	Marketable	Adjustable	Total
Low Cost	----	1	0	0.5	1	0	1	1	4.5
Durable	0	----	0	0	1	0	1	0.5	2.5
Comfortable	1	1	----	0.5	1	0	1	1	5.5
Mechanically Stable	0.5	1	0.5	----	1	0.5	1	1	5.5
User Friendly	0	0	0	0	----	0	1	0	1
Non toxic	1	1	1	0.5	1	----	1	1	6.5
Marketable	0	0	0	0	0	0	----	1	1
Adjustable	0	0.5	0	0	1	0	0	----	1.5

*Primary Objectives*

Our primary objectives for the device, based on the pairwise comparison chart in Table 5, were low cost, durable, comfortable, mechanically stable, and non-toxic. Our client has expressed that the prosthesis device should last at least a year and cost a few hundred dollars at most. The device will be used by canines to help them walk therefore, comfort is important. If the prosthesis is not comfortable, the canine may not be receptive to the device. Mechanical stability of the device is a primary objective because the device should be structurally sound and support the necessary amount of weight applied. In addition to providing support, the device also needs be able to withstand impact forces and produce minimal wear. Seeing as a dog’s front limbs holds about 60% percent of their body weight, the prosthesis should be able to hold 30% of the given dog’s body weight [25]. Along with mechanical stability, the device should provide an extra 2 cm to the height of the dog to account for the difference in length of the front limbs. To prevent slipping, the prosthesis developed must also have a similar coefficient of friction to a normal dog paw when on different surfaces.



### *Secondary Objectives*

Our secondary objectives include marketability, user friendly, and adjustability of the device. In order to maximize the impact of this project, the product should be applicable to the current market and be marketable to other cases. Marketability of the final product depends on several of our primary objectives and should be a competitive solution when compared to those already on the market. For this to be true, the product should be low cost, possibly have interchangeable parts, and be comfortable and less bulky than existing prosthetics. User friendliness of the device produced is determined by the ease of which it can be taken on and off, and the ease to which it can be cleaned. Lastly, the product should be non-toxic to prevent any negative impacts on the canine and it's caregivers. An additional feature that would be beneficial is the adjustability of the prosthetic, which would allow the prosthesis to be customized.

### 3.2.2 Constraints

The main constraints for this project are time, cost, the manufacturing process and Baxter's compliance. Baxter's immediate need for a solution places a time constraint on the project. The project budget limits the materials and manufacturing processes that can be used. Cost aside, the manufacturing processes are also limited to what is available for us. The nature of Baxter's disability and his owner's wishes limits the project solution to a non-surgical device. Standard prosthetics are typically designed for amputees. Lastly, Baxter's compliance to the device is another limitation of the design, as he must be willing to adapt to the proposed design in order for it to be feasible.

## 3.3 Design Standards

Many standards were considered in the ideation and fabrication of the prosthetic device. This section will go through standards that pertain to design and fabrication of the device.

### 3.3.1 Food and Drug Administration (FDA)

A medical devices is defined by the Food and Drug Administration as *“an instrument, apparatus, implement, machine, contrivance, implant, in-vitro reagent, or other similar or related article, including any component, part, or accessory, which is ... intended for use in the diagnosis*

*of disease or other conditions, or in the cure, mitigation, treatment, or prevention of disease in man or other animals, or [which is] intended to affect the structure or any function of the body of man or other animals ...." Further, a device "does not achieve its primary intended purposes through chemical action within or on the body of man or other animals, and ... is not dependent upon being metabolized for the achievement of its primary intended purposes [42]." The definition for medical devices in the FD&C Act includes veterinary devices; however the regulations are specific to human use devices. Code of Federal Regulations Title 21 section 820.1(a) (1) states that, "Current good manufacturing practice (CGMP) requirements are set forth in this quality system regulation. The requirements in this part govern the methods used in, and the facilities and controls used for, the design, manufacture, packaging, labeling, storage, installation, and servicing of all finished devices intended for human use [43]." This is to say that FDA does have the power over veterinary devices, however chooses not to regulate them at this time.*

### 3.3.2 International Organization for Standardization (ISO Standards)

The standards for rapid prototyping currently is limited to informal or industry standards. The current standards stand as followed [44]:

1. The STL data format for the interface between computer aided design (CAD) and rapid prototyping (RP) is an industry de facto standard.
2. ASTM subcommittee E28.16 on rapid prototyping has addressed mechanical testing standards, specifically for evaluation of the tensile strength of RP parts.
3. Several RP "benchmark" parts have been developed for particular user communities to evaluate RP processes. These benchmark parts are typically available for industry-wide use.
4. Various specifications for RP materials have been developed to describe material properties and characteristics. Many times these specifications have used a similar format to represent the material data.

### 3.4 Revised Client Statement

In light of the stated objectives, constraints, and functions-means chart the team revised the initial client statement. The revised client statement fully describes all aspects of the design and expected outcomes of the project.

*The objective of this project is to develop a low cost device that will enable dogs with front limb deformities to distribute their weight evenly without having to undergo surgery. This device will stabilize their walking gait, and increase their endurance relative to the initial testing results. The lifetime of the device should be at least one year.*

### 3.5 Project Approach

After completing the revised client statement, and ensuring that the primary goals of our project are reflected in the revision, the team went on to create a timeline on how to approach the problem and produce a solution in the time frame given. The basic outline of the project approach was to start by analyzing Baxter's gait, design and manufacture different iterations of the prosthesis, and test it with until a final prototype was developed. Once the final prototype was developed the team did post prosthetic testing and finally created a website displaying all of the design process to help others wishing to do the same.

#### 3.5.1 Technical Approach

The technical milestones our project team planned to accomplish were broken into four terms, according to the time period given. These milestones are displayed in Table 6.

**Table 5: Project milestones for the team**

Term	Milestones
A Term	<ul style="list-style-type: none"><li>● Background research</li><li>● Meet with the client and dog</li><li>● Identify project objectives</li><li>● Meet with veterinarians</li><li>● Pre-prosthetic testing</li><li>● Brainstorming sessions</li></ul>
B Term	<ul style="list-style-type: none"><li>● Brainstorming sessions</li><li>● Material research</li><li>● Communicate with prosthetist</li><li>● Conduct canine prosthetic company interviews</li><li>● Design prosthetic prototypes</li><li>● Begin manufacturing prototype parts</li></ul>
C Term	<ul style="list-style-type: none"><li>● Reiteration of design process with prototypes</li></ul>
D Term	<ul style="list-style-type: none"><li>● Provide client with prototypes for initial evaluation</li><li>● Manufacture final prosthetic</li><li>● Post-prosthetic testing</li><li>● MQP report writing</li></ul>

During A term, the team completed significant background research on canine anatomy, forelimb deformities, gait analysis methods and the current prosthetic market as well as design methods and materials. An initial meeting with our client and her dog was also conducted. This meeting provided the team with a greater understanding of the scope of the physical repercussions and limitations caused by the dog’s deformity. Once the team had a good grasp on the background information and the scope of the problem, two veterinarians were contacted to get professional advice and gain a depth of understanding on the type and anatomical abnormalities of the dog’s deformity. Pre-prosthetic testing was conducted on the client’s dog, Baxter, as well as an additional “healthy” dachshund dog to understand the baseline parameters and measurements. Conducting the tests with a “control dog” enabled the team to make comparisons when values

from the literature were not readily available. These measurements were taken with the intention that, at a later time, a comparison would be made to the post-prosthetic testing results to ensure that the quantitative goals and objectives were met.

The major goals in B term were to actively brainstorm ideas and create prototypes of devices that would fulfill the project objectives and client needs as well as selecting a final design. X-rays were considered initially, because it was assumed that no possible attachment points of the prosthetic to the limb could be made without the information regarding the anatomical physiology of the client's dog. However, once into the term, the decision was made to forgo the x-ray due to the project's financial constraints, as well as positive gait analysis results. The gait results showed that Baxter was more than able to endure loading on his deformed forelimb. In addition, communication with a prosthetist was conducted to understand the manufacturing process of the prosthetic. The results of this communication can be seen in Appendix H. Canine prosthetic company interviews were also conducted to gain an understanding of the processes, as well as the materials, used to create a functioning prosthetic. Computer Aided Design (CAD) software was used to model different design concepts. The various designs were manufactured and tested for functionality and fit. The final prototypes were selected on the basis of how well they met the teams expressed objectives, constraints and functions.

The major milestone set for C term was to continue with design iterations to perfect the prosthesis on Baxter. Along with this, the final material was selected through research and testing. In the week between C and D term, Baxter was given a prototype of the proposed final design. Baxter's owner was instructed to have him wear it in increasing increments throughout this time and document observations and issues with the design. A prosthetic trial protocol can be found in Appendix I. During D term post-prosthesis testing was conducted with the final prototype and the results were compared to the pre-prosthetic testing to validate that most of the project objectives and goals were met.

### 3.5.2 Management Approach

A Gantt chart was used in order to provide an outline of the project timeline. This Gantt chart can be seen in Appendix J for A through D term.

### 3.5.3 Financial Approach

A budget of \$250 per person was provided by the Department of Biomedical Engineering of Worcester Polytechnic Institute (WPI). That provided the team with a budget of \$1,250. The team's expenditure was split between acquiring materials, as well as the manufacturing and testing of the prototypes and final assistive device. Animal prosthetics typically cost above of \$1,000. Our client is willing to spend a couple of hundred dollars a year for a replacement assistive device for her dog Baxter. In order to make the designed prosthesis competitive in the market, the project team's goal is to keep the maximum manufacturing cost of the final device below \$200.

The materials used for the fabrication of the device were primarily purchased outside of the institute. The device used to test the mechanical integrity of the prototypes was provided by the biomedical engineering labs on campus. The manufacturing was also done in the biomedical engineering labs using equipment provided by WPI. An overview of the final device cost can be seen in Chapter 7.1.

## Chapter 4: Design Process

This chapter will explore the need for a device that accomplishes the objectives from Section 3.2. Once we expanded on the need for such a device, functional testing was done to aid in the design of the prosthesis. The team began with creating conceptual designs for attachment points and ground interfaces of the prosthesis. From the conceptual ideas, alternative designs were created by pairing an attachment point with a ground interface. These designs were then tested on Baxter. Based on this data the final design was selected.

### 4.1 Need Analysis

There are currently many companies that create custom made prosthetics for dogs. However there is a gap in this market for prosthetics for small dogs that have front limb deformities, like Baxter. The majority of prosthetics on the market today are targeted towards dogs with amputated limbs. Each company produces a product design that is customized to a specific canine's case. For example, one of the larger companies, OrthoPets, customizes their prosthetic design to each patient based off an arm cast and limb measurements. Whereas some of the smaller companies design multiple different types of prosthetics on a case by case basis to meet the specific needs of the patients. Dogs with front limb deformities would tend to need a more customized design as there is no readily customizable design on the market. The prosthetics on the market usually cost around \$1,000 to manufacture, and in many cases the more "customer-specific" designs can cost more [45]. These prosthetics often need to be replaced due to repeated cyclic stresses, which leads to material wear and failure [46] [47]. In addition, the physical characteristics of many prosthetics are heavy and bulky which could dissuade a dog from accepting to wear and use the prosthetic.

A prosthesis is intended to take the place and functionality of the missing limb. As a result, certain objectives were established to ensure the device's optimum functionality. The device and its components must be less expensive than the current prosthetics on the market. Additionally, the device should be comfortable and simple to clean. To ensure comfort, the device should be adjustable and allow for joint movement. Based on the client's need statement and objectives of this project, a table was created to depict the specific need criteria of the device. This can be seen in Section 3.2.1.

The device should add the missing height necessary to make each forelimb the same length. This value was determined by measuring limbs of the dog. The deformed forelimb was determined to be 2 centimeters shorter than the healthy forelimb. Therefore, the prosthesis should add 2 centimeters of height to Baxter's deformed forelimb. Other measurements were taken such as Baxter's weight, which is 16 lbs. This value was used to obtain the compressive force that the prosthesis should withstand. Dogs typically support 60% of their body weight on their front limbs, thus one forelimb supports approximately 30% of the dog's overall weight. If the assumption is made that the prosthesis is supporting 30% of Baxter's body weight, the estimated force that will be exerted on the prosthesis while standing in the compressive direction is about 21 Newtons. From the canine gait background research in Section 2.4, the team knows that the forelimbs have a shock absorbent nature. As a result, the forelimbs have to withstand up to 1.1 times the body weight, while walking, which in Baxter's case is 78.3 N.

## 4.2 Functional Testing

A series of functional tests were conducted to obtain patient specific information in order to determine the customizable aspects of the final design. A precursory palpitation analysis was also performed on Baxter's deformed leg and healthy leg. Pressure was applied on the medial, lateral, dorsal, and ventral sides of both front limbs (1.5 cm increments). The results indicated that Baxter could tolerate the device applying pressure on his deformed forelimb. In addition, several limb measurements were made, these values can be found in Appendix K.

### 4.2.1 Experimental Setup

Two force plates were set up next to each other and connected to a computer for data collection. Two clear barriers were created and placed on each plate, creating a path that would force the dog to walk on both plates. It ensured that his left side limbs contact the left force plate and his right side limbs contact the right force plate. This setup enabled the team to gather data of the force generated by each foot strike. Figure 11 depicts the setup of the force plate.



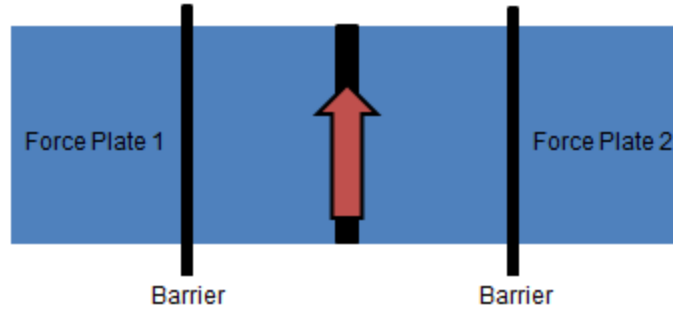


Figure 11: Force plate setup for gait trials.

During these gait trials, fiducial markers were attached to the major anatomical landmarks as seen in Figure 23. A total of 10 markers were placed on Baxter (Figure 12).



Figure 12: Baxter with the appropriate fiducial markers, walking through the experimental setup.

The video was analyzed by taking screenshots of the major gait cycle phases in regards to his abnormal limb. A total of eight video frames were included in this analysis. Video data was collected from a front view and side view simultaneously. The front view video was used to ensure that the dogs were only stepping on one force plate at a time, while the side view video was used for gait analysis.

#### 4.2.2 Paw Strike Analysis

Using the force plates, the team was able to determine the forces that the dog applies on each of his limbs at different stages of the gait. This information was needed for the design criteria in order to determine whether the design should load the paw and forearm of the deformed limb.

The data was collected and analyzed, and the forces of the limbs were graphed over time as shown in Figure 13.

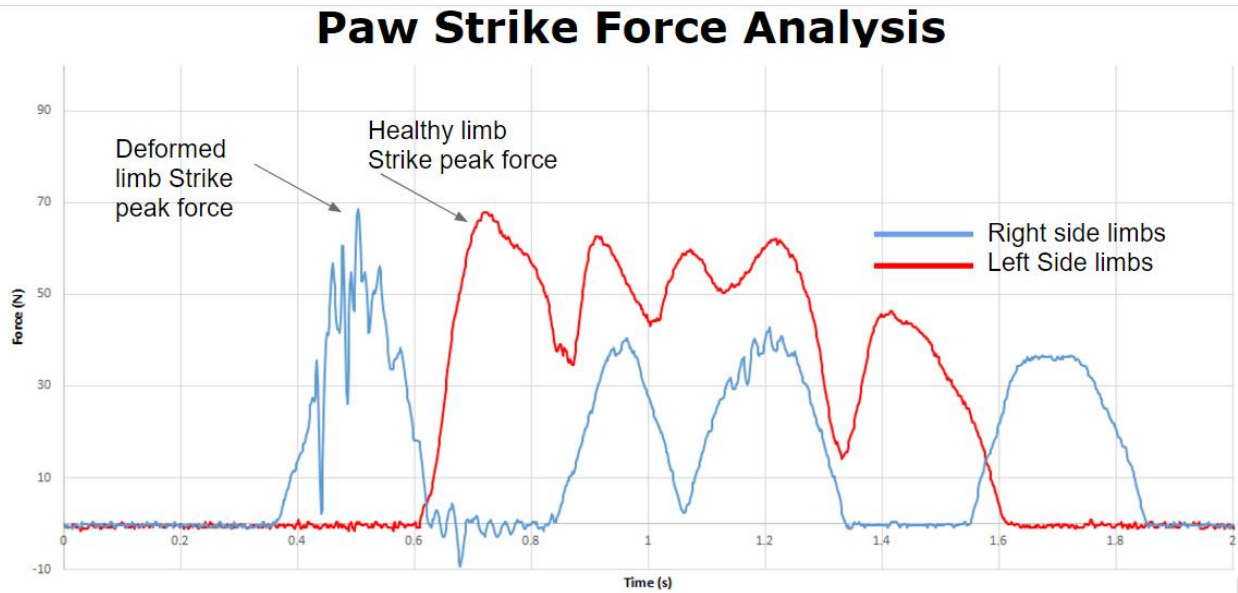


Figure 13: Force of Baxter's limb during gait analysis.

In this graph, each color represents the force generated by one force plate. The blue line corresponds to the forces of the deformed front limb while the red line corresponds to the forces of the left side limb. The first spike of the blue line represents to the foot strike of the front deformed limb, 68.6N. Similarly, the first spike in the red line represents the foot strike of the healthy front limb, 67.8N. From the data, the team was able to determine that the dog is able to exert a similar amount of force on both the deformed and healthy front limbs.

#### 4.2.3 Gait Analysis

Baxter, who has a front limb deformity, and Petey, a healthy dachshund, were videotaped walking across the force plate for three trials. The angles of the carpal (wrist) and elbow joints were analyzed by reconstructing the limbs into vectors connecting each fiducial marker and measuring the angles using ImageJ. The stride length was measured by taking the distance between toe-off and paw strike (Table 6).

**Table 6: Gait Analysis Results for both Petey and Baxter**

	Baxter	Petey
Stride Length	9.3 inches	13.2 inches
Elbow Flexion	87 - 112°	62 - 116°
Carpal Flexion	118 - 209°	87 - 249°

The carpal angle for Baxter showed a range of 118 to 209° in comparison to Petey’s 87 to 249° range of motion as seen in Table 6. This indicates that Baxter has a fairly small range of motion in that joint. In addition, most dogs experience a ‘paw drop’ during the swing phase in which the paw is dropped underneath the body and the carpus angle reduces to around 90°. In Baxter’s case however, his paw remains outstretched and parallel to the ground at a carpus angle of 177° (Figure 14).



**Figure 14: Baxter during the swing phase of the gait cycle.**

The elbow angle was measured to range between 87 and 112° (Table 6). Again Petey has a larger range of motion with elbow angles ranging from 62° to 116°. This is a fairly small range of motion for both dogs due to the fact that the majority of the limb propulsion comes from movement about the shoulder joint. The biggest impact of Baxter’s deformity is a decreased stride

length. Baxter has an average stride length of 9.3 inches while Petey's average stride length is 13.2 inches.

## 4.3 Conceptual Designs

From the testing mentioned in Section 4.2, the team gathered knowledge to develop designs for the prosthesis. When brainstorming designs for the prosthesis, the team decided to split up the designs into three major components; the attachment mechanism that attaches to the residual limb, the pylon, and the part that interfaces with the ground. These three components are separate entities, but come together to create one practical and fully functioning prosthetic.

### 4.3.1 Rigid Attachment Points

#### *Bent Elbow*

One of the primary concerns at the beginning of the project was loading weakened parts of the skeletal structure, such as the forelimb. The bent elbow design consists of a U-shaped elbow cup to transfer the ground reaction force to the upper limb to avoid loading the lower limb. Velcro straps would be used to hold the limb in place. This design restricts movement at the elbow joint. Once strapped in place the elbow would be set at 90°. The elbow cup would be constructed out of a lightweight plastic and would be lined with a shock absorbing material, such as a gel. Figure 15 shows this design concept. This design aids in the customizability of the prosthetic. Seeing as the bent elbow design does not interact with the deformed forelimb, it does not need to be customized to fit that part of the limb. This is significant because of the variability of the forelimb in canines with limb deformities. After determining that Baxter is able to load his limb, this design was eliminated because the drawbacks of restricting elbow movement outweighed the positive aspects of the design. Table 7 below shows the benefits and drawbacks of this design concept.

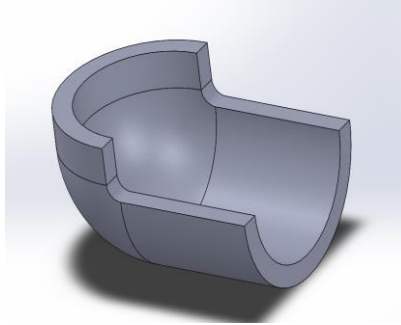


Figure 15: SolidWorks model of first iteration of attachment with a half-exposed cylinder

Table 7: Benefits and drawbacks analysis of the bent elbow attachment

Benefits	Drawbacks
<ul style="list-style-type: none"> <li>● Easily customizable</li> <li>● Doesn't load the lower limb</li> </ul>	<ul style="list-style-type: none"> <li>● Restricts elbow movement</li> <li>● Force is concentrated to one location</li> </ul>

### *Arm Splint*

Once it was determined that allowing joint movement was required to enhance the comfort of the design, the arm splint design was developed. In this design, the forelimb would be sandwiched between two straight plastic pieces on the lateral and medial sides of the lower forelimb. The lateral piece would then end in a circular disk which would form a pin joint with another segment that would cover the upper forelimb. The lateral and medial pieces would be secured via fabric straps. This attachment point would be lightweight and breathable while enabling complete natural joint movement. Figure 16 shows the attachment piece. However the two separate pieces on each side of the limb would be difficult to attach and the lightweight design could break easily depending on material choices. The determined benefits and drawbacks can be seen in Table 8.

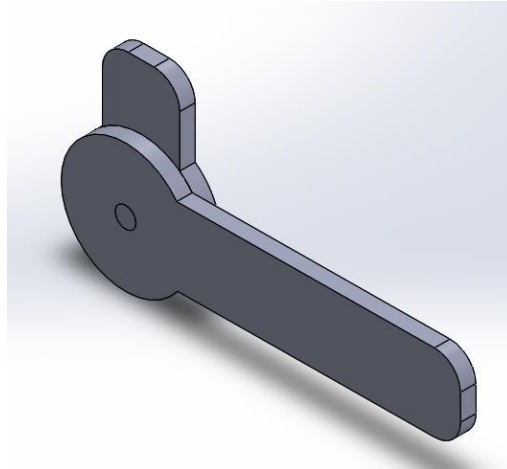


Figure 16: SolidWorks model of first iteration of arm splint attachment. This is one side of the splint concept, two sides would be necessary for this design.

Table 8: Benefits and drawbacks analysis of the arm splint attachment

Benefits	Drawbacks
<ul style="list-style-type: none"> <li>● Lightweight</li> <li>● Doesn't restrict movement</li> <li>● Breathable</li> </ul>	<ul style="list-style-type: none"> <li>● Difficult to secure</li> <li>● Very thin, possibly easy to break</li> </ul>

#### 4.3.2 Soft Attachment Points

Four designs were considered as viable soft attachment options; an elbow brace, a compressive sleeve, a harness attachment, and Velcro. The latter two soft attachment options, the harness attachment and Velcro, were purchased and implemented on various design concepts. In contrast, the elbow brace and the compressive sleeve were designed and fabricated by the team. Two separate materials were used in the fabrication of the attachments.

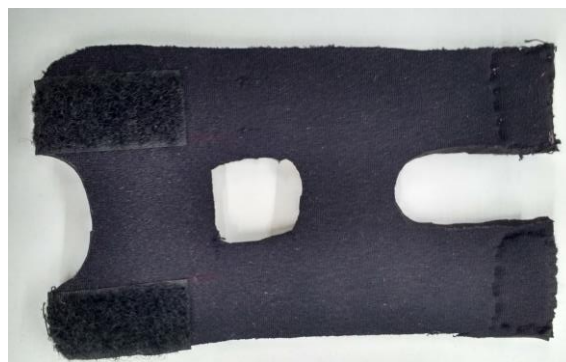
Polychloroprene, more commonly known as neoprene, was the material selected for the elbow brace. In contrast Polyurethane, or lycra, was used to make the compressive sleeve. The materials properties can be seen in Table 10. The neoprene was chosen to make the elbow brace despite the fact that its Young's modulus maximum is lower than the lycra's maximum. This decision was made due to the apparent sturdiness and thickness of the neoprene material in comparison with the lycra.

**Table 9: The mechanical properties of soft attachment materials are shown with maximum values [48]**

Soft Attachment Mechanical Properties			
Material	Young's Modulus (GPa)	Yield Strength (MPa)	Fatigue strength 10 <sup>7</sup> cycles (MPa)
Polychloroprene (Neoprene)	0.002	24	12
Polyurethane (Lycra)	0.03	51	38.3

### *Elbow Brace*

This design was a simple construction made out of neoprene. The dimensions of the brace were fabricated using the anatomical measurements from Baxter. Although the material did fulfill the main objective of providing an attachment point for the ground interface, and was relatively easy to place on, there were problems with this design. The interface of the neoprene interior to Baxter's fur was poor due to the low friction of the neoprene as well as the fur's smooth nature. Additionally the fit of the brace was poor because the flap of skin superior to the elbow joint was unaccounted for and hindered the placement of the upper strap. While the elbow brace design was an appropriate attempt at providing an interface between Baxter and the ground interface, it did not meet enough objectives to be deemed successful. This design is shown below in Figure 17 and Table 10 depicts the benefits and drawbacks of the concept.



**Figure 17: Neoprene elbow brace attachment.**

**Table 10: Benefits and drawbacks analysis of the elbow brace attachment**

Benefits	Drawbacks
<ul style="list-style-type: none"> <li>• Material thickness</li> <li>• Material is inexpensive</li> </ul>	<ul style="list-style-type: none"> <li>• Poor fit</li> <li>• Slipping</li> </ul>

*Compression Sleeve*

The second design made for the alternate soft attachment interface was the compression sleeve seen in Figure 18 below. Similar to the elbow brace, the compression sleeve was intended to be an intermediary between Baxter’s limb and the ground interface device. The compression sleeve was made out of lycra and fashioned to be implemented with the platform shoe ground interface. While the compressive sleeve was able to fit around Baxter’s wrist and deformed paw well, it did not provide the support expected. Similar to the neoprene elbow brace, the compression sleeve slipped constantly from Baxter’s paw. In terms of ease of attachment the compression sleeve was also not efficient. The attachment required a lot of effort and more than one pair of hands to get onto the paw. The sleeve provided little support and did not attach well to its designated ground interface. As a result the compression sleeve was also deemed unsuccessful. Table 11 shows the pros and cons of this soft attachment design.



**Figure 18: Lycra compression sleeve attachment.**

**Table 11: Benefits and drawbacks analysis of compression sleeve attachment**

Benefits	Drawbacks
<ul style="list-style-type: none"> <li>• Snug fit with paw</li> </ul>	<ul style="list-style-type: none"> <li>• Poor fit</li> <li>• Easily removed</li> <li>• Hard to put on</li> </ul>



## Harness

To provide a very stable attachment point to Baxter’s body with the pylon, a viable option chosen by the team was a harness that straps around the dog’s torso. This harness avoids the possibility of constricting the natural movement of Baxter’s arm when he undergoes his gait cycle, as well as securing the prosthetic the prosthetic in place. The prosthetic would be sewn into place on the harness Figure 19. Table 12 displays the benefits and drawbacks of the harness attachment.



Figure 19: Harness attachment for the prosthesis.

Table 12: Benefits and drawbacks analysis of the harness attachment

Benefits	Drawbacks
<ul style="list-style-type: none"><li>• Availability</li><li>• Material Thickness Design</li></ul>	<ul style="list-style-type: none"><li>• Ensuring proper fitting on the dog</li></ul>

### 4.3.3 Ground Interface

The ground interfaces that will be discussed in this section include the J shape, wheel shape, mushroom, and platform shoe. The part of the device that will be in contact with the ground will experience an enormous number of interaction cycles with various terrains, which can lead to wear. Therefore, attaching a rubber strip to the bottom of the pylon may improve the wear resistance due to rubber’s high wear resistance properties. This rubber can be applied to all ground interfaces discussed in this section.

#### *J-Shape*

The J-shaped ground interface will curve forward or backward from the chosen attachment of the prosthetic toward the ground. As seen in Figure 20, the loop to the “J” would be the piece that is interfacing with the ground. This J-shaped prosthetic is proven to provide smoother gait and is significantly more energy-efficient than other prosthetics [49]. The theory behind this J-shaped prosthetic is that it compresses by the body weight and returns to the original shape as the user

pushes off of it. This causes energy to be stored and then released as the user pushes off, which minimizes the energy spent [49]. It can be designed with a variety of materials that contain the desired mechanical properties including stiffness, density, and optimal coefficient of friction. Carbon fiber is the material that is used by athletic running prosthetics due to the light weight and high strength of the material [49]. Table 13 shows the benefits and drawbacks concerning the J-shape.

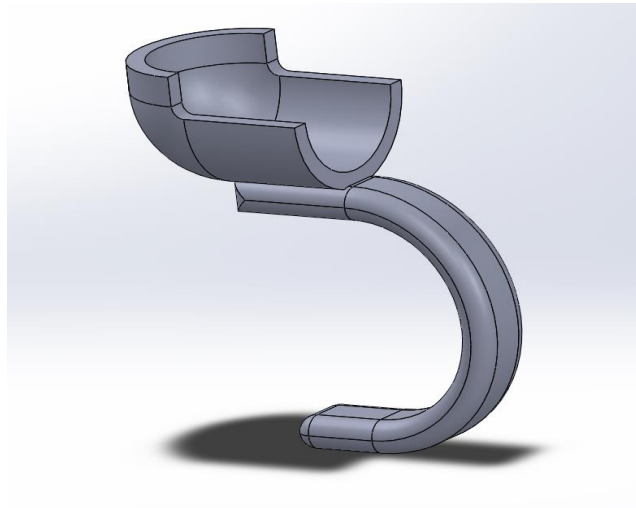


Figure 20: SolidWorks model for "J" shaped prosthesis with the half-exposed cylinder attachment.

Table 13: Benefits and drawbacks analysis of the J-shape

Benefits	Drawbacks
<ul style="list-style-type: none"> <li>Prevent slipping with a secure fit on the elbow</li> </ul>	<ul style="list-style-type: none"> <li>Doesn't allow for natural movement of the arm</li> </ul>

*Wheel*

The team also discussed the possibility of a wheel-shaped design that contains some flexibility. The CAD model is shown in Figure 21. Since some dogs, like Baxter, will be able to move their elbow joints relatively well, creating a flexible and supportive frame that allows for elbow contraction, such as an I-shaped prosthetic, would be beneficial. Theoretically, allowing the dog to move his elbow freely will prevent muscle atrophy and enhance the muscles strength and size. This would allow the dog to develop a stronger and more useable limb. Table 14 displays the benefits and drawbacks of this design concept.



Figure 21: SolidWorks model for a wheel-shaped prosthesis design.

Table 14: Benefits and drawbacks analysis of the wheel

Benefits	Drawbacks
<ul style="list-style-type: none"> <li>• Withstand compressive loading</li> </ul>	<ul style="list-style-type: none"> <li>• Doesn't allow for natural movement of the arm</li> </ul>

### *Mushroom*

Another conceptual design for interacting with the ground is an “upside down” mushroom-shape. This option operates in a similar mechanism to the J-shaped prosthetic in terms of providing smooth gate due to its curved shape. However, this option has the advantage of eliminating the need for precise orientation, as it can operate in 360°, Figure 22. Table 15 shows the benefits and drawbacks of the mushroom design concept.

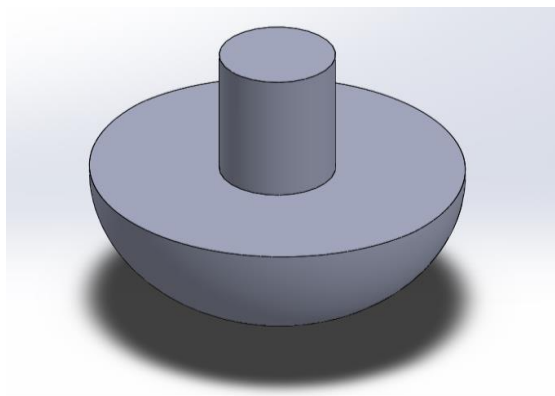


Figure 22: SolidWorks model for "upside down" mushroom shape prosthesis design.

**Table 15: Benefits and drawbacks analysis of the mushroom shape**

Benefits	Drawbacks
<ul style="list-style-type: none"> <li>Material thickness provides great compressive strength</li> </ul>	<ul style="list-style-type: none"> <li>Heavy due to material thickness</li> </ul>

## 4.4 Design Prototyping

To test the success of each design, the team fabricated various prototypes, which were then tested on Baxter. These designs tested with Baxter were the platform shoe design, as well as, various different J-shapes, including one with a fixed elbow support as seen in Figure 23. The compression sleeve attachment was used for the platform shoe prototype. While the elbow brace attachment was used for the j-shaped prototype. A metallic J-shape prototype was fabricated along with other 3D printed J-shaped prototypes. Table 16 shows the results of these prototypes.



**Figure 23: Prototype made of the fixed bent elbow attachment and J-shape ground interface with thermoform plastic. The thermoform was molded directly on Baxter to ensure accurate dimensions.**

**Table 16: A compilation of tested design results during the prototyping session**

Design	Materials/ Components	Benefits/ Drawbacks
Brace	Neoprene	<ul style="list-style-type: none"> <li>Barely any upper arm caused slipping down off upper arm onto forearm.</li> </ul>
J-shape	Stainless Steel	<ul style="list-style-type: none"> <li>Metal corners pointed</li> <li>Too long and digs into Baxter's skin</li> <li>90° angle too small</li> </ul>
Platform shoe	Compression sleeves: lycra Rubber sole	<ul style="list-style-type: none"> <li>One compression sleeve too big</li> <li>Other one fit well</li> <li>Easy to shake off</li> <li>Height of platform was good</li> </ul>
J-Shape	3D printed	<b>105°</b>

	Velcro Rubber sole	<ul style="list-style-type: none"> <li>● Angle too small, gap in corner where paw meets prosthetic needs support</li> <li>● Easily shaken off</li> <li>● Good traction grip on bottom and Velcro attachment points</li> </ul> <b>120°</b> <ul style="list-style-type: none"> <li>● Angle still too small</li> <li>● Velcro attachment good</li> </ul>
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The fixed elbow support J-shaped prosthesis was originally created to inform the team of Baxter’s reaction to having a fixed elbow. When the device was on Baxter, he would not walk and was visibly attempting to get the device off his arm. From these observations, the team decided to consider an attachment that would allow for movement of the elbow joint.

The brace was eliminated from consideration due to the lack of space on the upper arm. The team felt that with only 2cm to work with above Baxter’s elbow, a secure enough brace could not be fabricated. As shown in Section 4.3, the platform shoe concept is listed as one of our alternative designs. For prototyping session III, the team decided not to pursue this design due to the flaws in attachment and lack of attachment capabilities. However, we feel this design has potential and could be modified to achieve the objective of our project. The J-shape design proved to be the best option from the prototypes tested. While various different J-shape prototypes were tested, the design was considered in the chart as one. The angles on all the J-shaped prototypes were too small on the prototypes. After prototyping and testing, the angle necessary was determined to be 135° , which was a simple modification. Twisting and sliding of the prosthetic was observed for all variations of this design when placed on Baxter. The improvement that the team included was the addition of an inner lining to provide friction and prevent slipping. The team also decided not to pursue using metal as the final product. The metallic prototype was ~20 grams heavier than plastic versions.

A modified J-shape and arm splint were tested. The harness that the team had was too large for Baxter. However, the concept showed promise. Four trials were made with the modified J-shape with each attempt adding a different element to the device. The first trial was made with just the J-shape alone. The second trial added rubber to the sole of the device, while the third trial kept the rubber sole and added a latex inner lining. The final trial used the device plus the rubber sole with a rubber lining instead of the previous latex lining. During the progression of attempts, it was noted that twisting and slipping was a constant problem. Each trial attempted to correct this issue

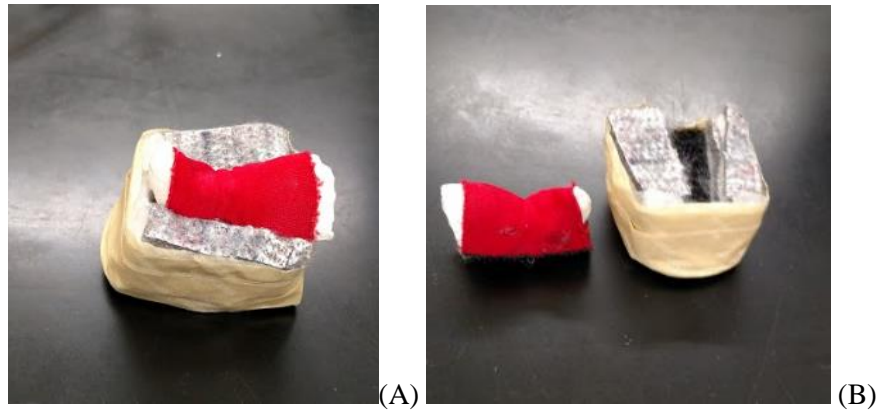
but was ultimately unsuccessful. This problem can possibly be fixed by implementing a wider base on the modified J-shape to provide more surface area and stability. A benefit to the J-shape design is that it can interface with Baxter through the harness, providing a needed increase in stability as well. Despite the twisting issue, Baxter was comfortable in the device. He did not try to shake it off and was comfortable standing with it.

## 4.5 Alternative Designs

Based off of the team's previous design concepts, alternative designs were produced by combining ground interface components with the attachments. These designs will be reviewed in these sections.

### 4.5.1 Alternative Design I: Platform Shoe

Alternative design one is our “platform shoe” design. The concept of this design is to create a shoe, of a similar size to the healthy paw, and attach it to the residual paw of the deformed limb. This should compensate for the missing limb height and the surface area at which the deformed limb applies force. There are many benefits associated with this design as well as a few disadvantages. Some of the major advantages include its light weight, which should allow him to maintain similar moment of inertia. Additionally, it would eliminate unnecessary attachment points at the forearm and upper arm, while preventing any slippage or twisting in his residual paw due to the large surface area of the shoe. However, one of the biggest disadvantages is the limited options for attachment points. This concept must use the paw compression sleeve as the method of attachment between the shoe and the limb. Therefore, all the disadvantages associated with compression sleeve are directly reflected in this design. Figure 24 demonstrates the concept of the platform shoe and the compression sleeve attachment on a cast of a residual paw.



**Figure 24: Complete platform shoe design as the dog would wear it, seeing as the compression sleeve attachment is on a mold of the dog's deformed paw (A); Individual parts of the platform shoe prototype, the compression sleeve goes on the dog's paw as a sock. The base of the shoe has a space for the paw to sit and attaches to the sleeve with Velcro (B).**

The attachment point for this platform shoe design is a major drawback. During the prototyping sessions, it was realized that it is extremely difficult for the compression sleeve to stay firmly on the dog's paw. Therefore, the dog was easily able to pull his paw out of the sleeve. However, due to the valuable advantages of this design, it has been selected as one of the few designs that the team should reconsider in the case that the current chosen design does not work as intended. If this design was reconsidered, an alternative attachment point must be created in order to ensure proper and secure attachment between the limb and shoe.

#### 4.5.2 Alternative Design II: J-Shape

Alternative design two would consist of the J-shape ground interface without a harness attachment. This can be seen in Figure 25. This design combines ideas of previous conceptual designs for attachments points and ground interface aspects of the prosthetic. After testing the previous prototypes, the team reiterated the overall design to include the positives of the previous designs. The new design includes a modification of the J shaped prosthetic and the ground interface. The ground interface being a platform shoe modification. The inside angle was increased to allow for a more natural and comfort fit for Baxter. Baxter wore this prototype with no irritation and did not try removing it from his arm. This design proved to be quite promising to be used for future prototypes and for the final design.



Figure 25: Image of the modified J prosthesis and platform shoe.

### 4.5.3 Alternative Design III: Arm Splint

This final design features the arm splint described in Section 4.3.1 attached to the harness as described in Section 4.3.2. The arm splint would then end in a ground interface similar to the platform shoe concept in Section 4.3.3 however the platform would be attached at a pin joint that would enable flexion of the carpal joint. This design is easily customizable, allows for natural joint flexion and can easily stay attached to the body via a harness. Figure 26 displays the arm splint design.

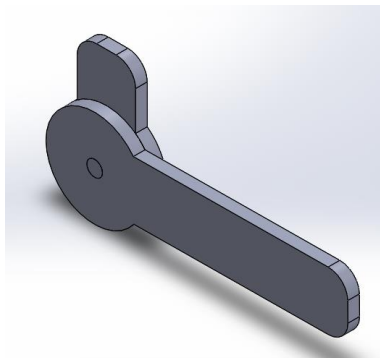


Figure 26: SolidWorks image of the arm splint concept.

## 4.6 Final Design Selection

After performing multiple prototyping and testing sessions, the team was able to figure out the proper prototype that is most suitable for Baxter. This prototype is the modified J-shaped prosthetic with 135 degree angle. This angle was found by further joint angle analysis using ImageJ. This value is the angle of the carpal joint when the paw is flush against the ground in the load bearing phase of the gait cycle. Due to the nature of the attachment of the J shape this angle



was taken from the ventral side of his limb rather than from the fiducial markers which are in the middle of his limb. This J shape forms the ground interface using the concept of the platform shoe. The attachment point to Baxter uses a harness that is attached to the partial arm splint that extends from the J-shape up the lateral and medial sides of the elbow. As mentioned before this arm split design will allow natural movement of Baxter's elbow. The harness will provide stability and secure the prosthetic in place on Baxter without allowing slipping and twisting to occur.

Baxter seemed to be very receptive to this design and did not show any irritation while wearing the initial prototype. This design provided a snug fit partially due to the fact that it is custom made to Baxter, using his natural flexion angle of 135 degrees. This prototype experienced good ground interaction because of the traction generated by the rubber sole attached to the bottom of the prosthetic. Furthermore, the inside of the J-shape was entirely covered with rubber, which created great attraction between the fur of his limb and the prosthetic and minimized the occurrence of slippage and twisting on Baxter's arm.

In order to further minimize the twisting and slippage at the interaction between the paw and foot platform, a few modifications will be made on the current prosthetic. One modification is increasing the surface area of the bottom of the foot platform. The other is creating an upward facing lip at the end of the foot portion of the pylon to prevent Baxter's toe from moving further forward. A final change is making the sides of the pylon that interfaces with Baxter's forearm curved to accommodate the curvature of the forearm. Figure 27 displays these modifications.



**Figure 27: Final design modifications include (A) splint attachment to harness; (B) inner lining to reduce slipping and increase comfort; (C) rubber to provide traction on bottom and Velcro attachment points.**

# Chapter 5: Final Design Verification

The team has set multiple design criteria for this prosthesis such as increasing the length of the deformed forelimb, being comfortable and lightweight, and improving the dog’s ability to distribute his weight evenly. Based on those design criteria, multiple tests were conducted to validate the components of the design. The breakdown of the criteria and validation methods involved are displayed on Table 17. Each validation method and its integration into the verification of the final design will be covered in the following sections.

**Table 17: Criteria and validation methods for verification of the designs**

<b>Objective</b>	<b>Design Criteria</b>	<b>Validation Method</b>
Increase length of deformed forelimb	2 cm	Length measurements using SolidWorks
Comfortable	Worn without irritation	Observational measurements of comfort and strap attachment
Mechanically stable (harness)	Withstand 130N force	Mechanical testing of harness material
Cost effective	Cost less than \$500	Cost comparison
Mechanically stable (pylon)	Withstand accidental bending loads	Three point bending
Lightweight	As light as possible	Weight measurement

## 5.1 Pylon Attachment

The pylon attachments from the pylon to the dog were tested qualitatively. The team created a scale to semi-quantitatively assess the effectiveness and comfort of the design iterations.

### 5.1.1 Attachment Testing

In order to validate the effectiveness of different pylon prototypes and their attachment mechanisms, two validation tests were performed. The first test, a comfort scale, focused on how readily the dog accepted the pylon. The second test, the strap scale, focused on the effectiveness of



the straps that held the pylon onto the dog's limb. These two scales can be seen in Table 18. These tests helped in guiding the final selection of both the pylon as well as the attachment mechanism.




**Table 18: Pylon attachment scale for comfort and strap attachment**







Pylon Attachment Scales	
Comfort Scale	Strap Scale
<ol style="list-style-type: none"> <li>1. Does not attempt to walk even with prompt</li> <li>2. Shakes leg until prosthetic is removed</li> <li>3. Walks, but attempts to remove the prosthetic once the prompt is removed</li> <li>4. Walks comfortably but attempts to remove the prosthetic after a minimum of 10 minutes</li> <li>5. Walks/runs confidently without trying to remove the prosthetic</li> </ol>	<ol style="list-style-type: none"> <li>1. Has to be adjusted after every trial</li> <li>2. Stays on for a couple of trials</li> <li>3. Stays well for testing period</li> <li>4. Stays for minimum of 10 minutes but has to adjusted</li> <li>5. Doesn't have to be adjusted after placement and after use</li> </ol>

Table 19 displays, chronologically, the ranking of the straps and pylon types based on the scales mentioned in the table above.

**Table 19: Chronological order of previous design iterations**

Straps	Rank	Pylon Type	Rank
 <p>Compression sock /Velcro</p>	1	 <p>Boot design</p>	1

 <p>Neoprene brace</p>	<p>1</p>	 <p>Stainless steel 90°</p>	<p>1</p>
<p>Velcro</p>	<p>1</p>	 <p>3D printed angle 105°</p>	<p>1</p>
<p>Velcro</p>	<p>1</p>	 <p>3D printed angle 120°</p>	<p>1</p>
 <p>Velcro</p>	<p>2</p>	 <p>Pylon with so</p>	<p>3</p>

 <p>Elastic w/ Velcro</p>	2	 <p>Wider base w/ curved front</p>	2
 <p>Elastic w/ Velcro</p>	2	 <p>Wider base</p>	3
 <p>Elastic w/ Velcro and arm splint</p>	3	 <p>Final prosthetics design</p>	3

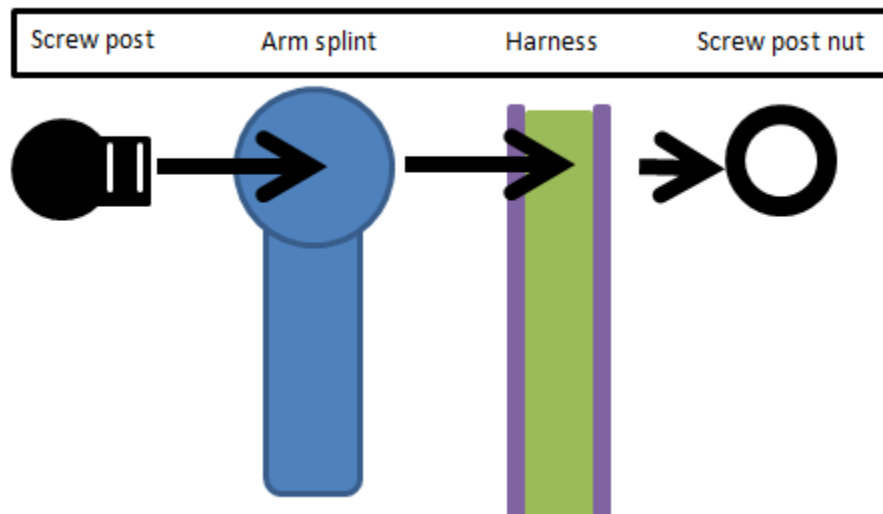
### 5.1.2 Attachment Results

This test was performed in order to semi-quantitatively assess the comfort of the pylon as well as the attachment of the straps. As mentioned in Section 5.1.1, two separate scales were used on video and photographic data taken during the testing of different iterations of the pylon and attachment types. These scales were used to determine where each design generation taken from the team’s ideation and manufacturing phase fit. If a design concept improved either scale it was kept and taken along in further iterations. However, if the design concept was not beneficial it was dropped or revised and re-evaluated. Having such a method allowed the team to ensure that the best possible prototype would be the result at the end of the process. From this data and our observations, the team determined elastic straps with Velcro on the ends were the best pylon to dog limb attachment. This attachment method was the most comfortable and effective attachment method. The Velcro straps alone did not perform well due to the dog being able to shake the prosthesis off. After introducing the elastic component, the attachment was able to stay on his limb

until after 2 trials were completed with the wider base prosthetic. Finally, the arm splint was the attachment mechanism providing the most secure attachment. This attachment design lasted for the entire testing period.

## 5.2 Harness Attachment

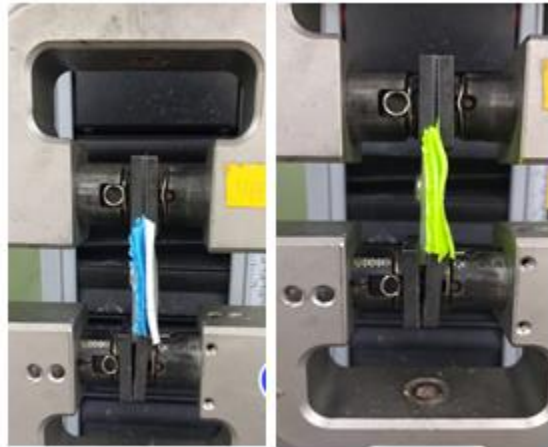
Mechanical tests were performed in order to understand how the harness material would impact the durability of our device. The materials focused on for mechanical testing were two harnesses, nickel screw posts, as well as a 3D printed model of the arm splint made out of transparent resin material. The materials were assembled so that the harness was flush with the screw side of the attachment and the pylon was between the front end of the attachment and the harness. Figure 28 shows the complete assembly. The goal of this test was to ensure that the screw post or the harness material will not fail at a known threshold of the pylons potential mechanical failure. This mechanical testing was used to validate that the pylon attachment to the harness was mechanically stable and realistic for different harness types.



**Figure 28: Model of assembly being tested. The screw post goes through both the arm splint and harness and is capped with the screw post nut.**

Four square samples with an unloaded size of approximately 35mm by 35mm was taken from the harness at locations that the pylon could potentially be attached onto for the final prototype. The samples were loaded in tension using the Instron 5544. A tensile test was conducted to mimic how this segment of the device would be loaded when in use. A Bluehill program was created to apply an automatic tare load of 2N and then begin the tensile test until the final

threshold was reached at a rate of 25mm/min. The purpose of the tare load was to take away unwanted slack of the harness fabric. An end of test condition was created so that the force could not exceed 130N. This condition was created based on the results obtained from the mechanical testing of the dog bone shaped plastics, which indicated that forces above 130N could lead to the failure of the pylon itself. The setup of the test can be seen in Figure 29.



**Figure 29: Orientation and placement of both harness materials. (A) blue harness; (B) yellow harness material.**

The results of the mechanical testing can be seen in Figure 30 and Figure 31. The results show that the weakest part of the assembly is the harness fabric. The blue harness, specimen 2, failed prior to reaching 130N. The screw posts withstood the 130N force. Failure in this context means that the fabric ripped through the screw post resulting in a 40% drop in load.

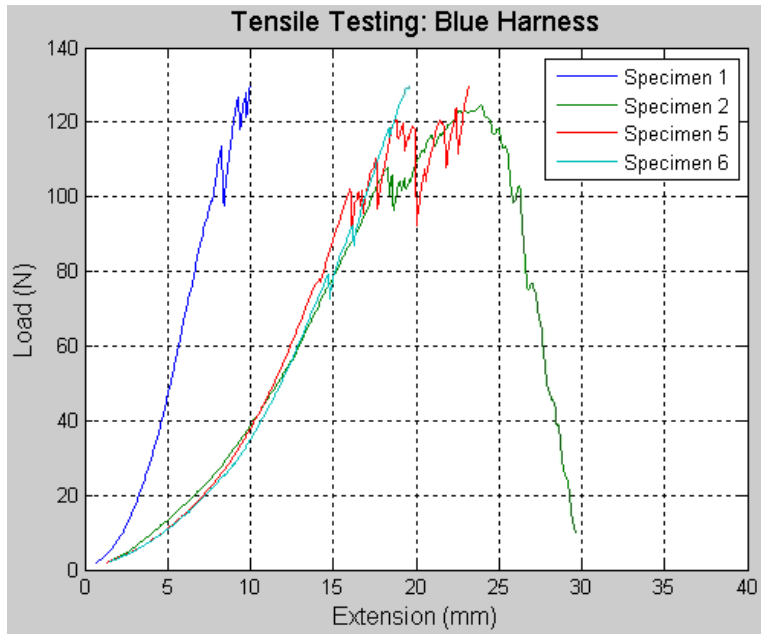


Figure 30: Tensile testing results from the blue harness.

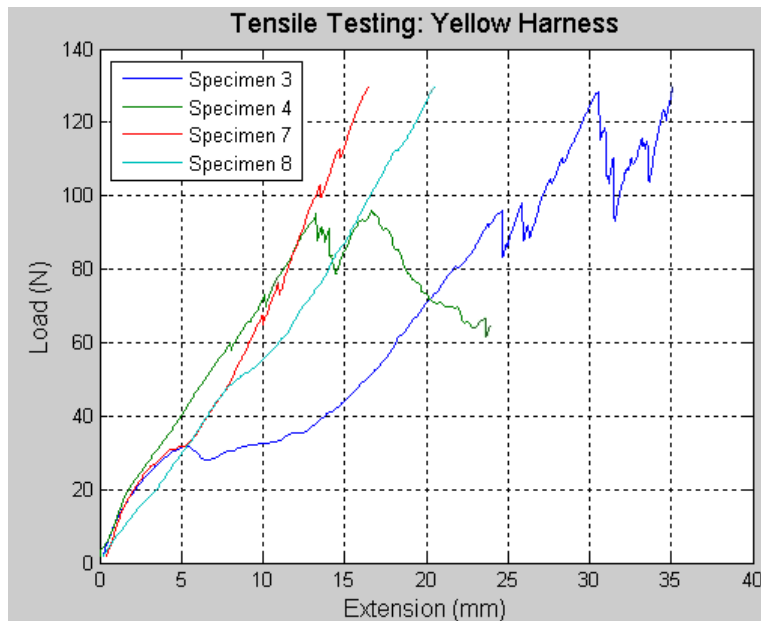
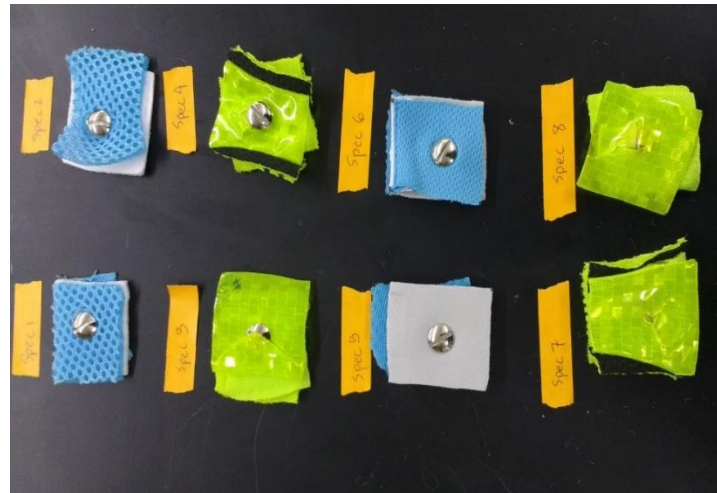


Figure 31: Tensile testing results from the yellow harness.

It should be noted that the results of specimen 4, the yellow harness, are inconclusive because the fabric slipped from the grips. Also, the results showed that harness type would impact the resilience of the attachment point. Figure 32 shows the eight specimens tested. It can be seen that the reflective layer of the yellow harness in all cases ripped off while maintaining the other layers of the fabric. As a result, it would be recommended when using this device to use a dog



harness that has little to no plastic layers. An alternative would be to make the attachment location in an area without this addition when possible.



**Figure 32: Image of all harness materials tested. It can be seen that the yellow harness material's top layer tore off while the remainder of the harness stayed intact.**

The results of these tests can be seen in Table 20. A two tailed t-test assuming equal variance was used in excel to determine whether there were any significant differences between the two harness types in tensile extension at the threshold load and Young's modulus. The variable "T.Test" was implemented. An equal variance was used because it was assumed that the variances are the same, until it is found that they are not. The null hypothesis for the t-test was that there is no significant difference between the yellow and blue harness types in both tensile extension and Young's modulus. An alpha of 0.05 was implemented for both t-tests. The results showed a value of 0.4582 for the tensile extension and 0.2063 for the Modulus. These results show that there is no significant difference in tensile extension and Young's modulus between the yellow and blue harness types. From this finding, that the harness materials are not significantly different in tensile extension and modulus, the team was able to ascertain that this component of the device can be purchased at the discretion of the owner.

Table 20: This table shows the results from blue and yellow harness' mechanical testing.

Specimen ID	Harness Type	Tensile Extension (mm)	Modulus (MPa)
#1	Blue	9.97	4.45
#2	Blue	23.94	3.21
#3	Yellow	35.13	3.89
#4 *slipped	Yellow	16.68	3.45
#5	Blue	23.16	4.60
#6	Blue	19.64	3.92
#7	Yellow	16.44	3.48
#8	Yellow	20.60	2.72

### 5.3 Final Materials Selection

Initially the team planned to implement a lightweight metal, like stainless steel as the material for the final device. However, due to the custom nature of this project and the manufacturing capabilities of the project team, 3D printing was chosen as the manufacturing method for the pylon. The cost, weight, and mechanical properties of several different 3D printed materials were compared before making the final material selection.

#### 5.3.1 Cost Comparison

The cost of each 3D printed material was compared to ensure that the overall price of the prosthetic was minimized. The cost of each material can be shown in Table 21 below. Acrylonitrile Butadiene Styrene (ABS) was found to be the cheapest option while the Nylon Copolymer was the most expensive.

Table 21: Cost comparison of the three different 3D printing materials

Material	Cost (unit)
Acrylonitrile Butadiene Styrene (ABS)	\$21.59 (1kg reel)
polyethylene terephthalate glycol-modified (PETG)	\$27.99 (1kg reel)
Nylon Copolymer (Alloy 910)	\$80 (1kg reel)

### 5.3.2 Material Properties

To validate which 3D printing material would be used, a 3 point bending test using the Instron 5544 was performed on three promising materials; nylon copolymer, Acrylonitrile Butadiene (ABS), and Polyethylene Terephthalate Glycol-modified (PETG). Three samples were printed out of each of the three materials. The team found that during testing, while the PETG and ABS plastics bottom layers broke partly or completely, the nylon copolymer did not. Figure 33 shows the setup that was used.

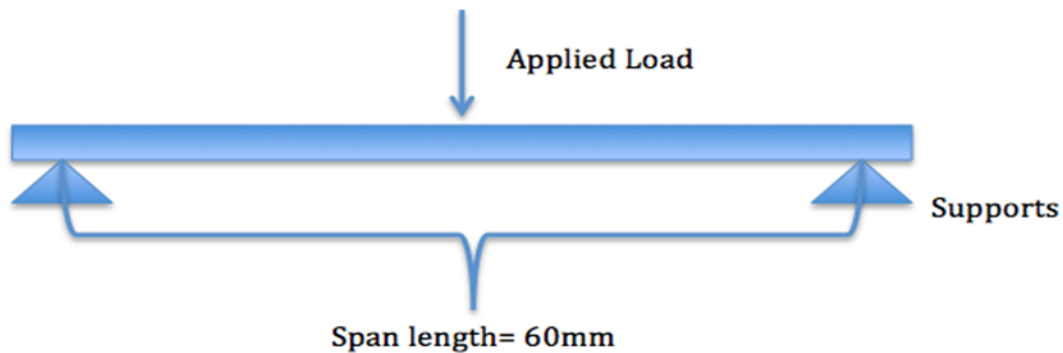


Figure 33: Instron setup for 3 point testing of 3D printed materials.

The end of test condition was initially set to a 40% decrease in force which would indicate that the sample had broken. However, due to the layer by layer nature of additive manufacturing, the 3D materials failed one layer at a time instead of undergoing a complete failure. Due to this phenomenon, the team decided to change the end of test condition to an extension of 9 mm. This measurement ensured that the test stopped before the Instron testing fixture contacted the base or was caught by the safety stop.

None of the nylon copolymers showed signs of complete failure in any of the layers; only plastic deformation was observed (Figure 34).



Figure 34: This image shows the plastic deformation of a nylon copolymer samples.

Furthermore, the maximum flexural stress values along with the material densities were used to aid the decision of the material selection. Since an objective for the device is lightweight, it was important to ensure that the material being selected would have as small of a mass as possible without sacrificing quality. The volume of the separate 3D printed prosthesis components was determined using SolidWorks. The total volume of the pylon is 17.01cm<sup>3</sup>, which was used to calculate the mass of the prosthesis.

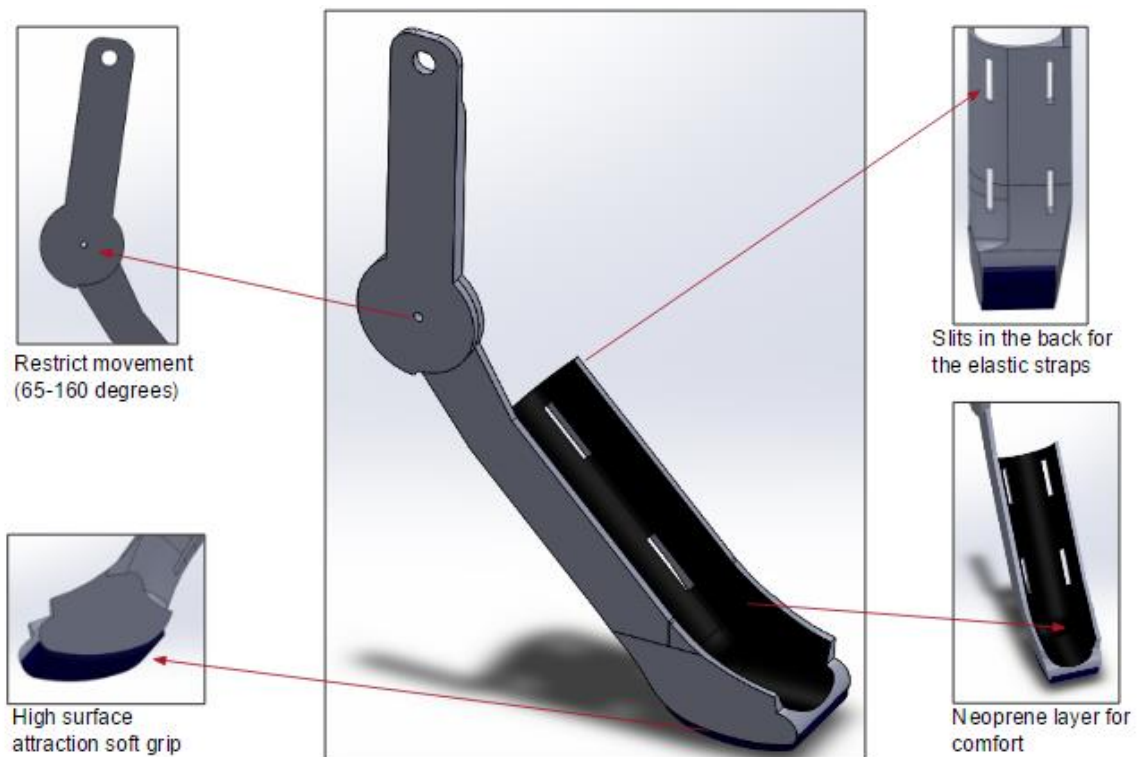
Table 22: The three selected 3D printing materials are compared in this table in regards to max stress, density and mass.

<b>Material Property Results</b>			
	Nylon copolymer	Acrylonitrile Butadiene Styrene (ABS)	Polyethylene Terephthalate Glycol-modified (PETG)
Max Stress (MPa)	110.53	132.38	148.01
Density (g/cm <sup>3</sup> )	1.15	0.9 - 1.53	1.38
Mass (g)	19.55	15.31- 26.02	23.48

The nylon copolymer was chosen as the final material. This choice was made based on the higher flexural stress values found in literature and the observations made during the bending test, as it was the only material not to experience fracture during the 3 point bending test.

## Chapter 6: Final Design and Validation

There are several important components included in the final design that ensure its success. A general overview of the final design parts include; the pylon of the prosthesis, the arms splint attachment, and the harness. As previously mentioned in Chapter 4, the harness is used to prevent the prosthesis from twisting and being removed. The arm splint is used to connect the pylon to the harness. The main features of the pylon are shown in Figure 35 below. These features were developed to enhance attachment, comfort, and safety.



**Figure 35: The final design includes (1) arm splint that restricts movement to 64°-160° using a mechanical stop; (2) slits for attachment of elastic straps; (3) high friction, soft grip is shock absorbent while preventing slipping; (4) neoprene layer added for comfort.**

To enhance attachment, the elbow joint movement was restricted. This prevents the dog's arm from reaching 180° which, in the past, has allowed him to pull his forearm arm out of straps and remove the prosthesis. The slits in the back of the prosthesis allow the elastic straps to pull the dog's forearm into the prosthesis. When compared to the previous design of having the straps in the outside of the prosthesis, this method was better at securing the arm in place. Comfort was addressed by adding a 4mm compressive layer of neoprene. When working with dogs, comfort is an important factor which ultimately determines if the dog will wear the designed prosthesis. The

bottom sole of the prosthesis includes a rubber-like material which provides grip and shock absorbance. This is a safety precaution the team took to prevent the dog from slipping, which could deter the dog from using the prosthesis altogether.

## 6.1 Experimental Methods

The experimental methods were performed to validate that our device meets our project objectives. Through the results and data, further iterations of the design were made, which lead to the final design.

### 6.1.1 Standing Weight Distribution and Paw Strikes

The final prototype of the prosthesis was tested on the dog using the force plate to determine the changes in the weight distribution with and without the prosthesis. For this test, two of the dog’s limbs were placed on two force plates at a time. From the data collected from this test, we determined the changes in weight distribution post prosthesis. As shown in Figure x below, the dog was able to incorporate his deformed limb while standing, which decreased the force exerted on the healthy front limb.

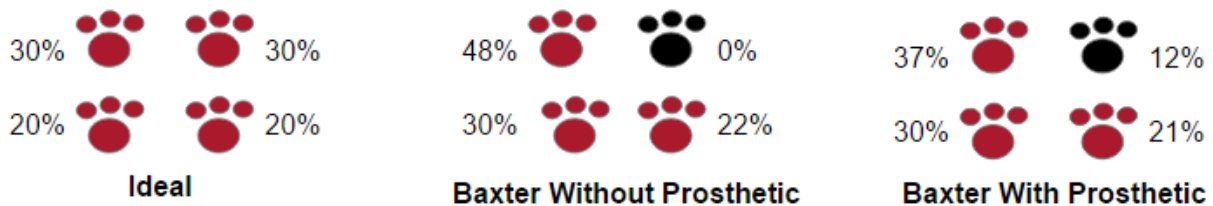


Figure 36: Weight distribution of the four limbs during standing gait.

The second type of test was to analyze the paw strike of the front limbs of the dog with and without the prosthesis. For this test, the same setup shown in Section 4.2.1 was used to monitor the paw strike forces. Table 23 below summarizes the force values with and without the prosthesis. The data show that Baxter exerted even lower force on the deformed limb with the prosthesis and higher force on the healthy limb. However, the device increased the duration of each paw strike with the prosthesis for both the healthy and deformed limbs.

**Table 23: Paw strike force and duration during walking gait**

	Force (N)		Duration (sec)	
	Without	With	Without	With
Healthy	50.0	54.1	0.34	0.70
Deformed	41.3	33.9	0.34	0.46

### 6.1.2 Kinematic Gait Analysis

The same gait analysis performed in Section 4.2 was reproduced for trials in which the dog was wearing the prosthetic. This testing allowed the team to ensure that the joint movement was not restricted as well as compare the gait patterns. Two separate analyses were conducted using collected video and photo data. This section will go over the experimental methods and findings.

### 6.1.3 Inversion of Shoulder Angle

Shoulder angle variations with and without the prosthetic were analyzed. The team performed an angle analysis of the shoulder in relation to the torso of the dog. That angle between the torso and shoulder without the prosthetic was compared to the angle that is generated with the prosthetic. Table 24 below shows the angle comparison. The average angle calculated for when the dog was wearing the prosthetic was 66.2°, which was higher than the 49.3° when the dog wasn't wearing the prosthetic. This indicates that the dog's forearm is more inverted while walking/running when he is not wearing the prosthetic. The inversion is not normal in healthy dogs. This inversion is due to compensation for the deformed limb and is also commonly seen in amputees. Using the prosthetic, the team attempted to increase the angle between the shoulder and torso, thus decreasing the inversion. This decrease in inversion widens Baxter's stance providing him more balance and stability. This inversion may also decrease over time as the dog gets more comfortable and accustomed to wearing the prosthetic, thus making the angle widen even when compared to a normal angle range.

**Table 24:** This table shows angle analysis data with and without the prosthesis of Baxter's shoulder inversion.

Situation	Trial 1	Trial 2	Trial 3	Average
With the Prosthetic	64.6°	66.9°	67.2°	66.2°
Without the Prosthetic	49.3°	50.0°	48.6°	49.3°

#### 6.1.4 Carpal and Elbow Joint Angle Rotation

In order to evaluate the dog’s carpal and elbow joint angle rotation, a video was taken of the dog wearing the prosthetic. Gait analysis was performed by taking nine individual chronological still frames from throughout the video. The results comparing Baxter and Petey’s gait can be seen in Table 25. The carpal and elbow joints angle were calculated using ImageJ following the same protocol as described in section 4.2.2.

**Table 25:** This table shows the elbow and carpal angle flexion as well as the stride length difference between Baxter and Petey during walking gait.

	Baxter	Petey
Stride Length	9.3 inches	13.2 inches
Elbow Flexion	87 - 112°	62 - 116°
Carpal Flexion	118 - 209°	87 - 249°

In order to quantify the effects of the prosthesis the same measurements were taken for Baxter with and without the prosthesis. This data can be seen in Table 26.



**Table 26: Data showing a comparison of Baxter's gait with and without the prosthesis is shown. Three different aspects are examined; stride length, elbow flexion and carpal flexion.**

	<b>With</b>	<b>Without</b>
<b>Stride Length</b>	13.5 inches	9.3 inches
<b>Elbow Flexion</b>	87-133°	87 - 112°
<b>Carpal Flexion</b>	135°	118 - 209°

## 6.2 Reproducibility Guidelines

A reproducibility guide was created with the intention to aid in the creation of custom prosthetics for canines with front limb deformities. The guide contains modifiable SolidWorks files and detailed instructions on fabricating your own prosthesis for your pet. Each solution costs under \$200 to fabricate and requires 3D printing technology. It includes a list of steps and tests that will help an owner determine the best solution for their pet. The guidelines can be found in Appendix L.

## 6.3 Project Considerations and Impact

Many factors should be taken into consideration in a design project. The project considerations and impacts discussed in the sections below are manufacturability, economics, environmental impact, societal influence, political ramifications, ethics, health, and safety issues.

### 6.3.1 Manufacturability

The final prosthesis given to the client at the conclusion of this project was customized specifically to the user. However this design could be reconstructed to fit the needs of another user using the SolidWorks model of the pylon (Appendix M) and the customizability guide Appendix L. Through the SolidWorks design the user could customize and print the pylon with the appropriate arm splint lengths and pylon dimensions. If this device were to be manufactured at a

larger scale the pylon pieces would be created via injection molding. Large scale manufacturability would also limit the customizability of the design. Instead of complete custom measurements the device would most likely have 3-4 different sizes corresponding to average canine limb dimensions.

### 6.3.2 Economics

The team's prosthetic device is projected to be significantly cheaper than the prosthetics currently available on the market. This is partly the result of the simplicity of the device as well as the materials used in manufacturing. Prosthetics on the market are frequently out of the pet owner's price range. The final device is able to fulfill the same function but it is cheaper. In addition, the device is also easy to machine and produce with minimal labor and many of the materials used can be found in general stores. For example, the harness is purchased as a separate component and the price range is totally dependent on the consumer's discretion. As a result this device economically has an advantage over other items on the market.

### 6.3.3 Environmental Impact

The proposed device has both positive and negative impacts on the natural environment. A known negative impact is the material that the pylon part is printed of, polycarbonate plastic. This plastic can be a serious issue as a waste product if not recycled properly. However the device was designed to be durable, lasting at least a year, so a large amount of plastic waste product is not anticipated. When comparing the device to other prosthetics on the market it is clear that the design is less bulky; using less material. As a result it can be said that the prosthetic is "greener" in that regards. The components outside of the pylon and the arm splint assembly can be found commercially, in local stores and online markets, so a new method of machining the raw parts is not needed. Therefore, the assumption can be made that the impact of the team's proposed device on the natural environment will be minimal.

### 6.3.4 Societal Influence

The pet industry is continuously growing with the increasing interest of owning pets by households in in the United States. According to the American Pet Product Association (APPA), consumers have spent 24 billion dollars on pet products in 2016 more than what was spent in 2010,

where prosthetics and splints are considered part of those pet products [50]. This increase in the spending on pets indicates that people are continuously considering pets more as part of their families. Therefore, providing the pets with tools that allow them to regain their mobility is becoming a very essential need. Providing this free process for making a prosthetic or a splint for dogs that are in need will influence people to provide more support for their pets while spending significantly less.

### 6.3.5 Political Ramifications

Considering this product is a free online tool or process that people can utilize to provide support to their pets, it would not cause any political ramifications at any level. However, if this product was ultimately decided to be manufactured and sold by the team, there is a potential that it will be manufactured outside the United States. The most obvious reason to do the production or manufacturing outside the United State is to lower the cost of production. This can potentially lead to political concerns.

### 6.3.6 Ethical Concerns

Success is defined differently for each user. The goal is to provide a product that makes the dog, which is the user, satisfied and happy. The prosthetic may not be as helpful to some dogs while others need it to walk. The prosthetic may not be right for the a specific dog's case, each situation requires something different in the solution for the problem that the team's prosthetic design may not address. Testing of the prosthetic was non-invasive and did not cause any pain or suffering to the canine. Keeping that in mind, other dogs that could potentially use the team's prosthetic design will not suffer, thus making it safe and ethical.

### 6.3.7 Health and Safety Issues

A prosthetic is meant to improve the quality of life of the patient; in this case the patients are canines. The team's prosthesis is intended to be used for dogs that struggle with walking due to a leg deformity. The team's purpose of the prosthetic is to improve the overall health of the dog while keeping them safe from injury and danger as much as possible. There is a possibility that the dog that uses the prosthetic may have an allergic reaction if their skin does not respond well to the contact with material of the pylon or any other portion of the prosthetic. That is unlikely given the

materials chosen are biocompatible with the body. The health impacts are positive. The dog's lifestyle will have to adjust to accommodate the use of the prosthetic. They will have to stay more active and physical training with the device.

### 6.3.8 Sustainability

In terms of sustainability of renewable energy, our prosthetic will be body powered, meaning it will move through the exertions of the canine wearing it and will not use an external power source. The prosthetic itself will be made of ABS. The device is made to be durable enough to withstand the cyclic loading forces experienced during the canine's gait cycle for at least a year. After a year the pylon of the device may need to be replaced, but other aspects of the design, such as the harness and arm pieces, can last longer depending on the growth of the canine. The pylon of the device should be properly disposed to prevent harm to the environment.

## 6.4 Comparison to Current Market Product

The team aimed to design a lightweight inexpensive prosthetic that allows dogs with deformities to walk and run easier. The team found and purchased a prosthetic with the same general concept from a company named Walkin' Splints. We found the product being sold through Amazon. The team ordered the smallest size, XXS, and it was still too big for Baxter's leg. Baxter's limb from Wrist to elbow (lateral measurement) is 7 cm long and the smallest available prosthetic for purchase is approximately 10 cm long and is not adjustable. A visual comparison can be represented in Figure 37 below. Thus the most accessible prosthetic that was found is not able to be adjusted and fit Baxter further supporting the need of the team's project of designing and fabricating a prosthetic for small dog limb deformities.



Figure 37: Comparison between the Walkin' Splints (left) and the project prosthesis (right).

## Chapter 7: Discussion

This section will outline how well the team met the objectives set at the beginning of the project. These objectives can be found in chapter 3.2 of the report and correlates with the revised client statement made by the team.

### 7.1 Low Cost

Due to the yearly turnaround of the prosthesis, cost is an important factor. Our client mentioned that she would be willing to spend approximately \$200. Early on, the team decided to pursue 3D printing as the method of manufacturing due to the cost in comparison to metal manufacturing. Other methods such as injection molding and casting methods are more expensive and is often used for mass production uses.

**Table 27: Cost breakdown of the final prosthesis**

<b>ITEM</b>	<b>TOTAL PRICE</b>	<b>UNIT PRICE</b>
Nylon Copolymer 3D Printer Material	\$80/kg	\$1.56
Cost to 3D Print	\$25.00	\$25.00
Dog Harness	\$16.01	\$16.01
Neoprene	\$16.94	\$2.12
Elastic	\$2.99	\$2.99
Nuts and Screws	\$10.36	\$0.10
Total Price	\$151.30	\$47.78

This table shows the total cost which is the retail price for each item. However, when the material is purchased for future use, not all of the product will be used. This is the case for the nylon copolymer, the neoprene, and the nuts and screws. Therefore, the unit price of the prosthesis was also included. The unit price only takes into account the price of the materials used. As seen in Table 33, the team's price goal was met.

## 7.2 Durable

While the durability of the prosthesis was a primary objective, due to time constraints, the team was unable to test the durability of the final prototype. The client was given a previous iteration for a short period of time, spanning about 1 week. Ideally, the team would like to test for a longer period of time; at least a few months. However if the team had been provided more time and the means to do so, cyclic loading would have been performed to discover the lifetime of the device.

In addition to the durability of the pylon itself the team performed mechanical testing on the harness material. The harness material component, along with the post screw and the top splint segment were able to withstand forces higher than what would be applied by the dog in the case study, Baxter. However, similar to the pylon, the lifetime of that assembly was not tested. If the testing had been performed, the team would have also conducted a cyclic test on the assembly.

## 7.3 Mechanically Stable

One of the device's main objectives was mechanical stability. This includes providing the intended mechanical functionality; such as equalizing the height of both limbs and preventing twisting. Additionally, it includes having a stable structure that is able to withstand various compressive and bending loads that the device might be subjected to. The gait analysis and force plate data have showed that the device has increased the height of the deformed limb to match his healthy limb. Only restoring the limb height did not allow the dog to exert equal forces between the healthy and deformed limbs. The arm split helped to achieve this objective of preventing twisting of the prosthesis.

When the device is in use, the main force that is applied to it is a compressive load exerted by the deformed paw to the base of the prosthesis. The results of the 3D materials testing showed that the selected material, Nylon Copolymer, is able to withstand significantly higher loads than the paw strike forces. However, bending tests were performed to determine the flexural strength of the materials to account for accidental bending forces that might be applied to the arm splint when it is not in use. The results have shown that the Nylon Copolymer was the strongest 3D printing material in bending due to its flexibility. Although metal such as aluminum or steel have extremely higher bending strength, their weight and manufacturability have been two major limitations.

## 7.4 User Friendly

The user interface is crucial for any device. The prosthesis was designed in a way to ensure ease of use. Considerations were made in designing a user friendly device. Some of these considerations include the use of straps as an attachment point as well as the incorporation of the harness. For the straps, the team found that having them on the outside and fastening the straps in place using a metal buckle made it easier for the user to attach the prosthesis on Baxter without the assistance of another person. As a result, this design concept was chosen as the attachment for our final device. The harness was another aspect that was made user friendly. The user can purchase any suitable harness for their dog, provided that it has enough material to attach the prosthesis. This provides the user more options in controlling not only the price of the whole component, but the appearance as well.

## 7.5 Non-toxic

The final material selection played a significant role during our design iteration process. The choice was between a lightweight metal, like stainless steel, or 3D printing using various plastics. Based on our case study objectives 3D printing was deemed more suitable due to four factors: cost, strength, accessibility, and customizability. Three different 3D printing materials were considered; nylon copolymer, ABS, and PETG. The nylon copolymer was chosen due to its resilience in bending and high max stress as mentioned in chapter 6.2. As a result nylon copolymer was chosen as the material for our final device. It is a plastic that is recycled well, and is not toxic if licked or chewed by a dog, barring a nylon allergy [51] [52].

## 7.6 Comfort

Lack of verbal feedback was one of the biggest challenges when working with canines. Since the team was unable to communicate with Baxter to receive feedback on the comfort of the design, a scale was used to quantify Baxter's reaction to the design. The results of this scale can be seen in Appendix N. Baxter's average score was a two out of five. Although Baxter's score is relatively low, it is most likely due to lack of adjustment to the design and not the overall comfort of the design itself. It is important to note that at the beginning of the design process, Baxter resisted any touching of the deformed limb and simple tasks such as measuring limb diameter were



difficult. However as time progressed Baxter became more receptive to handling of the deformed limb and as a result the project team predicts that his receptiveness to the prosthesis will improve over time.

# Chapter 8: Conclusions and Recommendations

## *Conclusions*

The purpose of this project was to create a low cost prosthesis device that stabilizes the gait of small dogs with front limb deformities. The project team collaborated with the client and her dachshund, Baxter, for a time period of nine months. The team used the experience with Baxter as a case study to develop a user guide for others to use if they would like to customize our design. A website was created to share the team's case study and allow other pet owners to recreate the team's final prototype. The website includes modifiable CAD files as well as the user guide. Images from the website can be seen in Appendix O. The user guide assists the pet owner in the process of designing their own custom prosthesis. It contains of detailed instructions on background tests and measurements that are necessary to obtain the correct data to modify the CAD files. The tests are taken directly from the processes the project team used to design Baxter's prosthesis. These tests include; palpation testing, joint angle measurements, and limb measurements. To recreate the prosthesis, minimal technical knowledge is required due to the simplicity of the user guide.

Throughout the duration of this project, the team performed various tests to ensure the fabricated device would complete the set objectives. The objectives included the prosthesis being low cost, durable, mechanically stable, comfortable, and user friendly. Mechanical stability was proven through the use of pre and post prosthesis force plate testing and kinematic gait analysis. The main improvement was the decreased inversion of Baxter's shoulder angle while using the prosthesis. For canine's, inversion is a result of compensating for the deformed or missing limb in tripods. This decrease allows Baxter to distribute his weight more evenly. Comfort and user friendliness was ensured through the use of scales that were developed by the team as well as observations made by the owner. The final prototype fabricated cost \$47.68 per prosthesis. This falls within the client's desired \$200 maximum price and meets the team's primary objective of being low cost. Due to the time constraint, the durability of our prosthesis was not tested. This is further discussed in the recommendations section.

One of the biggest challenges in creating a canine prosthesis was working with a dog. Unlike working with human subjects, canine subjects cannot tell you why they dislike a device or what is causing them discomfort, they can only provide a negative or positive response.

It was up to the project team to deduce the sources of potential discomfort and adjust the design accordingly. This was another setback in fabricating canine devices, each redesign took a significant amount of time and the team's rationale on which design aspects to change could be completely off the mark due to the absence of communication with the subject.

### *Recommendations*

Due to the project time limitations there are goals that were left unfinished. The final design that was selected was given to Baxter. As with Baxter's adaptation to the handling of his right forelimb, his reaction to the prosthesis could improve over time with therapy and consistent exposure and use. The team recommends that Baxter, and any other dog that is given a prosthesis device based on the methodology described in this report, be given time to adjust to the new device.

Given the time constraints, and available resources, the team was unable to address the device's durability, which is one of the project objectives. An option for the future would be to conduct cyclic loading of the prosthesis to ensure that it can withstand a year's worth of wear without mechanical breakdown. In addition to the durability of the prosthesis, the team was unable to completely correct the issue of the prosthesis slipping off as seen in Baxter's case study. The team recommends that, in future iterations, better attachments are made to ensure that the prosthesis is able to stay on for the duration that it is intended to remain on the dog.

The final prototype given to Baxter was printed on the Object 260 Connex rapid prototyping machine at WPI. Fabrication of this design could be printed on a lower quality printer, however it should be noted that modifications will have to be made. In the team's CAD design, the bottom sole of the prosthesis is created as a different material. Since the bottom piece most likely will not print on a lower quality printer, the team would recommend that, a material of similar mechanical specifications should be used as a replacement and added manually by the creator.

While the project team primarily focused on small dogs in the creation of the prosthesis, it was designed in a way that makes application to larger dogs possible. If an attempt is made to make this design concept applicable to larger dogs, the team would suggest that appropriate mechanical considerations of the device should be modified and tested prior to use. It should also be noted that such design modifications would increase the cost of the design, as more material would be necessary. In addition, depending on the size of the dog and the capabilities of the printer

used, the design may need to be broken into smaller components in order to be fabricated through additive manufacturing.

There is a larger market for dogs with amputations than for dogs with deformed limbs. The team acknowledges that the design and user guide could be implemented to create less expensive prosthetics for canines with amputations as well. The pylon could be modified to a socket design and the ground interface portion could be increased in length to accommodate a larger missing limb length. The hope is that a design of this nature would provide a customizable and inexpensive alternative to purchasing a prosthesis. Again, appropriate mechanical considerations of the device should be tested prior to use.

The team also recommends that an identification of a larger market for this device should be done. Approximately 6.5 million companion animals enter U.S. animal shelters every year, out of this 1.5 million are euthanized annually [53]. One can assume that dogs with deformities, particularly deformities that limit their mobility, are most likely the first to be euthanized. As a result there is a potential market for providing a low cost solution to these shelters with the hopes of possibly saving the lives of these dogs.

An affordable prosthesis for dogs with front limb deformities has the potential to improve the lives of not only the dogs that use the device but dog the owners as well. An inexpensive alternative allows owners who are unable to afford custom made prosthetics, which can cost upwards of \$1000, to customize and make their own based on their preference. The hope is that this device will have a major impact on the everyday life of both the dog and the caretaker.

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## Appendix A: Veterinarian Interview

1. How much would it cost to get an x-ray for Baxter?
  - Each x-ray would be 85\$ per region. For Baxter it was recommended that four x-rays should be taken, two of his normal forelimb and two of his abnormal one. That way the bones that are present or absent can be identified.
2. Points of attachment for prosthetic- how to decide this?
  - It was recommended that we contact a prosthetist, people whose job it is to create prosthetics, in order to get information about points of attachment for the prosthetic.
3. How to monitor pain in dogs? (Recommendations/Methods)
  - Pain scales based on behavior changes/vocalization for dogs can be found online.
4. How to define quality of life for a dog?
  - This can also be found online.
5. How much should the muscles be trained prior to doing the prosthetic tests? How long is adjustment period for dog to learn how to use prosthetic? How frequent should the training be? ( how long, intensity of training)
  - A rehabilitation therapist would be better equipped to answer this question. A list of rehabbers in Worcester was sent to us by email.
  - A recommendation was made to institute weight loss while implementing prosthetic in order to help with gait.
6. How often do they see dogs that have condition that could be similar enough to Baxter's condition?
  - Not very often.
7. Do they have an idea of what the cause of this deformity is? (How common it is?)
  - Based on the descriptions, images, and video presented it is possible that Baxter has radial agenesis, however this can't be confirmed without x-ray information.

## Appendix B: Animal Ortho Care Interview

1. What information do you collect from a client in order to create the prosthetic?/What is the bottom line necessary information that is required?
  - We just have them fill out the custom brace order form from our website. I need to know the length of the limb and if the dog is still trying to use the limb. I also have to know that the owner is suitable to fit the prosthesis
  - 1. Do you require x-rays?- not needed unless extreme case. Good to have though.
2. What materials do you use in your prosthetics?
  - polypropylene, aliplast liner, aluminum componentry when needed and rubber tread and velcro straps.
3. What is your manufacturing process? (if you are at liberty to say)
  - Google orthotic manufacturing process videos. More closely related to animal prosthetics than human prosthetic videos.
4. Do you have any prosthetics for dogs with front limb deformities? (not an amputation)
  - Sure we call them able-bodied prosthetics.
5. Do you have any limitations that would disqualify a dog from getting a prosthetic?
  - Yes, amputation level. Need the level of the tarsus or lower for the rear limb and to the level of 2-3 inches below the elbow in a forelimb.
6. What is the average cost of your prosthetics? Does this differ based on the size of the dog?
  - \$1,250
  - Does not differ.
7. How durable are your prosthetics?/How often do they need to be replaced/repared?
  - Shelf lasts for life. Have to replace treads and straps depending on dogs activity level .
8. Are your prosthetics suitable for different types of terrain?
  - Yes and they are mostly water proof.
9. Are the prosthetics designed to be worn full-time/part-time?
  - Always part time. Look at our wear and care form on our website.
10. Can the dog climb stairs with this prosthetic on?
  - Case specific.
11. Do you have the dogs go through a specific training using the prosthetic?
  - Yes, but I do not have one written down. that is really the physical therapists department.

## Appendix C: My Pet's Brace Interview

1. What information do you collect from a client in order to create the prosthetic?/What is the bottom line necessary information that is required?
  - Prosthetic: Have to come to the office. Mixed fit, have to come back several times
  - Diagnosis of the injury from the vet, with name and contact information
  - Doesn't have to be an x-ray, just a diagnosis
  - Orthotic: Come here or come to local vet: cast of the dog's leg
2. What materials do you use in your prosthetics?
  - Human grade stainless steel and copolymer plastic
  - Lining: medical grade plastics (propolymer)
  - Glues: approved, antibacterial foam for the padding, stainless steel screws and velcro straps
3. What is your manufacturing process? (if they are at liberty to say)
  - Orthotic:
    - Come to building evaluation and casting during appointment
    - Not able to come: work with local vet
  - Video: request vets to look at first, cast is shipped to them
  - Everything is formed around that mold.
4. Do you have any prosthetics for dogs with front limb deformities? (not an amputation)
  - No, do not have any prosthetics for dogs with front limb deformities
  - Amputation: not complete amputation
5. Do you have any limitations that would disqualify a dog from getting a prosthetic?
  - A complete amputation.
  - Couldn't come to the building site.
6. What is the average cost of your prosthetics? Does this differ based on the size of the dog?
  - Knee braces: weigh breakoff 105 pounds or lower 799\$ or 105 pounds and higher 949\$
  - Prosthetics: around 1250\$
7. How durable are your prosthetics?/How often do they need to be replaced/repared?
  - Brace: last lifetime
  - Straps: will wear out or stitching might come out . Straps are easily replaced and ACL pads as well.
8. Are your prosthetics suitable for different types of terrain?
  - It is suitable for any time of terrain.
9. Are the prosthetics designed to be worn full-time/part-time?
  - Designed to be worn part time: not when sleeping/nighttime or crated.
10. Can the dog climb stairs with this prosthetic on?
  - Yes.
11. Do you have the dogs go through a specific training using the prosthetic?
  - Rehabilitation would be helpful. Water therapy, a vet or physical therapist would discuss that with them.

## Appendix D: OrthoPets Interview

1. What information do you collect from a client in order to create the prosthetic?/What is the bottom line necessary information that is required?
2. What materials do you use in your prosthetics?
3. What is your manufacturing process? (if they are at liberty to say)
4. Do you have any prosthetics for dogs with front limb deformities? (not an amputation)
5. Do you have any limitations that would disqualify a dog from getting a prosthetic?
6. What is the average cost of your prosthetics? Does this differ based on the size of the dog?
7. How durable are your prosthetics?/How often do they need to be replaced/repared?
8. Are your prosthetics suitable for different types of terrain?
9. Are the prosthetics designed to be worn full-time/part-time?
10. Can the dog climb stairs with this prosthetic on?
11. Do you have the dogs go through a specific training using the prosthetic?

## Appendix E: K-9 Orthotics and Prosthetics Interview

1. What information do you collect from a client in order to create the prosthetic?/What is the bottom line necessary information that is required?
  - We require a cast moulding of the residuum and a correct length measurement, at a minimum, along with the client particulars.
2. What materials do you use in your prosthetics?
  - Thermoset plastics, the same as in the human market.
3. What is your manufacturing process? (if they are at liberty to say)
  - Same as in the human market, but I am unable to go into detail.
4. Do you have any prosthetics for dogs with front limb deformities? (not an amputation)
  - Depends on the deformity and the range of motion in the limb, not a straightforward question or answer.
5. Do you have any limitations that would disqualify a dog from getting a prosthetic?
  - Very short or no stump at all.
6. What is the average cost of your prosthetics? Does this differ based on the size of the dog?
  - \$1200 to \$3000
  - Yes, but in combination with the length of residuum.
7. How durable are your prosthetics?/How often do they need to be replaced/repaired?
  - Very durable, the soling needs to be maintained/replaced, and overall cleaning. As long as there are no major changes in the limb the prosthesis could potentially last the life of the dog.
8. Are your prosthetics suitable for different types of terrain?
  - Yes.
9. Are the prosthetics designed to be worn full-time/part-time?
  - Depends on the needs of the patient, but must be removed at night when sleeping
10. Can the dog climb stairs with this prosthetic on?
  - Usually.
11. Do you have the dogs go through a specific training using the prosthetic?
  - We do provide info on acclimatizing to wearing a prosthesis, but in general just patience, consistency and hands on observation, the owners may wish to work with a physiotherapist.

## Appendix F: Quality of Life Scale for Canines

Quality of Life Scale	
Score	Criterion
0-7	<p><b>Pain</b></p> <ul style="list-style-type: none"> <li>_ displays high level of pain based on pain scale</li> <li>_ limps (if pet limps they are in pain)</li> <li>_ pants frequently, even at rest</li> <li>_ respiration is forced, exaggerated, not normal</li> <li>_ licks repeatedly at one site of body near prosthetic</li> <li>_ guards area of body and may snap when area is approached or touched</li> <li>_ posture is abnormal or different than normal</li> </ul>
0-6	<p><b>Appetite</b></p> <ul style="list-style-type: none"> <li>_ doesn't eat his/her normal food anymore</li> <li>_ picks at his/her food but never used to</li> <li>_ walks over to his/her food but won't eat or walks away from the food</li> <li>_ doesn't want food treats/snacks/human foods anymore</li> <li>_ acts nauseated or vomits</li> <li>_ loss of weight</li> </ul>
0-3	<p><b>Hydration</b></p> <ul style="list-style-type: none"> <li>_ doesn't drink as much water as prior</li> <li>_ frequently has dry, sticky gums</li> <li>_ is vomiting or has diarrhea</li> </ul>
0-4	<p><b>Hygiene</b></p> <ul style="list-style-type: none"> <li>_ hair is matted, greasy, rough looking, dull or foul smelling</li> <li>_ has stool passed around his/her rectum or his/her hair</li> <li>_ smells like urine or has skin irritation from urine</li> <li>_ has pressure sores/wounds around area of prosthetic that won't heal</li> </ul>
0-5	<p><b>Activity/Mobility</b></p> <ul style="list-style-type: none"> <li>_ cannot get up without assistance</li> </ul>

	<ul style="list-style-type: none"> <li>_ does not feel like going for walks, playing ball, or things he/she used to do</li> <li>_ has a hard time getting around/ or limps</li> <li>_ lays in one place all day long</li> <li>_ falls frequently</li> </ul>
0-4	<p><b>Happiness/Mental Status</b></p> <ul style="list-style-type: none"> <li>_ does not express joy and interest in life</li> <li>_ does not respond to people that he/she used to respond to</li> <li>_ does not want to play with toys or things that he/she used to enjoy</li> <li>_ appears depressed, dull, not alert</li> </ul>
0-5	<p><b>General Behaviour Patterns</b></p> <ul style="list-style-type: none"> <li>_ hiding or sleeping in odd places</li> <li>_ not greeting owner when he/she comes home a he/she used to</li> <li>_ is overly clingy and he/she never used to</li> <li>_ other pets are treating this pet differently, over attentive or ignoring him/her completely</li> <li>_ pet doesn't care about what is going on around him/her</li> </ul>

# Appendix G: Colorado State University Canine Pain Scale



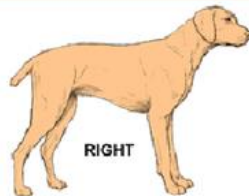
Date \_\_\_\_\_

Time \_\_\_\_\_

Colorado State University  
Veterinary Medical Center  
Canine Acute Pain Scale

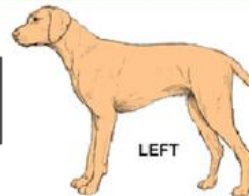
Rescore when awake  Animal is sleeping, but can be aroused - Not evaluated for pain  
 Animal can't be aroused, check vital signs, assess therapy

Pain Score	Example	Psychological & Behavioral	Response to Palpation	Body Tension
0		<input type="checkbox"/> Comfortable when resting <input type="checkbox"/> Happy, content <input type="checkbox"/> Not bothering wound or surgery site <input type="checkbox"/> Interested in or curious about surroundings	<input type="checkbox"/> Nontender to palpation of wound or surgery site, or to palpation elsewhere	Minimal
1		<input type="checkbox"/> Content to slightly unsettled or restless <input type="checkbox"/> Distracted easily by surroundings	<input type="checkbox"/> Reacts to palpation of wound, surgery site, or other body part by looking around, flinching, or whimpering	Mild
2		<input type="checkbox"/> Looks uncomfortable when resting <input type="checkbox"/> May whimper or cry and may lick or rub wound or surgery site when unattended <input type="checkbox"/> Droopy ears, worried facial expression (arched eye brows, darting eyes) <input type="checkbox"/> Reluctant to respond when beckoned <input type="checkbox"/> Not eager to interact with people or surroundings but will look around to see what is going on	<input type="checkbox"/> Flinches, whimpers cries, or guards/pulls away	Mild to Moderate Reassess analgesic plan
3		<input type="checkbox"/> Unsettled, crying, groaning, biting or chewing wound when unattended <input type="checkbox"/> Guards or protects wound or surgery site by altering weight distribution (i.e., limping, shifting body position) <input type="checkbox"/> May be unwilling to move all or part of body	<input type="checkbox"/> May be subtle (shifting eyes or increased respiratory rate) if dog is too painful to move or is stoic <input type="checkbox"/> May be dramatic, such as a sharp cry, growl, bite or bite threat, and/or pulling away	Moderate Reassess analgesic plan
4		<input type="checkbox"/> Constantly groaning or screaming when unattended <input type="checkbox"/> May bite or chew at wound, but unlikely to move <input type="checkbox"/> Potentially unresponsive to surroundings <input type="checkbox"/> Difficult to distract from pain	<input type="checkbox"/> Cries at non-painful palpation (may be experiencing allodynia, wind-up, or fearful that pain could be made worse) <input type="checkbox"/> May react aggressively to palpation	Moderate to Severe May be rigid to avoid painful movement Reassess analgesic plan



RIGHT

○ Tender to palpation  
 X Warm  
 ■ Tense



LEFT

Comments \_\_\_\_\_



# Appendix H: Prosthetist Phone Interview

## Interview with: Nellie Zarif

1. What is your design process when creating a prosthetic and what are the steps used to reiterate the design until a final device is ready to be implemented?
  - a. Evaluation of the skin type and cause of amputation:
    - What type of suspension?
    - Dexterity/integrity of skin?
  - b. Measurement:
    - 3D digital scan (mark out bony landmarks)
    - Hand cast (tape measure, cast under vacuum)
    - Distribute forces over areas that can tolerate pressure
  - c. Check socket sitting:
    - Try out the socket, to ensure no areas of high pressure
    - Dynamic alignment.
    - Prototyping
    - Double checking (thermoformable material that can be modified)
  - d. Socket device is based on the patient
  - e. Prefabricated components:
    - Ground interface
  - f. Foot/pylon is based on patients activities
2. What approach and specifications do you require when fabricating a design?
  - a. Is gait analysis implemented, and if so what measurements
    - Look more at muscles (muscle weakness/laxity)
    - Dynamic alignment (change prosthetic to optimize gait)
  - b. What methods,if applicable, are used to take accurate molds of the limb in need of a prosthetic?
    - Plaster/fiberglass (full extension)
3. What materials are used when manufacturing the prosthetic and for what portion of the prosthetic do these materials specifically apply to (the part interfacing with ground vs part interfacing with the limb)?
  - Gel liner (with skin) interface with frame and skin
  - Flexible inner socket and rigid frame (carbon fiber and resin frame)
  - Pylon (make socket attack to foot) titanium/aluminum or stainless steel (based on weight and alignment)

# Appendix I: Prosthetics Trial Protocol

## Protocol

- Apply pressure to and/or massage Baxter's deformed limb for at least 15 minutes a day
- Procedure: Have Baxter wear the prosthetic for at least 15 minutes twice a day
  - Record any observations such as if Baxter chews/bites the prosthetic, attempts to shake/bang the prosthetic off
    - Include in the notes of observations what time of day as well as terrain, including weather
    - Document what number on scale 1 (Below) and scale 2 (Below) Baxter falls under
- Once Baxter responds better to having the prosthetic on, have him wear for a longer period of time and try walking/running on it

### **Scale 1:**

1 to 5 Comfort/effectiveness of prosthetic

1. Doesn't attempt to walk even with prompt
2. Shakes leg until prosthetic is removed
3. Walks, but attempts to remove the prosthetic once the prompt is removed
4. Walks comfortably but attempts to remove the prosthetic after an extended period of time
5. Walks/runs confidently without trying to remove the prosthetic

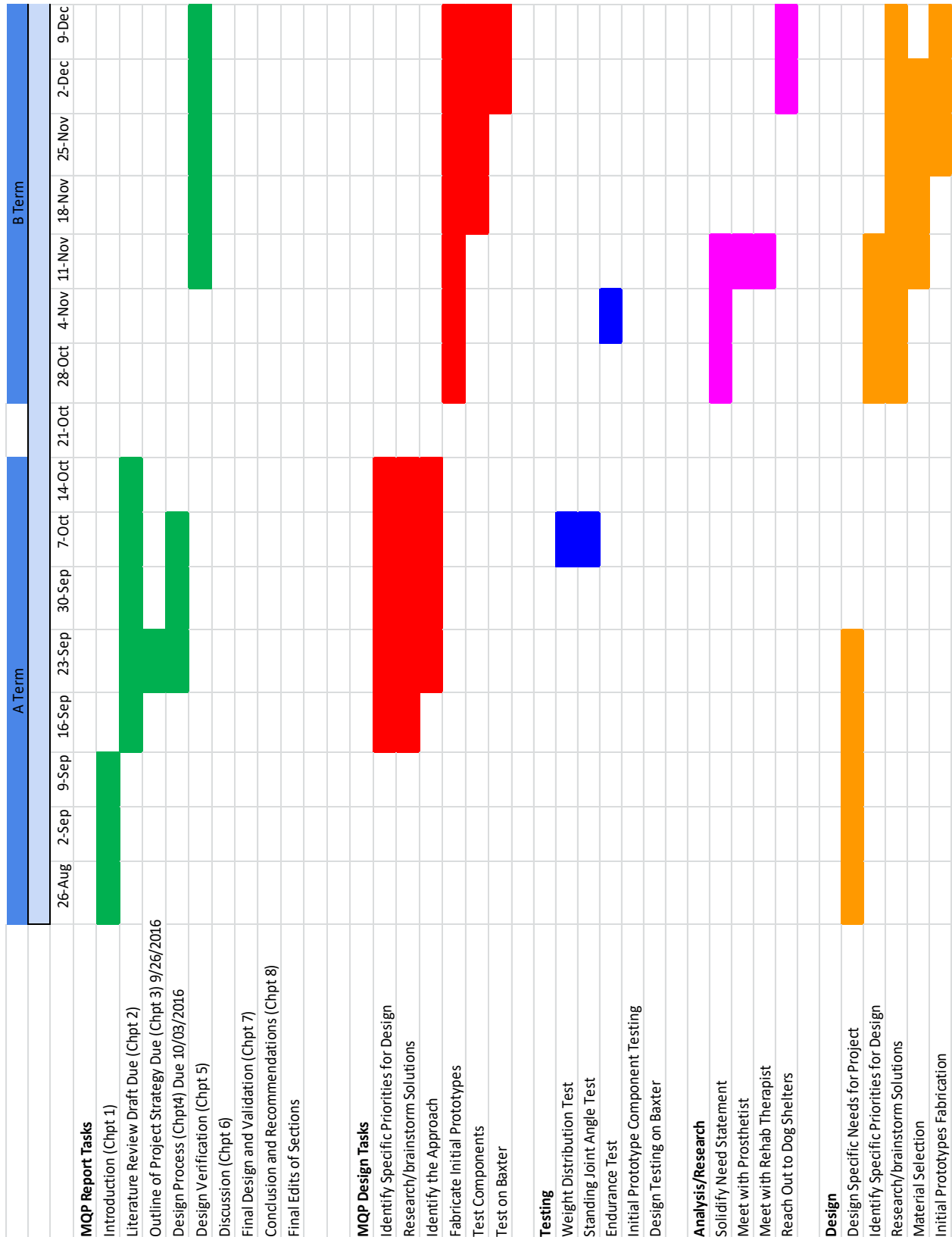
### **Scale 2:**

1 to 5 Prosthetic attachment

1. Has to be adjusted after every trial
2. Stays on for a couple of trials
3. Stays well for testing period
4. Stays for extended period of time but has to adjusted

Doesn't have to be adjusted after put on and after use

# Appendix J: Gantt Chart Outlining Project Milestones



	C Term										D Term					
	20-Jan	27-Jan	3-Feb	10-Feb	17-Feb	24-Feb	3-Mar	10-Mar	17-Mar	24-Mar	31-Mar	7-Apr	14-Apr	21-Apr	28-Apr	5-May
<b>MQP Report Tasks</b>																
Introduction (Chpt 1)																
Literature Review Draft Due (Chpt 2)																
Outline of Project Strategy Due (Chpt 3) 9/26/2016																
Design Process (Chpt4) Due 10/03/2016																
Design Verification (Chpt 5)																
Discussion (Chpt 6)																
Final Design and Validation (Chpt 7)																
Conclusion and Recommendations (Chpt 8)																
Final Edits of Sections																
<b>MQP Design Tasks</b>																
Final Material Selection																
Final Design manufactured																
Website creation																
Guide creation																
<b>Testing</b>																
Final Design Testing																
Final Design Validation																
Train/Adjust Baxter to Final Design																
Harness Material Testing																
Plastics material Testing																
<b>Design</b>																
Final Prototype																
Final Design Fabrication																

## Appendix K: Limb Measurement Values

Anatomical measurements (in cm)				
Baxter				
Anatomical Landmarks	Measurement	Right- Baxter	Left- Baxter	Notes
Foot	Circumference	5.5	10	* taken right below the last nail
Wrist to elbow (lateral measurement)	Length	7	8	
Top forearm (proximal)	Circumference	7	10	
Lower forearm (distal)	Circumference	6	6	
Wrist to nail lateral measurement	Length	4	5	* Baxter only has one nail
Wrist to nail medial measurement	Length	5	8	
Scapula to elbow	Length	12	12	
Shoulder	Circumference	12	13	

Anatomical measurements (in cm)				
Petey				
Anatomical Landmarks	Measurement	Right- Petey	Left- Petey	Notes
Foot	Circumference	11	11	* taken right below the last nail
Wrist to elbow (lateral measurement)	Length	8.5	8.5	
Top forearm (proximal)	Circumference	13	13	
Lower forearm (distal)	Circumference	8.5	8.5	
Wrist to nail lateral measurement	Length	6.5	6.5	
Wrist to nail medial measurement	Length	8	8	
Scapula to elbow	Length	9.5	9.5	
Shoulder	Circumference	14	14	

# Appendix L: Reproducibility Guidelines

## **Prosthetic Pawsibilities: A Guide to Modifying and Manufacturing Custom 3D Printed Solutions for Canine Limb Deformities**

### **Introduction**

This guide is intended to aid in the creation of a custom prosthesis for canines with front limb deformities such as congenital deformities and post-surgical applications for conditions such as elbow dysplasia and angular growth deformity. The guide contains detailed instructions on modifying SolidWorks files and fabricating your own prosthesis for your pet. Each solution costs under \$200 to fabricate and requires 3D printing technology. The following list of steps and tests will help you determine the best solution for your pet. The guide is compiled in such a manner that reiteration of certain components may be necessary to ensure optimal fit and performance. Good luck!

### **Step 1: Goal Setting**

At this stage you've identified some issues with your canine companion's gait and movement, maybe their walking endurance has decreased, they are having difficulties moving around the house, or they were born with a defect that is decreasing their quality of life. You care about your pet so you want them to have the best life possible. It's the time to identify the realistic improvements you wish to make by creating this device. Our goal for Baxter was to enable him to redistribute some of his standing weight to his deformed limb and increase his walking endurance to approximately 2 miles.

### **Step 2: Background Information**

Now that you've decided what your goals are for this device, it's time to quantify some of the physical limitations your pet has to overcome. This section includes various types of simple tests and measurements which will be used in later fabrication. If a test does not apply to your pet, skip it and move on to the next section.

### **Pressure Sensitivity**

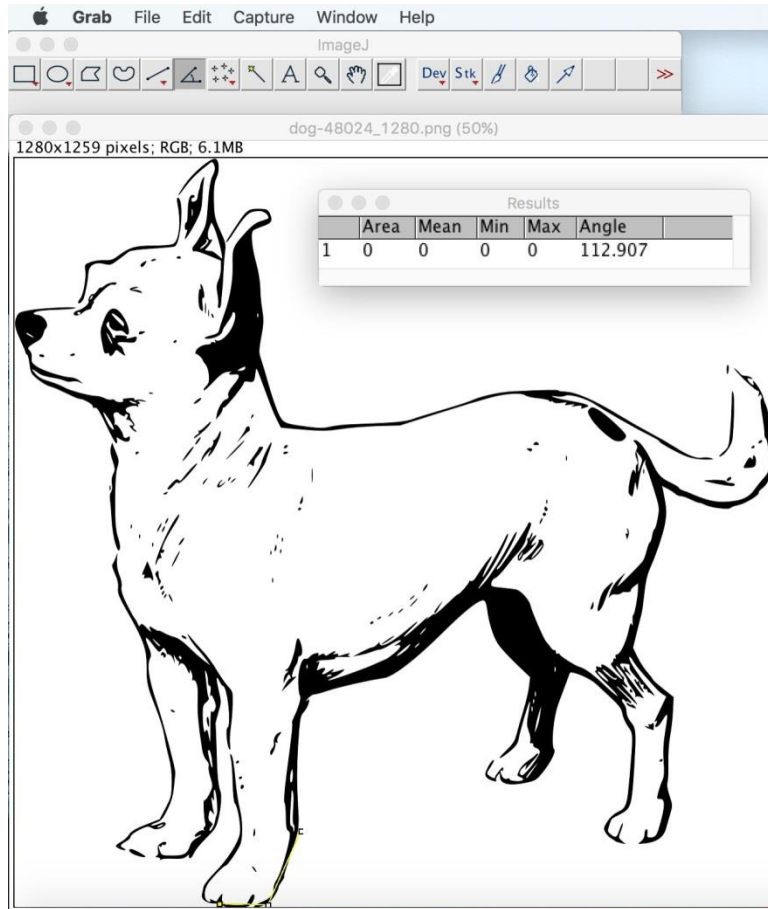
A palpitation test can help identify any sensitive areas on your pet's leg that could become irritated by the prosthesis. Moving by approximately 1.5 cm increments along the affected limb and apply moderate pressure on the lateral and medial sides of the limb using your index finger and thumb. Take note of any areas in which your pet becomes uncomfortable. Repeat this method on the top/bottom of the affected limb. For comparison and to distinguish pain caused by the deformity from normal discomfort, perform the palpation test on a healthy limb, if available. You know your dog best, moving forward avoid designs that apply pressure to any problem areas you may have identified through this test method.

*\*Note: if your pet experiences extreme discomfort/pain during palpation a custom prosthetic is not recommended and veterinary consult is suggested\**

### **Dimensions**

In order to ensure optimal fit, take the following measurements of your pet's affected limb(s):

- Tip of the toe to wrist
- Wrist to elbow
- Elbow to shoulder
- Upper and lower limb diameter
- Missing limb length
- Elbow angle rotation
- Standing carpal (wrist) angle
  - This is easiest done by using ImageJ (free software found here: <https://imagej.nih.gov/ij/download.html>) to analyze a picture of your pet standing



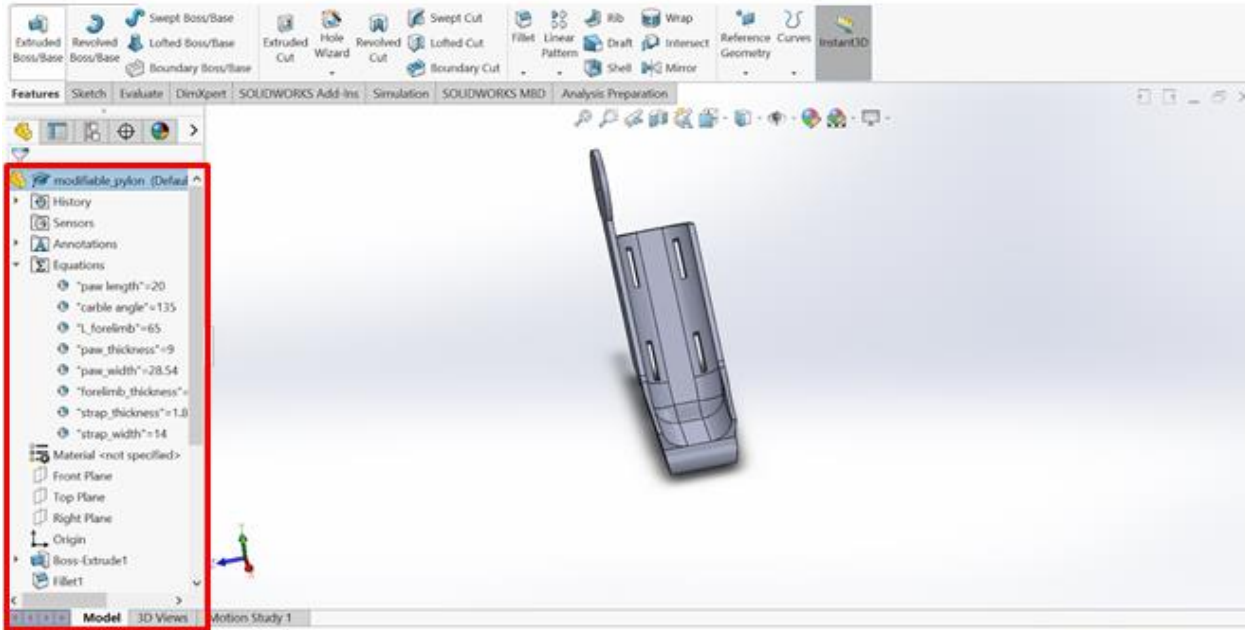
- For this measurement, take the angle between the contact surface and the back of the limb, as seen by the yellow lines in the image above
- If you are unfamiliar with ImageJ, steps for its use can be found in the ImageJ User Guide (<https://imagej.nih.gov/ij/docs/guide/user-guide.pdf>). Specific information about angle measurements can be found in section 19.4 of that guide.

### Step 3: Modifying and Printing a CAD File

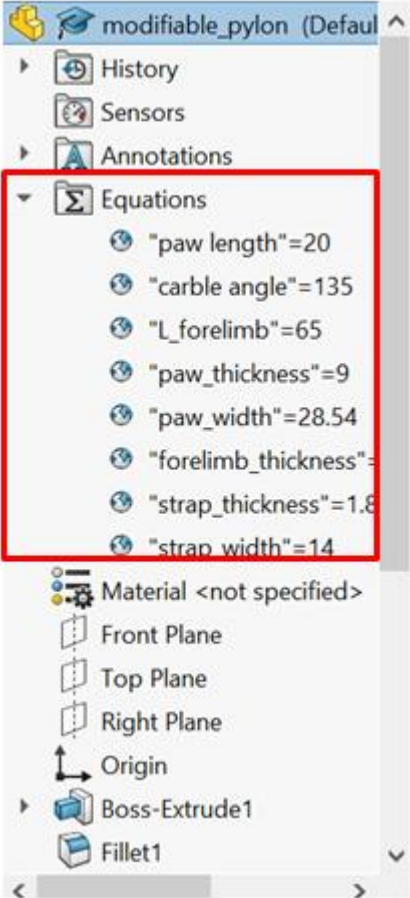
#### Applying your Dimensions

Our CAD files are modifiable, if you have access to SolidWorks 2016 or above, you will be able to open the SolidWorks file. This is the simplest way to modify the device. To modify the CAD files in SolidWorks start of in the main user interface of SolidWorks.





On the leftmost corner you will see a tab labeled Model. Click fourth icon in the tab, labeled equations, and a dropdown box will appear.



Right click any of the dimensions, like the “paw length”. When you click on the “Manage Equations” option it will bring you to a new interface labeled “Equations, Global Variables, and Dimensions.” This is where you can adjust the dimensions to match your case.

### **Choosing a Printing Material**

There are several types of 3D printing materials to consider. The cost of each 3D printed material was compared to ensure that the overall price of the prosthetic was minimized. The cost of each material can be shown in the table below. Acrylonitrile Butadiene Styrene (ABS) was found to be the cheapest option while the Nylon Copolymer was the most expensive. The nylon copolymer has the highest strength which accounts for the higher cost. Lower strength materials may need to be replaced more frequently.

Table 1: Cost of the three 3D printing materials

<b>Material</b>	<b>Cost (unit)</b>
Acrylonitrile Butadiene Styrene (ABS)	\$21.59 (1kg reel)
polyethylene terephthalate glycol-modified (PETG)	\$27.99 (1kg reel)
Nylon Copolymer (Alloy 910)	\$80 (1kg reel)

### **Step 4: Fitting the Prosthesis**

#### **Getting a Harness**

Choose a harness that fits your pet snugly and has enough fabric on the shoulder area to allow for attachment of the arm splint. The splint is best attached through a screw cap such as these (<https://www.amazon.com/dp/B004KF2V08>). Punch a hole through the shoulder of the harness and screw the arm splint into place.

#### **Connecting the Arm Splint**

The pylon and arm splint have matching holes that can be connected by a small screw and nut. Make sure that the screw is loose enough to allow elbow rotation.

#### **Adding Comfort Material**

We chose to add a 4mm layer of neoprene to our final design to increase comfort. We suggest that you choose a comfort material to add to the device as well. Remember to incorporate the thickness of your comfort material into the CAD model specifications.

### **Ensuring Grip**

Add a small patch of non-slip material on the bottom of the prosthetic. We suggest some type of rubber. Ensure that the non-slip material is not too thick as to not add any unwanted height.

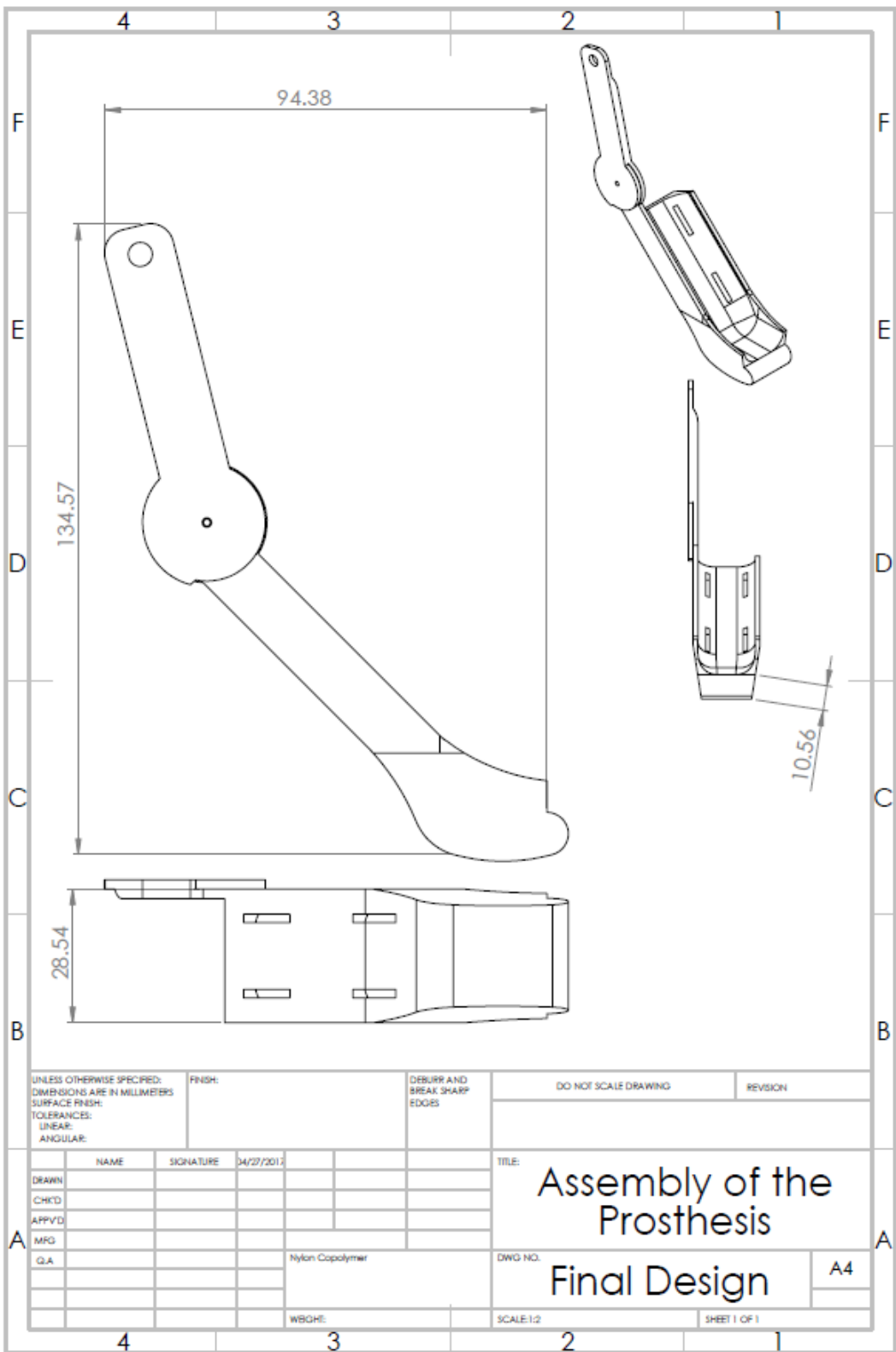
### **Attachment Points**

The team used ½ inch elastic straps with Velcro sewn on to the ends. The straps should go through the slits in the back of the prosthesis so that the loop is in the front and the ends are coming out of the back. The length will be dependent on the amount of elastic it takes to wrap around your dog's forearm. The elastic straps should not be too short; otherwise it will lead to discomfort when wrapped around the forearm. The straps will then attach on the side of the pylon to the opposing Velcro side.

### **Step 5: Evaluating Success**

Congratulations you're finished!! Time to relate back to the goals you make in Step 1! The easiest way to evaluate the effectiveness of the prosthetic is to compare a simple task with and without the use of your pet's new prosthesis. For example, if you wanted to increase your pet's walking endurance, see how far they can walk with and without the prosthesis. These changes may be gradual so don't get discouraged. Continue to work with your pet and reward them when they use the prosthesis correctly.

# Appendix M: SolidWorks Model



# Appendix N: Prosthetic Scale Results

## Scale 1:

1 to 5 Comfort/effectiveness of prosthetic

1. Doesn't attempt to walk even with prompt
2. Shakes leg until prosthetic is removed
3. Walks, but attempts to remove the prosthetic once the prompt is removed
4. Walks comfortably but attempts to remove the prosthetic after an extended period of time
5. Walks/runs confidently without trying to remove the prosthetic

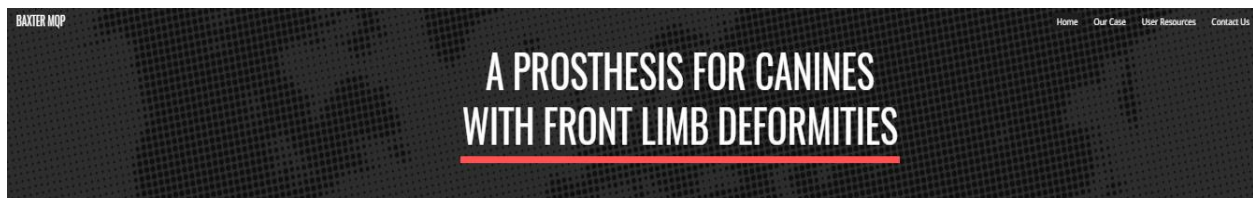
## Scale 2:

1 to 5 Prosthetic attachment

1. Has to be adjusted after every trial
2. Stays on for a couple of trials
3. Stays well for testing period
4. Stays for extended period of time but has to adjusted
5. Doesn't have to be adjusted after put on and after use

Date	Scale 1	Scale 2	Comments
March 8	3	1	Performed in the afternoon, indoors, chews and bites at it
March 9	2	1	Performed in the evening, indoors, chews and bites at it. He also snapped the plastic in half but I was able to repair it
March 10	1	1	Performed in the evening, indoors, continues to chew and bite. Elastic too tight
March 11	2	1	Performed in the morning. Indoors and outdoors. Same issues
March 12	2	1	Performed indoors and outdoors, bites at it. Finding that the elastic becomes too tight because it's the only way to keep the prosthetic on
March 16	2	1	Performed indoors, morning. It is becoming difficult getting him to cooperate. He does not want to wear it. Once food is gone he's done
March 17	3	1	Performed indoors in the afternoon, continues to get out of it within seconds
March 18	2.5	1	Performed indoors and outdoors, continues to bite at it. It appears to cause him discomfort because of the elastic
March 19	2	n/a	Indoors, off within 2 seconds. He runs away when we try to reattach
March 20	n/a	1	Performed indoors and outdoors, without food he refused to let us put it on

# Appendix O: Website Images



## OVERVIEW

For our major qualifying project (MQP), we were tasked to design a prosthesis for a canine with a deformity on one of his front limbs. As a result, we have created a modifiable Computer Aided Design (CAD) File which can be 3D printed. The design can be seen in the image to the right.

There are several important components included in the final design that ensure it's success. These components include a harness, the main body of the prosthesis (called a pylon), and an arm splint attached to the harness. The harness is used to prevent the prosthesis from twisting and slipping off of dog. The arm splint is used to connect the pylon to the harness. The main features of the pylon are shown in the image. These features were developed to enhance attachment, comfort, and safety.



## ABOUT US



We are students at Worcester Polytechnic Institute (WPI) completing our MQP. Within our group of five, three of us are Biomedical Engineering Majors and two of us are Biomedical Engineering and Mechanical double majors. By combining our love of animals and unique skill sets, we were able to create this modular prosthetic to improve the lives of man's best friend.



## ACKNOWLEDGEMENTS

We were able to complete this project with the guidance and help from the Professors and Laboratory Managers in the Biomedical Engineering Department at Worcester Polytechnic Institute as well as the owner of the dog used in our case study.

# MEET BAXTER

Baxter is a 2 year old Dachshund that was born with a congenital front paw deformity on his right side as seen in the images below. Baxter compensates for his deformity, which effects his endurance and causes him to become tired very quickly. Unlike other dogs, he cannot go on long walks. Baxter's owner does not want him to undergo amputation for multiple reasons.

As a result, we developed a low cost device that will enable small dogs with front limb deformities to distribute their weight evenly without having to undergo surgery. This device aims to stabilize walking gait, and increase their endurance relative to initial testing results. The minimum lifetime of the device should be at least 1 year.

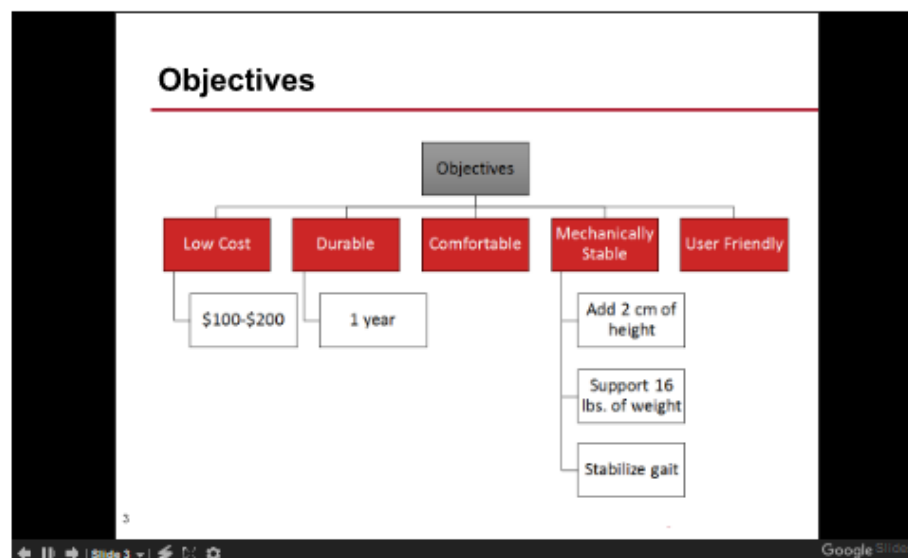


## TEAM'S APPROACH TO BAXTER'S SITUATION

This is a link to a detailed description of the team's project in the form of a report, starting from an introduction & in depth background research to conclusions & recommendations. The report also explains the objectives of the project, the entire design process, and experimental/testing methods.

\*\*\*\*insert link to paper here\*\*\*\*

Below is the slide show for the final presentation given on this project. It outlines Baxter's case, the current market for canine prosthetics, the team's prototype iteration process, material selection, and before & after prosthesis testing results.



# USER GUIDE/CAD FILES

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## GUIDELINES FOR CREATING A CUSTOMIZABLE PROSTHETIC

**User Guide:** <https://drive.google.com/drive/u/1/folders/0B-HC5pqZAKmTXdTTEt1OTlxY3c>

This user guide can be used in addition to the modifiable CAD files to instruct the user with a step by step by process on how to create a customized prosthesis for their dog.

## THESE CAD FILES WERE ORIGINALLY CREATED USING SOLIDWORKS.

**Pylon Solidworks File:** <https://drive.google.com/drive/u/1/folders/0B-HC5pqZAKmTXdTTEt1OTlxY3c>

This file was made with SolidWorks 2016 and contains editable equations to quickly size the part to a specific dog.

**Arm Splint SolidWorks File:** <https://drive.google.com/drive/u/1/folders/0B-HC5pqZAKmTXdTTEt1OTlxY3c>

This file was made with SolidWorks 2016 and contains editable equations to quickly size the part to a specific dog.

# CONTACT US

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If you have questions, comments, or concerns then you can contact us at: [baxtermqp@gmail.com](mailto:baxtermqp@gmail.com)