Veterinary Bone Marrow Aspirate Model

Preliminary Report

BME 200/300

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Abstract

Many veterinary surgical procedures exist that can be practiced using cadaver animals. However, some procedures cannot accurately be performed on a cadaver due to the altered characteristics of atrophied cells as opposed to living cells. One such surgical procedure is bone marrow aspiration, the accuracy of which relies on bone marrow cells to be alive to gain the full experience of aspirating bone marrow. For this reason, the client Dr. McLean Gunderson has requested that a model be created in the place of a cadaver to simulate the process of aspirating bone marrow from an animal. There are currently no models on the market for veterinary bone marrow aspiration. The proposed final design is a veterinary bone marrow aspiration model that models the right scapula, proximal humerus, ulna and radius of a 30 pound beagle with an articulate shoulder joint. The model proximal humerus contains a replaceable component with an inner cavity that allows for pseudo-bone marrow to be injected and extracted from the model. The proposed final design is a cost effective model whose material mimics the feeling of a dog's skin, muscle, and bone when aspirating. Additionally, the material for the model bones has been qualitatively tested for its mechanical accuracy leading to a final choice of polylactic acid (PLA) for bone material choice and informing the ultimate thickness of the bone in the final design. Future quantitative testing of PLA, ABS, and PETG strengths compared to cortical bone is planned following fabrication.

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Introduction

A. Impact and Motivation

It is important for veterinary students to have experience in the process of conducting surgical procedures before performing them on living animals. Cadavers allow veterinary students to execute procedures without the potential consequences that accompany living animals; they also aid students in understanding the process of surgical techniques and an animal's anatomy [1]. Ideally, cadavers would provide an accurate experience of all veterinary surgical procedures. In the cases where cadavers cannot provide the similitude of a living animal, models may be used instead [2]. The procedure of veterinary bone marrow aspiration is one such operation that a model may be of better use than a cadaver. Veterinary bone marrow aspiration is a procedure that is intended to take bone marrow samples from bones and analyze them for abnormalities [3]. To accurately simulate the procedure of veterinary bone marrow aspiration, the bone marrow would ideally be alive. However, given the nature of cadavers, this is not always feasible, thus highlighting the need for a model to be used in its place.

As no current bone marrow aspirate models exist for use of veterinary students, this model may act as a guide for subsequent veterinary bone marrow aspiration models. This model is intended to educate veterinary students at the School of Veterinary Medicine and allow them to accurately simulate aspirating bone marrow from a dog.

B. Existing Methods

While no veterinary bone marrow aspiration models exist, there are human bone marrow aspiration models that are being sold for use. The Bonnie Bone Marrow Biopsy Trainer [4] and the Anatomy Lab's Adult Bone Marrow Aspiration model [5] are models for human bone marrow aspiration and do not provide the anatomical accuracy needed for veterinary procedures. Furthermore, these models can be expensive ($2,214) and are not cost effective or realistic for veterinary purposes [4]. However, the materials used for these models are similar to the materials used to fabricate the preliminary design. They also are models of specific parts of the body; the preliminary design will also model a specific part of a dog's body where bone marrow aspiration is typically performed.

C. Problem Statement

Veterinary professionals commonly collect bone marrow aspirates from three main sites in dogs and cats: the iliac crest, the trochanteric fossa, and, mostly commonly, the proximal humerus [6]. Currently no veterinary bone aspiration models exist for students to practice on, requiring the use of cadaver dogs. Cadavers can only be used for about 5-10 insertions of the Illinois bone marrow biopsy needle per site, but do not contain live bone marrow that can be collected. This project aims to create a low-cost 3D anatomically correct model of the humerus with relevant soft tissue structures, mimics the consistency and structure of the bones, and allows for insertion of "bone marrow" for collection, allowing veterinary students to practice the skill of bone marrow aspiration.

Background

A. Biology and Physiology

The purpose of bone marrow sampling is to examine both the fluid and the tissue of the marrow. There are two ways to obtain bone marrow: a core biopsy and a needle aspiration, in which aspiration is less invasive compared to biopsies [2]. For the bone marrow aspiration procedure, a small incision is made in the site where the sample is collected. The three main sites for bone marrow extraction in dogs and cats are, the iliac crest, the trochanteric fossa, and most commonly, the proximal humerus. The part of the bone where the needle is inserted is the cortical bone. The Illinois needle is then inserted at a perpendicular angle to the bone and pushed in a “clockwise-counterclockwise” rotation until it has fully advanced into the marrow cavity. After the needle has been fully inserted, the stylet is removed, and a syringe is used to aspirate roughly 0.5 mL to 2 mL of bone marrow [3]. The bone marrow is then tested for abnormalities.

Some of the abnormalities in bone marrow include non-regenerative anemia, myelofibrosis, leukemia [7]. This procedure is not common and is only prepared when they detect that there might be abnormalities in the blood. After the bone marrow is extracted the samples are placed on a slide and sent to the laboratory for analysis.

B. Client Information

Dr. McLean Gunderson is an Doctor of Veterinary Medicine and an Assistant Teaching Professor in the comparative biosciences department. She is a course director and instructor for Anatomy of Large Domestic Animals, Fundamental Principles of Veterinary Anatomy, and a Clinical Skills Elective.

Preliminary Designs

Overall Design

All of the preliminary designs share some key aspects, as specified by the client. The bone structure will include a 3D printed scapula, fully articulable shoulder joint, humerus, and elbow joint fixed at a 120° position. The proximal humerus will include a replaceable 3D printed section containing a hollow cavity which will be filled with an artificial bone marrow, fabricated by the client. The skeletal structure will be covered with relevant muscles and soft tissue. Skin, fabricated out of neoprene and pourable silicone by the client, will be affixed over the top of the model to give an accurate look and feel to the limb. Finally, the whole model will be affixed to a base to create stability and position the limb accurately for performing the bone marrow aspiration simulation.

Design 1: Screw Method of Attachment

The Screw Method design features a 4 cm section at the proximal end of the humerus which attaches to the distal portion of the humerus through threaded ends that screw together. The removable piece of the proximal humerus has a 3 mm wall thickness to accurately mimic the feeling of real cortical bone. The removable end of the Screw Method design is hollow and features a port for filling bone marrow simulating fluid in the base of the threaded end. The design would require reattachment to the scapula every time it is replaced.

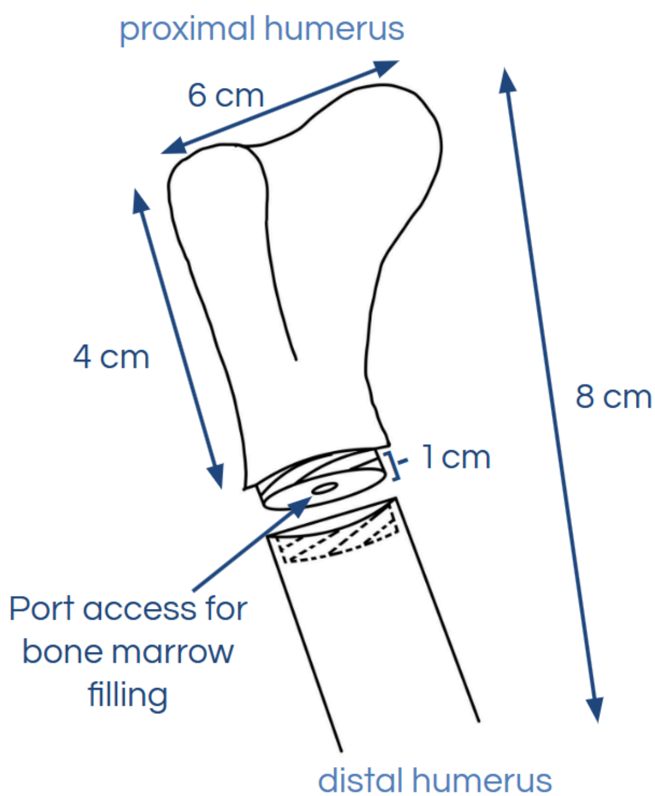


Figure 1: Drawing of the Screw Method of attachment

Design 2: Slide Method of Attachment

The Slide Method design features a 3 x 2.5 cm oval section of the proximal humerus that slides into place with the help of a tab. The tapered sides and 0.5 cm tab along the length of the removable section help to provide a one-way fit, ensuring the section is installed in the correct orientation. The replaceable section is hollow, and on the side facing inwards, there is a port for filling the simulated bone marrow solution. The surface of the section is rough and mimics the shape of the bone, with 3 mm walls to accurately simulate puncturing cortical bone while performing the bone marrow aspiration procedure.

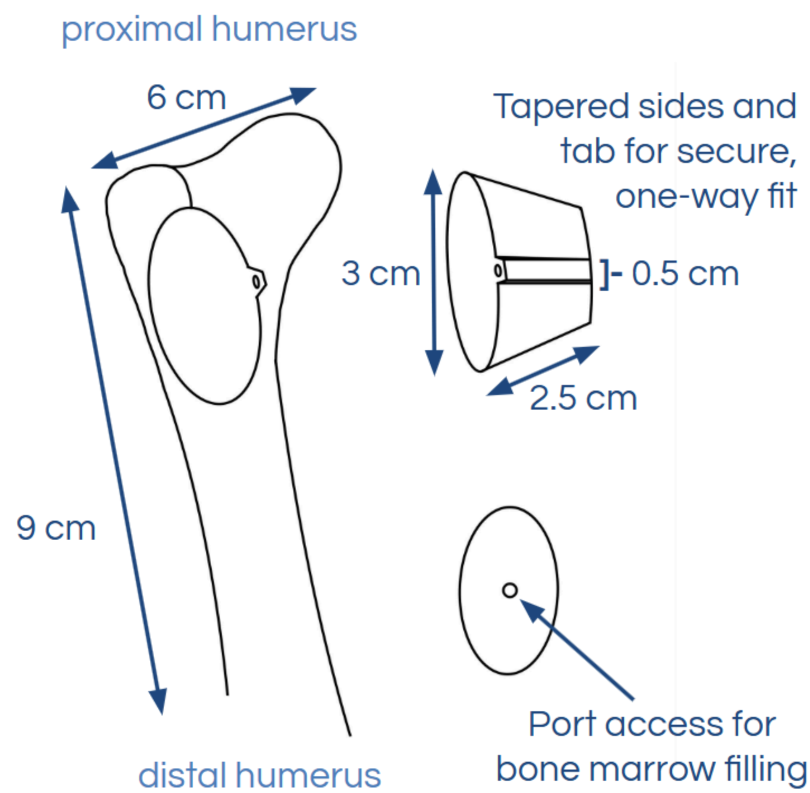


Figure 2: Drawing of Slide Method of attachment

Design 3: Velcro Method of Attachment

The Velcro Method design features a 5.5 x 1.5 cm removable section on the cranial lateral aspect of the proximal humerus. The replaceable section is fixed in place using self adhesive velcro on the inner facing side of the bone, while the base is left uncovered to allow access to the bone marrow port. The replaceable section of the Velcro Method design is hollow to allow the simulated bone marrow fluid to be filled via the port in the base, and features 3 mm walls with texture that mimics real cortical bone. There is some potential for interference with the shoulder joint when replacing the velcroed section.

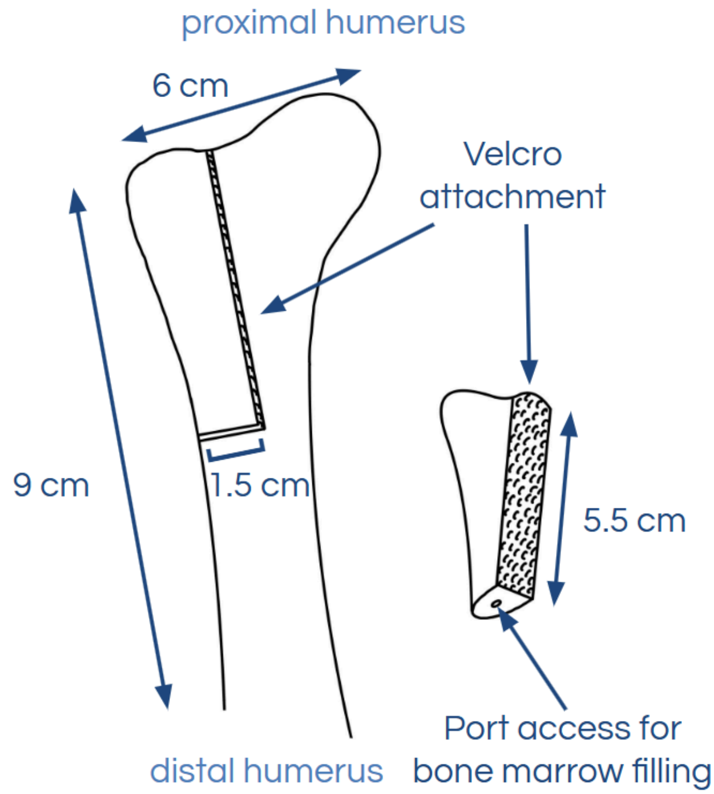
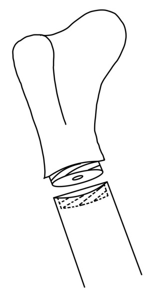
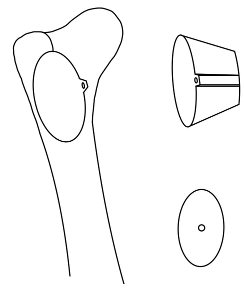
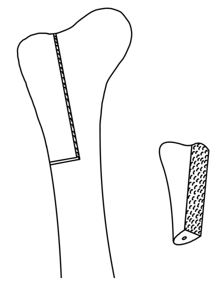


Figure 3: Drawing of the Velcro Method of attachment

Preliminary Design Evaluation

Table 1: **Replaceable Component Design Matrix:**

							
	Weight	**Screw Method**		**Slide Method**		**Velcro Method**	
Joint Interference	20	2/5	8	5/5	20	1/5	4
Ease of Fabrication	20	2/5	8	4/5	16	3/5	12
Ease of Use	15	2/5	6	4/5	12	3/5	9
Durability	15	2/5	6	4/5	12	2/5	6
Bone Marrow Access	15	5/5	15	4/5	12	2/5	6
Cost	10	2/5	4	5/5	10	3/5	6
Safety	5	4/5	4	3/5	3	3/5	3
Total	**100**	**51**		**85**		**46**	

Replaceable Component Design Matrix Summary

The slide method scored highest in the categories of joint interference, ease of fabrication, ease of use, durability, and cost. It scored the highest in the joint inference category because the slide piece is only affecting the aspiration site, while the other two models would attach to the joint and would interfere with the joint when replacing the piece. As for ease of fabrication the slide method scored the highest because it is considerably much smaller, and could be replicated easily on any printer. The size factor of this method also makes it easier to replace, and reduces the cost significantly compared to the other methods.

The screw method scored the second highest because it has the best bone marrow access with a port just inside the screw on the "cap" of the bone. This is very crucial for the project as the bone marrow element is what makes this model such an effective teacher, however while the screw cavity is helpful in this way, it interferes heavily with the shoulder joint as the entire top of the bone would have to be replaceable. Additionally with such a large replacement piece it would be quite costly and time consuming to replace, and with the thread required it would require high levels of accuracy affecting its ease of fabrication as well. While this is a hindrance the large surface area of this piece really expands the target area and would prevent the model from getting regularly damaged, and would keep the needle from slipping into these damaged spots, giving it a higher score in safety than the others. It is also less durable than the slide method because the thread will get chewed up over time.

The Velcro method scored the lowest overall for many reasons. Primarily it was the least safe option, as there is worry that the velcro would not be strong enough when students use the model, and when the needle is pulled out of the aspiration site the velcro could give and the whole bone piece could potentially come off. Additionally it would interfere heavily with the joint because it stretches almost to the top of the bone. The velcro also makes it slightly more costly to replace, and makes the piece itself less durable as the velcro would get weaker and weaker over time. This could also impact the security of the bone marrow fluid within the bone and could lead to movement of the internal components. Full criteria definitions are available in Appendix B.

***Table 2:* Material of Replaceable Component Design Matrix:**

	Weight	**PLA**		**ABS**		**PETG**	
Mechanical Accuracy	25	5/5	25	2/5	10	1/5	5
Strength	20	3/5	12	5/5	20	2/5	8
Ease of Fabrication	20	5/5	20	2/5	8	4/5	16
Texture	15	4/5	12	3/5	9	2/5	6
Disposability	10	5/5	10	1/5	2	3/5	6
Cost	10	5/5	10	3/5	6	2/5	4
Total	**100**	**89**		**55**		**45**	

Material Design Matrix Summary

Polylactic acid (PLA) scored the highest in the categories of mechanical accuracy, ease of fabrication, texture, disposability, and cost. It scored the highest in mechanical accuracy compared to acrylonitrile butadiene styrene (ABS) and polyethylene terephthalate glycol (PETG) because of its ability to mimic the characteristics of native bone tissue in tensile strength. PLA is also cheaper than both ABS and PETG and takes the least amount of time to fabricate in a 3D printer. Given the versatility of PLA structures and the qualities of the material itself, it scored the highest in the category of texture due to the range of patterns, textures, and layers it can be used to print.

ABS scored the highest in the category of strength due to its capacity to have a large tensile strength. However, it scored lower than PLA for mechanical accuracy because it may not accurately represent native bone tissue because its tensile strength value is higher than that of bone. This would also contribute to a model made of ABS to be more rigid than bone tissue, thus being less accurate than PLA in terms of tensile strength and elastic modulus. Compared to both PETG and PLA, ABS takes the longest to fabricate in a 3D printer. Additionally, the disposability of ABS was rated very low out of all the material options because it is not biodegradable and can only be recycled a few times before it's rendered unusable. Considering the frequency with which the replaceable component will need to be replaced, this is an important factor to consider. It also costs slightly more than PLA, but lower than PETG.

PETG was rated the lowest overall based on the grading criteria. It scored the lowest in mechanical accuracy because the highest tensile strength it can reach is lower than that of bone; it is also more elastic than PLA or ABS. PETG has the ability to be more brittle than PLA or ABS if printed incorrectly, and may be slightly deformed upon repeated use because of its low tensile strength. A lower tensile strength would not mimic the feeling of native bone; thus PETG scored the lowest in Texture. While PETG does not print as fast as PLA typically does, it prints faster than ABS and was thus scored higher in ease of fabrication. While not biodegradable like PLA, PETG can be recycled significantly more times than ABS, and scored higher than ABS for disposability. PETG was rated the lowest for cost because it is the most expensive material to buy out of the three options. Full criteria definitions are available in Appendix B.

Proposed Final Design

The final design features the Slide Method of attachment for the design of the replaceable component. The oval section will be hollow to allow the client to fill the simulated bone marrow fluid into the port in the base of the design. The tab allows the user to easily orient the removable section correctly and slide it into place. Both the replaceable component and the rest of the bony structures (scapula, humerus, and fixed elbow) will be 3D printed using PLA. Surrounding the bones will be relevant musculature made from soft silicone which will further help the replaceable component remain in place when the needle enters and exits. The simulated skin, fabricated by the client out of neoprene and pourable silicone, will be affixed over top and will help to hold the musculature and bones in an anatomical position.

Fabrication

Materials

The main skeletal frame will be 3D printed using polylactic acid (PLA). The replaceable component will also be 3D printed in PLA, but will have a cavity meant to store bone mimicking fluid in the piece. For models where fluid is not involved, styrofoam will be used to fill the cavity. This foam will let the user know that the cortical bone piece has been successfully punctured. The top of the model will begin at the scapula of the dog, then down to the humerus and reach a fixed elbow joint. In order for the leg to realistically move, a ball and socket joint will be used to imitate the shoulder joint and at the same time fix the leg to a board in order to mimic a dog laying on its side. Pourable silicone will be used to model the muscle structure, and a thin layer of silicone over neoprene netting will be used to create a skin-like surface over the aspiration site. This will allow for an accurate representation of creating an incision during the procedure.

Methods

In order to fabricate the skeletal structure, bones of an approximately 30 pound (lb) beagle have been selected from the veterinary school. These bones will be 3D scanned at the Makerspace in order to create STL files from these. The STL will be modified in CAD software to include the replaceable component and create a system to attach a ball and socket joint to the scapula. The infill of the bone will also be edited to create a more realistic structure for the cortical bone. A sealable cavity will be created in the replaceable component to hold bone marrow mimicking fluid supplied by the client.

Final Prototype

Fabrication of the final design has not yet been completed, and thus the final prototype will be included in the final report.

Testing and Results

A. Material Testing

Table 3: **Material Testing**

Material	Thickness (mm)	Outcome (Pass or Fail)
PLA	1	Fail
PLA	2	Pass
PLA	3	Pass
ABS	1	Fail
ABS	2	Fail
ABS	3	Pass
PETG	1	Fail
PETG	2	Fail
PETG	3	Fail

Material testing was conducted to find which of the 3D printing filaments of the design matrix would mimic bone the best. In order to evaluate the different types of 3D printing, filament samples were made of polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), and polyethylene terephthalate glycol (PETG). Each sample was 38.1 mm x 25.4 mm, and had three different thicknesses of 1 mm, 2 mm and 3 mm. These were each placed on a foam block and one of the client's team members, Dr. Calico Schmidt, used an Illinois needle to puncture each material at each thickness. Tests were considered a pass if the puncture felt accurate to performing the procedure on live bone, and were considered a failure if they did not. After testing all of the samples and thicknesses, Dr. Schmidt determined that the most comparable material was the PLA at 2 mm and 3 mm. She found that ABS also felt accurate to the procedure but only at 3mm thickness, and PETG was overall too weak and too slippery for the needle. These results lined up very well with the design matrix and led PLA to be the final choice.

This was important to establish what material in its baseline form most closely resembles the texture and strength of bone. Literature values state that humerus bones have a tensile strength of at least 68 MPa. Compared to this, PLA has a baseline tensile strength of 40 MPa, and ABS and PETG have tensile strengths of 30 MPa [8]. As the project progresses, aspects of the 3D print can be manipulated to better replicate cortical bone, such as the infill pattern, thickness and outside texture, but this test was important to establish that PLA was strong enough to withstand the aspiration force of the Illinois needle without breaking or bending. This testing was qualitative and somewhat inaccurate, given that it was done before a specific dog breed was chosen for the model and each dog's bone structure is different. Now that a specific breed has been chosen, further testing and research can be conducted to ensure that the model more accurately represents the actual bone.

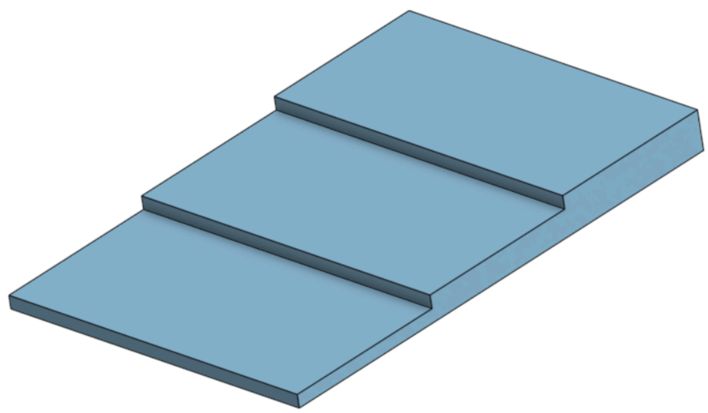


Figure 4: Material Test Swatch CAD Design

B. Tolerance Testing

In order to test that each printed copy of the replaceable component will fit in the model correctly, tolerance stack ups will be mocked up, and testing will be done to measure that the piece will fit in the model even when printed on different printers. More specifically, pieces will be printed from the 3D printer at the veterinary school to ensure the client is able to replace the component in house. This reveal variance in the printing and fit capabilities

C. Pressure and Material Testing

To test the exact force required to aspirate on the humerus, testing will be conducted on a cadaver bone using an MTS machine to test tensile and compressive properties of the bone. This will provide a more accurate value that would be precise to the specific dog that the model takes after, as there are so many factors that can affect the strength and thickness of the bone including age, gender, and size [9]. This pressure testing will also be conducted on the 3D printed PLA filament, as well as on the other materials (ABS and PETG) once they have been printed. This will be used to ensure that past testing was accurate.

Discussion

There has been no quantitative testing conducted so far, but there has been quantitative testing completed by Dr. Schmit to test various materials and thicknesses of the aspirate site. This quantitative testing has shown that the material and its thickness most similar to bone is 3D printed PLA at a thickness of 3 mm when punctured over styrofoam. While this testing has been helpful to determine which material to make the aspiration model out of, it has its limitations in the sense that the testing was not quantitative. Bone characteristics in dogs like density and strength vary with many characteristics like genetics and bone disorders [9, 10]. These variations make it difficult to pinpoint ideal target values to compare the aspiration model to.

In the future, testing will be done to quantify the strength of the PLA model. These values could then be compared to literature values of canine bone properties. ABS and PETG may also be tested to verify that PLA has the closest strength compared to bone. With this testing though, there are potential sources of error that could arise which include:

- Uneven surface of the material.
- Wide variety of target values.
- Operator error.
- Sensors being incorrectly calibrated.

Changes will then be made to the model based on the results of this testing. These changes could include alterations to the infill of the model, the thickness of the aspiration site, and the material chosen. Depending on the outcome of testing, it may be useful to choose an alternative material to PLA. This material could potentially be Tough PLA, which has a similar Young's Modulus to PLA, but its impact resistance is much larger [11]. It is important to conduct testing to ensure that the model is accurate since it will be learned as a learning tool for veterinary students.

Conclusions

Bone marrow aspiration is a procedure done to provide morphological details of cells and conduct tests on the bone marrow [12]. Veterinary professionals perform this procedure on dogs and cats in sites such as the proximal humerus, iliac crest, and trochanteric fossa. Students typically practice this procedure on cadaver dogs, which has many limitations. First, cadavers are not an accessible resource, especially considering the large number of students that need to practice bone marrow aspiration multiple times. Second, there is no live bone marrow in cadavers, so students cannot practice aspiration or know if they are properly aspirating. The goal of this project is to create a 3D printed model of an anatomically correct canine humerus and its surrounding soft tissues and bones.

Based on research and testing that was done, it was found that PLA at a 3 mm thickness placed over styrofoam is the most similar feeling to performing bone marrow aspiration on a dog's proximal humerus. PLA is the material that shares the most similar properties like tensile strength and texture to cortical bone as compared to ABS and PETG [13]. The 3 mm thickness was chosen because it closely mimicked the feeling of the amount of force required to puncture the bone.

While qualitative testing has been helpful to begin the fabrication process, it has not provided any definitive values to guide the project further. In the future, tests will find and compare the strength of PLA, ABS, and PETG to cortical bone. In addition, further research regarding specific values of bone will also need to be completed to compare the materials to bone. Also, 3D scans of the scapula, humerus, radius, and ulna will be done to obtain STL files and begin 3D printing the model. The preliminary design process has highlighted the importance of accuracy in order to allow veterinary students to receive the most useful training possible. This is why it is important to conduct further research and testing as well as begin fabrication.

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Appendices

A. Product Design Specifications (PDS)

Function

Veterinary professionals commonly collect bone marrow aspirates from three main sites in dogs and cats: the iliac crest, the trochanteric fossa, and, mostly commonly, the proximal humerus. Currently no veterinary bone aspiration models exist for students to practice on, requiring the use of cadaver dogs. Cadavers can only be used for about 5-10 insertions of the Illinois bone marrow biopsy needle per site, but does not contain live bone marrow that can be collected. This project aims to create a low-cost 3D anatomically correct model of the humerus with relevant soft tissue structures, mimics the consistency and structure of the bones, and allows for insertion of "bone marrow" for collection, allowing veterinary students to practice the skill of bone marrow aspiration.

Client requirements

- Functional model that allows the client to replace the simulated bone marrow and proximal humerus insertion site every 5 procedures performed.
- The model should include the right scapula, shoulder joint, humerus, elbow, proximal radius and ulna, and surrounding muscles and soft tissues. The shoulder joint should be fully articulable, while the elbow should be fixed in a flexed position.
- The client will assist with the fabrication of the skin and bone marrow materials. The model should include a way to attach the skin and insert the bone marrow into the humerus.
- The proximal humerus will include a removable section that is replaced every 5 procedures and filled with the bone marrow solution. Muscles will be replaced every 20 punctures.

Design requirements

1. **Physical and Operational Characteristics**
    a. **Performance Requirements**
        - The model will be an anatomically correct proximal scapula, humerus, shoulder joint, and elbow joint of a 13.6 kilogram (kg) dog. The shoulder joint will replicate a ball and socket joint, and the elbow joint will be fixed in a 120 degree angle.
        - A small, removable section of the humerus will be replaced every 5 uses. This section will be the flat surface on the humerus in which the bone marrow aspiration needle penetrates.

- The muscle material covering the bone will be replaced every 20 uses.
- The model will be held stably to the table to prevent movement during the procedure.

b. **Safety**
- The model will come equipped with safety instructions that detail steps of use, hazards, and proper sanitation.
- There will be no live tissue components that can cause harmful exposures.
- The procedure on the model should be done with proper technique so as to not cause injury by the Illinois needle.
- The replaceable components of the model should not be used more than 20 times for the muscle and 5 times for the humerus piece.

c. **Accuracy and Reliability**
- The punctured humerus will only be used 5 times before it needs replacement so that students do not repeatedly enter the same puncture.
- The muscle covering the bone will be used 20 times before it needs replacement for the same reason as the humerus, but since it is a softer material it will receive less damage.
- The model should be similar in size, shape, and feel of a 13.6 kg dog.
- The model should be able to aspirate 0.5-2 mL of bone marrow [1].

d. **Life in Service**
- The model must withstand 5 years of in-class use with components that are replaced as needed.
- The punctured section of the humerus will be replaced every 5 uses, and the muscle will be replaced every 20 uses.
- The model will be used for multiple semesters of 96 students in which each student practices the procedure 3 times. Each practice procedure will take 3 minutes to complete.
- The model will be able to withstand the moderate force used to puncture the humerus with the Illinois needle.

e. **Shelf Life**
- The model should be kept in a cool environment, away from direct sunlight.
- If stored in the proper conditions and without the "bone marrow" component, the model will last 10 to 12 years.

f. **Operating Environmen**t
- The model will be used in a simulated clinical setting during practice procedures.
- The device will be used in a standard indoor environment with temperature (20-25 ℃) and humidity (40-60 %) [2].

- This model is designed for UW-Madison Veterinary students, and should be used for learning purposes only.

g. **Ergonomics**
    - The force used to puncture the bone should be a firm pressure similar to that on a real animal [3].
    - When not in use, the model should be handled delicately.
    - The Illinois needle should only be inserted within the replaceable region of the humerus.

h. **Size**
    - The model should be similar in size to a 13.6 kg dog, with a proximal humerus that is 14-15 cm [4].
    - With the added elbow and shoulder joint, the total length of the model will be 25 cm.
    - The section of humerus that is being replaced is a 3x3 cm section. The soft tissue encasing the bone can be removed to access the bone for replacement.

i. **Weight**
    - The weight of the model will accurately represent the weight of the anatomical structures used in the model. This will be no more than 2 kg.

j. **Materials**
    - The model can be split into four different categories of materials based on the anatomy of a dog:
        - The materials of the skin, as provided by the School of Veterinary Medicine, will be composed of mesh fabric fused to silicone. This material imitates the extent of the skin's elasticity.
        - The muscle of the model should mimic the feeling of penetrating the muscle on the proximal humerus. The muscle covering over the humerus has little thickness and thus should not be difficult to pierce. This is the quality that makes the proximal humerus favorable for bone marrow aspiration [5]
        - The density of the model's proximal humerus should be roughly the same density as real dog bones. Thus, a material mimicking the density of a dog's humerus is preferred, which is roughly 27.1 μg/mg for a dry bone [6]. The material should respond to the clockwise and counterclockwise rotations of the Illinois needle used for veterinary bone marrow aspirations without cracking [7].
        - The bone marrow will be fabricated by the School of Veterinary Medicine. The bone marrow material will be a thicker liquid with small bone particles mixed in.

k. **Aesthetics, Appearance, and Finish**

- It is important for the model to be anatomically correct and feel like a real dog to the user.
- The appearance of the model, while not as important as the materials, should at least be concise and neat in its presentation. The model should prioritize the feeling of performing bone marrow aspiration rather than the appearance of a real dog.

2. **Production Characteristics**
    a. Quantity:
        - There will be one main model with replaceable parts. Replaceable parts will be provided upon the full delivery of the product; subsequent replaceable parts may be able to be fabricated with 3D printing files.

    b. Target Product Cost:
        - This model is intended to be a low cost solution and thus would preferably be under the $1,600 budget. A portion of the budget is intended for the replaceable components of the model.

3. **Miscellaneous**
    a. **Standards and Specifications**:
        - There are no standards that this model must meet in order to be used, as it is not coming into contact with patients, and is a model for practicing use only.

    b. Customer:
        - The customer would like a model that is made for right handed users, specifically a model of the right proximal humerus, extending from the scapula to just below the elbow.
            - The shoulder must move as a typical ball and socket joint, and the client would like the movement to expose the humerus from the muscle and skin that is around it when it is relaxed.
            - The client would like the elbow to be fixed at 120 degrees.
        - The client would like a model that can be refilled with a fluid that mimics bone marrow.
        - The cortical bone should be physiologically accurate.
        - It is important that the aspiration site on the humerus is flat and rough compared to the rest of the bone, so that the needle will have more traction.

    c. **Patient-related concerns:**
        - As this model will not have any direct contact with patients, there is no concern of saving and protecting patient data.
        - A concern that this model might raise is that it must be anatomically accurate. This is difficult because the procedure will vary depending on the animal, its maturation, and its weight.

d. **Competition:**

- There are no models that currently exist for a veterinary bone marrow aspiration procedure, however cadavers are regularly used despite their inaccuracies. The problem with cadaver models is that the bone marrow has dried up and cannot be extracted using a needle. Another issue with using cadavers, is they have a shorter shelf life, and they can really only take 4-5 punctures per site before the bone has degraded and is no longer an accurate representation of the procedure.
- There are models for human bone marrow aspirations such as Bonnie Bone marrow biopsy skills trainer, however this is not accurate to dogs, and a bone marrow biopsy is a different procedure targeting the solid aspects of bone marrow. This model is also extremely costly [8].
- Another model of bone marrow aspiration is . This is also an expensive model and despite having fluid within the model for practice the targeted area is a human hip, which is very different from the aspiration site on most animals (the right proximal humerus) [9].

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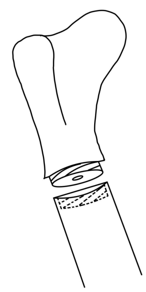
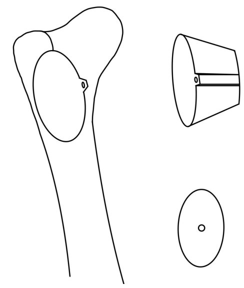
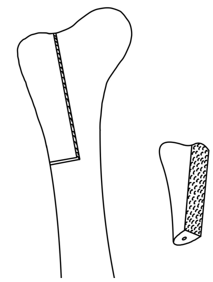
B. Design Matrices

***Table 1:* Replaceable Component Design Matrix:**

							
	Weight	**Screw Method**		**Slide Method**		**Velcro Method**	
Joint Interference	20	2/5	8	5/5	20	1/5	4
Ease of Fabrication	20	2/5	8	4/5	16	3/5	12
Ease of Use	15	2/5	6	4/5	12	3/5	9
Durability	15	2/5	6	4/5	12	2/5	6
Bone Marrow Access	15	5/5	15	4/5	12	2/5	6
Cost	10	2/5	4	5/5	10	3/5	6
Safety	5	4/5	4	3/5	3	3/5	3
Total	**100**	**51**		**85**		**46**	

Criteria Definitions:

Joint Interference: Joint interference refers to how easily replaceable the removable component is with respect to the shoulder joint, while still allowing the joint to be articulable. The section of the proximal humerus will need to be replaced frequently, so design that does not require any involvement of the shoulder joint to be replaced would score the highest. Joint interference is weighted at a 20 because the component must be easily replaceable without much interference with the shoulder joint.

Ease of Fabrication: Ease of fabrication refers to how easy the design is to model, 3D print, and assemble. This includes the time it takes for the 3D printer to fabricate the design, which is influenced by the size, density, and detail of the replaceable component. It is also important that the design can be replicated on different 3D printers, and methods with a reduced need for exact accuracy with printing would score higher. Ease of fabrication is weighted at a 20 because it is important that the full design is feasible to fabricate within the semester and that the replaceable components are able to be easily fabricated by the client.

Ease of Use: Ease of use refers to how easily the components can be replaced and how easy it is for the Veterinary student to interact with the model in the same way they would a patient. A design that has easier access to replace bone marrow fluid and the section of the proximal humerus would score higher. Ease of use is weighted at a 15 because it is important that the user experience is simplified as much as possible.

Durability: Durability refers to the expected life of the model, taking into account chosen materials and how replaceable components interact with the rest of the model. A simple design for the replaceable parts that limits wear and tear on the surrounding surfaces is desired so that the non replaceable components will last for a period of 5 years. Durability is weighted at a 15 because it is important that the design maximizes the lifecycle of the product.

Bone Marrow Access: Bone marrow access refers to how easily the client is able to refill the model with bone marrow between each procedure. This includes difficulty in placing the bone marrow within, as well as if the replaceable part would cause any leakage of the bone marrow. Bone marrow access is weighted at a 15 because making sure the user can easily fill and can extract bone marrow is crucial to the functionality of the model.

Cost: Cost refers to how much the replaceable component will cost based on the size of the 3D printed piece repeatedly replaced and if there are any additional costs for supplemental materials that are needed to secure the replaceable component to the model. A model that requires less material will cost less and be scored higher in this category. Cost is weighted at a 10 because it is important that the material cost of replacement components are minimized.

Safety: Safety refers to the security and stability of the replaceable component within the model. It is important that the component stay seated within the non-replaceable bone component so that it does not interfere with the aspiration process. A replaceable component that does not come out of the model with the needle or fracture upon pressure and break into potentially harmful pieces of plastic would be rated higher. Safety is weighted at a 5 because the safety risks of performing the procedure should be similar to that of performing the procedure on a live animal.

Component Design Matrix Summary:

The slide method scored highest in the categories of joint interference, ease of fabrication, ease of use, durability, and cost. It scored the highest in the joint inference category because the slide piece is only affecting the aspiration site, while the other two models would attach to the joint and would interfere with the joint when replacing the piece. As for ease of fabrication the slide method scored the highest because it is considerably much smaller, and could be replicated easily on any printer. The size factor of this method also makes it easier to replace, and reduces the cost significantly compared to the other methods.

The screw method scored the second highest because it has the best bone marrow access with a port just inside the screw on the “cap” of the bone. This is very crucial for the project as the bone marrow element is what makes this model such an effective teacher, however while the screw cavity is helpful in this way, it interferes heavily with the shoulder joint as the entire top of the bone would have to be replaceable. Additionally with such a large replacement piece it would be quite costly and time consuming to replace, and with the thread required it would require high levels of accuracy affecting its ease of fabrication as well. While this is a hindrance the large surface area of this piece really expands the target area and would prevent the model from getting regularly damaged, and would keep the needle from slipping into these damaged spots, giving it a higher score in safety than the others. It is also less durable than the slide method because the thread will get chewed up over time.

The Velcro method scored the lowest overall for many reasons. Primarily it was the least safe option, as there is worry that the velcro would not be strong enough when students use the model, and when the needle is pulled out of the aspiration site the velcro could give and the whole bone piece could potentially come off. Additionally it would interfere heavily with the joint because it stretches almost to the top of the bone. The velcro also makes it slightly more costly to replace, and makes the piece itself less durable as the velcro would get weaker and weaker over time. This could also impact the security of the bone marrow fluid within the bone and could lead to movement of the internal components.

***Table 2:* Material of Replaceable Component Design Matrix:**

	Weight	**PLA**		**ABS**		**PETG**	
Mechanical Accuracy	25	5/5	25	2/5	10	1/5	5
Strength	20	3/5	12	5/5	20	2/5	8
Ease of Fabrication	20	5/5	20	2/5	8	4/5	16
Texture	15	4/5	12	3/5	9	2/5	6
Disposability	10	5/5	10	1/5	2	3/5	6
Cost	10	5/5	10	3/5	6	2/5	4
Total	**100**	**89**		**55**		**45**	

Criteria Definitions:

Mechanical Accuracy: Mechanical accuracy refers to how similarly the printed plastic can mimic the mechanical properties of native bone tissue. A plastic with a tensile strength comparable to bone (67 MPa at the least) and similar density would score highest. Mechanical accuracy is weighted highest at a 25 because it is important that the bone model accurately represents native bone for practicing the procedure.

Strength: Strength refers to how well the material holds up against the needle. The bone model needs to be able to be punctured at least five times before the section of the proximal humerus is replaced, a material that is too brittle will not stand up to multiple punctures. A material that is not brittle would score highest. Strength is weighted at a 20 because it is important that the material can stand up to five punctures to increase the usability of the model.

Ease of Fabrication: Ease of fabrication refers to how easily and quickly the material can be printed. A material that prints at a high quality with minimal modification to print settings to make it accessible for Veterinary School staff to quickly print replacement components is desired. Ease of fabrication is weighted at a 20 because the material must be feasible for someone not previously familiar 3D printers to work with.

Texture: Texture refers to how similar the material is to the feeling of native bone, accounting for the adherence between layers of the print, flexibility, and interaction with the needle. A material with similar flexibility and surface finish to bone is desired without need for additional post print processing. Texture is weighted at a 15 because the surface finish should be similar to bone to best mimic the procedure.

Disposability: Disposability refers to how sustainable the material is and the ease of disposing of the replacement components. Since the proximal humerus is replaced every five punctures, a lot of plastic waste may be created. A material that is biodegradable and/or recyclable would score highest in this category. Disposability is weighted at a 10 because it is important that the waste material from the model can be disposed of in a sustainable manner.

Cost: Cost refers to how much the 3D printer filament typically costs per spool. Since the client will be printing a large volume of replacement components, it is important to keep the ongoing cost of material low. A filament that is low in cost per spool would score the highest. Cost is weighted at a 10 because the client desires a low cost prototype solution.

Materials Design Matrix Summary:

Polylactic acid (PLA) scored the highest in the categories of mechanical accuracy, ease of fabrication, texture, disposability, and cost. It scored the highest in mechanical accuracy compared to acrylonitrile butadiene styrene (ABS) and polyethylene terephthalate glycol (PETG) because of its ability to mimic the characteristics of native bone tissue in tensile strength. PLA is also cheaper than both ABS and PETG and takes the least amount of time to fabricate in a 3D printer. Given the versatility of PLA structures and the qualities of the material itself, it scored the highest in the category of texture due to the range of patterns, textures, and layers it can be used to print.

ABS scored the highest in the category of strength due to its capacity to have a large tensile strength. However, it scored lower than PLA for mechanical accuracy because it may not accurately represent native bone tissue because its tensile strength value is higher than that of bone. This would also contribute to a model made of ABS to be more rigid than bone tissue, thus being less accurate than PLA in terms of tensile strength and elastic modulus. Compared to both PETG and PLA, ABS takes the longest to fabricate in a 3D printer. Additionally, the disposability of ABS was rated very low out of all the material options because it is not biodegradable and can only be recycled a few times before it's rendered unusable. Considering the frequency with which the replaceable component will need to be replaced, this is an important factor to consider. It also costs slightly more than PLA, but lower than PETG.

PETG was rated the lowest overall based on the grading criteria. It scored the lowest in mechanical accuracy because the highest tensile strength it can reach is lower than that of bone;

it is also more elastic than PLA or ABS. PETG has the ability to be more brittle than PLA or ABS if printed incorrectly, and may be slightly deformed upon repeated use because of its low tensile strength. A lower tensile strength would not mimic the feeling of native bone; thus PETG scored the lowest in Texture. While PETG does not print as fast as PLA typically does, it prints faster than ABS and was thus scored higher in ease of fabrication. While not biodegradable like PLA, PETG can be recycled significantly more times than ABS, and scored higher than ABS for disposability. PETG was rated the lowest for cost because it is the most expensive material to buy out of the three options.

In conclusion, because PLA was given the highest overall score, it is the material that has been chosen to fabricate the replaceable component in the veterinary bone marrow aspiration model.

C. BPAG Expense Sheet

Item	Description	Manufac-turer	Mft Pt#	Vendor	Vendor Cat#	Date	#	Cost Each	Total	Link
Category 1										
Material test swatches	PLA, ABS, and PETG test swatches	UW Makerspace		UW Makers pace		9/26/ 2024	3	0.17	$0.51	
									$0.00	
Category 2										
									$0.00	
									$0.00	
								TOTAL:	**$0.51**	