Structural And Mechanical Function Of Canine Forelimb

Biomedical Engineering Design

Department of Biomedical Engineering

University of Wisconsin-Madison

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Client

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Abstract

First-year veterinary students must learn the anatomy and physiology of canines in detail. This information is complex and can be difficult to learn, with physical models providing a valuable way to more quickly and accurately absorb this information. Canine cadavers are commonly used, but they fail to show the dynamic functions of muscles and can pose financial challenges. Therefore, a relatively inexpensive model that reinforces the mechanical and anatomical properties of a canine's musculoskeletal system is required. Current models fail to meet needs in an array of ways such as a lack of detachable muscles, dynamic movement, and visually inaccurate muscles among other anatomical issues. To attack this challenge, the team decided upon a model in which canine forelimb bones are 3D printed using tough polylactic acid (PLA), and muscles are molded from silicone with color-coded embedded fabric. The components are connected at anatomically correct attachment points using neodymium magnets. These magnets have a strength at which they can easily be attached and detached, yet not fail under the tension of the muscle. A mechanical testing system (MTS) was used to determine the strength of the muscle and the attachments ensuring the durability and accuracy of the model. Additionally, a survey was given to students to assess the intuitiveness and accuracy of the model. An accurate and durable model provides students with an effective and more cost-effective way to learn the anatomy and physiology of canine musculature

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Introduction

Motivation

First-year veterinary students must learn anatomy, histology, and physiology in great detail to prepare for the rest of their education and their careers. However, the structure and function of bones, joints, and muscles are very complex and therefore difficult to learn. Hands-on learning is the best way for students to gain a deep understanding of these concepts, but rigid cadavers do not help show the functions of different muscles and current models are inaccurate or incomplete. The motivation for this project is to create an easy-to-use yet accurate model to reinforce critical anatomical and mechanical properties of the musculoskeletal system of an animal.

Problem Statement

The group is creating a realistic model of a canine forelimb to replicate muscle and bone interactions in the canine's forelimbs. The model should be easily moved and act as a training model for veterinary students to learn the mechanics of the important joints in those animals. This includes detachable muscles, muscles with similar mechanical properties to real muscle, and the model moving as expected when applied with external forces.

Background

Anatomy of The Canine Forelimb

The canine forelimb is a complex system of skeletomuscular systems with important physical characteristics as well as some key differences from the same systems in humans. Although there are similar naming conventions as the arm of a human, there are clear distinctions that must be made. The canine forelimb has four tricep heads compared to three in a human tricep, and a canine's bicep has one head rather than two. Additionally, there are many attachment points that differ from a human arm to the forelimb of a canine. These distinctions must be learned and understood by veterinary students in order to paint an accurate picture of a canine forelimb.

Existing Devices and Current Methods

Figure 1: Vetwho Bone Model [1]

Figure 2: Anatomy Warehouse Model [2]

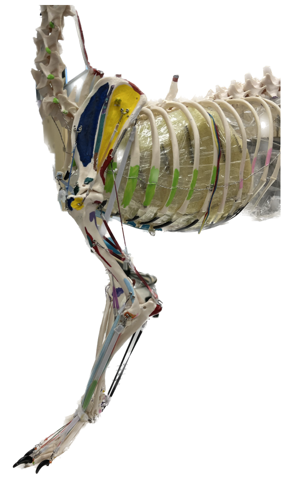

Figure 3: Dr. Gunderson's Model

Three competing solutions currently exist. The first is a simple bone model made by Vetwho. It is sold for $78 and includes all of the bones found in the forelimb of a canine [1]. This model is good because it can bend at the joints, but it does not include any muscles. A near-identical model is also sold by Axis Scientific [2]. The second design is a full model of a canine with muscles and organs, created by Anatomy Warehouse. This is sold for $365 and does include muscles but is completely static and does not have bones [3]. The final competing solution is the current model being used to teach veterinary students. This model is an Axis Scientific bone model that has been modified with pins, hooks, and elastic bands to include detachable muscles that allow the model to move similarly to an actual limb. The largest issues with this model are that the bands do not look realistic, and the pins and hooks are a less intuitive attachment system. Additionally, over time, durability issues arise with the bands stretching out and losing the tension needed to effectively counterbalance each other and hold the limb in the correct position.

Available Modeling Data

In order to create an accurate model, accurate information about the properties of the forelimb must be acquired. During a study of a canine's forelimb [4], lots of valuable information about the morphometric and anatomic properties was gathered. Using information such as the muscles' physiologic cross-sectional areas (PCSA) and muscle insertion and origin points, the team can ensure proper muscle placement as well as accurate muscle force outputs. For example, the biceps brachii has a mean mass of 27.92 g, a mean length of 11.05 cm, a mean fiber length of 2.65 cm, and pennation angle of 15.89°, and a PCSA of 2.04 cm [4]. Using this valuable data, it is possible to ensure the model can accurately represent that of an actual canine forelimb.

Mechanical Properties of Ecoflex Silicone and Canine Skeletal Muscle

A major goal of the project is for the muscle in the model to simulate native canine skeletal muscle as closely as possible. To do this, it is important to understand some mechanical properties of both silicone material and native canine muscle. In a study of Ecoflex silicone and native animal muscle tissue [5], the stress/strain and biomechanical aspects of Ecoflex 00-30 and 00-10 were compared to those of animal muscle tissue. After performing tests, stress distribution trends in both the muscle [6] and Ecoflex 00-30 were quite similar, but the stress magnitudes were higher in the silicone than in the muscle. This information, paired with knowledge of the physical properties, allowed the team to create a model that is able to mechanically and anatomically replicate the muscles of a canine's forelimb.

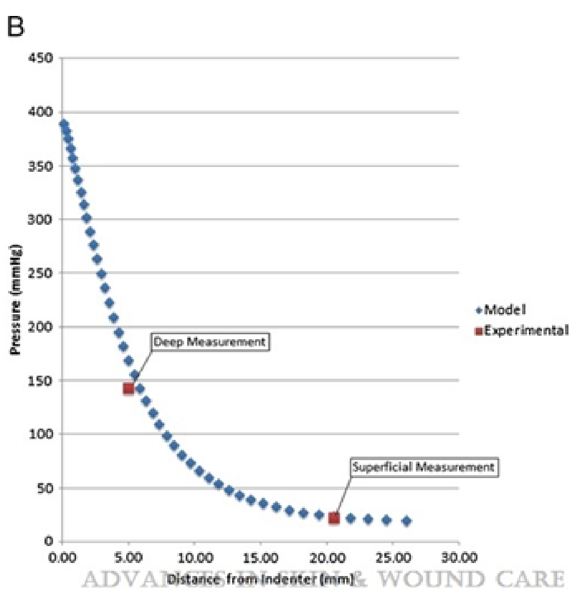

Figure 4: Ecoflex 0030 Finite Element Model at Maximum Indentation [5]

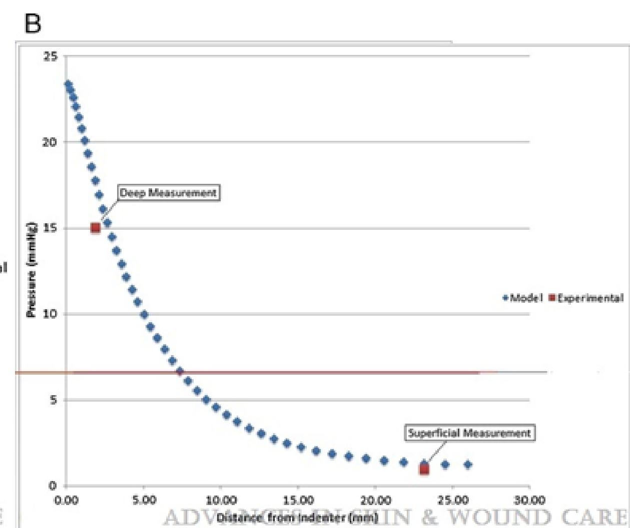

Figure 5: Porcine Muscle Finite Element Model at Maximum Indentation [5]

Client Information

Dr. McLean Gunderson is a professor in the Department of Comparative Biosciences at the University of Wisconsin's School of Veterinary Medicine. She is the lecturer for Veterinary Anatomy, the class that all first-year veterinary students must take to learn anatomy, histology, and physiology of animals.

Client requirements

The client requests an anatomically accurate model of a canine's forelimb with accurate bone structure, functional muscles, and removable muscle attachments. Ideally, the model contains the tricep, bicep, brachialis, and anconeus muscles, and differentiates between muscle and tendon tissue. The model must be durable enough to withstand usage throughout four weeks, four times a week, by about 100 students, and then still be functional after long periods of storage. The model should be able to withstand this cycle of use and storage for several years. The muscles on the model must have an attachment strength such that it can be detached with a small pulling force, but such that the force of the muscle itself does not cause a detachment. Additionally, the tensile strength of each opposing muscle group must be considered so that they do not overpower each other and affect the movement or structure of the model.

Design Specifications

The device is a model of the forelimb of a medium-sized canine for the use of first-year veterinary students. The model uses 3D-modeled bones and muscles to replicate the connections, functions, and appearance of the full limb of the canine. The model should be easily used by the students to get an understanding of muscle connections and functions. In terms of safety, the device should be made of materials that can be sanitized after many students repeatedly use it, and the materials should be strong enough and the tensions weak enough to prevent the model from snapping and hitting someone. Because the model will be used in a classroom, it will be exposed to regular room temperatures around 20-22 °C and typical conditions of 30-60% humidity. The weight of the model should not exceed 10 kg to allow for easy transportation. The materials for the bone must be durable and they must be usable in a 3D printer. The materials used for the muscles should be as close to native canine muscle as possible, ideally with a Young's Modulus of 24.7 ± 3.5 kPa [13], and length and PCSA that matches that of the study aforementioned [4]. Additionally, the elasticity of the muscle should not degrade over time, keeping a length within 5% of the original after cyclic loading.

Preliminary Designs

Chosen Bone Design

To design the bone model that the muscles will be attached to, bones from a cadaver were needed. These bones were scanned using a hand scanner to obtain stereolithography (STL) files, which were then scaled to the size needed in the model. From there, the files were edited to add holes that can be used to run string through, attaching the bones to one another. This allowed for an accurate rotation of the joints, creating a more interactive and less rigid model than those such as the Anatomy Warehouse model [2], which is a fully static model.

Muscle Design 1: Elastic Bands

The elastic bands' design consists of elastic bands of varying strengths that mimic the action of muscles. The bands would be made of different colors to distinguish between the different muscles. The size and shape of the elastic bands could not be manipulated to mimic the size and shape of real muscles, but the tensile forces could be varied such that opposing muscles could counteract each other in a way that mimics real muscles. The elastic bands will need to be attached to the muscle and bone using hooks, as magnets and Velcro will not be feasible attachments for elastic bands.

Muscle Design 2: Resin

The resin model would be molded by pouring the resin into 3D-printed casts that could perfectly match the size and shape of specific muscles in a canine's musculature. The group will print the negative area of the muscle tissue using a PLA material, and sand it down to create a smooth material. Before pouring, the group would be able to easily dye the resin to match whichever color is decided to be used for our muscle material. Next, the group will pour the resin into this mold, and wait for it to harden. Next, either a magnet attachment will be added during the hardening portion, or a Velcro attachment will be attached using glue after the resin hardens.

Muscle Design 3: Silicone and Fabric

The silicone and fabric model would involve a similar method to the resin model. It would start by combining the design and solutions of an EcoFlex solution into a 3D-printed cast. This cast would be done in the same way as the previous design choice, using PLA material. There are varying EcoFlex solutions of different hardness levels that will be chosen to mimic the tensile strengths of the different muscles. A chosen color of spandex fabric will be laid into the mold, and the chosen strength of EcoFlex silicone will be poured into the mold. The desired attachment would either be glued to the outside of the mold or placed in the chosen position before the silicone cures.

Attachment Design 1: Velcro

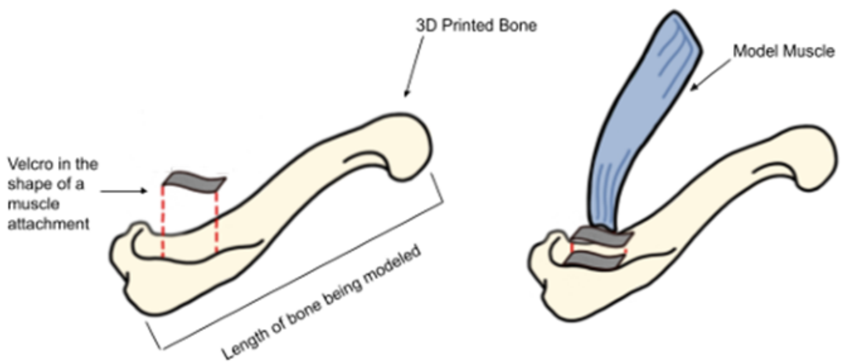

Figure 6: Velcro attachment design with a piece of Velcro on the bone and a matching piece on the muscle

This attachment design consists of complementary Velcro pieces adhered to the modeled bone and muscle/tendon. The Velcro would be placed at the proper attachment point and cut down to match the anatomical muscle connection of a canine as closely as possible without substantially sacrificing the strength of the bond. Once cut, the Velcro pieces would be secured in place on the bone and muscle via glue. Users would then be able to intuitively attach and detach the muscle to bone by connecting and separating the Velcro.

Attachment Design 2: Magnets

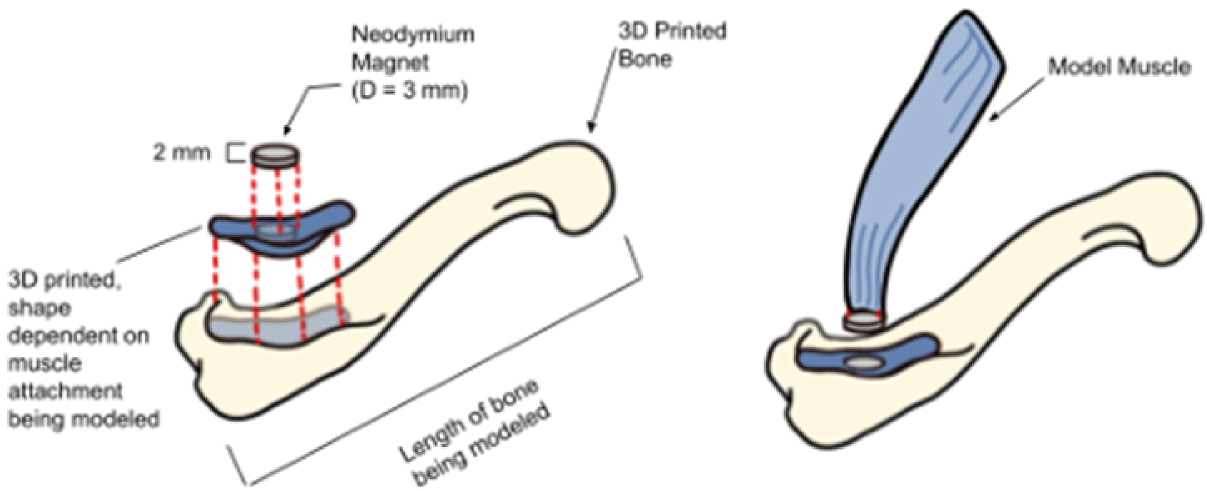

Figure 7: Magnet attachment design with embedded magnet housing

The second attachment design uses integrated neodymium magnets to secure the fabricated muscle/tendon. Anatomically correct muscle attachment locations would be identified, and the 3D model of the bone would be altered to include an indented housing for a magnet in that area. One magnet would be inserted into the housing within the bone and another adhered to the corresponding attachment point on the muscle. The best method of adhering a magnet to the fabricated muscle would need to be tested; such as gluing the magnet to the surface of the muscle or embedding it during the muscle molding process. Once complete, users could easily remove and reattach the muscle from the bone through magnetism.

Attachment Design 3: Button Release Pin

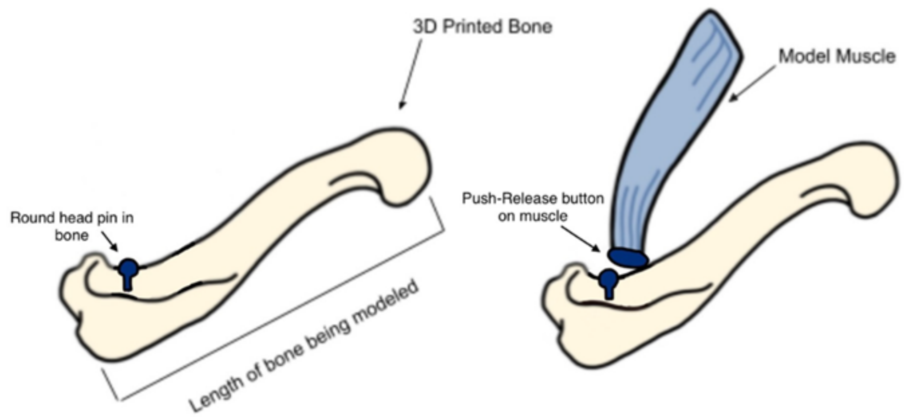

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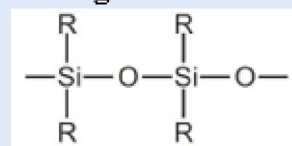
Figure 8: Button release pin attachment design with round head pin in bone and matching button on muscle

The third design uses embedded pins with a button attachment/release to secure the fabricated muscles to the modeled bone via a ball and socket joint. A bolt with a round head would be inserted into an anatomically correct attachment location in the bone. The button head would be attached through the fabricated muscle so that the push button is on one side, while the insertion point is on the other. Users would then be able to attach the muscle to the bone by applying force at the attachment point and intuitively detach the connection by pressing the push button and pulling the two components apart.

Design Evaluations

Muscle Design Matrix

Table 1: Design Matrix for Muscle Material

Design Criteria	Design 1: Elastic Band 		Design 2: Resin 		Design 3: Silicone 	
Ease of Fabrication (20)	**5/5**	20	**5/5**	20	**4/5**	16
Durability (20)	**4/5**	16	**4/5**	16	**5/5**	20
Mechanical Similarity to Muscle (20)	**3/5**	12	**2/5**	8	**4/5**	16
Safety (15)	**2/5**	6	**3/5**	9	**4/5**	12
Appearance (15)	**1/5**	3	**3/5**	9	**4/5**	12
Cost (10)	**5/5**	10	**4/5**	8	**5/5**	10
Total (100)	**67/100**		**70/100**		**86/100**	

Muscle Design Criteria

Ease of Fabrication

The Ease of Fabrication category refers to the model's capacity for production during the prototype stage. It specifically relates to the capability to construct a functioning muscle prototype. The team decided to weigh this category as a 20/100. Although the main focus for this semester is to fabricate a prototype, the ability to fabricate the muscle material efficiently is important in terms of long-term manufacturing.

Durability

The durability of the model is how the muscle tissue will degenerate or wear over time. The material for the muscle tissue of the model needs to be strong enough to be used by many students over a long period. The model will be under intense use by around 100 first-year veterinary students for around 4-5 weeks, so the muscle material must not degenerate after being handled over time. With that being said, the team weighed this category at 20/100.

Mechanical Similarity to Muscle

The mechanical similarity between the model muscle and actual native muscle tissue is crucial to accurately represent the physiological properties of a canine forelimb. To give veterinary students the most beneficial learning experience when utilizing the model, the muscle material must mimic key mechanical properties of native canine muscle such as hardness and flexibility. With this information in mind, the team weighed this criterion at 20/100.

Safety

The safety category was weighted at 15/100. The model must be safe for its users; more specifically, the muscle material must not have any impurities that could cause harm. Additionally, the material should not be toxic chemically. Although there is a minor risk when handling the muscle material, it is still a respected criterion for the design.

Appearance

It is best for the anatomical appearance of the muscles in the model to be similar to that of native canine muscle tissue. However, the physiological function of the model can still be adequate even if the model does not look like actual muscle tissue. The overall appearance of the muscles in the model can be helpful for visualization in learning. The weight of the appearance category for the muscle material received a 15/100 for said reasons.

Cost

The category of cost relies on the budget provided by the client of $500. While it is important to stay under budget and satisfy the client's needs, the cost category was only weighed as a 10/100 since the team is certain that the muscle material will be relatively inexpensive. With that, the cost category is a low priority.

Muscle Design Matrix Evaluations

Elastic Bands

The elastic band design received an overall score of 67/100, making it the lowest score out of the 3 designs. Although the design had some strengths, it had many points of concern compared to the other 3 designs. Some high-scoring aspects of the elastic band design were the ease of fabrication and cost categories. These categories both scored a 5/5. The elastic band design is simple to fabricate as the team would just have to buy the bands and hook them to the model. Also, these bands are very inexpensive. On the other hand, this design had major flaws in the safety and appearance categories. The elastic band design received a 2/5 on safety and 1/5 on appearance. The main concern of this design is the appearance of the bands on the bones. Since bands do not have the same size or shape as muscles, it may be difficult for students to learn the different muscles. Overall, this design was scored the lowest for its lack of educational functionality whereas the other designs excelled.

Resin

The resin design had the 2nd highest design score at 70/100. Although only slightly higher than the elastic band design, the team believes that the resin provided better attributes overall.

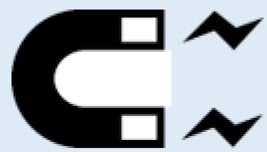
The resin has better appearance qualities as it has the shape and size of actual muscle; also, the resin can be colored easily which can help students identify the different models. This model lacks mechanical similarity to the muscle category as it scored a 2/5. The mechanical properties of the resin are not similar to that of native canine muscle which would negatively impact the learning experience for a veterinarian student. Overall, the resin design offered some advantages in terms of appearance, but its lack of mechanical similarity to native muscle poses a potential limitation for veterinary students' learning experience.

Silicone and Fabric

The silicone design was the highest-scoring design at 86/100. It was the leader of almost every criteria category and will be the team's selected material. The ease of fabrication of the silicone model received a score of 4/5, slightly lower than the other two designs. The cause of this is that the silicone also needs to be poured onto a piece of fabric which is harder. The silicone's most appealing qualities are mechanical similarity, ranked as a 4/5, and durability ranked as a 5/5. The team can purchase different types of silicone material that will cure at various hardness ratings. This will give the team the ability to replicate the mechanical properties of native canine muscle. Overall, the silicone design has the highest ratings and will provide the best muscle functionality for the model.

Attachment Design Matrix

Table 2: Design Matrix for Attachment Method

Design Criteria	**Design 1: Velcro** 		**Design 2: Magnets** 		**Design 3: Button Release Pins** 	
Attachment Strength (20)	**3/5**	12	**4/5**	16	**5/5**	**20**
Ease of Fabrication (10)	**3/5**	6	**4/5**	8	**3/5**	6
Durability (20)	**2/5**	8	**5/5**	20	**5/5**	**20**
Ease of Use (15)	**3/5**	9	**5/5**	15	**4/5**	12
Appearance (15)	**3/5**	9	**4/5**	12	**2/5**	6
Cost (10)	**5/5**	10	**4/5**	8	**3/5**	6
Safety (10)	**5/5**	10	**3/5**	6	**5/5**	**10**
Total (100)	**64/100**		**85/100**		**80/100**	

Attachment Design Matrix Criteria

Attachment Strength

The attachment strength category refers to the capability of the attachments to be strong enough to prevent slipping and falling off, but also weak enough to be easily removed. The attachment strength category was crucial during the design process, as last year's group ran into problems with their magnets lacking the required strength. The client specifically requested we improve the connections, so it was rated at 20/100 as it is critical for the design to match the standards set by the client.

Ease of Fabrication

The ease of fabrication category was rated 10/100 and involves the complexity of the design of each muscle. Since the attachments must connect to the muscles in specific spots to mimic tendons attaching muscles to bone, accurate fabrication was considered in this criterion. This category did not receive as much weight, as the time constraints of a semester should not present manufacturing challenges.

Durability

The durability category received the maximum weight of 20/100, matching the attachment strength criterion. Since the model will be under intense use by around 100 first-year veterinary students for around 4-5 weeks, making the attachments capable of detaching and reattaching without wear and tear is paramount. The model must also be able to sit in storage for around a year after the period of intense use without damage or deterioration.

Ease of Use

The ease-of-use criterion refers to the simplicity of the attachments on the model and received a weight of 15/100. The muscles on the model must be easy to detach and reattach, so making sure that the design is not too complicated was an important consideration of this criterion. Another factor considered was making sure the attachments are not too strong that they are impossible to remove, and not too weak that they can detach without use.

Appearance

The appearance category refers to how the attachments mimic muscle connections/attachments in an actual canine and received a weight of 15/100. A major consideration of this category was making sure the attachments did not appear too clunky or overbearing so that they did not detract from the appearance of the model. The coloration of the attachments was also considered so that they looked like tendons on a canine.

Cost

Cost corresponds with the budget allocated by the client of around $500. The client gave the impression that the budget was relatively fluid, so there was no truly defined maximum price for the design and fabrication of the model. While it is important to stay around the $500 figure given by the client for reference, the cost category was weighted 10/100 to reflect the lack of priority placed on the budget.

Safety

Safety for attachments refers to the connection points of the muscles not being able to harm the user and was weighted at 10/100. While user safety is integral for strong design, it did not receive as much weight/attention as other categories because there was not a strong differentiator between proposed designs and their respective safety.

Attachment Design Matrix Explanations

Velcro

The Velcro design involved attaching cut pieces of Velcro to the 3D-printed bone material to connect the muscles and tendons. It received a 3/5 for attachment strength because it can withstand 195 N of force in shear while fresh [7], but it is considerably weaker than other attachments available, like magnets, or even buttons. It also scored a 2/5 in durability, a heavily weighted category, because the loops on the velcro will wear down over time, and eventually become unusable. Velcro scored a 5/5 in the cost and safety areas, as it is a very cost-effective design, and because of the lack of pinch points as seen in magnets, or button release systems. Since these categories were not weighted heavily by the team, these stronger scores in the less prioritized categories, combined with weaker scores in more heavily weighted areas led to it receiving a score of 64/100, the lowest of the attachment groups.

Magnets

The magnet design involves drilling small bits into the bone model to insert magnets which would have an opposing magnet on the muscle for connection. Magnets received a 4/5 on both ease of fabrication and attachment strength because once holes are drilled into the tough PLA bone material, the magnets are easily embedded. With respect to attachment strength, the magnets can withstand a force of up to 21.8 [14]. While they did score a lowly 3/5 in the safety category, this category was not weighted as heavily. Overall, the magnet design scored 85/100 on our design matrix, the highest of the designs for its ease of fabrication and its more natural appearance than velcro or a button release system. The team believes this attachment style will be the best for the final design.

Button Release Pin

The button release pins design involved attaching pins as muscle connections that could be clicked into place and detached using buttons. The button release pins received a 5/5 on attachment strength as they are easily attached and reattached through pins leading to no wear and tear that could impact attachment strength down the line. Size would also not have to be considered like with a smaller magnet. This design received a 5/5 on durability because the buttons would not wear down at all over time. They would also be able to withstand unaccounted forces applied by users. With respect to Velcro, the button system would be able to withstand much more prolonged use. Button release pins received a 2/5 on appearance because the system would be large and clutter the bone material. The connection would also not resemble muscles at all and not be easily colored to the “muscle color.” While this system scored highly in key areas, its overall score was dragged down by lesser ranking, yet still important categories such as cost and appearance. It received 80/100 but was not enough to beat out the magnet design.

Proposed Final Design

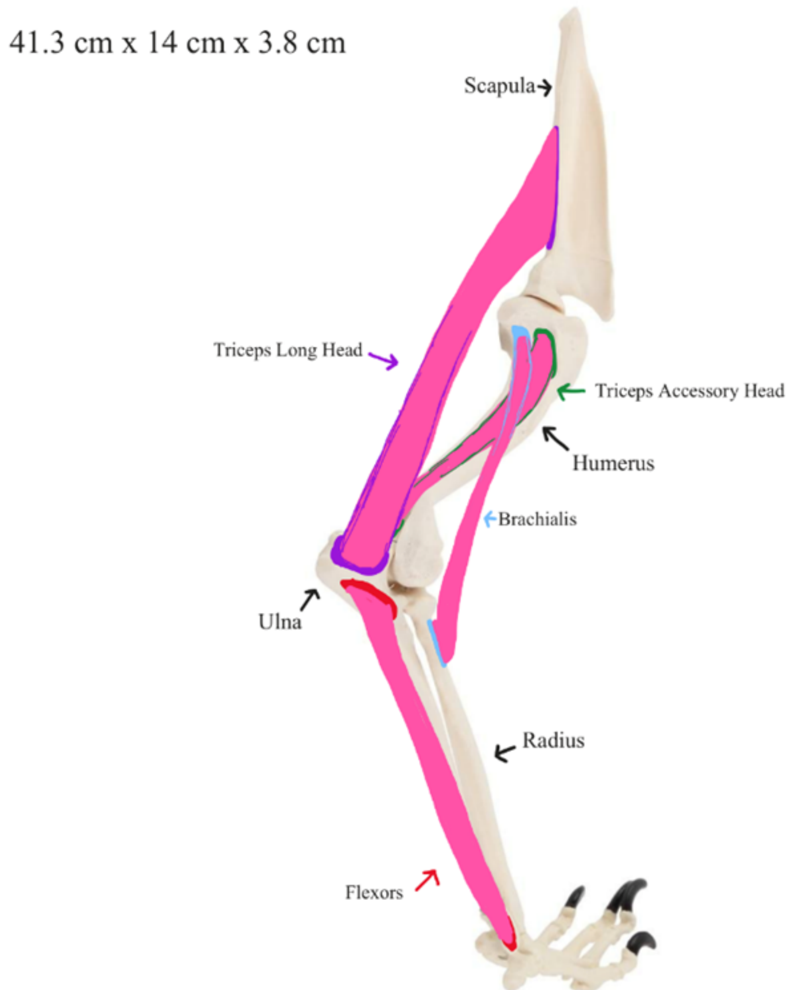


Figure 9: Proposed Final Design with magnet attachments as previously described and silicone muscle groups

The proposed final design consists of 3D-printed bone, silicone and fabric muscles, and magnet attachments to model the forelimb of a canine. The bone will be modeled based on the bones of a beagle and printed using PLA. The bones will be held together by string to tie the joints together. Silicone and fabric are used to most accurately represent the mechanical properties and appearance of canine muscle. Tendons will be represented by different colors and denser fabric to identify individual muscles and give them a denser feel than the muscle itself. Magnets are utilized for the attachment of the muscle to allow for easily removable and long attachments that can withstand movement and constant use by veterinary students. The model will be held up with a test tube stand and frame to keep the model vertical and elevated.

Final Design

Figure 10: Final Design Model

As seen in Figure 10, the final design is very similar to the proposed final design. The four bones of the canine forelimb (scapula, humerus, radius, and ulna) were printed and then connected to each other with elastic cord in the same way as Dr. Gunderson's model, which created secure attachments that were able to move in an anatomically correct way. The four muscles selected for the final design were the biceps (long head), triceps (medial, lateral, long, and accessory heads), brachialis, and anconeus. These muscles were selected because they are the major muscles of the upper forelimb and they are sufficient to demonstrate opposing muscle forces during flexion and extension as a result of their antagonistic properties [Canine Forelimb - Anatomy & Physiology - WikiVet English]. The attachment design used involved neodymium magnets attached to the surface of the bones and colorful tendon components with corresponding magnets sewn onto the muscles. Colored markers were used for the attachment sites to make the site more anatomically correct and to match the tendon colors. This made it easier to identify which attachment corresponds with each muscle.

Fabrication and Development

Materials

The bones were 3D printed out of tough PLA and connected with elastic cord. Attachment sites were created using neodymium magnets, epoxy, colored markers, and clear nail polish. Muscles were created using EcoFlex 00-35 and mesh, and the molds they cured in were formed from modeling clay. Tendon attachments made of cotton-rubber elastic fabric were sewn onto each end of the muscles, with a different color corresponding to each individual muscle. Finally, a corresponding neodymium magnet was sewn into the tendons to create detachable connections to the sites on the bones.

Fabrication Process

The bones of the canine forelimb were scanned in the Makerspace using the HandyScan 700 to obtain STL files. After post-processing, the bones were printed on an Ultimaker with 50% infill and 0.1 mm resolution. The models were scaled up 136.52% to make them the same size as the VetWho bone model and the previous year's model. The bones were connected with joints made of elastic cord.

To create attachment sites for the muscles on the 3D-printed bone, neodymium magnets were cemented to the bones using epoxy. To make the attachment sites more anatomically correct, colored markers were used to draw in the entire site of muscle insertion. A coat of clear nail polish was also applied to prevent wearing or fading of the color.

For the muscles, simple molds were created using modeling clay, keeping in mind the scaled-up lengths and PCSA values to create an accurate size, and a piece of mesh was then placed into the center. These muscle molds were created based on the scale of the previous year's model, and four different fabrication sessions occurred, for the anconeus, the brachialis, the biceps, and the triceps. EcoFlex 00-35 silicone was then poured into the clay mold so that it cured around the mesh. In some cases, the silicone was trimmed down to make the muscle the appropriate size and weight for the model.

To create the tendon attachments, elastic fabric was cut into 2”x 2” squares and sewn onto the ends of the muscles through the embedded fabric. Four different fabric colors were chosen to correspond to the four separate muscles, with the colors matching those applied at the bone attachment points. Neodymium magnets that matched the attachment sites on the bones were then sewn into each tendon, and any excess fabric was cut off.

Testing

Materials Test System (MTS) Tensile Testing

Figure 11: Tendon fabric at the start of tensile test inside of the MTS Machine

MTS tensile testing was performed to determine the materials Young’s modulus, peak force, and peak deflection of each material used in our project. The materials used for testing include the muscle fabric, the tendon fabric, pure solidified silicone, silicone with the muscle fabric inside, and a fully assembled muscle with muscle fabric inside of the silicone and the tendon sewn into the fabric from inside the muscle. Three separate samples of silicone with muscle fabric were tested. The materials were spare materials that were assembled for testing. The final muscles used in the model were not used in the tensile testing. The materials were loaded into tensile grips with a 10 kn load cell and put through a tensile test at a rate of two millimeters per second. The test would go until failure of the material or until the material slipped from tensile grips. The force vs. displacement collected from testing was then converted to stress and strain using Matlab as seen in Appendix Matlab Code.

Cyclic Loading

A stress relaxation cyclic loading test was conducted to determine how much the fabricated muscles stretched out over repeated use. An upper threshold of 5% relaxation was determined to ensure that the model can be used by many students while retaining its ability to accurately replicate muscle material. The muscles should not stretch past the threshold to retain the opposing forces of antagonistic muscle groups. The brachialis and biceps muscles were selected for testing because they are both long and uniform, which made the measurements easier to collect. Both muscles were pulled to 25% strain for 50 cycles based on the assumption that the model would not be stretched to that extent in regular use.

Survey

A survey using Google Forms was completed by visitors during the poster presentation and by roommates and friends of group members to obtain feedback on the performance of our design as a training model for veterinary students. The survey asked respondents to grade the model on a scale of one to ten, with ten being the best, and allowed for possible explanations for their grades. The data surveyed the anatomical accuracy of the model, the intuitiveness, the durability, the mechanical similarity, and the usability of the muscle attachments.

Results

Through the testing methods of the project, the team was able to obtain results regarding the durability, functionality, and realism of the model.

Materials Test System (MTS) Tensile Testing

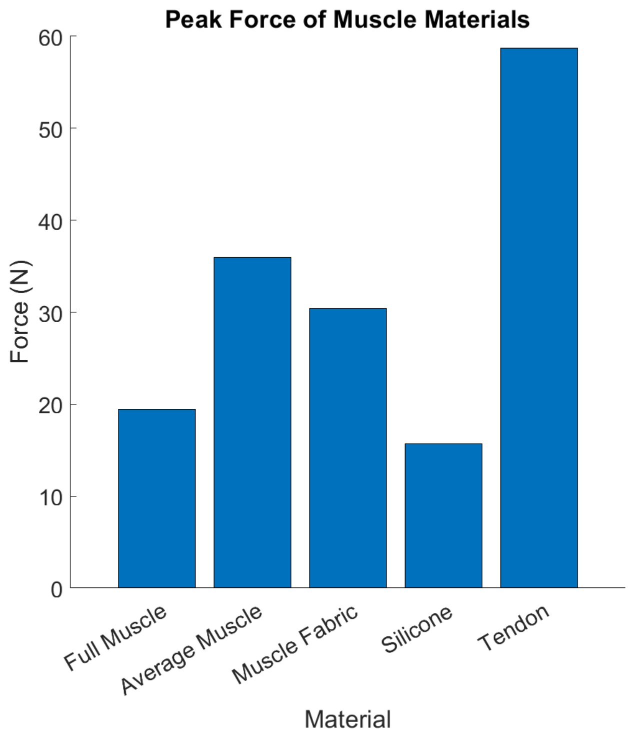


Figure 12: Bar graph showing the peak force in Newtons that each material in the muscle model obtained during MTS testing.

The team used tensile grip attachments on the MTS machine to collect peak force data of each muscle model component. The Full Muscle assembly with the silicone, muscle fabric, and tendon fabric obtained a value of 19.47 Newtons. However, this is not the failure point as the MTS forceps pictured in Figure 11 could not grip down on the tendon fabric sufficiently. This caused the tendon fabric to slip out of the grips and result in a 19.47 N peak force. The Average Muscle bar is the result of tensile testing three different samples of silicone with the muscle fabric embedded in it. The average peak force of these samples was 35.97 Newtons, with a standard deviation of 2.50. Similar to the full muscle assembly, these muscle samples would slip out of the MTS grips before the breakage point. Moving on to the fabrics, the muscle fabric and tendon fabric obtained a peak force of 30.42 N and 58.72 N respectively. These peak force values are accurately representative of the break point of the material as no slippage out of the forceps occurred. Lastly, the tensile testing of just the silicone material resulted in a peak force of 15.68 Newtons. However, this value is not the true breaking point as slippage out of the forceps occurred.

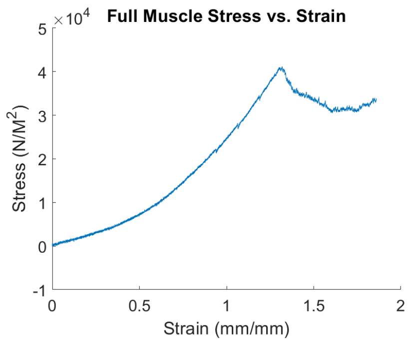


Figure 13: Stress vs. Strain of the complete muscle assembly

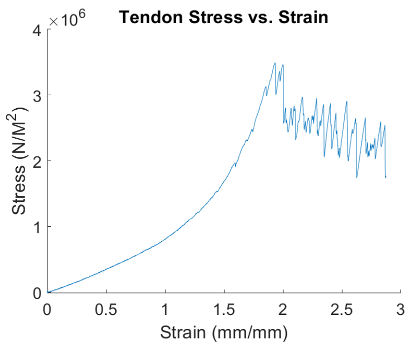


Figure 14: Stress vs. Strain of the tendon fabric by itself

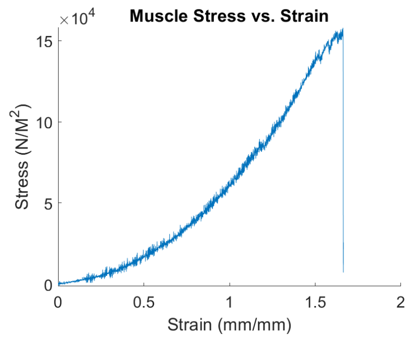


Figure 15: Stress vs. Strain of the muscle silicone alone

Stress vs. Strain curves were obtained to examine the Young's modulus in the elastic region of the curve. Stress was placed on the Y-axis and calculated by using (axial force/area); where the peak force in Newtons was divided by the cross-sectional area in square meters. Strain was placed on the X-axis and calculated by using ($\Delta Length/Length_{initial}$). Starting with the full muscle assembly (Figure 10), Young's modulus was 160 KPa. The tendon material (Figure 11) obtained a Young's modulus of 6 MPa, and the muscle fabric (Figure 12) obtained a Young's modulus of 5 MPa.

Cyclic Loading

Completed tests prove the longevity of the muscle-tendon groups of our design as follows. The initial length of the brachialis muscle was 13.8 cm. After the cyclic loading, the final length was 13.9 cm. This is a 0.725% increase in length. For the biceps, the initial length was 13.8 cm and the final length was 13.9 cm, which calculates to a 1.299% increase in length. The average percent relaxation for the tested muscles was 1.012%, which is well below the 5% threshold set.

Survey

A Google Form survey was created to collect both qualitative and quantitative data on the different aspects of the final designs' appearance and performance. Protocol C in the Appendix lists the questions that are asked on the survey. Due to timing and client availability constraints, the team was unable to give the model and survey to Dr. Gunderson to give to her first-year veterinary students. However, a sample of convenience was used to score the final design, and the team received 10 survey responses. The average score out of 50 was 44.6 or 8.92/10. Overall, the survey respondents had a positive reaction to the functionality and usability of the model.

Discussion

Implications

The completed testing showed that aspects of the model created for this project are comparable to other teaching models used to teach canine anatomy. The MTS testing showed that the muscle materials are able to withstand sufficient force to be used for the model, and the cyclic loading test proved that the model will be able to tolerate repeated use. The MTS testing also showed that the Young's Modulus of the components chosen for the current model is not within the acceptable range to be considered realistic compared to actual muscle material. The initial survey results show that the model received overwhelmingly positive feedback, so it is likely that students using the model will find it helpful for their education.

Ethical Considerations

There are no clear moral or ethical dilemmas presented by this project. However, it is possible that the cost of the model, if produced, would be a barrier making it inaccessible as a widespread educational tool.

Sources of Error

Potential sources of error include improper setting up of the MTS machine. Only the tendon fabric and internal muscle fabric were able to be tested fully to failure, with the assemblies containing silicone slipping before the test could reach completion. This might be mended by using stronger tensile grips to reduce slipping and reach the material breaking points. Another error could come from the fact that only one muscle comparable to the fabricated brachialis was used in testing. The results may not be wholly representative of other muscles with differing thicknesses and shapes.

Future Work

In the future, the group would consider using less dense silicone so that the Young's Modulus for the fabricated muscles (160 KPa) would be closer to the target values set by the rat skeletal muscle (24.7 +- 3.5 KPa) [13]. With respect to design, the group would also look to address the limitations that the usage of clay molds for muscle fabrication brought. Either 3D printing molds, or outsourcing the creation of molds were options the group considered for the future. This could feasibly address the problem of accuracy in the muscle creation process and also allow the group to fabricate more muscles for a more complete-looking model. Additionally, the survey should be completed by more people, especially veterinary students who are more qualified for assessing the accuracy of the model.

Conclusion

To conclude, the team was tasked to design a realistic model that imitates the skeletomuscular interactions of a canine forelimb. This model is to be used to aid first-year veterinary students in their learning of anatomy. To achieve this goal the final design consisted of tough PLA 3D-printed bones with fabric-embedded silicone muscles. These muscles were attached to the bone by elastic fabric directly sewn onto the muscle and complimentary neodymium magnets; one sewn into the elastic fabric and one adhered to the bone.

The fabrication of 3D-printed bones from files of beagle bones, and of silicone muscles from clay molds was successful, however, there is room for improvement. Initial plans to mold attachment sites directly on the bone with magnets laid into them were unsuccessful, but the neodymium magnets were able to adhere directly to the bone.

To improve the current model, additional muscles and attachments should be added and current muscles may need to be remodeled to be more accurate. With further attachments, it is likely magnets will be less effective and a transition will be made to buttons. Attachment sites will be further labeled to avoid confusion on the correct muscle orientation.

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Appendix

Testing Protocols

Protocol 1: MTS Tensile Testing

Materials:

1. Material samples
2. Mechanical Testing System (MTS) machine
3. 10 KN load Cell
4. Tensile Grips
5. Caliper
6. Adjustable wrench

Procedure:

1. Load up software and load into example tensile test - 2021
2. Load the 10 KN load cell into the MTS machine
3. Place the tensile grips inside of the MTS machine and lock into place with the metal keys.
4. Take measurements of the sample, assuming rectangular width, height, and gauge length are needed.

5. Load sample into tensile grips so that the gauge length is vertical between the two grips. If needed, use the control, which has to be unlocked to move, to lower or raise the machine as needed to ensure secure grip on the sample.
6. Raise the top bar slowly until the sample just gets to positive tension and lock the controller.
7. Zero both the crosshead location and the force by right clicking and clicking zero.
8. Click run the test and set the speed at desired speed, 2 mm/min was used during testing.
9. Once failure has been reached the machine should stop collecting data, if it doesn't click the stop button.
10. Save data to analyze later.

Protocol 2: Cyclic Loading

Materials:

1. Full muscle-tendon groups
2. Tape measure
3. Method of securement

Procedure:

1. Measure the muscle-tendon group and record the initial measurement
2. Calculate the length needed for 25% strain, using the yield strength to determine the max strain
3. Secure one end of the group
4. Pull the other end to the 25% strain length for 50 cycles
5. Measure the final length of the group after testing
6. Calculate the percent relaxation by dividing the final length by the initial length and multiplying by 100
7. Calculate the average percent increase by adding percent relaxations for each trial and dividing the total by the number of trials

Protocol 3: Survey

Materials:

1. Google Forms

Procedure:

1. On a scale of 1 - 10, how anatomically accurate is our model?
    a. If you'd like to explain your score, please list it and then describe here. (Optional)
2. On a scale of 1 - 10, how intuitive is our model? (Easy to use and conveys differences in muscle and tendons)
    a. If you'd like to explain your score, please list it and then describe here. (Optional)
3. On a scale of 1 - 10, how mechanically similar is our model to a canine forelimb?
    a. If you'd like to explain your score, please list it and then describe here. (Optional)
4. On a scale of 1 - 10, how usable are the muscle attachments?
    a. Please list your score and explain here.

Product Design Specifications

1. **Physical and Operational Characteristics**
    1. *Performance Requirements:*

The device will be used four times a week by roughly 100 first-year veterinary students for the first four weeks of the fall semester (16 times annually). This is not accounting for unscheduled usage.

2. *Safety:*

The primary safety concerns of this device are the muscles causing either the bone or muscle to snap towards an individual using the device, or the device not remaining sanitary after being used by many students repeatedly touching and using the device.

3. *Accuracy and Reliability:*

The device should be able to accurately represent the anatomical bone and muscle connections of the forelimb of a medium-sized canine. The device needs to have muscle connections that can reliably be removed and added hundreds of times a day with no significant change in strength or connection.

4. *Life in Service:*

The model must be able to withstand usage throughout a four-week period, four times a week, from over 100 students each year. These periods of time would involve near-constant removal and attachment of the muscles, so the attachments must not wear down over time. The model should also last for several years.

5. *Shelf Life:*

The model must be able to maintain functionality during nearly a year in storage, without the attachments wearing down.

6. *Operating Environment:*

The model will be exposed to normal room temperatures of around 20-22 °C and typical conditions of around 30 to 60 percent humidity. The device will be highly used for some periods of time and will go long periods of time without use.

7. *Ergonomics:*

Opposing muscles must have equal tensile strengths, and tensile strengths must allow the user to be able to easily remove and attach the muscles.

8. *Size:*

The size of the model has no true restrictions. However, a larger muscle will cost more, and a smaller muscle will make accuracy and strong connections more difficult. The client suggested modeling from a medium-sized canine such as a retriever or pit bull.

9. *Weight:*

No weight requirements are given by the client; weight will be dependent on the selected size. The weight should not exceed 10 kg to allow for easy transportation.

10. *Materials:*

The material used for the bone must be durable and able to be 3D printed. A plastic filament such as PLA will likely be used. The material for muscle must have the same qualities as the muscles of the animal. The material needs to provide spring force and be able to snap back to its original shape without any issues over heavy usage.

11. *Aesthetics, Appearance, and Finish:*

The model will be formed accurately to the bone and muscle structure of a medium-sized retriever. The bones will be colored white/off-white with rough texture. The muscles and tendons will be textured as similar to living muscles and tendons as possible while having easily differentiable colors.

2. **Production Characteristics**
    1. *Quantity:*

One model forelimb of a canine will be produced; more if time allows for it.

2. *Target Product Cost:*

The budget given is $500, but more can be allotted if a larger quantity of limbs is created.

3. **Miscellaneous**
    1. *Standards and Specifications:*

There are no standards- neither national nor international- to meet because the product will not be patented or regulated by the Food and Drug Administration (FDA). Additionally, the model will be used for educational purposes which makes it exempt from many regulations.

2. *Customer:*

The customer liked the start of the previous year's model. She thought they had a good start but wants this model to be more complex and have a higher quality. Namely, our design should have more muscles that can lock the joints in place when attached and accurately represent the agonist and antagonist properties of muscle pairs. Also, we need to find a better way to attach the muscles to the model because last year's team had difficulties finding strong enough magnets for some of the smaller attachments.

3. *Patient-related Concerns:*

This device is recommended to be cleaned with non-alcoholic cleaners as many students will be touching and manipulating the model within a short amount of time. It should be cleaned more often during frequent use to help prevent unsafe bacteria and viruses from collecting and transmitting from the device.

4. *Competition:*

There are similar competitions with this device that our client has access to. The currently used device mimics the muscles with elastic bands instead of the designed muscles. A bone model on the market is relatively inexpensive and can bend at the joints but does not include any muscles.

Conversely, a different model on the market has all of the muscles and organs of the canine but cannot move and has no bones.

Materials List

Budget: ~ $500											
Item	**Description**	**Manufacturer**	**Mft Pt #**	**Vendor**	**Vendor Cat#**	**Date**	**QTY**	**Cost Each**	**Shipping**	**Total**	**Link**
Attachment Components											
Neodymium Magnet	Magnetized Through Thickness, 1/8" Thick, 1/4" Od	Unknown		McMaster-Carr	5862K103	10/19/2023	6	$0.90	$7.81	$13.21	https://www.mcmaster.com/5862K103/
Neodymium Magnet	Magnetized Through Thickness, 1/8" Thick, 3/8" Od	Unknown		McMaster-Carr	5862K104	10/19/2023	6	$1.26		$7.56	https://www.mcmaster.com/5862K104/

Neodymium Magnet	Magnetized Through Thickness, 3/16" Thick, 1/2" Od	Unknown		McMaster-Carr	5862K112	10/19/2023	6	$2.17		$13.02	https://www.mcmaster.com/5862K112/
Swimsuit Fabric	Muscle colored fabric	Unknown				N/A	4			$0.00	From Client
Epoxy	Extra fast set epoxy	Royal Adhesives & Sealents		Hardman		11/29/2023	4	$6.33		$6.33	From Maker space
Epoxy	Extra fast set epoxy	Royal Adhesives & Sealents		Hardman		12/2/2023	3	$4.75		$4.75	From Maker space
Neodymium Magnet	Magnetized Through Thickness, 1/8" Thick, 1/4" Od	Unknown		McMaster-Carr	5862K103	12/1/2023	20	$0.90	$7.76	$25.76	https://www.mcmaster.com/5862K103

											/
Neodymium Magnet	Magnetized Through Thickness, 1/8" Thick, 3/8" Od	Unknown		McMaster-Carr	5862K104	12/1/2023	10	$1.26		$12.60	https://www.mcmaster.com/5862K104/
Muscle Components											
Ecoflex 00-35 silicone	2 part fast acting silicone rubber	Ecoflex	00-35			N/A	1				From Client. Amazon Link
Super Sculpey	Oven-Bake Clay	Polyform Products				10/25/2023	1	$16.14		$16.14	Amazon Link
Terracotta	Terracotta modeling clay	DAS Terracotta		Fila Solutions		11/29/2023	1	$14.02		$14.02	From Makerspace
Bone Components											
Beagle Bones	Scapula, humerus, radius, ulna	N/A				N/A	1				From Client
3D Printed	Tough PLA 3D printed bones:					11/9/2023	1	$11.84		$11.84	N/A

bones	Scapula, humerus, radius, ulna										
3D Printed bones	Tough PLA 3D printed bones: Scapula, humerus, radius, ulna					11/30/2023	1	$10.96		$10.96	N/A
3D Printed foot	Tough PLA 3D printed canine foot					12/1/2023	1	$3.26		$3.26	N/A
									TOTAL:	**$139.45**	

Material Data

Name	D1(mm)	D2(mm)	Area(mm^2)	Gauge Length (mm)	Peak Force (N)	Strain at failure (mm/mm)	Peak Stress (N/M^2)	Young's Modulus (N/M^2)
Muscle 1	17.15	13.9	238.385	41.3		1.6641	155767	167 KPa
Muscle 2	13.3	9.3	123.69	13.3/53.9		1.66589	295532	356 KPa
Muscle 3	11.18	12.5	139.75	29.9		1.78871	236805	196 KPa
Full	15.3	30.9	472.77	105.6	19.4719	1.3	40830	160 KPa
Silicone	4.3	29.2	125.56	25.2	15.6856	1.65755	124925	100 KPa
Tendon _Mat	0.41	41	16.81	51.1	58.7232	1.93291	3486240	6 MPa
Muscle _Fabric	0.29	46.6	13.514	58.4	30.4192	1.05064	2241080	5 MPa
avg muscles	N/A	N/A	N/A	N/A	35.9704	1.706233333	229368	239.667 KPa

Matlab Code

```
close all;

clear all;

% load data

Full = readtable("Full Musce_Tendon.txt");

Mus3 = readtable("Muscle #3.txt");

Mus2 = readtable("Muscle#2.txt");

Mus1 = readtable("Muscle#1.txt");

Mus_Mat = readtable("Muscle_Mat.txt");

P_Sil = readtable("Pure_Silicone.txt");

S_Fab = readtable("Silicone_Fabric.txt");

Tendon = readtable("Tendon.txt");

% Extract columns of interest

disp_Full=table2array(Full(:,1));

force_Full=table2array(Full(:,2));

time_Full=table2array(Full(:,3));

disp_Mus3=table2array(Mus3(:,1));

force_Mus3=table2array(Mus3(:,2));

time_Mus3=table2array(Mus3(:,3));

disp_Mus2=table2array(Mus2(:,1));

force_Mus2=table2array(Mus2(:,2));

time_Mus2=table2array(Mus2(:,3));
```

```
disp_Mus1=table2array(Mus1(:,1));
force_Mus1=table2array(Mus1(:,2));
time_Mus1=table2array(Mus1(:,3));
disp_Mus_Mat=table2array(Mus_Mat(:,1));
force_Mus_Mat=table2array(Mus_Mat(:,2));
time_Mus_Mat=table2array(Mus_Mat(:,3));
disp_P_Sil=table2array(P_Sil(:,1));
force_P_Sil=table2array(P_Sil(:,2));
time_P_Sil=table2array(P_Sil(:,3));
disp_S_Fab=table2array(S_Fab(:,1));
force_S_Fab=table2array(S_Fab(:,2));
time_S_Fab=table2array(S_Fab(:,3));
disp_Tendon=table2array(Tendon(:,1));
force_Tendon=table2array(Tendon(:,2));
time_Tendon=table2array(Tendon(:,3));
% Calculate tendon stress and strain, being careful to use consistent units.
stress_Full=force_Full./472.77e-6;
strain_Full=disp_Full./105.6;
stress_Mus3=force_Mus3./139.75e-6;
strain_Mus3=disp_Mus3./29.9;
stress_Mus2=force_Mus2./123.69e-6;
strain_Mus2=disp_Mus2./53.9;
stress_Mus1=force_Mus1./238.385e-6;
```

```
strain_Mus1=disp_Mus1./41.3;

stress_Mus_Mat=force_Mus_Mat./13.514e-6;

strain_Mus_Mat=disp_Mus_Mat./58.4;

stress_P_Sil=force_P_Sil./125.56e-6;

strain_P_Sil=disp_P_Sil./25.2;

stress_S_Fab=force_S_Fab./501.27e-6;

strain_S_Fab=disp_S_Fab./13.3;

stress_Tendon=force_Tendon./16.81e-6;

strain_Tendon=disp_Tendon./51.1;

% Find max force for each material

max_Full = max(force_Full);

max_Mus3 = max(force_Mus3);

max_Mus2 = max(force_Mus2);

max_Mus1 = max(force_Mus1);

avg = (max_Mus1 + max_Mus2 + max_Mus3) ./ 3;

max_Mus_Mat = max(force_Mus_Mat);

max_P_Sil = max(force_P_Sil);

max_S_Fab = max(force_S_Fab);

max_Tendon = max(force_Tendon);

mus = [max_Mus1 max_Mus2 max_Mus3];

std_mus = std(mus);

f_Max = [max_Full avg max_Mus_Mat max_P_Sil max_Tendon]

names = ["Full Muscle", "Average Muscle", "Muscle Fabric", "Silicone", "Tendon"]
```

```
% Plot tendon stress and strain

%hold on

%xlabel("Strain (mm/mm)");

%ylabel("Stress (N/M^2)");

%fontsize(scale = 1.5)

%plot(strain_Mus1, stress_Mus1)

%hold off

hold on

xlabel("Material");

ylabel("Force (N)");

fontsize(scale = 1.5);

bar(names, f_Max);

hold off
```