Final Report: Structural and Mechanical Functions of Bones, Muscles and Joints by use of 3D Models in Veterinary Medical Education

Biomedical Engineering Design

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Client

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Abstract

Veterinary students must learn the anatomy and physiology of animals in great detail. Physically seeing and touching an animal to understand its musculoskeletal system is a very valuable experience, but often poses a problem for professors. The use of cadavers is most common, but there are ethical and financial concerns that arise with those [1], so people have begun to turn to 3D printed models. Currently, most models do not match the detail in the structure or function of the animal as is necessary, and while there are numerous skeleton models and even some musculoskeletal models, none of the existing products have muscles and bones that articulate and can attach/detach the muscles. Taking on this challenge, the team decided to design a model made of 3D printed dog hindlimb bones and attaching silicone muscles to the bones at the proper insertion points. To attach the muscle to the bones, magnetic strips were superglued to both the bone and muscle, cut to a shape representative of the actual surface area of the bone that the muscle attaches to. The model was tested to determine durability and accuracy, finding no changes in attachment force as the model was flexed and extended a fifty times and verifying through a survey presented to first-year veterinary students that the model accurately and intuitively represented a dog hindlimb. With an accurate, reliable model, veterinary students will learn dog anatomy more easily, safely, and cost-effectively.

I. Introduction

A. Motivation

The motivation for this device was to create a veterinary cohort that is better trained and can better treat the animals that come through their clinics. Current veterinary models used for teaching are historically expensive and lack certain features that could help students learn anatomy at a more intimate level. The advancement in design for a veterinary model could easily be translated into a human anatomy model that could help medical students better treat their patients as well.

B. Competition

There are many competing models on the market; however, none of them satisfied the client's needs. The client needed a model that could teach students how muscles control movement and stabilize the skeletal structure. For instance, there is a detailed Articulated Hindlimb by Axis Scientific that is about $72 [2], but this model does not contain muscles and therefore cannot demonstrate the relationship between muscles and skeletal structure. Another competitor is Anatomy Lab which has a $312 model that shows many levels of detail of muscles and organs [3], but this model lacks articulation. Without articulation, students would not be able to understand how muscles flex. There are also cheaper models such as a $26.95 model created by 4D Master [4], but it has the same issues as Anatomy Lab's. On the other end of the price spectrum, 3B Scientific has an articulated dog skeleton that costs roughly $2500 [5], but it lacks muscles. The client also started to develop a model, and, while it has elastic bands to represent the muscles, it is too simplistic. The elastic bands don't show the organic, 3D forms of dog muscles whereas the model developed by this team focused on recreating these forms. Another flaw is that the elastic muscles only connect at a maximum of 2 points of the bone structure. Because there isn't a firm connection across the entire surface area, or the proper number of insertion and origin points per muscle, when a student bends Dr. Gunderson's model the bones don't move appropriately.

C. Problem Statement

In their first semester of graduate school, veterinary students learn the anatomy and physiology of the dog in great detail, and greatly benefit from working with the bones and muscles that they learn about in class. Traditionally, this knowledge is solidified through the use of cadavers, but such methods pose many ethical, safety, and cultural concerns, along with the monetary cost required to obtain them [1]. With the rise of 3D printing technology, teachers have been moving towards using 3D printed animal models since they are cheaper, longer lasting, and safer [6]. Therefore, the client requested that a durable, functional, and accurate 3D model of a dog hindlimb be constructed for use in veterinary education, which includes an anatomically accurate dog skeleton with correctly functioning muscles and joints.

II. Background

A. Concerns of Cadaver Use in Medical Education

The use of cadavers in medical education has a long history. The first cadavers were used in the 3rd century BC in Greek in order to practice dissections [7]. Cadavers have been used ever since and are an effective way to learn anatomy and physiology. It is unlikely that the use of cadavers will ever go away since the hands-on learning of a real animal allows for an anatomically correct model that is the same as what they will be performing surgeries on in the future [8]. However, there are many ethical concerns with how cadavers have been acquired and how they can be used as a product sold by large organizations. With the rise of augmented reality there have been some new and innovative ways to teach medical students anatomy. There are even medical schools using Microsoft's hololens to teach anatomy which was unfathomable just a few years ago [9].

B. The Rise of 3D Printing in Medical Education

With the advent of affordable and accessible 3D printing in the past 20 years, there has been a transition to using 3D printers to construct anatomical models. 3D printing has allowed for models to be iterated upon quickly and for final designs to be created to be more anatomically correct [10]. Previous models used manufacturing techniques such as stamping plastics to the correct shapes, which requires expensive tooling and you need to change out many aspects of the machine if you are to create a new design. This contrasts with 3D printing where you can easily change designs and the 3D printer should not need to be changed in any way, making it useful and efficient for producing all kinds of models.

C. Research Required for Prototype

The team conducted research on each of the different components of the 3D printed model. Initial research was centered around different materials that could be used in the design. For muscles, this meant research was conducted on different fabrics and elastic materials that could replicate the shape of a real muscle and be elastic in order to retract the muscles. The three different materials chosen were elastic bands, fabric (spandex/nylon), and silicone rubber. Each of these have their own respective pros and cons which is elaborated on in section *IV D: Design Matrix 2*. The team also conducted research on potential attachment methods for the muscle to the bones. This research yielded three potential options. The first was using magnets which would allow for a small attachment point with sufficient strength in between still. The second option was velcro which would be able to easily cover the surface area required. Finally, hooks could be used like the model used by the client.

D. Client Information

The client, Dr. McLean Gunderson, is a professor of small and large animal anatomy at the University of Wisconsin School of Veterinary Medicine. They are interested in creating 3D models that students can use while learning about dog musculature.

E. Client Requirements

The client requested several elements be kept in mind during the development of this model. The most important element is that it is anatomically correct; the muscles and bones need to closely resemble real bones. In order to do this successfully, textbook and online references will be reviewed and the bones will be examined by first-year students to determine if they are accurate enough. In addition, the muscles must attach at the proper location, rather than a single point. Secondly, the budget of this project should not exceed $500 USD. The muscles and flexion and extension are the primary focus of this model as it will be used to show how muscles control movement; therefore it is important that the muscles are made of flexible materials that can stretch and contract back to their original shape. Finally, the model is intended to be used by first-year anatomy students and so it is important that they are kept in mind during the development of this project.

The customer expressed a variety of preferences and dislikes during client meetings. The customer prefers that the model be able to detach and reattach muscles one at a time to allow for students to properly understand the function of each muscle. She also indicated that the muscles should be color coded, as this would support ease of memorization of muscle function. However, she was concerned about students overly associating the muscles with a color instead of the name and function of the muscle. The customer has a strong interest in having a detailed model of the dog skeleton that accurately depicts all of the bumps and ridges of the bone. She specified that plastic models that can be purchased online are not accurate enough. The customer dislikes that the original model only connects to the bone at a single point rather than the full surface area of muscle attachment.

Additionally, the client requests an anatomically correct model of a dog joint with both accurate bone structure and properly functioning muscles and joints. It must either model the shoulder or the hip joint of a dog skeleton, as students struggle with these areas the most, and should be mounted on a raised structure for appropriate use. The model must also contain a simple and reliable way to attach and detach muscles to demonstrate movement, along with having accurate attachment points onto the bone, with reasonable mass and surface area measurements that match the anatomy of the dog.

The model should be of appropriate level of detail for first semester veterinary students, which ranges in ages but on average is 23 years old [11]. For the team’s purposes, an appropriate level of detail for first year veterinary students is defined by skeletal diagrams in Miller's Anatomy of the Dog by Drs. Howard Evans and Alexander de Lahunta [12].

F. Design Specifications

The client tasked the team with fabricating an anatomically and mechanically correct model of a dog hindlimb for first-year veterinary students. The model must be able to withstand flexion and extension of the muscles 100 times a day, and should be able to last for use by 96 veterinary students for about 12 hours a week for 5 years with minimal repairs. The model muscles must attach to the 3D printed bones at the correct position and total surface area of attachment in real dogs. In addition to this, it should be anatomically correct as evaluated by veterinary students, and should cost no more than the client determined budget of $500. The full description of design specifications is located in *Appendix A: Product Design Specifications*.

III. Preliminary Designs

A. Attachment Design 1: 3D printed plastic base with integrated neodymium magnets

This design utilizes magnetism to attach muscles to the bone on the 3D printed model. More specifically, one magnet would attach to the model muscle while its counterpart would attach to a 3D printed base that curves to the shape of the bone. This 3D printed base attached to the bone would have a shape that closely resembles the surface area of muscle attachment on the bone of a real canine. The base will be designed so that a small (2 mm in height, 3 mm in diameter) neodymium magnet can be placed inside of it. The magnets allow for an easy attachment and removal mechanism that can withstand adequate pulling force.

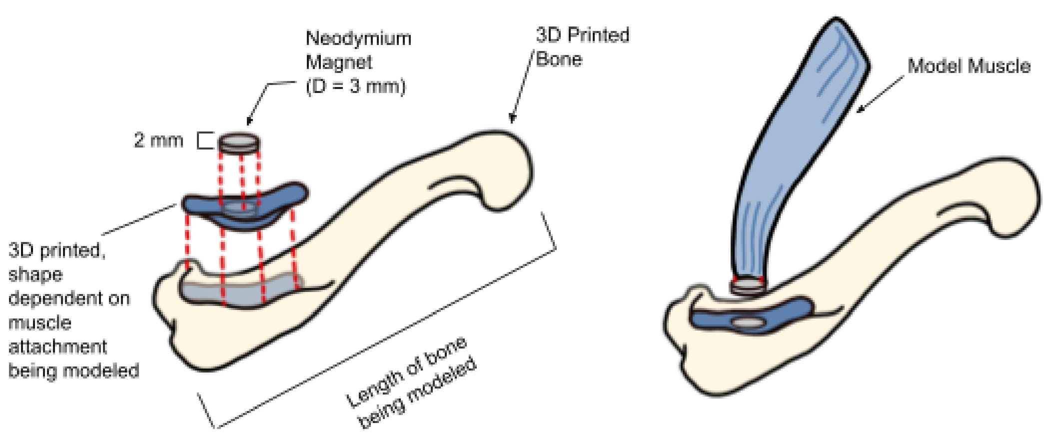


Figure 1. The left part of the image shows how a neodymium magnet would fit into a 3D printed piece the size of the proper muscle attachment, which would then be glued to the 3D printed bone. The right side of the image shows how the magnet would be attached to the end of the model muscle and could attach to the other magnet on the bone.

B. **Attachment Design 2: Velcro cut to shape of muscle attachment area**

The second design utilizes velcro to attach the muscles to the 3D printed bones. The velcro pieces would be cut to the anatomically correct shape based on the actual muscle attachments in dogs. The velcro pieces would then be glued to both the 3D printed bone as well as the model muscle so that a student could easily attach (i.e. stick the velcro pieces onto one another at attachment points) and detach (i.e. separate two velcro pieces) the muscles in the model.

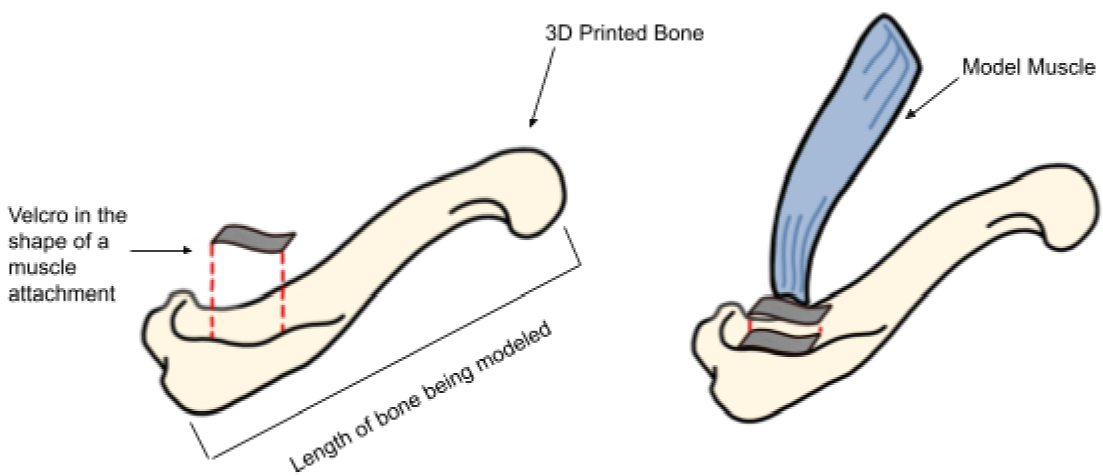


Figure 2. The left image shows velcro cut to the shape of the modeled muscle attachment, at the proper muscle attachment point on the 3D printed bone. The image on the right shows how the velcro would be attached to a model muscle and could attach/detach to the velcro on the bone.

C. **Attachment Design 3: Hooks 3D printed into bone**

This final design utilizes 3D printed hooks. The model muscle would have a loop to be able to attach to the hook. This attachment design would be similar to the original prototype created by the client, but the hook attachment would be integrated into the 3D printed bone. This method would eliminate the need to attach the hooks to the bone, whether by adhesives or by screwing J-hooks into the bone. A method to attach the hooks to the ends of each muscle would need to be derived, which would be a difficult task given the soft and flexible nature of the muscle material. The hook would need to be securely fastened to the muscle without presenting the possibility of tearing at the attachment points or a decrease in overall elasticity. The team would have to test multiple attachment techniques for muscle materials to create a final attachment method. These techniques could be gluing the hook, sewing the hook into the material, tying the hook, or curing the hook into the material.

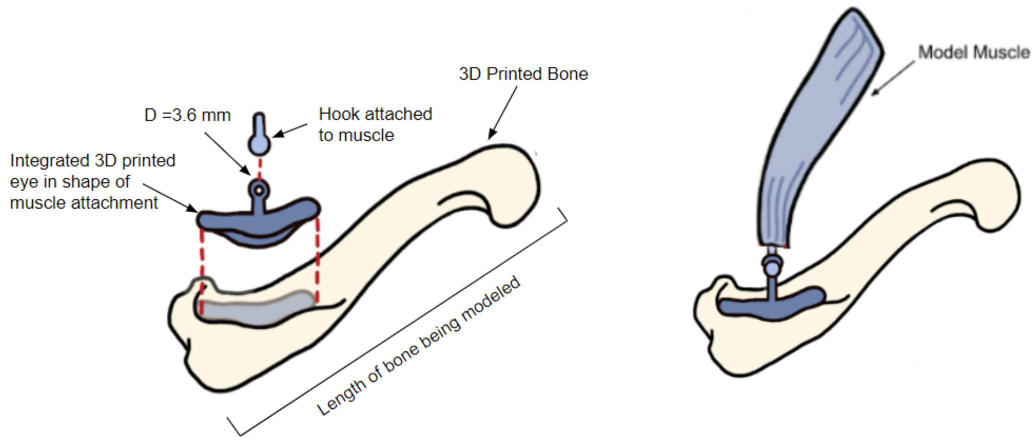


Figure 3. Left image shows how the integrated eye will be 3D printed to anatomically correct attachment surface area. Right image shows how the hook will be attached to the model muscle.

D. **Muscle Design 1: Latex Band**

The first of the potential muscle material designs is latex. This design would utilize exercise resistance bands as the base material. A muscle cut-out pattern would be created for each individual muscle, taking into account the shape of the muscle and its attachment points. Each muscle would be cut to the correct shape according to the muscle cut-out patterns. The neodymium magnet would then be glued to the ends of the muscle to allow for attachment to the 3D bone.

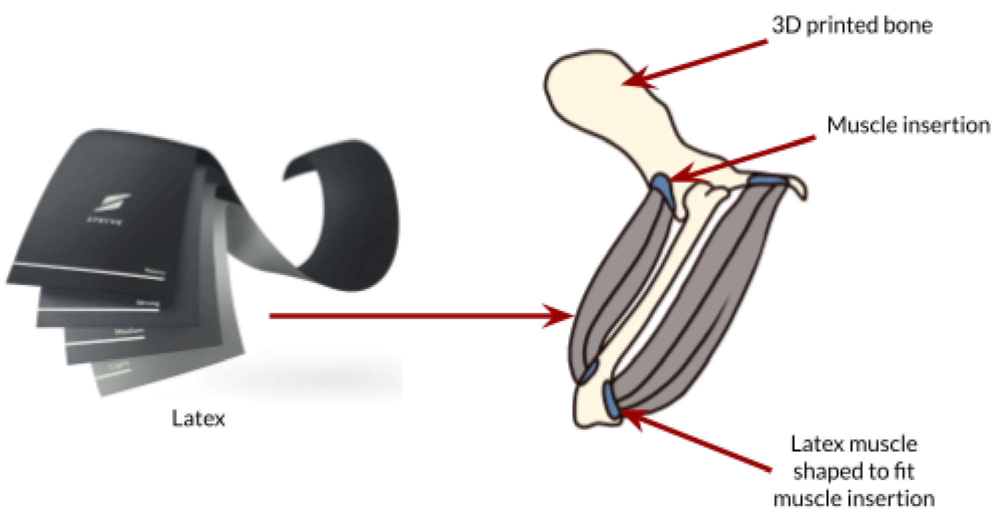


Figure 4. The left image shows the original exercise resistance band before being cut to shape. The image on the right shows how the latex muscle would be attached to the 3D printed bone after being cut to shape and glued to the magnet.

E. **Muscle Design 2: Nylon/Spandex Fabric**

The team's second muscle material design consists of muscles made of colored nylon/spandex fabric and lightly packed with stuffing. More specifically, the fabric chosen would be 80% nylon and 20% spandex material, as this blend is lightweight, durable, and can resist repetitive stretching without deformation. Different colors would be used for different muscle groups for both differentiation and visual appeal purposes. A sewing pattern would be created for each individual muscle, taking into account muscle dimensions and attachment surface areas. Each muscle would be sewn according to this pattern and then lightly stuffed to create realistic muscle volume. The outer neodymium magnet would be sewn on the interior of the muscle pattern in order to allow for the muscle to attach and detach from the 3D printed bones.

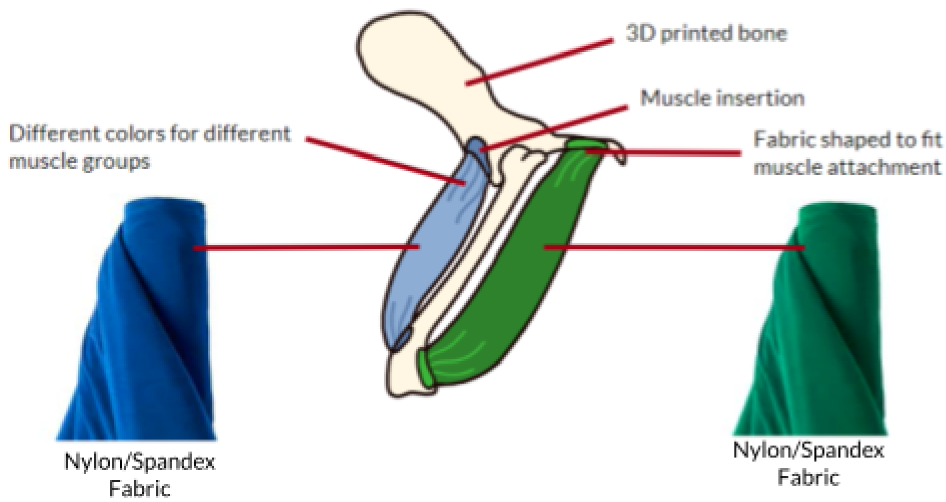


Figure 5. The left and rightmost images depict the nylon/spandex fabric blend before being cut to shape. The middle image shows how the fabric muscle would be attached to the 3D printed bone after being cut to shape, stuffed, and glued to the magnet.

F. **Muscle Design 3: Silicone Rubber**

Using silicone rubber for muscle material would involve the pouring of liquid silicone rubber to cure in individual muscle molds. For this method, the team would have to construct male and female molds for each muscle shape. Male molds could be fabricated out of a wide variety of viscoelastic materials including putty or clay. Through this technique the team would replicate the general shape and dimensions of the actual muscle. Female molds could be made from pre-existing mold kits on the market or by the silicone caulk gun into soapy water method. The chosen attachment method would either be glued onto the attachment points of the silicone muscle or placed inside the silicone ends before completion of curing. The silicone rubber method would allow for multiple copies of muscles to be made for testing.

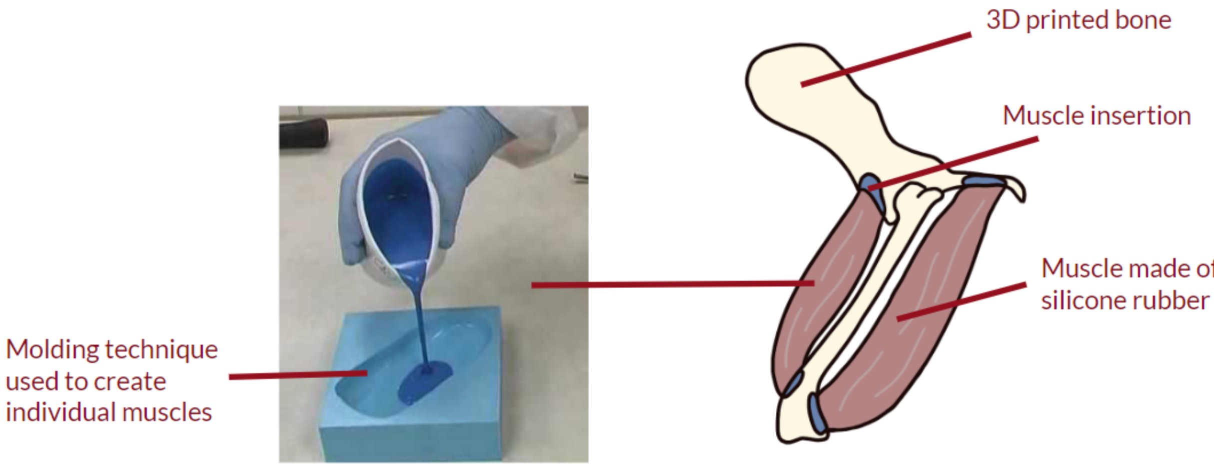


Figure 6. Image left shows an example of liquid silicone being poured into a female mold. Image right shows how molded silicone will be attached to the 3D printed bone via muscle attachment technique.

IV. Preliminary Design Evaluation

A. Design Matrix 1 Criteria

a. Functionality

The functionality criterion was weighted 30/100. Functionality refers to the device's ability to meet all client requirements while performing within the project design specifications. More specifically, this means the 3D anatomical model must closely resemble the anatomy of a canine, perform flexion and extension in a way that mimics canine movements, and be used successfully in a classroom setting. In terms of muscle attachments, the model should allow for straightforward fastening and removal of the muscles from the model. Furthermore, the muscle attachment mechanism should remain fixed to the bone with 13.3 N (3 lbs) of force applied, and should stay attached when the model is extended and flexed during normal use. The model's muscle should also reflect the actual surface area of the canine muscle. The attachment mechanism should be able to vary in size depending on the muscle and the size of the insertion on the bone, again reflecting the actual dimensions of the canine. The functionality criterion was weighted the highest because the ability for the muscle attachments to function correctly determine the success or failure of the device.

b. Intuitiveness

The intuitiveness criterion was weighted 25/100. In terms of muscle attachments, intuitiveness refers to the ability for the veterinary students to successfully be able to comprehend the muscle attachments of the 3D anatomical model, understand how the muscle attachments of the model resemble typical canine flexion and extension, and maneuver the model as such. Further, veterinary students should be able to understand how the model may be utilized for teaching and studying without extensive demonstration or tutorials. The intuitiveness criterion was weighted very highly because the ease of use of the muscle attachments of the model is essential to the device's success in teaching.

c. Durability

The durability criterion was weighted 20/100. Durability in terms of muscle attachments involves the muscle attachments being able to withstand detachment and reattachment on the model by 96 students in small groups for 12 hours a week for up to 5 years. This criterion was weighted 20/100 because longevity is a key requirement from the client due to cost constraints, but it is not as important as criteria like functionality and intuitiveness since it must be working and easy to use and then can meet the long-lasting durability that is required.

d. Cost

The cost criterion was rated 10/100. In terms of muscle attachment, cost refers both to the client-set budget as well as the cost of procurement of materials relating to the muscles and their attachment points. The client gave the team a starting budget of $500, and the team allocated $200 of that amount to be put towards manufacture of muscles and related structures. Further, the components for attaching the muscles portion of the overall design should not incur significant costs. The cost criterion was rated significantly lower than functionality, intuitiveness, and durability due to the fact that the client budget was fairly flexible and not a large barrier to production.

e. Ease of Fabrication

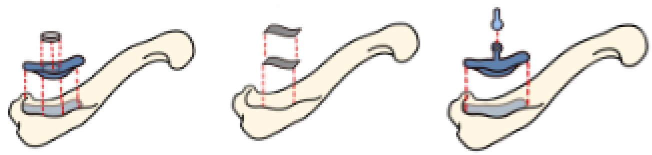
The ease of fabrication was rated 10/100. Ease of fabrication in terms of muscle attachments refers to the effort required to manufacture the modeled muscles, including design complexity, amount of materials required, and time of fabrication. The criterion was rated 10/100 because although the time constraint of one semester provides challenges to the team, all three proposed designs are manageable to complete with the resources provided.

f. Safety

The safety criterion was weighted 5/100. Safety refers to the overall risk of user injury while attaching and detaching muscles on the 3D model. Overall, safety is not a very important differentiator between the three proposed designs because muscle attachments on each design will not be ingested by, applied to, or have much contact with the user. Therefore, the safety criterion was given the smallest weight, at 5/100.

B. Design Matrix 1

Table 1. Design matrix containing muscle attachment mechanism design options and how they were each ranked based on the specified criteria.



Design		Magnets		Velcro		Hooks	
Criteria	Weight						
Functionality	30	5/5	30	2/5	12	1/5	6
Intuitiveness	25	5/5	25	4/5	20	3/5	15
Durability	20	4/5	16	1/5	4	1/5	4
Cost	10	3/5	6	5/5	10	4/5	8
Ease of Fabrication	10	3/5	6	4/5	8	3/5	6
Safety	5	3/5	3	5/5	5	4/5	4
Total	100.0	86/100		59/100		43/100	

Design 1: 3D printed plastic base with integrated neodymium magnets

The first proposed muscle attachment design is the 3D printed plastic base with integrated neodymium magnets. Overall, this design was given the highest rating, with 86/100.

Design 1 scored a 5/5 for the functionality criterion. The 3D printed base would allow for the contact patch of the muscle to be mimicked extremely accurately and the magnets would keep this contact patch in place firmly. With a relatively small surface area, the magnets would be able to withstand flexion and extension movements from the user that would closely resemble that of a canine.

Design 1 was given a 5/5 for the intuitiveness criterion as well. The magnetic attachment would allow the user to place the muscle in the correct area and snap into place, negating any potential user error. By using magnets, the force of removal may be easily manipulated to meet client requirements simply by changing the size and strength of the magnet used.

The durability of Design 1 was given a 4/5 due to the negligible degradation over time when stored in a controlled environment. The design should last for years while still maintaining its magnetic nature and should not be in need of replacement curing the product lifespan. That being said, the factor potentially limiting the durability of this design is the 3D printed component, which could eventually become weak or even warp if left in direct sunlight.

For Design 1, the cost criterion was given a 3/5. The magnets should cost less than $10 and are easily procurable. The 3D printed bases should be cheap as well due to their small size and cheap PLA material. Although magnets and 3D printing are cheap, they are not as cost effective as other options in the design matrix, which do not require the cost of 3D printing.

The 3D printed base with magnetic attachment design was given a 3/5 for the ease of fabrication criterion. 3D printing adds an additional level of complexity for fabrication, however, it also allows for the model to be more anatomically correct, which is the ultimate goal of the device. Complexities of the base include: a divot for magnet attachment or a cave for friction fitting.

Design 1 was given a 3/5 for safety. There is a slight risk associated with the use of small magnets. For example, if not appropriately attached to the model, the magnets could become a swallow hazard. That being said, this is a very unlikely situation, so the design was still rated with a moderate score for the safety criterion.

Design 2: Velcro cut to shape of muscle attachment area

The team's second proposed design involves velcro which would be cut to resemble the surface area of muscle attachment. Overall, Design 2 scored moderately on the design matrix with a rating of 59/100. While it addresses the limitations of Design 3, this design does not sufficiently meet client requirements as its criterion was less than impressive.

Design 2 was rated 2/5 for the functionality criterion. If velcro was used for muscle attachments, the attachment points would not accurately represent canines attachment points, since they would be flimsy and flexible instead of rigid. Because of this fact, the model would not accurately represent typical flexion and extension of the muscle, a key factor of success of the device. Therefore, Design 2 was rated as the least functional of all design options.

In terms of the intuitiveness, Design 2 was rated 4/5. The overall concept of velcro is easily comprehensible, and does not require extensive demonstration in order to understand. However, this aspect of the design did not score as highly as Design 1 due to the essentially effortless application of magnets.

Design 2 was rated 1/5 for durability, the lowest of all three proposed designs. When compared to magnets and hooks, velcro is considerably less durable, as it may lose functionality by various liquids, adverse conditions, or misuse. Additionally, velcro is significantly less long-lasting, and its ability to attach/detach will most likely not last the client's requirement of 5 years, needing replacement, significantly hindering its durability rating.

In terms of Cost, Design 2 scored the highest of all three proposed designs at 5/5. Velcro is the cheapest material of the three, with over 15 feet purchasable for less than twenty dollars. Additionally, the material is widely available at many different vendors and locations.

Further, Design 2 was rated 4/5 for the ease of fabrication criterion, the highest score of all three proposed designs. Since velcro has an adhesive layer already integrated into its design, additional attachment methods would not be required. This is a significant advantage that this design has over Designs 1 and 3, which both required additional 3D printing to attach their components to the model.

Finally, the safety criterion scored 5/5 for Design 2. Risk of injury is basically negligible with the use of velcro.

Design 3: Hooks 3D printed into bone

The team's third and final proposed design involves hooks 3D printed into the bone models. Overall, Design 3 was rated 43/100 and had the lowest score on the design matrix. This is primarily due to not doing well in highly weighted criteria.

In terms of functionality, the hooks were rated 1/5 because it would not represent the true surface area that the muscle attaches to the bone since a hook would be concentrated at a specific point on the bone. It would not be able to significantly vary in size. Also, since the hooks would be relatively small, they may not be very strong and able to withstand much force when a student is extending the muscle, so it was rated less than the other designs.

In terms of ease of use, this design was rated 3/5. It was not given the highest score because it could be hard to get the muscle onto the small hooks since the loops on the muscles would have to be small to keep from falling off the hooks during movement. It was also not rated too low because it would not take as much effort to correctly attach the muscle as velcro might since the velcro would have to be properly aligned.

As for durability, the 3D printed hooks were rated 1/5 due to their small size resulting in the PLA or ABS being able to be broken easily. Over time and with lots of use, the forces on the plastics could wear them out until they bend or snap. This is a significant limitation to the design.

The cost PLA, ABS, or whatever material is chosen to be used in the 3D printing process would not be very high for such a small piece. Thus, the hook design was rated 4/5 in this category.

This design would be moderately hard to produce, which is why it was rated 3/5 in the ease of fabrication category. Once the hook was designed online, the same design could be applied to each of the areas on the bones, but this would require alterations to the online file made from scanning the bones. This could be tough to do, but the actual printing process would not require the 3D printer to go through much extra work.

In terms of safety, Design 3 was rated 4/5. The hook appears to be a pretty safe design, but if the end was not properly rounded when printed it could be a bit sharp if students accidentally caught their finger on it when attaching/detaching the muscles. This is unlikely, but it was deemed less safe than velcro so was not given full points.

C. Design Matrix 2 Criteria

a. Functionality

The functionality criteria was weighted highest at 30/100. It is imperative that the detachable muscles meet client requirements and product design specifications. The model muscles must be able to mimic the movement of specific muscles on a dog limb by flexing and extending easily with maximum applied force of 13.3 N (3 lbs). Therefore, the material chosen must have elastic qualities that allow the material to be stretched and then return to its original size and shape afterward. The material must be able to vary in size given the assorted surface areas of muscle attachments required of the model. Further, the specific characteristics of the material must allow it to be modified to take the form of irregular and organic shapes like a muscle. The functional requirements are by far the most important to the design, and therefore were rated as such.

b. Accuracy

Accuracy was highly weighted at 20/100 because the purpose of the model is to teach first-year veterinary anatomy students about the muscle-bone interaction in the hindlimb of a dog. In order to rate highly in this category, it is important that the chosen material anatomically resembles that of a canine muscle. This involves the material being able to be shaped or sewn into the appropriate shape of each muscle. If the material is difficult to shape or cannot maintain its shape, then the accuracy of the muscle will be significantly reduced. Further, the chosen material must allow the muscle to mimic the extension and contraction of true canine muscles. The material should attach at the appropriate points on the dog skeleton; if the material cannot maintain the shape of the attachment points then it will not meet the accuracy requirements. Color is not currently a criteria of accuracy as the client expressed interest in the muscles being color coded.

c. Durability

The durability criteria was weighted second highest at 20/100.This criteria is an important consideration due to the fact that each muscle must withstand multiple hours of extension and compression per week for multiple years. The muscle material must also be able to extend to twice the original length of the muscle and return to its original shape over the same time period listed above without failure. This criterion evaluates the length of time each potential material can withstand the given forces without breaking or deforming from the original shape.

d. Ease of Fabrication

The ease of fabrication criteria was weighted as 10/100 because the team found that the overall functionality and accuracy of the model took precedence over the team's ability to work with materials that are generally considered to be standard. This criterion evaluates how feasible the fabrication of each respected material to adequately resemble and function as a muscle would be theoretically. The versatility and the estimated time of fabrication for each material was taken into consideration.

e. Cost

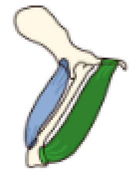
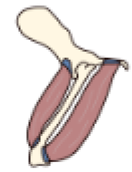
The cost criterion was rated 10/100. In terms of muscle materials, cost refers both to the client-set budget as well as the cost of procurement of materials that will model the muscles. The client gave the team a starting budget of $500, and the team allocated $200 of that amount to be put towards manufacture of muscles and related structures. Further, the components for the muscles portion of the overall design should not incur significant costs. The cost criterion was rated significantly lower than functionality, intuitiveness, and durability due to the fact that the client budget was fairly flexible and not a large barrier to production.

f. Safety

The safety criterion was weighted 5/100. Safety refers to the overall risk of user injury while attaching and detaching muscles on the 3D model. Overall, safety is not a very important differentiator between the three proposed designs because muscle attachments on each design will not be ingested by, applied to, or have much contact with the user. Therefore, the safety criterion was given the smallest weight, at 5/100.

D. Design Matrix 2

Table 2. Design matrix containing muscle design options and how they were each scored based on the previously described criteria.

Design		Elastic Band		Fabric (ex. Spandex)		Silicone Rubber (Ecoflex)	
Criteria	Weight						
Functionality	30	3/5	18	4/5	24	2/5	12
Accuracy	20	2/5	8	5/5	20	4/5	16
Durability	20	4/5	16	5/5	20	4/5	16
Cost	15	5/5	15	4/5	12	2/5	6
Ease of Fabrication	10	4/5	8	3/5	6	2/5	4
Safety	5	4/5	4	2/5	2	5/5	5
Total	**100.0**	69/100		84/100		59/100	

Design 1: Latex Band

The latex band material type utilizes pre-existing stock material that can be cut to desired length and/or shape depending on the width of the stock material. Examples of latex band stock materials include rubber bands, exercise resistance bands, and sewing elastic. These materials would be glued or sewn to the attachment mechanism that would allow it to attach to the model bones.

The latex band design was rated second highest overall with a rating of 69/100. This was a result of scoring highly in some categories and low in others. The latex band design scored highest in the functionality, cost, and ease of fabrication categories compared to the others, and scored lower in the remaining categories.

The functionality of the latex band design was rated a 4/5 because this material is easy to extend and returns back to its original shape with no effort on the users part. The latex band design did not score higher in this category because it cannot easily be shaped into the natural shape of canine muscle.

The accuracy of the latex band design was rated a 2/5 because it is difficult to shape latex bands into the natural shape of a canine muscle. It is difficult to give latex bands volume without doubling the amount of necessary materials and to give them specific widths without compromising the structural integrity of the material.

The durability of the latex band design was rated a 4/5 because it is able to withstand excess amounts of extension without breaking or deviating from the original shape. This design did not score higher because, while latex bands can withstand lots of extension, it often does not last long, especially when considering the sheer volume of use these muscles will see.

The cost of the latex band design was rated a 5/5 because it is very cost effective. Latex bands typically come in large quantities (5 or more meters) for less than $10. This material also is readily available to the team either online or at local craft stores.

The ease of fabrication of the latex band design was rated a 4/5 because the material is very easy to work with, as it requires no specialized tools. Latex bands are able to be cut with standard craft scissors and sewing supplies (sewing machines, sewing needles, thread, etc.), making it simple to manipulate the material into the desired shape. This material will also be simple to attach to the attachment mechanism described above.

The safety of the latex band design was rated a 4/5 because there is a small risk that the latex band could snap. Some latex bands also may include carcinogenic materials, which can pose a threat to the user's health.

Design 2: Fabric (Spandex or Nylon)

The fabric materials consist of nylon or spandex that is sewn into the shape of muscles using patterns. Spandex options such as Lycra allow for the creation of stretchable muscles that maintain their shape after many uses. Lycra is a brand of spandex that is often used in exercise clothes due to its significant elasticity and strength. Muscles made out of Lycra can be cut and sewn into any shape.

The fabric design was rated highest at 84/100 due to its excellent score in functionality, accuracy, and durability. The other ratings for fabric in ease of fabrication and cost are also average, 3/5 and 4/5 respectively. The lowest rating for fabric is in safety.

Fabric got the highest score in functionality, 4/5, because it can stretch to potentially five times its length and still return to its original shape. It is also possible to create an attachment point with magnets or velcro through sewing. Spandex and other fabrics are easy to stretch therefore the strength required to flex the muscles shouldn't apply too much force on the attachment points allowing them to stay attached and last longer.

Fabric once again got the highest score in accuracy, 5/5. This is because of the elastic nature of spandex which allows them to return to its original shape. With other options, the materials may not be able to fully flex or return to its original shape. If the original shape is not maintained then the model will not be accurate. Fabric can also be shaped into the irregular and organic shape of the muscle. This means that when students observe the model they will not just see a piece of cloth in the location of the muscle, but a model of the muscle itself allowing them to better understand the anatomy of that region.

Fabric also received the highest score in durability, 5/5, because spandex and nylon are well known for their durability. Spandex and blends of fibers that contain spandex are used throughout the athletic industry to make stretchy, tight fitting clothing that lasts for years. Spandex and nylon have the ability to maintain their shape, which is important because the models are estimated to be stretched 100 times a day each semester for five years.

Fabric was not the first in cost because latex bands are cheaper to purchase. Fabric blends that contain spandex or other stretchy materials are more expensive. According to Mood Fabrics, you can buy 1 yard of spandex for about $12.79. This particular fabric can stretch 25% its length and 50% its width. Buying enough fabric to prototype and create models should be within the $200 budget which is why it was given a 4/5.

Fabric was only given a 3/5 for fabrication because it will take time to create patterns to sew. In addition, sewing stretchy fabrics can be difficult because you don't want to interfere with the way it stretches. It will take a long time to sew every single muscle, and it won't be quick or easy to create duplicates.

Fabric's lowest score was in safety, only a 2/5, because the materials used to create spandex contain carcinogenic chemicals like polyurethane. These chemicals could cause issues for the skin after long term use. However, no individual is expected to stay in contact with the model for an extended period of time.

Design 3: Silicone Rubber

The silicone rubber material type utilizes poured molds to create muscles of detailed shape and dimension. Pourable silicone such as Dragon Skin allow for easy application of the poured silicone method through its use of 1:1 mix ratio of components that do not require gram scales by weight or other precise measurements. Dragon skin can cure with minimal shrinkage at normal room temperatures (20-22 C) for a total cure time varying between 30 minutes and 16 hours depending on the type of silicone mix used.

The silicone design was rated the lowest overall at 59/100. This was due to the fact that the material rated the lowest in functionality, the highest weighted category. While silicone rated highly in the accuracy, durability, and safety category, the hit that silicone took in the functionality category could not make up for it.

The functionality of silicone rubber was rated 2/5 because the tough nature of silicone made it the least flexible material of the three choices and would therefore require greater amounts of force to flex and extend on the model. The greater amounts of forces on the model would decrease its durability and would require more maintenance over time. The tougher nature of silicone would also hinder the ability of muscle attachments such as magnets and velcro to properly fasten the muscles to the model given the increased forces of flexing and extending.

Silicone was rated 4/5 for accuracy because the fabrication of silicone muscles requires the use of molds that would both aid in the accurate creation of the asymmetrical shape of muscle and allow for fabrication of multiple copies of muscles that could be used for testing.

For the durability criteria, silicone rubber was rated 4/5 given the strong but flexible nature of silicone. Silicone can be stretched many times without tearing and can rebound to its original size with minimal distortion. However, the repair of a silicone tear would be difficult in that it would require a binding material that is homogeneous to the composition and texture of silicone.

The cost of silicone was rated 2/5 because it requires the purchasing of both mold-making materials as well as the silicone mix itself. A pint unit of Dragon Skin costs around $50 on Amazon and a single silicone mold-making kit costs around $32 on Amazon. Given that the team would likely require more than one pint unit and mold kit for experimentation and testing, the costs may exceed or be close to the $500 budget.

The ease of fabrication of silicone rubber was rated 2/5 because the team would need to fabricate accurate molds of muscle tissue. That obstacle alone causes silicone to be the most difficult muscle option to fabricate out of the three options.

Silicone was rated 5/5 for safety because silicone is generally recognized by experts to be chemically stable and therefore non-toxic. Unlike the latex band and spandex fabric options, silicone does not contain any carcinogenic materials. It is important that the materials used must be safe to touch because the model will be handled without any PPE extensively.

E. Proposed Final Design

After considering all 6 design options and evaluating how well suited each option was for the problem at hand, the 3D printed plastic base with integrated neodymium magnets design and fabric were chosen as the best combination of design options. The final design will consist of 3D printed bones with an additional 3D printed attachment base that a neodymium magnet will be glued into. Having the muscle attachment point 3D printed along with the bone will ensure a tight connection between the bones and the muscles during flexion and extension, and the base will accurately represent the proper area of the bone that real muscles attach to. The muscles will be made of a nylon-spandex fabric because it is elastic and can be formed into the appropriate shape. It also provides the benefit of being durable and cost effective. The fabric will be stuffed with polyester stuffing and neodymium magnets will be sewn into each end of the fabric such that the magnet can attach to the magnets in the attachment base, and it should be strong enough to be able to flex and extend the muscle but also be able to be detached from this point. Lastly, the whole model will be attached to a stand attached at the uppermost part of the design to that the student can more easily play around with the model.

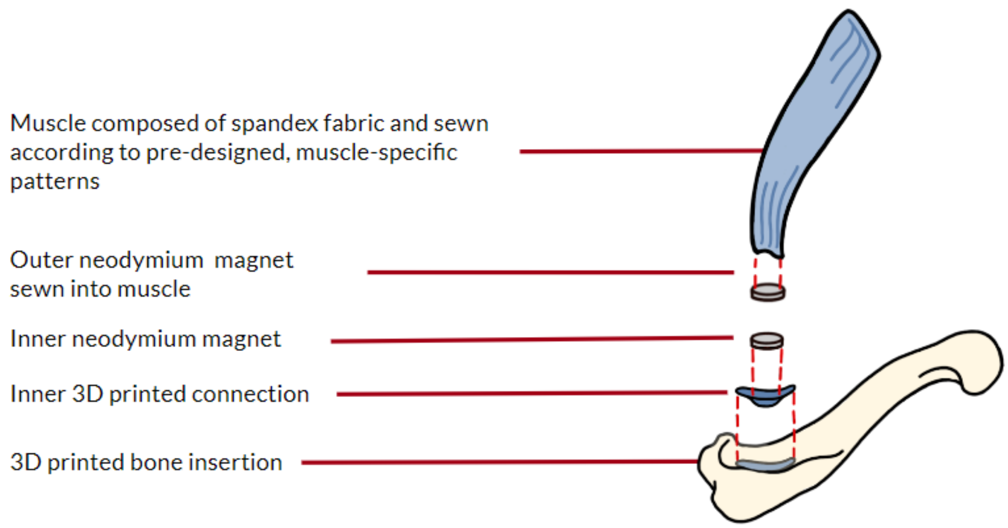


Figure 7. The image above shows the proposed final design, putting together the 3D printed bone, the magnet attachment mechanism design, and the spandex/nylon fabric blend chosen to represent the muscle.

V. Fabrication/Development Process

A. Materials

The canine bones will be 3D printed in Tough PLA, which is durable and can be post processed easily . Ultimaker PLA filament is an engineering material compatible with the Ultimaker 3D fused filament fabrication (FFF) 3D printer [13]. PLA is inexpensive at $0.08/gram. It has a low melting temperature of 140-160 C, good tensile strength and surface quality, and is extremely user friendly, making it a suitable material for the muscle attachment mechanisms.

The muscles are shaped in clay and then casted in plaster. The molds will then be sprayed with mold release which will allow for easy removal. Two part Ecoflex™ 00-50 [14] silicone will be mixed and poured into the molds, after they have set for at least one hour, if not three. They are removed from the mold and additional silicone may be poured on top to smooth any rough edges. The silicone has a tensile strength of 315 psi and is translucent in color. If added strength is necessary, it is possible to add any sort of net fabric with nylon or spandex fibers [15]. The fabric used in this project was provided by the client and was not specified. A muscle colored fabric would be ideal to give the impression of a real muscle.

The magnet attachment mechanisms will be composed of Strongman Tools Neodymium Magnetic Tape Strips. [16] This comes with the strips that are 2mm thick and is built for heavy duty applications. In addition it has strong adhesive backing that will be reinforced by super glue.

B. Methods

The 3D printed muscle and bone canine model for first year vet students was constructed using a variety of manufacturing methods. The bones were first 3D scanned with a Creaform Handyscan 700, then 3D printed using the Ultimaker S5 fused filament fabrication 3D printer. The 3D printed bones were then sanded down as supports were removed, and holes were drilled into the ends of the bones such that elastic string could be inserted to connect the bones and allow them to articulate. The canine foot was not 3D printed due to its complexity, it was taken from an Axis Scientific model and repurposed for this model.

The three muscles were produced by first being modeled in clay based on pictures from Miller's Anatomy of the Dog. Plaster was made by mixing the powder with water, stirred, and then the clay (which was first sprayed with a mold release) was pressed into the wet plaster. After this dried, the clay was removed, the mold was sprayed with silicone mold release, and silicone, made of equal parts A and B, was poured in. Following the silicone pouring, nylon/spandex mesh fabric was cut into small strips and placed in the silicone as it hardened, giving the silicone a stronger resistance to tears and a more realistic color. They were left to dry for roughly a day in most cases and then removed from the mold.

After constructing both the bones and muscles, magnetic strips were cut to the shape of the proper muscle attachments and superglued to the correct location on the bone and muscle, respectively. Once this dried, the muscles were able to attach to the bone correctly and the product was finished. More detail on fabrication can be found in *Appendix C: Fabrication Plans*.

C. Final Prototype

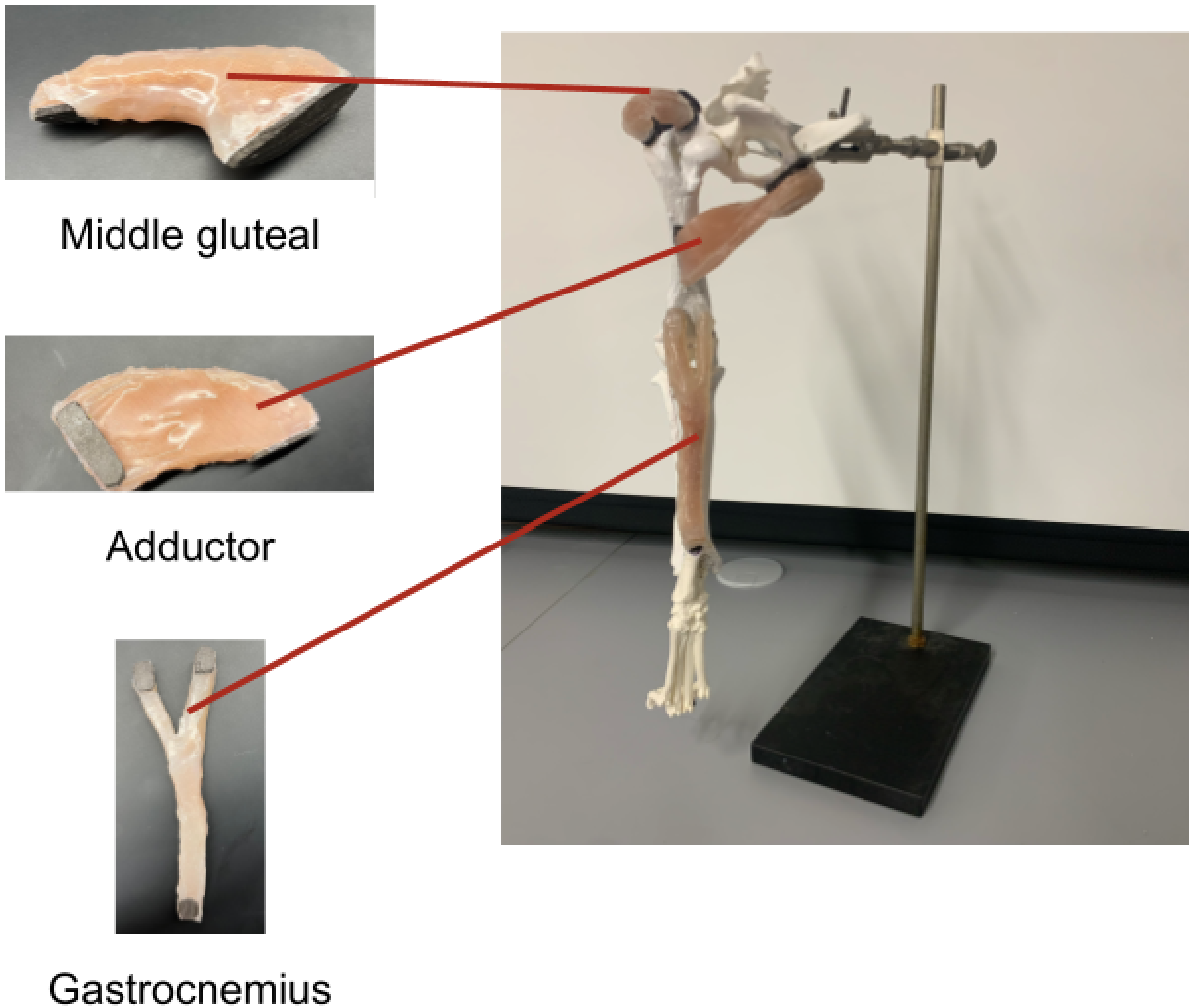


Figure 8. Final prototype with 3D printed pelvis (20 cm x 12 cm x 4 cm), femur (length: 22 cm, minimum diameter: 3.0 cm), and tibia/fibula (length: 25 cm, minimum diameter: 2.0 cm) with magnetic muscle attachments and silicone-fabric middle gluteal (maximum length:10 cm, thickness: 4.0 cm), adductor (maximum length: 12 cm, thickness: 1.0 cm), and gastrocnemius (maximum length: 24 cm, thickness: 1.0 cm) muscles. Model measures 120 cm x 40 cm.

D. Testing

1. Flexion/Extension

In order to test the life in service criteria, repeated flexion and extension tests were performed on the gastrocnemius muscle to simulate a typical classroom setting and short-term frequency of use. The gastrocnemius muscle connects the bottom of the femur to the tip of the hock joint (ankle), spanning the entire length of the tibia. The gastrocnemius was chosen for flexion/extension testing due to having the smallest surface areas of attachment of all three muscles modeled. The muscle attachments of the gastrocnemius needed to withstand 45 degrees of flexion and extension 50 times with negligible decrease in attachment force. These amounts were derived from a typical first year lab session of 30 students for 4 hours and the overall degree of movement of the gastrocnemius muscle.

Each of the three attachments on the gastrocnemius were measured in attachment force via spring force scale (Newtons) three times each prior to flexion and extension. The model was then stabilized with a lab stand and clamp. A flat surface was held in front of the stifle (knee) joint in order to standardize the movement of the tibia forwards and backwards. The tibia was then extended forward until the tip of the foot touched the flat surface and then flexed backward 50 times. After movement, the measurement process was repeated on each attachment. From the raw data a grouped bar chart was derived based on the averages of the three trials before and after as depicted in Figure 9. Ideally, the averages of attachment force before and after movement should have a negligible difference in order to meet the life in service criteria. This result would reflect that the magnetic attachments can withstand short term repeated use within a typical first-year veterinary anatomy lab period. Test variance and possible sources of error include reaction time to spring force measurement when magnet detaches.

2. MTS Testing

The 3D printed femur of the final design was 3 point bend tested using a MTS (Mechanical Testing System) machine. This was then compared with the same test done on the Axis Scientific femur. These tests were used to determine if we could meet criteria for durability. The goal of the test was to withstand greater than 890N since this is the equivalent weight of a 220 pound person stepping on the model. Additionally, the test was conducted in order to assess whether the 3D printed model would sustain higher loads than the Axis Scientific model prior to both fracture and plastic deformation. To conduct the tests, the models were placed horizontally in the 3 point bend fixture (see in Appendix D) with a test rate of 1 mm/min. The test concluded when the model underwent fracture and the load returned to baseline levels. The Axis Scientific model underwent plastic deformation before its failure, whereas the 3D printed PLA model deformed very little before its breaking point. The team determined that having little to no plastic deformation is ideal. If the model is deformed permanently the muscles will not fit onto the model normally and the model can no longer be used correctly.

3. Vet Student Survey

To test the accuracy and intuitiveness of the device, veterinary students from the University of Wisconsin's School of Veterinary Medicine were asked to come in to test the device and describe their experience. They were given some information on the purpose of the model and how it was made, and then were given time to use the model. Following this, they completed a survey. The survey that they filled out asked them to rank the accuracy, durability, and intuitiveness of the model, along with their own level of knowledge of anatomy, on a scale from 1 to 10. They were also asked to answer other questions like how helpful the model was (1 to 10) and how it could be improved (open response), but the overall purpose was to get feedback on the accuracy and intuitiveness of the design since those are key criteria required for this model. The full list of questions can be found in *Appendix E: Veterinary Survey*.

VI. Results

1. Flexion/Extension

After completing the Flexion/Extension test, the average force needed to remove the muscle from the muscle attachment and the standard deviation were calculated for each muscle attachment both before and after extended use. The calculated averages were then combined into the graph seen in Figure 9. The standard deviation was found to be 0.05 N. A two-tailed T-test was also performed; this test returned a p-value of 0.68. This p-value proves that the difference between the average force required to remove a muscle from its attachment point before extended use and after extended use is not statistically significant. As a result of these analyses, it can be stated that there were no measurable differences between the attachment force of the magnets before and after extended use. These results also mean that the magnetic attachments are durable enough for long term use in a classroom environment and that the Life in Service design criteria has been met successfully by the model.

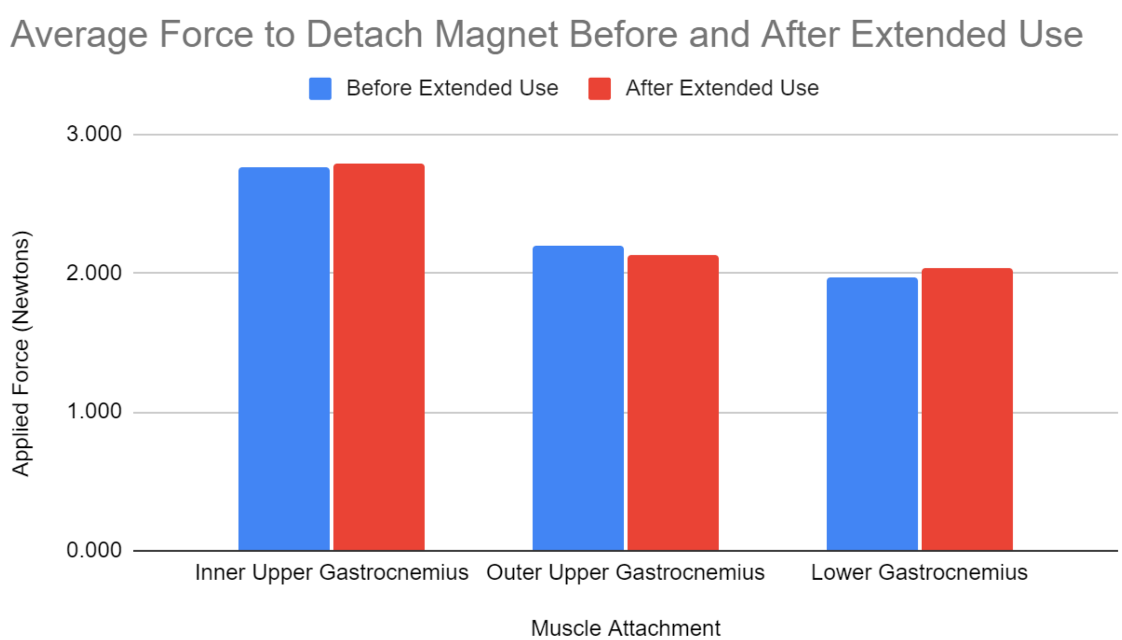


Figure 9. Double bar graph depicting attachment force of each attachment of the gastrocnemius before and after repeated flexion/extension. The x axis denotes muscle attachments and the y axis represents applied force with the spring force scale.

2. MTS Testing

After completing the MTS tests, graphs were collected from the MTS software, which can be seen in Figures 10 and 11. The MTS test of the Axis Scientific canine femur resulted in a peak load of 791.425 N. The Axis Scientific canine femur MTS test did not result in catastrophic failure of the bone, as the material exhibited plastic deformation. The MTS test of the 3D printed Tough PLA canine femur resulted in a peak load of 1225.161 N. The Tough PLA canine femur MTS test did result in catastrophic failure of the bone. These results show that the 3D printed Tough PLA canine bones can withstand more force than both the Axis Scientific model and the estimated force of a 200 lb person standing on it. These results also mean that the Durability design criteria has been met successfully by the model bones.

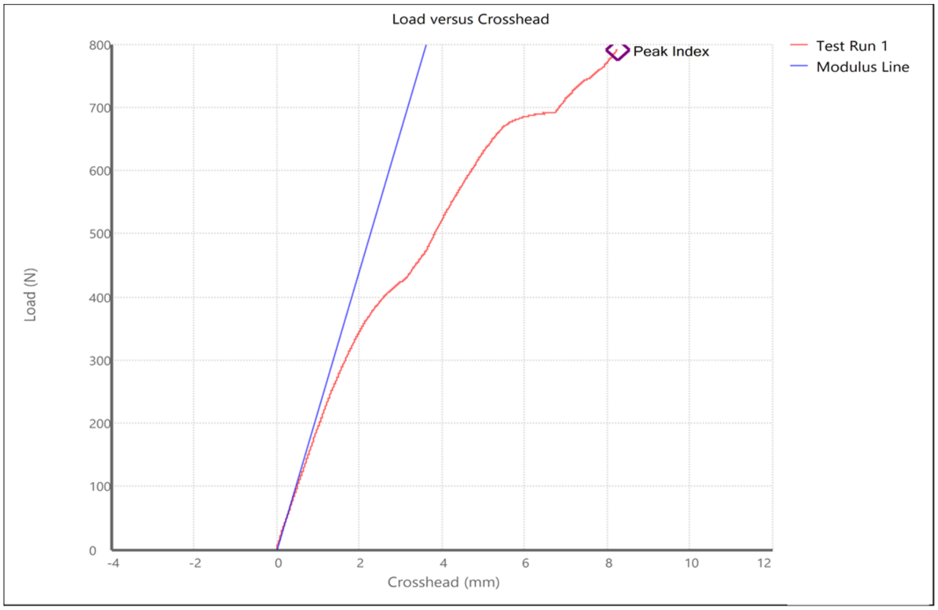


Figure 10. Stress vs. strain curve of an Axis Scientific canine femur.

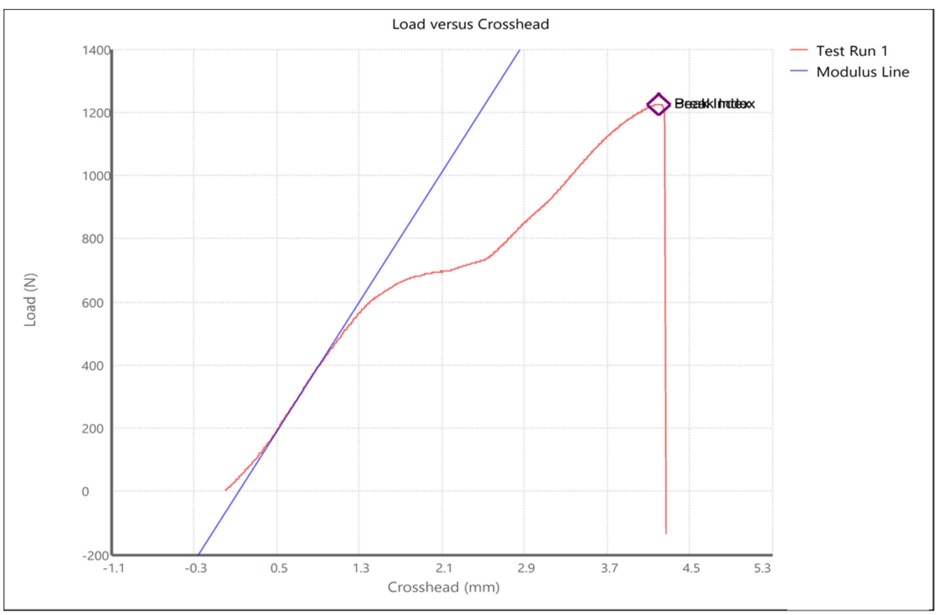


Figure 11. Stress vs. strain curve of a PLA 3D printed canine femur.

3. Vet Student Survey

There were 38 students that tested out the model and took the survey. Raw data can be found in *Appendix F: Veterinary Survey Results*. After analyzing the results from the Qualitative Survey from UW Veterinary Medicine students, the results were combined into the graphs seen in Figures 12, 13, 14, and 15, which show the responses to the accuracy, durability, intuitiveness, and helpfulness questions. The graphs show an average rating of 8.43/10 for accuracy, 7/10 for durability, 8.38/10 for intuitiveness, and 8.77/10 for usefulness in learning canine anatomy. Based on these results, it can be assumed that the model is accurate, durable, intuitive, and useful enough to be used in canine anatomy education. These results also show that the Accuracy and Intuitiveness design criteria have been met successfully.

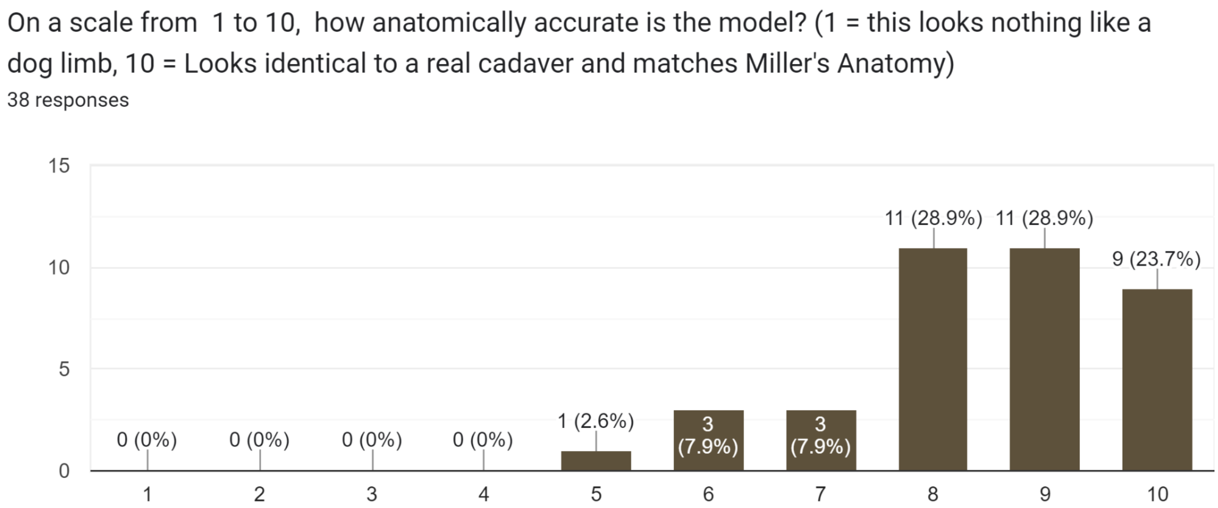


Figure 12. Bar chart depicting the scores given by vet med students answering how durable the model is (n=38).

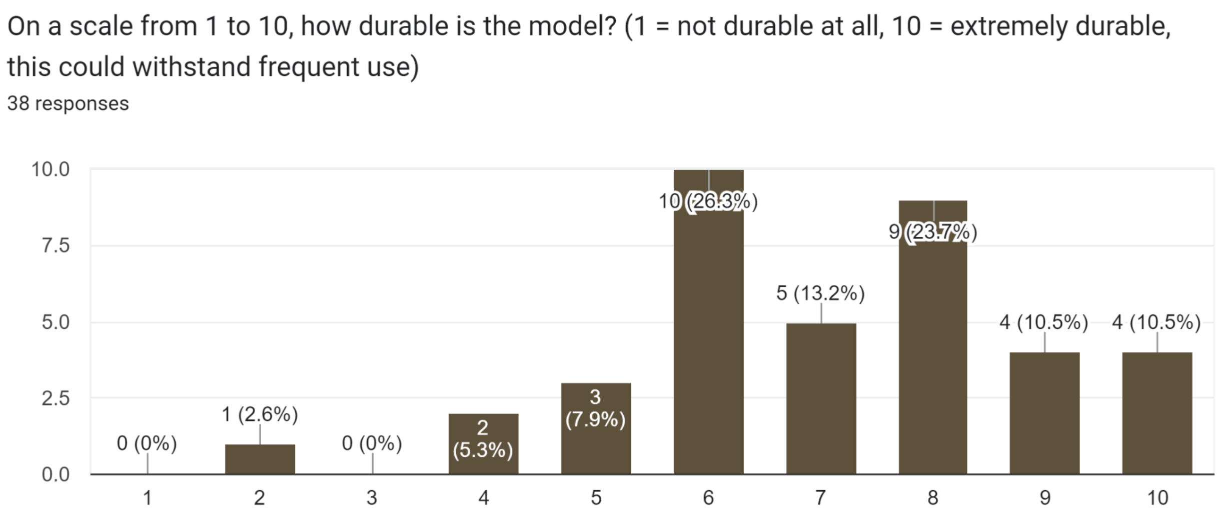


Figure 13. Bar chart showing the ratings given by vet med students answering how accurate the model is (n=38).

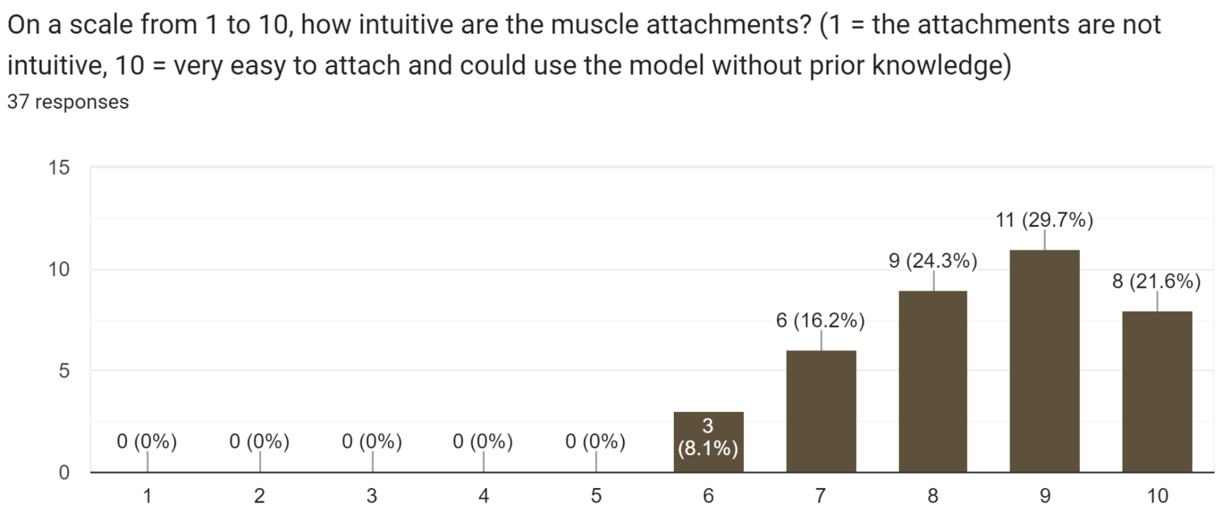


Figure 14. Bar chart of the intuitivity scores of the model given by vet med students (n=37).

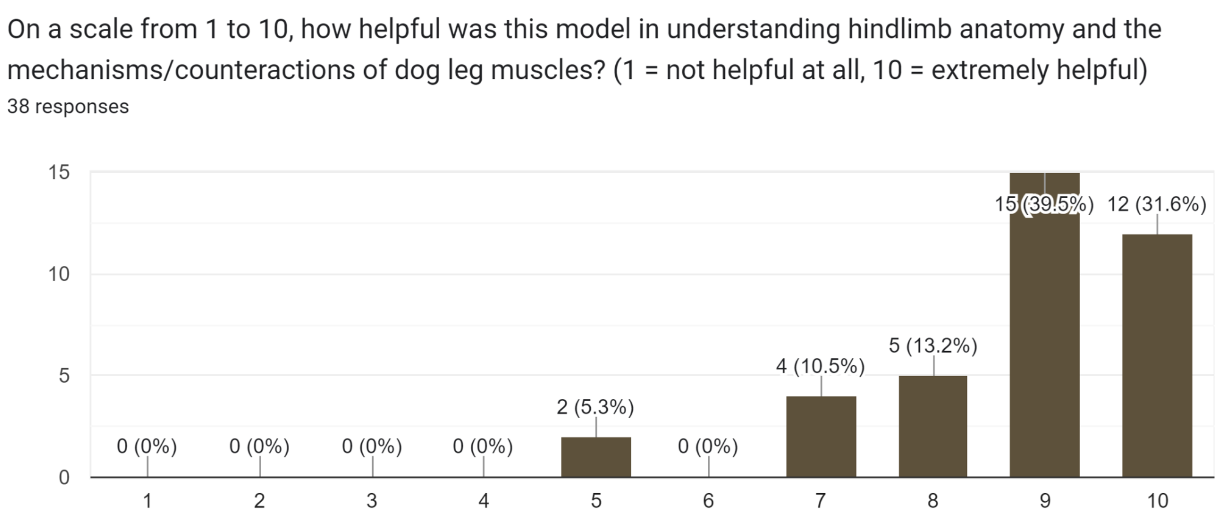


Figure 15. Bar chart of the ratings given by vet med students answering how helpful the model is (n=38).

VII. Discussion

With research and testing finished it is possible to examine the implications of this project and its results. The answers to the survey overwhelmingly expressed a need for models and educational materials for veterinary students. Many students expressed interest in testing the model and knowing how it will develop further. This shows that even though the market is not very big, those who are in it are interested in the model (see Appendix F). However, many students were concerned with the durability of the model; 26.3% gave it only a six out of ten. From the comments left by the students, the concern mostly stemmed from the weak magnetic attachments between the muscles and bone as well as the possibility of the silicone and fabric muscles degrading over time. The attachment points are a main focus of future work and so further development will happen. However, despite the concerns of the silicon's durability, their website lists its tensile strength at 315 psi which is significantly over how much force will be applied on average. In addition, the elongation at break is listed to be 980% [14]. With both the length needed to break and the tensile strength being significantly higher than the average expected force applied, the muscles should be durable enough to last the time specified by the design specifications. The magnetic attachment points, although not strong enough yet, don't lose much strength after many uses. This means that if it is possible to obtain a stronger magnetic tape it could still be a viable option for attachment. As for the bones; the tough PLA withstood large force and will not break even if stepped on by a 220 pound person. In comparison with the Axis Scientific model; this model withstood higher forces and therefore it is more resilient to breaking.

Conducting the research did not bring to light any significant moral or ethical dilemmas, however the conflict between making money and providing affordable educational tools to all does exist. If the model went into production, difficult decisions would have to be made as the market for dog hindlimbs is not very large, compared to human models, and so it would have to be sold at a higher cost.

After evaluating the end result, the attachment magnets will need to be significantly stronger as they detach too easily. In addition, it may be a good idea to layer the fabric in the muscles in a neater way so that they do not need to be covered in an additional layer of silicone to be smoothed out further.

Possible sources of error include, incorrect use of the MTS machine. There were many difficulties in getting the machine to work; in addition, the bone's strength was only tested in one way, so from other angles the bone may be more fragile. Also, not all of the bones were tested, the femur was tested in the MTS machine and assumed to be representative of the other bones due to them being printed in the same material and having the same infill. Certain bones like the tibia and fibula might be more fragile, especially the fibula which is particularly thin. Another source of error could come from the magnet durability testing as the tester may have gotten tired from stretching the muscles repeatedly and slowly decreased the force they were applying to the muscles.

VIII. Conclusions

In conclusion, the client requested a design that could properly represent the musculoskeletal structure and function of a canine hindlimb to be used in an anatomy class for first-year veterinary students. To complete this goal, a design was created involving fabric reinforced silicone muscles attached to PLA 3D printed bones via neodymium magnetic strips.

The team successfully 3D scanned and 3D printed canine bones using PLA, created plaster molds and fabric-reinforced silicone muscles, and utilized neodymium magnetic attachment surface areas. Preliminary plans to fabricate muscles out of nylon/ spandex material as well as the use of neodymium magnetic disks were both unsuccessful.

In terms of next steps, the prototype will need to be expanded upon to include more complex muscles and attachments, such as the quadriceps. Mechanical properties of each muscle will be calculated and stronger attachment mechanisms will be fabricated to withstand such force. Additionally, the muscles will be re-casted in colored silicone to further aid veterinary medical students with study strategies.

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Appendix

Appendix A: Product Design Specification

Function

In the first semester of veterinary school, students learn the anatomy and physiology of the dog in great detail, and greatly benefit from working with the bones and muscles that they learn about in class. Traditionally, this knowledge is solidified through the use of cadavers, but such methods pose many ethical, safety, and cultural concerns, along with the monetary cost required to obtain them [1]. With the rise of 3D printing technology, teachers have been moving towards using 3D printed animal models since they are cheaper, longer lasting, and safer [6]. Therefore, the client has requested that a durable, functional, and accurate 3D model of a dog hindlimb be constructed for use in veterinary education, which includes an anatomically accurate dog skeleton with correctly functioning muscles and joints.

Client Requirements

- The client requests an anatomically correct model of a dog joint with both accurate bone structure and properly functioning muscles and joints.
- The joint modeled should either be the shoulder or the hip of a dog skeleton, as students struggle with these areas the most.
- The joint should be mounted on a raised structure for appropriate use.
- The model should be of appropriate level of detail for first semester veterinary students, which ranges in ages but on average is 23 years old [11]. For the team's purposes, an appropriate level of detail for first year veterinary students is defined by skeletal diagrams in Miller's Anatomy of the Dog by Drs. Howard Evans and Alexander de Lahunta.
- The model must contain a simple and reliable way to attach and detach muscles to demonstrate movement.
- The muscles on the model must have accurate attachment points onto the bone, with reasonable mass and surface area measurements that match the anatomy of the dog.

Design requirements

1. Physical and Operational Characteristics
    a. Performance requirements

The model shall be able to perform reliably for 3 classes of 32 students each for 12 hours spread throughout three use sessions per week per class. Reliable performance may be defined as the ability to withstand 13.3 N (3 lbs) of tension on an MTS machine. The model must also have muscle attachments that are reliably able to attach and detach at correct insertion points on the model (see Section 1c: Accuracy and Reliability).

b. Safety

The product must be safe for first-year veterinary students to use (ie. students must not suffer injury from any components during use). While there are standards regarding the use of small or detachable magnets in products, the use of them in this project would not require following the standards since educational products are exempt [18]. Other materials that may be used in the product, like Velcro and PLA, do not have any regulations or harmful effects on the user either. It should be noted, however, that bacteria may grow if the model is not properly cleaned, which could be unsafe for the user. Thus, the model should be sanitized weekly with a non-alcohol based cleaner (alcohols can cause plastics to crack) so that it will be safe for users and last longer [19]. While no safety warnings are required and sterilization of the product is unnecessary, light cleaning directions are recommended.

c. Accuracy and Reliability

The veterinary model will be fabricated such that the modeled muscles can be removed and replaced in the correct position 100 times a day with no detectable decreases in attachment force or elasticity of the muscle models. The design must also be anatomically correct and represent a real dog hindlimb as evaluated by veterinary students.

d. Life in Service

This product must be able to be used by about 96 students in small groups for 12 hours at a time. It should be able to last for about 5 years before needing to be fully replaced, but can be fixed with spare parts throughout that time. The model will be flexed and extended, along with the simulated muscles being removed and replaced by students, so the materials used must be durable enough to handle such use throughout the semesters for 5 years.

e. Shelf Life

The model must be compact enough such that it can be easily stored in provided cabinets or shelving, which typically range from 40 - 61cm in depth [20]. The model should also be able to withstand typical indoor temperatures around 20-22 C (68-72 F) and pressures around 1 atmospheres [21], as it will be stored out in the skills lab or in a plastic storage container in the closet. If the model requires the use of adhesives and that replacement adhesives be stored in the facility, they must be stored between 25-28 C for up to 2 years (or prior to expiration date). The device itself should also not be subject to temperatures outside of this range in order to retain ideal bond strength of the adhesive [22]. Other than the potential use of adhesives, the product has no shelf-life considerations for components given that the model does not require batteries or contain chemicals.

f. Operating Environment

The model should be able to withstand consistent use from first year veterinary students. This is defined by withstanding use by 96 students in small groups in separate sessions for a cumulative 12 hours per week for roughly 5 years with minimal maintenance. The bones themselves should not need to be changed in any multi year time frame. The device should be used indoors in a controlled environment (see Section 1e: Shelf Life) and should not be left in direct sunlight, as this could cause warping of the 3D printed components.

g. Ergonomics

The product should be anatomically similar to a medium sized canine (54.6 cm to 62.2 cm in height, and 29.5 kg to 36 kg in weight), as evaluated by first-year veterinary students [23]. There should be no large discrepancies in dimensions between the model and real bones except for when modifications help in efficiency of design, aesthetics, and aid in better teaching as deemed by the client and students (ex: slightly thicker muscle attachment to aid in teaching and visibility). The device does not need to withstand the forces a normal canine may exert on their bones since this is a model used for seeing the movement and locations of anatomy and not for stress testing in any way. The model should be handled with care and in turn should not be dropped. The bones should be able to withstand double the forces expected during normal use (ie. 26 N of tension on an MTS machine) while extending and retracting the hindlimb and attaching/detaching muscles.

h. Size

This product should be anatomically correct with exceptions that can facilitate better learning or a more economical design (see Section 1g: Ergonomics). The model should attach to a stand and should be able to comfortably fit in a 2 foot by 2 foot cardboard box.

i. Weight

The product does not have strong limitations with regards to weight. The density of bone structure in the 3D printed model will differ significantly from the density of an actual dog bone, therefore, a minimum or maximum weight cannot be decided until materials have been obtained. However, the 3D model cannot contain over 5 lbs of 3D printed material, as this will result in over-spending (see Section 2b: Target Product Cost).

j. Materials

The model bones will be 3D printed. The material must also have a coefficient of friction less than 0.5 to allow for natural canine movements at the joints [24]. The bones should not deform at all when being handled. Potential materials include PLA, Tough PLA, and other plastic filaments [25].

The model muscles can be 3D printed or made of existing stock materials. The material needs to withstand being elongated to twice the original length 100 times a class (12 hours a week per class for 9 weeks each semester) for about 5 years. The material also must return to its original shape after every elongation. Potential materials that meet these requirements include Formlabs Elastic 3D printer filament, rubber, silicone, elastic, and various fabrics [25].

k. Aesthetics, Appearance, and Finish

The model bones need to resemble real bones to the greatest extent possible, as verified by first-year veterinary students. If not using a color-coded method in the design, this requires that the model bones must be white or cream in color, accurately shaped and sized when compared to real canine bones, and rough in texture. Also, the model muscles need to have attachment points that replicate the surface area of real attachment points in medium sized canine dogs.

2. Production Characteristics

a. Quantity

One model canine hindlimb will be manufactured this semester.

b. Target Product Cost

The product should not exceed $500 to prototype and manufacture, a budget determined by the client.

The 3D printing of the bone model will be the most expensive aspect of production, and should not exceed $300. This was determined by the approximate cost of 3D printing filaments and resins along with the maximum expected weight. For example, the bone model itself is expected to weigh under 2.26 kilograms. It is expected to use plastics such as PLA; however, the possibility of resin must not be ruled out. If the product weighed 2.26 kilograms and was made out of PLA, the cost of production would be $180.80. The highest cost expected would be $293.80 if CPE was used. In general, resin is 24 cents per milliliter [25].

Therefore, if the cost of 3D printing the bone model must be kept under $300, the cost to manufacture the muscles should not exceed $200, in order to stay within the predetermined budget of $500.

3. Miscellaneous

a. Standards and Specifications

It is not required that the product meet any international and/or national standard due to the fact that the product will not be patented or regulated by the FDA.

b. Customer

The customer expressed a variety of preferences and dislikes during client meetings. The customer prefers that the model be able to detach and reattach muscles one at a time to allow for students to properly understand the function of each muscle. She also indicated that the muscles should be color coded, as this would support ease of memorization of muscle function. However, she was concerned about students overly associating the muscles with a color instead of the name and function of the muscle. The customer has a strong interest in having a detailed model of the dog skeleton that accurately depicts all of the bumps and ridges of the bone. She specified that plastic models that can be purchased online are not accurate enough. The customer dislikes that the original model only connects to the bone at a single point rather than the full surface area of muscle attachment.

c. Competition

In terms of price, there is a lot of competition and variety. You can find models as cheap as $26.95 made by 4D Master [4]; it includes few details of muscle, bone, and even organs, but the model is not articulated, has reduced detail, and is not to scale with an actual dog. Higher quality, mid-range dog models, like one made by Axis Scientific, can cost anywhere between $200 unarticulated [26] and $400 articulated with a base [27], but none of these models contain muscles for students to identify, attach/detach, and understand their use. It is also possible to buy sections of skeletons made by Axis Scientific for $72 [2], but again none of these models contain muscles; they are just plastic bones. Other models are made of real dog bone and can be moved at the joints properly, but they do not include muscles and cost thousands of dollars. For example, 3B Scientific has an articulated dog skeleton that costs roughly $2100 [2]. There are also 3D models that show the movement of a dog's muscles and their connections to the skeleton [28], but most of these are online simulations that do not allow the students to feel and see the actions of each muscle individually like the client requests. Following a search for patents on anatomical dog models, it was found that Ms. Pawana Chuesiri has three patents for anatomical dog models [29]; however, these are not patents in the U.S.. The customer attempted to create a model; however, there are two primary elements she would like to change. Firstly, on her model, the attachment points are just at one point on the muscle rather than the full surface area where the muscle would normally attach. Secondly, the muscles are simply represented by rubber bands and do not mimic the real shape; this project will create muscles that mimic the shape and function of real dog muscles.

Appendix B: Materials List

Table 1. List of materials, descriptions, cost, and quantity for items used in producing the product. Split into sections based on what part of the product it was used for.

Item	Description	Manufacturer	Part Number	Date	QTY	Cost Each	Total	Link
Attachments								
Disk Magnets	Heavy Duty Neodymium Magnets	TRYMAG	MIX 255Pc	10/2/2022	1	$16.99	$16.99	Magnets
Neodymium magnet tape	neodymium magnetic tape strips, 2 pack	Strongman Tools	2100GS	11/6/2022	1	$22.99	$22.99	Magnetic Tape
Gorilla Glue	Gorilla Super Glue Gel	Gorilla Glue	N/A	11/6/2022	1	8.88	8.88	Gorilla Glue
Muscle Materials								
Polyester Stuffing	3.5oz Premium Fiber Fill Stuffing	NOV WANG	Z-37_28	10/2/2022	1	$8.49	$8.49	Stuffing
Nylon Spandex	1/2yd Nylon Spandex Matte Tricot Fabric***	FabricLA	Precuts	10/2/2022	5	$9.90	$49.50	1/2yd Fabric
Silicone	Smooth-On Ecoflex 00-50 Platinum Silicone 2 lb Kit	River Colony Trading		11/12/2022	1	39.49	39.49	Silicone
Plaster	50 lb Diamond Veneer Plaster Finish	USG	1836857	11/15/2022	1	0	0	Plaster
Silicone Mold Release	mitreapel silicone mold release spray (14.4 oz) release agent aerosol	Benasse	N/A	11/12/2022	1	16.99	16.99	Mold Release
3D Printing								
Bone print	Dog hindlimb bones: pelvis, femur, tibia	UW Makerspace	N/A	11/10/2022	1	4.8	4.8	N/A
Silicone Mold	Mold for pouring silicone	UW Makerspace	N/A	11/15/2022	1	10.8	10.8	N/A

Misc.								
Surgical Tubing	3/8" OD Latex Surgical Tubing	SUCOHANS	N/A	10/2/2022	0	$8.99	$0.00	Surgical Tubing
Lab Stand	Chemical Resistant Steel Lab Stand Set	Eisco	FBA_LABSTANDSET	10/2/2022	0	$37.89	$0.00	Lab Stand
Hindlimb Model	Axis Scientific Canine Hindlimb with Foot	Axis Scientific	A-109194	10/2/2022	1	$72.00	$72.00	Axis Scientific
						TOTAL:	**$250.93**	
	***for fabric, get colors white, yellow, green, red, and blue							

Appendix C: Fabrication Plans

The team planned on assembling the two main components of the final prototype two weeks prior to the final poster presentation in order to allow for ample time for testing with both the MTS machine along with allowing the vet students to get hands-on experience with the model to facilitate feedback. The muscles were created via a multiple step process that was tailored to each individual muscle. The process for fabricating each section of the model is listed below:

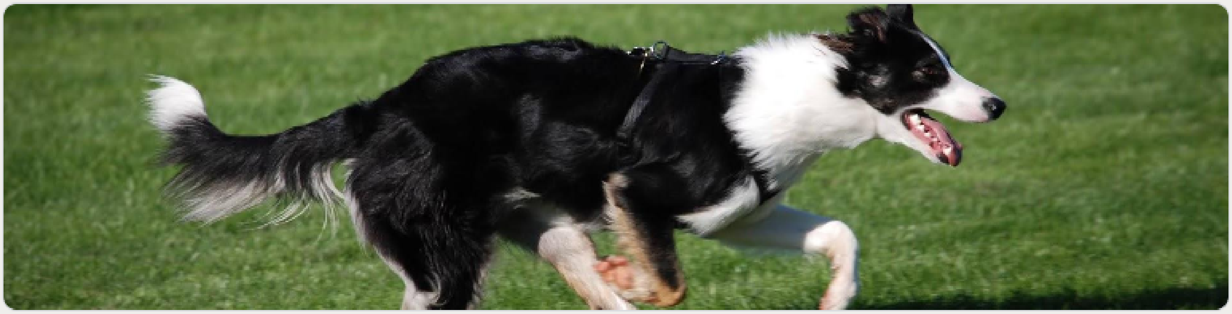
1. Real canine hind limb bones were first scanned in the makerspace using the Creaform handyscan, creating STL files. The files were then printed using tough PLA. The supports were removed, the bones were sanded, and a drill was used to put holes in the ends of the bones so that elastic string could be used to attach any two bones together. All of the bones were then attached together and the model was further sanded down and painted white for aesthetics. The only part of the bone model not 3D printed was the foot since it was deemed too complex by our client and in this case we attached the Axis Scientific foot to our model.
2. The muscle dimensions were determined from Dr. Gunderson's model that had the attachment points of each muscle painted. The dimensions were then used to create a mock muscle made out of clay that was the exact shape of the desired final product. This clay was then cast in plaster to create a female mold for the muscle. Next, the clay was removed and the mold was cleaned. Then, the mold was sprayed with a releasing agent which prevents the silicone from sticking to the walls while curing and spandex fabric was placed in the well along the wall in order to give the final muscle additional strength and durability. Two part silicone was mixed (equal ratio of Part A to Part B) and then poured into the well. The silicone was left to activate for one hour and then the whole muscle was removed. Any rough edges or imperfections were removed with a knife and additional silicone could be added to further smooth the surface area. Next, magnetic tape was cut to size (the muscle attachment surface area as indicated on Dr. Gunderson's model) and one piece of magnet was super glued to the bones and the attaching side was super glued to the silicone muscle.
3. Lastly, all of these components were attached together and mounted on a stand that was provided by the client.

Appendix D: Testing Plans

The MTS machine was set up with the 3d bend fixture and the 10 KN load cell. The rate was set to 1mm/minute and the samples were all placed into the machine in the same orientation. The cross sectional area was measured using calipers and this data was then input into the computer for the stress calculations. Upon failure, the computer displays a stress vs strain graph that was then saved and used for the final poster.

Figure 16. MTS machine with the 3 point bend fixture testing the final femur in compression

Appendix E: Veterinary Survey



Dog Hindlimb Model Survey

What is your expected graduation year?

- ○ 2023
- ○ 2024
- ○ 2025
- ○ 2026
- ○ Other: ______

Do you have any prior knowledge or experience with canine anatomy? (1= I have no prior experience or knowledge, 10= I have intimate knowledge about canine anatomy and have worked with a cadaver or other canine muscle models in labs or real life)

1	2	3	4	5	6	7	8	9	10
○	○	○	○	○	○	○	○	○	○

On a scale from 1 to 10, how anatomically accurate is the model? (1 = this looks nothing like a dog limb, 10 = Looks identical to a real cadaver and matches Miller's Anatomy)

1	2	3	4	5	6	7	8	9	10
○	○	○	○	○	○	○	○	○	○

On a scale from 1 to 10, how durable is the model? (1 = not durable at all, 10 = extremely durable, this could withstand frequent use)

1	2	3	4	5	6	7	8	9	10
○	○	○	○	○	○	○	○	○	○

On a scale from 1 to 10, how intuitive are the muscle attachments? (1 = the attachments are not intuitive, 10 = very easy to attach and could use the model without prior knowledge)

1	2	3	4	5	6	7	8	9	10
○	○	○	○	○	○	○	○	○	○

On a scale from 1 to 10, how easy is it to stretch the muscle material? (1 = it would be hard to do on a consistent basis, 10 = I can stretch them quite easily)

1	2	3	4	5	6	7	8	9	10
○	○	○	○	○	○	○	○	○	○

On a scale from 1 to 10, how helpful was this model in understanding hindlimb anatomy and the mechanisms/counteractions of dog leg muscles? (1 = not helpful at all, 10 = extremely helpful)

1	2	3	4	5	6	7	8	9	10
○	○	○	○	○	○	○	○	○	○

What was done well on the model?

Your answer

How could be the model be improved on? (We would love as much feedback as possible so we can improve the model in the future)

Your answer

Any other thoughts? Questions?

Your answer

Submit

Clear form

Appendix F: Veterinary Survey Results

Questions were shortened into Q1-Q10 in this table so that it is easier to view results in a readable format.

Table 2. Results of the UW SVM Student veterinary survey.

Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10
2025	10	10	10		10	10	The muscle composition and flexibility	Try with other muscles on different parts of forelimb and hindlimb	
2025	10	8	7	9	9	9	Very well done	Making sure the muscles don't pop off as easy	
2026	10	10	6	8	10	10	It was very neat seeing the muscles as silicone and watching them constrict and relax!	Stronger magnets to hold the muscles better would be a good idea for the future. It could also be neat to create different muscles in different colors to better visualize different muscles if you were to add more groups of muscles to the model.	Great job! You guys are awesome!
2026	10	10	10	10	10	10	The choice of silicone for the muscles was great. Being able to visualize the 3D aspect of the muscles is great for understanding the attachments.	if there was a way to indicate which side of the muscle go to which bone attachment would be great to help with understanding especially with taking apart and building the model	Do you intend to do all of the muscles of the limbs? if so how do you intend to include all of the muscles on one model/do multiple models for different sets of muscles? I wish I had one of these models during my muscles unit of anatomy :)

2024	9	9	8	10	10	7	Magnets were great Simple attachment points Bones are accurate	Would be really cool to see models of a healthy hindlimb stifle cranial and caudal cruciate ligament and then one with a tear and another with how the tears are surgically repaired. Would be cool to see more muscles on the limb and how they interact with each other Muscles don't stretch like they would in life and they pop off	Great job! Great enthusiasm!
2026	10	8	7	9	8	5	I like the magnets a lot. Also the larger size makes it very helpful to visualize. And the actual surface area of the attachment makes it more realistic.	More moveability in the muscles to show flexion and extension and action/function of the muscle	How would insertions of muscles on similar/close parts if the bones work for gluing the magnet? Any way to add ligaments and tendons? I know it’s for muscles but that would be cool too!
2024	7	8	8	10	4	9	The magnets are good. Would work well over time and wouldn’t wear out.	More muscles, including a patella, including ligaments and tendons (ex cranial and caudal Cruciate ligament).	Looks really good! It’s great when people make things for vet med because most of the money and research goes into human medicine!
2026	9	5	6	8	7	9	Very well done	Add more of the muscles	

2026	10	10	7	7	10	9	The model was very accurate and I was able to identify the muscles they have chosen to demonstrate. It works really well for antigravity muscles and understanding of attachments that you can't always see on a cadaver dog.	The model could be improved using stronger magnets so that the muscle attachments stay on while moving the model.	
2026	5	10	8	9	9	9	I thought that the models of the bones and muscles were really well done and anatomically correct.	I think that if the magnets were a little bit stronger the model would be perfect!	
2024	10	9	9	10	10	9	Seeing how muscles move and work together in space	Colors!	
2026	8	9	8	9	8	9	Very accurate!		
2026	9	9	6	7	7	9	The attachments/magnets are accurately located.	I feel like the magnet are still not strong enough to withstand stretching, maybe using Velcro would help?	NA
2026	8	9	8	10	8	10	The attachments and pours were really cool!	A little more stretch in the muscles	Awesome idea!
2026	9	8	6	8	7	8	The overall attachments and being able to add/remove various muscles was very helpful!	I think the one thing that could be improved was the attachment of the magnets. When trying to flex the tarsus, the gastrocnemius would pop off pretty easily which doesn't really show accurate flexion/extension of muscles	
2026	9	10	8	9	9	10	The bones were very well made with bony prominences visible and clear. The muscles attach at	Maybe make the magnets more powerful so you can feel the tension of one muscle vs the other	

							anatomically correct points.		
2024	8	8	6	9	6	9	The 3D reconstruction of the limb	Make the magnets stronger and muscle more elastic	Color code muscles
2026	10	10	10	7	10	10	I liked you could move the lumb and see the muscle extend and/flex	I think color coating it will help. This will allow a key to be made and then you can layer muscles on top of each other and still be able to differentiate them.	I really liked it. This makes me excited for future classes.
2024	10	8	2	10	5	10	The muscles and bones look great	Something different for attachments so the limb can be flexed and extended without the magnet coming off	
2026	6	9	10	9	8	9	I think the bones looked very accurate and it was helpful	I think it was very well built	No
2024	10	8	7	9	9	10	I like the magnet concept for the attachments- in our anatomy course they really stress knowing the attachments and it's a nice way to visually see them to understand the muscle mechanism	Different colors with a key would be nice :)	
2026	9	7	6	8	8	8	The idea is really interesting and I would love to see it further along in the process. The medium used was a good choice, holds its shape, but is still malleable.	The attachment points are a bit too flimsy for true flexion/extension abilities of the model. Perhaps use eyelet joints would allow for quick detach/reattachment, but a little sturdier when it comes to movement	
2026	7	10	9	6	5	10	The use of magnetic attachments so you can easily see what happens when you attach it	I think color coordination would be good	

2026	10	8	6	8	6	9	Placement, shape, visualization	Mechanisms for attachment to integrate pin point attachments. Maybe even a representation of tendons and ligaments.	This is fantastic. One of the biggest idea to improve is just to color code different muscles within a muscle group.
2024	10	8	9	10	8	10	I liked the material choice for the muscles	Including more muscles down the road would be great!	
2026	10	6	7	6	4	8	I liked the size of it and the bones looked good. I like the fact that you can attach and detach the muscles fairly easily from the bones. It was nice to be able to see all of the attachments for each muscle.	I would like to see the muscle attachments made a bit stronger so that we could pull on the muscles to see their mechanism of action without them detaching from the bones. Also, some sort of color coordination for the muscle attachments would be helpful. I think that as you add more muscles to the model the anatomic accuracy of muscle shape and thickness will need some improvement to be able to accommodate all of the muscles.	I feel like the gel used to make the muscles may start to break/tear with frequent bending. Overall, I think this would be a really helpful model to help learn the muscle attachments.
2026	4	7	5	6	8	8			
2026	10	9	5	8	4	7	The design using magnets was innovative and could be a very useful tool if it is developed further!	The muscle material likely needs to be something that was “contract” and “relax” like a muscle, so it needs more give without being too flaccid in a resting position (to help prevent detachment). The magnets might become cumbersome when there are multiple muscles attaching to the same/similar location.	Very cool model - thank you for spending the time to help Dr. Gunderson and us :)
2026	7	8	6	7	7	9	accurate representation.	stronger magnets but otherwise cool model!	
2026	10	9	6	8	7	10	It’s a realistic representation of the muscles and the attachments	Stronger attachments for when we try to flex the limb	This would be an excellent learning tool.

2025	10	8	4	7	4	7	Accurate and simplistic 3D attachment allowing us to see how injury can affect range of motion.	More muscles and limbs built with stronger materials to allow leg to be moved in normal range of motion without the magnet of the muscle disconnecting from the skeleton	More flexible muscles and stronger magnets maybe like a magnet key like the hardware that's used for small children to prevent them from slamming their fingers in a cabinet with an "unlock" the magnet to allow removal of muscle
2026	9	6	4	8	9	5	The material was interesting and the perfect amount of stretch for the desired purpose. The attachments coming apart was nice to see the free movement of the joints.	Stronger muscle attachments would be helpful, with future projects more muscles especially at a similar attachment spot (like the CCT/calcaneus) would be interesting	
2026	8	6	8	9	10	8	The ability to detach and reattach the muscles is useful and could possibly be explored to layer additional muscles on the model	It's difficult to produce a model that is identical to cadavers-- however if this type of model is to be used for official instruction it would be nicer to have the muscles appear more similar to their appearance on the body (adductor muscles in particular on other cadavers tend to be much thicker)	The model is a unique and exciting idea! I'd love to learn more about future veterinary model designs
2026	8	9	5	8	5	9	The model appears a anatomically correct which would be helpful for learning attachments and limb movements.	As was noted by the students, the attachment mechanism for the muscles to bones needs to be improved, some of them fall off too easily.	
2026	10	9	8	9	8	9	It looked real and would be helpful to study the muscles.	May need thinner silicon or a different way to attach the muscles as it would be hard to attach all the muscles in the future.	This was cool!

2026	10	9	9	9	5	9	The accuracy of the muscles in terms of attachments was correct.	I think you would either need multiple models to display all the muscles on the limb or to make tendon like attachments to the muscles to bones. This would allow for elasticity in the "muscles" and perhaps allow for more attachments to one area on the bone.	I think it's an amazing start to a project! It would help a lot of students visualize the attachments 😊
2025	10	7	6	7	9	7	The bone printing was really good, the sturdiness of the muscle pours was good	Definitely an alternative to the magnets or just stronger magnets so that they stay in place more easily. I think it would also be helpful if there were some contractile properties for what you used for the muscles because contraction is really what indicates what the muscle's action is	I love the idea! I'm glad there will be better models to use in the future. The pieces of tap representing the muscles was less than ideal
2024	10	10	8	10	7	10	I really like how the bones look.	The bones look really well done. Shape the muscles to look more like muscles, otherwise looks good.	I would add the quads and the patella ligament attachments to furthered represent the hind limb anatomy.