Canine Abdominal Palpation Training Device

A Major Qualifying Project Report submitted to the faculty of
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfillment of the requirements for the degree of Bachelor of Science

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April 28, 2016

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Acknowledgements

The team would like to thank Dr. Michael Stone (DVM) for providing the inspiration for this project and his unwavering support and guidance. Special thanks goes to Thomas Partington for his assistance in the design and manufacturing of the devices. We would also like to thank Lisa Wall and Elyse Favreau for their help in acquiring materials. Finally, we would like to extend sincere thanks to Professor Zoe Reidinger for advising our project and her continued encouragement.

Abstract

Palpation is used in medical diagnostics to determine the conditions of underlying parts or organs using the pressure of the hands and fingers on the surface of the body. It is a non-invasive procedure, but critical information is gathered to diagnose pathologies and affect clinical results. It is a skill used daily in clinical medicine, but there are no existing devices that teach abdominal palpation of small animals to veterinary students. The purpose of this project was to design and create a haptic teaching device for use by veterinary students to learn canine abdominal palpation skills. The device simulates the tactile sense of a canine abdomen including palpable organs and abnormalities to teach students diagnostic skills and the ability to identify abdominal abnormalities in canines. The design team developed ten palpation devices with a soft tissue component, hard tissue component, three palpable objects, and two abnormalities in each device. Validation from the client, veterinary professional feedback, and mechanical testing confirmed the device met the objectives of realistic, accurate, durable, and reusable.

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Chapter 1: Introduction

Palpation is a skill learned and used by almost all medical professionals in both human and veterinary clinical medicine. It is a physical examination in which pressure of the hand or fingers is applied to the surface of the body to diagnose the condition of an underlying part or organ (Palpation, n.d.). Palpation of the abdomen is a non-invasive, simple procedure from which critical information can be gathered. It is used in both routine physical health examinations as well as in evaluating abdominal pain or abnormalities. Such abnormalities include tumors, infections, enlarged organs, and foreign objects (Davies, 1993). In canines, the bladder and colon can be palpated if they contain urine or stool, respectively. Anything else found during this examination is considered abnormal (Ferguson, 1990). Abdominal palpation is a critical skill in veterinary medicine for assessing the health of a patient.

Although abdominal palpation is a simple procedure, it is surprisingly difficult to both learn and teach since it can only be learned through practice. Abdominal palpation is a complex, open-ended task that seeks an undefined solution (Aubin, 2014). In human medicine, synthetic abdominal palpation models are available as teaching tools. However, to date there are no small animal synthetic devices for teaching palpation skills in veterinary medicine, and veterinary students must learn palpation techniques using live animals. The Cummings School of Veterinary Medicine at Tufts University found that with classes of approximately 80 veterinary students, teaching palpation techniques is a difficult and tedious task for both the professor and students. The learning of the students is limited due to a low availability of live animals and the low tolerance of the animals to palpation. In addition, students cannot learn to find abnormalities on live animals because it would cause additional stress and discomfort for a sick animal.

The objective of this Major Qualifying Project was to design and create a series of training devices for the purpose of teaching abdominal palpation techniques and recognizing abnormalities on canines for veterinary students at the Cummings School of Veterinary Medicine at Tufts University. These devices were designed to mimic the abdomen of a *canis lupus familiaris*, more specifically, a beagle because Tufts veterinary students typically train on live beagles. The devices aimed to be anatomically correct, mimic the taction and texture of a canine abdomen, and the device simulates different medical conditions within the abdomen, including healthy conditions as well. The foundation of the palpation devices consists of various layers that represent the fur, skin, fat, and muscle, as well as abdominal filler and bones. Each device is designed to simulate a different medical condition within the abdomen, and these conditions include a healthy colon and healthy bladder, constipated colon, bladder with stones, enlarged spleen, enlarged liver, mid-abdominal foreign bodies and masses, and an overweight abdomen. The devices should assist in simulating different scenarios that could occur in a clinical setting.

Researching canine anatomy was integral to the design and creation of the device. The orientation of a canine's abdominal anatomy is different than typical human abdominal anatomy. For example, in a canine, the organs hang down and are supported by the skin and muscle layers below them. The focus of the team's background research was to determine the placement and palpable behavior of the normal bladder, colon, and any abnormal abdominal organs or conditions, as well as the specifications, textures, and mechanical behavior of these organs. Veterinarian class structures and syllabi were also useful in understanding how palpation is taught and learned.

The final device was designed and constructed in two parts. The hard tissue aspect of the device consisted of the skeleton. This included the ribcage, spine, pelvis, and four legs. The second aspect of the device was the soft tissue. This included all organs and soft biological tissues that were created out of various materials to simulate skin, fat, the colon, and the bladder. This is how these two aspects will be referenced throughout this paper. The hard tissue part of the device was designed first based on the background research of canine anatomy and a clinician's physical approach to palpation. The team produced a series of alternative designs of the skeleton, but ultimately, the design that was both the most cost effective and representative of canine anatomy was chosen for the final design. A prototype was constructed, and the soft tissue design process ensued.

A variety of materials based off of the team's research were selected to construct sample models of the layers that would represent skin, fat, fascia, and muscle. To validate the material choices, the team consulted and surveyed veterinarians, simulation technicians, plastination experts, and other professionals in the field. The materials were then tested to compare the mechanical properties to living tissue and organs, and the optimal materials were chosen. Once the most accurate compilation of materials was selected, a full sized prototype of the abdomen was built using the hard tissue model as a base structure. This selection process was repeated to build and test internal organ structures and abnormalities. The optimal soft tissue materials were produced through multiple iterations of designs and evaluations of how closely the materials met the device requirements. Each device in the series was constructed to be almost identical, with the only variability being the added normal or abnormal medical condition.

Information gathered from interviews with the client and field professionals, as well as the literature review allowed for a better understanding of abdominal palpation techniques, beagle anatomy, existing human models, and materials that applied to the project. This knowledge assisted in the formulation of design criteria and drove the development of preliminary prototypes. To ensure that they met the design criteria, the prototypes were tested for realistic feel and mechanical properties. The final designs incorporated the best features of each successive prototype. The success of the final device was determined by the qualitative feedback from veterinarians and the quantitative similarities between the mechanical properties of the device and living tissue. Once the device was deemed successful by these standards, manufacturing methods were researched to make suggestions for altering the device for marketing. Recommendations for future improvements were made for the design of this device as well.

In this project, the client was provided with a series of ten different upright beagle abdominal palpation training devices that veterinary students may use in a classroom setting to learn abdominal palpation and diagnostic techniques. Another goal of this project was to create a series of training devices that may be used in many veterinary schools to teach small animal abdominal palpation techniques. The ultimate goal is that these devices accelerate and improve the abdominal palpation learning experience of veterinary students, therefore leading to more accurate diagnoses in clinical veterinary medicine for faster and more appropriate treatment plans for small animals.

Chapter 2: Relevant Literature

2.1. The Importance of Veterinary Medicine

Veterinary medicine is defined as the study of the prevention, control, diagnosis, and treatment of animal diseases, as well as the overall biology and care of animals, which contributes to human health and quality of life (Future directions, 1989). In addition to treating animals, veterinary medicine helps keep people safe from the risks associated with animals and animal products, sparks new advances in human biology and medicine, and helps maintain the quality of the environment (Future directions, 1989). Many animals, such as cats and dogs, are used in human biomedical research in cardiovascular studies, orthopedic development, and cancer research (Biomedical Research, 2015). One subdivision of veterinary medicine is "companion animals," which include for example dogs, cats, and horses. Over 62% of American households have a companion animal, and these pets are typically considered members of the family. Companion animals play a dominant role in the quality of life of an increasing portion of society. These household animals tend to have a positive impact on the physical health of their owners as long as the animals are treated for disease through veterinary medicine (Casciotti, 2015). In 2015, approximately $16 billion dollars were spent in the U.S. on veterinary medicine and care for household pets (Pet Industry, 2015). As the concern over the health, welfare, and lifespan of companion animals increases, veterinary research continues to emerge. This creates a growing demand for research on companion animal health (National Research, 2005).

2.2. Abdominal Palpation in Veterinary Medicine

Palpation is the physical examination in medical diagnosis by pressure of the hand or fingers to the surface of the body, especially to determine the condition (such as size or consistency) of an underlying part or organ (Palpation, n.d.). Animal patients can be examined from behind and/or from the side while the animal is standing on four legs. The animal is upright, and their abdomen is in a hanging orientation. The orientation of an abdominal examination of a canine is depicted in Figure 1 (Stone, 2015).

Figure 1: Canine abdominal palpation (Stone, 2015)

In human palpation, the patient is lying supine while the examiner palpates the abdomen. To avoid discomfort of the patient, the flats of the fingers, not the fingertips, are used to slowly feel through the skin and abdominal wall to palpate the internal organs (Stone, 2015). During an examination, normal canine and feline organs that can be palpated include the colon if stool is present, the bladder if it is filled with urine, both kidneys in felines only, and possibly the prostate in intact male canines (Stone, 2015). A general, seven-step palpation method has been developed as a proposal to develop palpation skills through practice (Aubin, 2014). These seven steps are shown below:

Table 1: Seven-step palpation method

Seven Step Palpation Method	
1. Position	The clinician must be in a comfortable position, and the patient must be held in place. A stable and relaxed environment is optimal for accurate palpation.
2. Anatomy	The clinician must visualize the complex 3D anatomic structure within the abdomen to prepare for the organs their hands will search for through the skin.
3. Level	The controlled depth of palpation is important for accurate palpation. The level must not be too superficial on the surface of the abdomen, but it must not be too deep either. Palpation that is too superficial will not yield any meaningful information. Too much depth will cause the patient unnecessary pain and highly distort the organs being palpated.
4. Purpose	The clinician must identify the intention and outcome of the abdominal palpation to locate and diagnose with clarity.
5. Ascertain	Utilize an initial point of reference to mobilize the organ being palpated. This contact point allows the clinician to have control and recognition over the position of the organ being palpated.
6. Tweaking	Fine-tuning of the previous steps and further perceptual investigation can be used to gain both qualitative and quantitative knowledge of the components of the abdomen.

7. Evaluate/Normalize	The clinician should apply the parameters of each technique to compare the feedback from the tissue after it has been palpated with the normalized tissue.

2.2.1. Importance of Palpation

Veterinarians use palpation as part of many clinical examinations (Parkes, 2009). Animal abdominal palpation serves many purposes. It is first and foremost used to evaluate the health of an animal in a routine examination. During this examination, potential problem areas in the abdomen are identified and the examiner recommends measures to prevent diseases or illnesses from occurring. The examiner uses their hands and fingers to feel organ shapes, surfaces, and consistencies, as well as tissue texture, density, elasticity, vitality, and temperatures (Aubin, 2014). This information is used to determine the states of each organ and to find abnormalities. The veterinarian has an understanding and “feel” for the normal state of the abdomen through practice and routine clinical check-ups. Any abnormal areas and organ states are used to make a diagnosis or to prescribe further diagnostic testing. The examiner can identify if the patient has a disease or illness through abdominal palpation and determine possible pathologies or if additional diagnostic testing is necessary. For example, a normal bladder has a certain, known texture and consistency, and it is either filled with urine or empty. If the bladder is abnormal, such as it contains a hard mass or a different stiffness of the tissue is palpated, this would lead to further diagnostic testing. Abdominal palpation is used to find the source and cause of abdominal pain or discomfort in an animal through a veterinarian’s knowledge and their sense of touch (Blakely, 2002).

2.2.2. Project Significance

There are currently 30 schools of veterinary medicine in the U.S. that give the credential of a Doctor of Veterinary Medicine (DVM) that are accredited by the American Veterinary Medical Association (AVMA) (Media Frequently, 2015). Each year in the U.S., 3,000 students graduate from colleges of veterinary medicine (Media Frequently, 2015). According to the team’s client Dr. Michael Stone from the Cummings School of Veterinary Medicine at Tufts University, palpation is one of hardest skills to acquire as a veterinary student. Veterinarians practice the skills of palpation for the rest of their lives; it is never completely mastered (Stone, 2015). Abdominal palpation is an open-ended task that seeks an undefined solution. Veterinarians cannot verbally communicate with the patient being examined to identify the location or degree of the pain, so they must search for the source of the problem without visually identifying the parts of the abdomen they are palpating (Aubin, 2014). Animals tend to have a low tolerance for abdominal palpation as well. Abdominal palpation can be uncomfortable for the animal and cause them to tense up or move around. According to the client, an animal will only tolerate palpation a few times in a row before the animal becomes uncomfortable, tense, and tired. Occasionally, this requires the assistance of another person to hold the animal in place. Learning diagnostic techniques on an unhealthy animal is considered unethical because it causes the animal more unnecessary pain without the benefits and professionalism of a clinical diagnosis. A teaching device that simulates both normal and abnormal conditions is the best way these skills can be practiced. Palpation requires knowledge, perceptual skills, motor skills, and significant amounts of practice (Aubin, 2014). This is why the MQP will allow veterinary students to practice palpation skills on a series of devices that are realistic and accurate in comparison to a beagle abdomen.

2.3. Conditions of the Abdomen in Canines

Abnormal findings from palpation may include pain, fluid, masses, lesions, cancerous growth, foreign objects, and enlargement of normally non-palpable organs, such as the liver or spleen (Stone, 2015). Many abnormal abdominal conditions can be detected by inducing a pain response from the animal during palpation. These conditions include, but are not limited to, the following displayed in Table 2 below (Hansen, 2009).

Table 2: Sources of abdominal pain in canines

Organ or Organ System	**Possible Conditions**
Abdominal Wall	Contusions, herniation, rupture, laceration, trauma of the diaphragm
Gastrointestinal	Distension, volvulus, gastroenteritis, incarceration, strangulation within a hernia, intestinal obstruction, mesenteric torsion, thrombosis, toxicities, ulceration, perforation
Hepatic	Necrotic cholecystitis, portal hypertension, ruptured bile duct, infection canine hepatitis
Musculoskeletal	Intervertebral disc disease, discospondylitis, thoracolumbar trauma
Pancreas	Pancreatitis, pancreatic abscess
Peritoneum	Peritonitis, cholangiohepatitis, uroabdomen, sclerosis
Reproductive System	Labor/dystocia, metritis, prostatitis, ruptured pyometra, uterine torsion
Spleen	Distension, infraction, torsion

Systemic	Hypoadrenocorticism, leptospirosis
Urinary System	Acute renal injury, cystitis, neoplasia, obstructive calculi in ureter or urethra, pyelonephritis, urethra obstruction, uroperitoneum

The location of abdominal pain combined with the animal's behavior and symptoms may allow the veterinarian to narrow the list of possible abnormal conditions. Abdominal pain may be shown in a patient by a decrease in appetite, behavioral changes, gastrointestinal distress such as diarrhea or vomiting, restlessness, discomfort while lying down, guarding of the abdomen, a stiff gait, and difficulty in posturing while urinating or defecating (Hansen, 2009). Abdominal pain caused by underlying abnormalities can be palpable to a veterinarian, possibly leading to further examination and a diagnosis.

2.4. Existing Abdominal Palpation Training Devices

2.4.1. Animal Palpation Training Devices

Currently, one feline and one canine palpation training device have been designed. The first is a mixed media reality simulator for feline abdominal palpation training. This device consists of a stuffed toy cat with a metal skeleton and synthetic organs that are paired with a virtual simulation program (Parkes, 2009). This unpatented model has been designed, produced, and an online report is available to describe the function of this device. However, only one model has been produced for the use of the researchers who built it, and there are no indications of any further production. The device is created with the assistance of PHANToM Premium 1.5 haptic devices as well as OpenHaptics and ProtoHaptic software. The software is used to create a virtual model that defines the force resistance of the feline chest and abdomen. The PHANToM devices provide the associated force feedback and a varied range of motion and stiffness. The user places his or her hand under the toy cat, placing the thumb on the right PHANToM device, and the fingers on the left PHANToM device. The devices are then squeezed, and they produce force resistance to simulate the resistance of the portion of the abdomen that the user is palpating. The combination of these devices, software, and a modified toy cat provide a virtual and physical representation of the feline chest and abdominal organs.

The second device is a patent for a canine abdominal palpation simulator. This patent consists of a design of a canine body that contains internal artificial organs controlled by switches for feedback devices. The publication describes the device consists of a base, simulated canine body, artificial organs supported within the body, vibrator connected to each artificial organ for identification, and a control panel connected to vibrator feedback (Bunch, 1997). This patent does not include details and specifications of materials used or the mechanical properties of the design. As far as research has shown, this device has not been created or produced; it only exists as a patent created in 1997 (Bunch, 1997).

2.4.2. Human Training Devices

Extensive work has been done to develop human palpation training devices, and they are used in almost all medical schools across the world. These palpation devices range from extremely simple models created and designed by engineers in simulation labs made from household objects to complex, electronic full-body models that can be purchased online for thousands of dollars. Many different companies sell the commercially produced complex models, and they have the ability to simulate a pulse, breathing, childbirth, and other bodily functions. The fully functioning models can also be used for practicing surgeries, giving injections, diagnostics, and many other procedures. Although many different types of human training models exist, there are only a few commercially produced, non-electric models for abdominal palpation. Abdominal palpation is a skill that is easier to learn on humans than animals, and many complex models include palpation abnormalities as a function of the model. Since humans can vocalize their symptoms, doctors are able to more accurately predict the pain that correlates to a condition, and with actors or volunteers, more accurate training simulations can be produced. The mass produced models are used for more invasive learning, while volunteers or actors are utilized for medical students to learn abdominal palpation. The commercially produced abdominal palpation models are designed for palpating the fetus within a pregnant patient.

One existing human abdominal palpation model allows students to perform Leopold's maneuvers and practice abdominal palpation techniques regarding fetal positioning (Abdominal Palpation, 2008). Leopold's maneuvers are performed on pregnant women to reveal the number of fetuses, the fetal position, and the presenting part, attitude, and position. It also assists in the learning simulation of finding the optimal location for listening to the fetal heartbeat and how far the fetus has descended into the pelvis (Abdominal Palpation, 2008). Other human models include a geriatric manikin with palpable latex veins, a palpable arm, chest, and upper leg for injection practice, and a rectal model for prostate palpation training. These models are all readily available for purchase from Mentone Educational Centre, a company dedicated to selling medical teaching aids (Mentone Educational, 2015).

2.5. Beagles

Beagles are a breed of *canis lupus familiaris*, which is the classification for a domestic dog. Beagles are used in numerous biomedical and veterinary studies for research, and they are used at the Cummings School of Veterinary Medicine as research and practice models for veterinary students (Biomedical Research, 2015). The palpation training devices that the team created were designed to represent the look and feel of an adult male beagle. It was important that the device has the same exterior and internal characteristics as a real beagle. This includes the look and feel of the epidermal layers, as well as the size, shape, and texture of the organs. The training device was designed based on the specifications of an adult male beagle's tissue and organs. The average weight of a male beagle is 9 kg. The various weights of the organs within the beagle were found as well. The liver is 268.40 +/- 41.36 g, the kidney is 39.95 +/- 4.72

g, and the spleen is 27.44 +/- 5.11 g. The average volume of the male bladder is 195.50 +/- 67.15 mL (Choi, 2011).

The internal abdominal anatomy of a canine is the same within all canines, and the only difference between palpating different breeds is the external size and shape of the canine. As mentioned before, the two palpable organs in a healthy canine are normally the colon and the bladder. When there are abnormalities in this abdomen, these are often times palpable as well. The colon extends parallel with the spine at the rear of the abdomen to the rectum, and the bladder hangs down near the front of the colon, tucked in between the hind legs. Most of the other organs in the abdomen including the stomach, liver, spleen, and kidneys are tucked behind the ribcage. The intestines are not necessarily palpable as organs, so they were considered soft abdominal filler in the design of this training device. Figure 2 depicts the anatomy of a canine, which can be used to represent beagle anatomy.

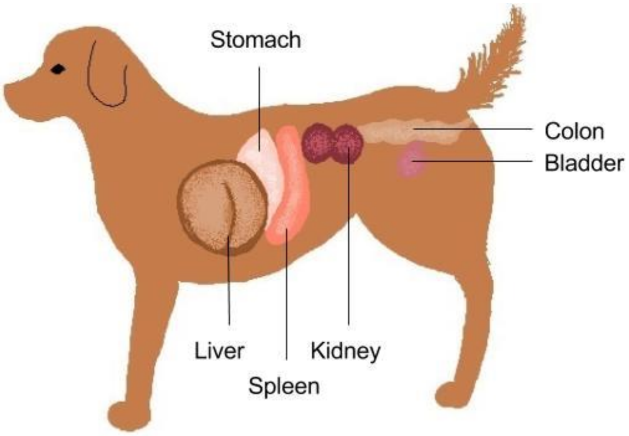


Figure 2: Simplified anatomy of canis lupus familiaris

2.6. Material Properties & Characteristics of Biological Tissues & Organs

Researching the material properties and characteristics of biological tissues and organs was necessary for the design of the palpation training devices. Understanding how biological tissue responds to palpation and feels gave an accurate comparison to the specifications and mechanical properties of materials that were used in this device. Research of the specifications of the properties and characteristics of organs and tissue within a beagle assisted in creating an accurate, realistic device designed closely to the proper specifications of a live beagle. Organ and fluid behavior of a 10 kg canine is described in Table 3 and the elastic modulus of organs can be found in Table 4 (Davies, 1993). The elastic modulus was used throughout the project as a mechanical behavior indicator for comparison of materials to biological tissue. The elastic modulus is the ratio of the force exerted upon an object to the resulting deformation, and it indicates the elasticity or stiffness of the material. These organs and volumes are slightly larger than those of a beagle, but the fluid behavior is extremely similar.

Table 3: Biological tissue and organ behavior in a 10kg canine (Davies, 1993)

Organ	Fluid Volume Capacity	Organ Weights
Bladder	80 mL	45 g
Gut	480 mL	260 g
Liver	480 mL	320 g
Kidneys	60 mL	50 g
Spleen	36 mL	25 g

Table 4: Elastic modulus of healthy tissue and diseased organs and tissue (Lee, 2011)

Organ	Healthy Elastic Modulus	Diseased Elastic Modulus
Bladder	1-8 kPa	5-23 kPa
Liver	10-40 kPa	110 kPa
Kidneys	10-30 kPa	6-21 kPa
Adipose	11.7 +/- 6.4 kPa	17 kPa

2.6.1. Skin

Skin is a physical barrier that protects the body and consists of three layers, which include the epidermis, the dermis, and the hypodermis. From a biomechanical standpoint, skin is a material that is nonlinear, pre-tensioned, and viscoelastic. The epidermis determines the extensibility of skin, which is the maximum deformation skin is able to undergo without rupture. The type I collagen fibers of the dermis dictate the tensile strength and anisotropy of skin. The fibrous network of elastin in the dermis affects strain recovery of the skin when a stress is applied, and it has a minimal contribution to the elastic modulus of skin. The orientation of the collagen and elastin fibers influence the properties of skin under deformation, such as mechanical relaxation and energy dissipation (Bismuth, 2014). The average thickness of canine skin, including the dermis and the epidermis, is 0.5 - 5mm thick, and it is typically on the thinner end of the range on the abdomen (Bismuth, 2014). In Table 5, the mechanical properties of skin are depicted from the literature (Fung, 1993) (Silver, 2001). The mechanical properties of skin were important in determining the materials that were used to simulate skin in the devices.

Table 5: Tensile Properties of Skin: UTS (Fung, 1993) & Elastic Modulus (Silver, 2001)

	Ultimate Tensile Strength	**Ultimate Tensile Strain**	**Initial Elastic Modulus**	**Final Elastic Modulus**
Skin	1-20 MPa	30-70%	0.10 MPa	18.8 MPa

2.6.2. Adipose Tissue

Adipose tissue, also known as fat, is a loose connective tissue composed primarily of lipid-filled cells called adipocytes. The role of adipose tissue is to provide thermal insulation and protection (Alkhouli, 2013). Subcutaneous fat in canines is typically a thin layer under the skin. Subcutaneous fat is an important part of the modeling necessary for the external layers of the training device. The elastic modulus for subcutaneous fat in a beagle is shown in Table 4, showing that diseased adipose tissue has a higher stiffness than healthy adipose (Alkhouli, 2013). Due to the hanging orientation of the abdomen, the mechanical properties of adipose were useful in determining the types of materials that were used in the device.

2.6.3. Muscle

The rectus abdominis is the prone muscles on the underside of the canine, and the external oblique muscles are the muscles on the sides of the abdomen. These are two of the main muscle groups that make up the canine abdomen. The rectus abdominis is suited for the function of constraining the core abdominal muscles while standing and the external oblique muscles fit the function of assisting in breathing (Farkas, 1998). This muscle functioning in the abdomen serves as another layer that a veterinarian must palpate through. Modeling materials after the physical properties of muscle allowed the design of an accurate and realistic training device.

2.6.4. Bladder

The urinary bladder is a muscular organ that temporarily contains urine until it is full. It is located in the back of the abdomen, in front of the pelvis pubic bone. Bladder compliance allows storage of increasing amounts of urine with a low bladder detrusor pressure change until the capacity is reached (Spielman, 2015). The pressure exerted on the bladder contents is known as the vesical pressure. The detrusor muscle contracts to push the urine out during urination, creating this pressure (Fu, 2013).

A canine's bladder can hold approximately 80 mL of urine, and other properties of the bladder are depicted in Table 3 (Davies, 1993). The maximum urinary flow rate is 5.93 mL/s. At maximum urinary flow rate, the vesical pressure is 57.10 cm H_2O. The detrusor pressure at maximum urinary flow rate is 48.44 cm H_2O. The maximum pressure of the detrusor is 49.57 cm H_2O [30]. Although these flow rates were not ultimately necessary for the design of the device, these values may be used in future improvements of the device to include a dynamically filling bladder.

When palpating, there is a significant haptic difference between a full bladder, an empty bladder, and a partially filled bladder. A full bladder is more tender and tight to palpate, while an empty bladder is significantly more difficult to palpate. Veterinarians must be able to feel through palpation the different conditions of the bladder to compare between a healthy and abnormal bladder.

2.6.5. Colon

The colon is a part of the large intestine and is used to maintain hydration homeostasis within the body by absorbing water and sodium from feces. It is also a temporary storage location for feces as it passes through the last part of the digestive system. Viewed from a mechanical standpoint, the colon has three layers: mucosa, circumferential, and longitudinal muscular fasciae. It is divided longitudinally into the ascending, transverse, and descending colon (The Canine, n.d.). The colon is composed of various layers of fiber-reinforced biological tissues, so it exhibits anisotropic and nonlinear mechanical behavior (Carniel, 2014). The colon is approximately 65 cm long (Department of Anatomy, 2013). The colon is one of the organs that can be palpated in a canine, so the properties and condition of the colon were simulated by the training devices. Materials were used to mimic the colon with stool and a constipated colon.

In Table 6 below, the mechanical properties of bowel tissue under uniaxial tension tests found in literature are shown (Christensen, 2015).

Table 6: Mechanical properties of bowel tissue under uniaxial tension (Christensen, 2015)

	Ultimate Strength	**Elongation at Failure**	**Elastic Modulus**
Porcine	0.58 MPa	113.19%	1.83 MPa
Human	0.87 MPa	62.81%	5.18 MPa

2.6.6. Material Science

There are several different equations that help identify various characteristics of different material such as elasticity and viscoelasticity. These characteristics were taken into consideration when designing a device that mimics the properties of biological tissue. Young's modulus, also known as the modulus of elasticity or elastic modulus, was used as part of

Hooke's law to calculate elasticity of the material in comparison to biological tissue. The elastic modulus is equal to the stress proportional to load divided by the strain proportional to the deformation. A stress-strain curve graphed from data from a mechanical tension test can be used to find the elastic modulus from the initial or final linear region of the curve by calculating the slope.

2.6.7. Materials Similar to Biological Tissue and Organs

There are many different materials used to replicate biological tissue and organs. Artificial tissues can be seen in simulation models as well as other training devices used in human and veterinary medicine. One of the most common materials used to mimic biological tissue is silicone. Some applications of silicone are artificial skin and organs. Silicone comes in different durometers or "hardness" making it suitable for different applications ranging from skin to an organ such as the bladder. Some issues presented by silicone include that it is susceptible to creep and rather expensive. An advantage of silicone for biological tissue applications is that it has a high elasticity that closely mimics biological tissue. Similar to silicone is vinyl. Vinyl can also be used as artificial skin due the similarity in texture to skin. It is commonly used in injection simulations as it can be repeatedly injected with a needle syringe (Mentone Educational, 2015). Latex is another material used in many applications. Latex has similar properties as silicone, but it is less expensive. The limitation of latex, however, is that latex allergies are common. In a canine palpation simulator patent, it was stated that polyethylene sheets may be used along with a water-based lubricant to replicate an internal lining of fatty tissue. This same patent also states that polyester can be used as fur (Bunch, 1997). The material choices made by the design team are further discussed in Chapter 4.

Chapter 3: Project Strategy

3.1. Initial Client Statement

Initially, the client requested the design and creation of an animal abdominal palpation model that veterinary students can use to learn palpation skills in the classroom. The client statement from Dr. Michael Stone stated, “Our MQP would be the creation of models useful for training veterinary students in the skills of abdominal palpation of cats and dogs.” The client originally requested the design of one model with interchangeable parts. These interchangeable parts would simulate both healthy and abnormal conditions within the abdomen and eliminate the need for multiple models. There would be synthetic organs that represented a healthy and abnormal colon and bladder, an enlarged spleen, tumors, and foreign objects. The bladder and the colon would be dynamic and have the capability to have a varied volume.

3.2. Revised Client Statement

After numerous meetings with the client, the client statement evolved and was made more concise. Overall, this project aims to design a series of ten haptic, upright beagle abdominal palpation training devices that veterinary students will use to learn diagnostic palpation techniques on in a classroom setting. It was decided that these devices would be modeled after a beagle because the students of Tufts Veterinary School use live beagle models to currently learn veterinary palpation. Therefore, the training devices created for this project would be used concurrently with or in replacement of the live beagle models to maximize abdominal palpation training. The client specified that the most important aspect of the devices was haptic accuracy. In relation to haptic accuracy, it was important that the training devices were also anatomically correct.

The client’s final vision for this project was for ten main devices that each represents an abdominal condition to be designed and created. Originally, there was only going to be one device with interchangeable parts. The limitation of this is that only one condition can be simulated at a time. With multiple models, different conditions may be palpated in series and compared. The ten designs will include simulating a healthy colon and healthy bladder, constipated colon, bladder with stones, enlarged spleen, enlarged liver, mid-abdominal foreign bodies and masses, and an overweight abdomen. In the client’s experiences as a Doctor of Veterinary Medicine, he found that these are the most common conditions and abnormalities found during abdominal palpation of canines. The client also advised the team that the colon and bladder can almost always be felt during abdominal palpation, so all devices will include a palpable colon and bladder.

3.3. Objectives and Constraints

The client statement and the design team determined the objectives and constraints for this project. The goal of the project was to create a series of devices that realistically simulates the abdomen of a beagle standing on four legs and the various abdominal conditions that can be palpated in a canine abdomen. The abdomen must hang down so the students can learn one-handed or two-handed canine palpation techniques of both normal and abnormal conditions. Materials must be used to realistically simulate a beagle abdomen to accurate specifications. The devices must be portable for the ease of use for professors teaching classes on palpation. The design must be simple and cost effective in order for it to be reproduced easily.

According to the client, the final beagle abdominal palpation training device must be realistic, accurate, durable, reusable, portable, and reproducible. A pairwise comparison chart found below in Table 7 was completed by the design team to prioritize these objectives and determine whether they are primary or secondary.

Table 7: Objectives in a pairwise comparison chart. Realistic and accuracy were rated as the highest objectives

	Realistic	**Durable**	**Reusable**	**Portable**	**Reproducible**	**Accurate**	**Total**
Realistic	/	1	1	1	1	0.5	**4.5**
Durable	0	/	0.5	1	1	0	**2.5**
Reusable	0	0.5	/	1	1	0	**2.5**
Portable	0	0	0	/	0.5	0	**0.5**
Reproducible	0	0	0	0.5	/	0	**0.5**
Accurate	0.5	1	1	1	1	/	**4.5**

3.3.1. Primary Objectives

The primary objectives for the project were accuracy, realistic feel, durability, and reusability. According to the client, the main focus of the device was to mimic the feel of a real beagle abdomen. The devices must be realistic to create the illusion of palpating a live beagle. For the device to serve as a valid training device for beagle palpation techniques, it must be anatomically accurate. Durability and reusability are interchangeable for the purposes of this project. Multiple classes of veterinary students will use the final training devices frequently, so these devices must be durable. Table 8 below displays the design team's primary objectives along with descriptions of how they are going to be achieved.

Table 8: Primary objectives

Objective	Description
Realistic	Haptically identical to a beagle abdomen, simulates diagnostic conditions, simulates normal abdomen, similar weight and shape as beagle.
Accuracy	Anatomically correct, organ dimensions and mechanical properties similar to beagle organs.
Durable & Reusable	Durable materials, long lasting, preservation techniques, replaceable materials.

3.3.2. Secondary Objectives

The secondary objectives of this project are portability and reproducibility. These were ranked fifth and sixth amongst the other objectives. Although they are ranked low, they are of equal value compared to each other. In terms of being portable, the veterinary professor must be able to easily bring the devices to and from classrooms and buildings. Lastly, the devices must be reproducible. Individual parts must be reproducible so they can easily be replaced if they are broken or lost. In addition, the devices should be reproducible to allow for the creation of more devices for other veterinary schools. The secondary objectives are displayed in Table 9 below along with descriptions of ways to achieve them.

Table 9: Secondary Objectives

Objective	Description
Portable	Lightweight, easy to carry, packaged as a whole
Reproducible	Simple design, cost effective, easily available materials

3.3.3. Project Constraints

Some constraints of this project include time, cost, information availability, and teaching limitations. The complexity and development of this training device were limited by the allotted time for this project. Secondly, research has shown that realistic and durable materials are typically more expensive. The availability of relative information was also a constraint. There are no existing physical canine palpation devices, so the information needed to determine viable materials and simulation device methods were determined by researching human models, making educated assumptions, and completing trial and error testing. The knowledge constraint in regards to human device research was that the companies that produce devices that teach human palpation do not release the materials used in these devices. Lastly, the teaching limitations are due to the fact that the beagle devices may not be versatile. This series of devices may not necessarily be a suitable teaching method for abdominal palpation of all canines or other species.

3.4. Project Approach Outline

The goal of this project was to design a series of haptic, upright beagle abdominal palpation training devices that veterinary students will use to learn diagnostic palpation techniques in a classroom setting. In order to achieve this goal, the design team worked closely with the client, Dr. Michael Stone, as well as other veterinary professionals and students at Tufts University's Veterinary School of Medicine. The first step of the project approach was to research and test applicable materials. Once the necessary research and testing was complete, the optimal materials were compiled. While this was occurring, alternative structure designs were created for the hard tissue aspect of the device. The choice of the final design of the base structure was determined by identifying the design that best met the objectives of portable, reproducible, durable, and accurate. The soft tissue material compilation that best achieved the objective of realistic feel was used in the creation of prototypes. The hard tissue and soft tissue prototype designs were combined together, and they were then tested. Based on the feedback from veterinary students and professionals and the results of mechanical testing, the design was modified and finalized.

3.4.1. Material Research and Testing

The first step of the project approach was to research applicable materials. Relevant literature and patents were read to find materials used in similar applications. Another valid source was researching the materials used in human palpation devices. While there are many distinct differences between the human and canine anatomy, many of the materials used in human models were applicable to this project. Once a list of potential materials was formed, research on the mechanical properties of each material was performed. Elastic modulus and maximum stress were the mechanical properties of interest. Next, samples of these materials were collected from companies such as McMaster-Carr, Smooth-On, Reynolds, and craft stores such as Joann Fabrics. The individual fabric samples and latex materials were both mechanically and haptically tested. The haptic and mechanical properties of each material assisted in determining which part of the model it was most suited for.

3.4.2. Fulfilling the Objectives

The design phase of this project began by combining different material samples to mimic the different layers and organs of the beagle abdomen. Once different options for the external layers, abdominal filling, and organs were selected, the design team began brainstorming different methods to form the structural foundation of the devices. The hard tissue foundation of the device had to be sized and shaped accurately in comparison to the dimensions of an average beagle. It acted as the skeleton of the entire device, and was designed and created before the soft tissue aspect of the device was created. The soft tissue designs were supported by the hard tissue design.

3.4.3. Prototype and Testing

The next step of the project approach was to create successive prototypes. The most important aspect of this project was the haptic accuracy of the tissue layers of the abdomen as well as the internal organs. Therefore, the first priority of the prototyping stage was to determine the most accurate representation of the skin, muscle, abdominal filling, and organs. With this in mind, the skeletal structure of the first prototypes was the most basic and reproducible design, and different combinations of skin and abdominal filler were created around the hard tissue design. Veterinary professionals tested the different combinations of skin and abdominal filler for accuracy, and modifications were made based on this feedback. Together, the skeletal frame and abdominal layers formed the “shell” of the prototype. The next step in the prototyping stage was to create the internal organs needed to simulate the determined conditions. Different materials and designs for normal and abnormal organs were created. These organs were inserted into the prototype and were tested by veterinary professionals. Based on this feedback, modifications were made.

3.4.4. Design Finalization

The final design was determined and validated by feedback from veterinary professionals and mechanical testing. Once the primary testing was complete and the final prototypes were created, each prototype was tested by veterinary professionals. Veterinary professionals were given a survey to rate how accurately each prototype simulates each condition. This feedback allowed the finalization of the design. Once the feel of the model was determined haptically accurate, the model was modified for parts to remain more fixed and the model to appear more like a beagle.

Chapter 4: Design Process

4.1. Needs Analysis

The need of this MQP was a series of functional abdominal palpation training devices to effectively increase the amount of diagnostic conditions veterinary students learn in the laboratory from palpation sessions. In turn, these devices should prepare the students to successfully palpate live animals and use their knowledge to proceed with necessary diagnostic procedures. There is a significant market for these devices. There are currently 30 AAVMC accredited schools of veterinary medicine in the United States, and 3,000 students graduate each year in the U.S. from colleges of veterinary medicine (Media Frequently, 2015). All of these students must learn to palpate, as it is a skill used in virtually every clinical examination. As of 2014, there were 108,427 certified and employed veterinarians working in both private and public positions in the United States (Market Research, 2014). With approximately 16 billion dollars being spent in the U.S. on veterinary medicine and care for household pets in 2015, there is a significant need for successfully trained veterinarians (Media Frequently, 2015). Abdominal palpation training devices would improve the training of veterinary students across the country, as no device is currently used in veterinary school curriculums across the country. No such device even exists for the purpose of teaching small animal abdominal palpation.

As these devices are for the purpose of learning, they required certain specifications that were used to accomplish their functions effectively. The absolute requirements of these devices were that they must be accurate and precise in relation to beagle structural specifications in a standing orientation. This also includes that the devices must mimic the canine abdominal anatomy and taction. These devices must be physically translatable to a live canine, specifically a beagle, so veterinary students can translate their learning on the device to a live animal palpation experience. These devices must also simulate disease states for students to learn how to palpate various abnormal physical conditions. Desirable requirements included that the devices must be fairly lightweight and portable, as well as durable. The devices must have parts that are easily and inexpensively replaced when necessary. Physical needs of the devices included a palpable bladder and colon, which should be felt through a layer of skin, fat, and muscle. A base structure must support the palpable region in the orientation of a standing canine. The devices must be created out of various materials that accurately mimic the texture of a live canine's abdominals. Table 10 depicts the specific needs criteria of the devices.

Table 10: Needs criteria

Needs Criteria	
Indication	- Students learning abdominal palpation on small animals in veterinary schools
Location	- Veterinary school classrooms and laboratories
Procedure time	- Standard class time: 50 minutes - Palpation time: 5 minutes for trained veterinarians, longer for novice veterinary students
Procedure frequency	- (Each class taught) x (Number of students per class)
Follow-up	- Devices should be effective for at least 2 years before minor replacement parts are needed
Efficacy	- Devices should decrease the number of live animal models palpated as teaching devices - Device should limit the amount of live animals given sedatives for student learning purposes - Devices should increase amount of abnormal conditions learned in a laboratory palpation session
Complication rate	- Solution shall not introduce new complications - Solution shall not cause excessive damage should there be organ rupture
Value	- Less than $500 if lifespan is over 5 years
Comparative pricing	- There are no other solutions that can be purchased
Human factors analysis	- Solution must easily integrate into the existing learning structure and curricula of veterinary schools - Devices should facilitate student learning of palpation and diagnostic skills

	• Skills learned on the devices should be transferrable to a live small animal palpation procedure
Attributes	• The main characteristics of the devices are the mechanical and material properties of materials chosen

4.2. Functions and Specifications

The functions of the canine abdominal palpation devices allowed the devices to serve as successful teaching models in veterinary schools. There were several different functions the design team determined for the series of canine abdominal palpation devices. These functions included mimicking the structural specifications of a beagle, properly orienting the device, simulating canine organs, and imitating the dermal, fat, and muscle abdominal layers of a beagle. It was important that the specifications of the devices were met so they are as accurate as possible and serve as useful tools for veterinary students. The specifications are the measurements and numbers that were used to achieve the functions of the devices.

Structural specifications of the devices included mimicking the proper bone structure of the beagle surrounding the abdominal area. The bone structures that frame the abdomen of a canine that may be encountered during palpation include the rib cage and the pelvic bone. The rib cage area of the devices must have a diameter of approximately 8 inches, and the devices must taper to a 3-inch area width that simulates the pelvic bone. From the rib cage to the pelvic bone, there is a region approximately 6 inches long that is exposed for palpation. The length of the region from the rib cage to the pelvic bone in the devices must be approximately 10 inches (Choi, 2011).

The orientation of the devices includes both the way the whole structure is oriented and the way that the organs are positioned inside the devices. The devices must be approximately 6 inches off the ground to mimic a beagle standing on all four legs. This is the typical orientation of canines when palpated by veterinarians. The organs most important to create within these devices were the bladder and the colon. The colon is approximately 65 cm long and runs straight through the digestive tract located in the gut of the canine. The colon ends at the rectum of the canine. The bladder is located underneath the colon, at the rear of the abdominal region.

Not only was it important that the colon and bladder were in the right position, it was important they had matching physical characteristics to those in a live canine. The colon should feel different when it contains stool and when it does not, and the bladder volume changes based on the amount of urine it contains at any given time. The device must mimic a colon with stool and a colon that is constipated, or overly full with hard, large stool. When there is little stool in the colon, it is more difficult to palpate; furthermore, the presence of stool makes the colon more easily identifiable. A colon that is constipated is much easier to identify through palpation. The bladder temporarily contains fluid until it is full, meaning it could have several different palpable volumes. When full, the volume of a normal beagle's bladder is 80mL, and the bladder also has an elastic modulus of 1-8kPa. Both the colon and the bladder are held in the gut of the canine. It was important that the devices simulated these characteristics as best as possible because they determined how realistic the organs in the devices felt (Davies, 1994).

The last functions of the devices were to simulate the dermal, fat, and muscle layers of a beagle. This included the skin in the abdominal region, the adipose tissue, and the rectus abdominis. The skin is 0.5 - 5mm thick and is usually thinner around the abdomen, so the devices must have a skin thickness of 0.5 - 1.5mm (Bismuth, 2014). The next layer was the adipose tissue, or the fat. The devices must include a layer of adipose tissue that has an elastic modulus similar to 11.7 +/- 6.4kPa (Alkhouli, 2014). The adipose tissue and skin must be connected to move together as two separate layers adhered to each other. An added layer of fat in the device served as a textured layer that adds thickness. Lastly, the thickest part of the muscular layer that is palpated is the rectus abdominis. This is a quarter-inch thick and lies deeper than the other layers (Brown, 2012). A final specification includes that the organs within the device cannot break under normal palpation forces and extension. Below is an image of a canine skeleton with dimensions that was used for dimensional guidelines for the abdominal palpation devices.

Figure 3: Skeleton dimensions of canine abdominal region

Table 11 depicts the general functions determined for the device with specifications that were used as benchmarks for testing the device and accomplishing those functions.

Table 11: Functions and specifications of the devices

Functions	Measurements & Specifications	
Mimic the structural specifications of a beagle	Rib cage diameter	8 inches
	Pelvic diameter	3 inches
	Palpable region length	6 inches
	Height from ground to abdomen	6 inches
	Overall height	16 inches
Proper orientation	Standing upright on four limbs, organs properly oriented in hanging position	
Simulate the organs of a canine	**Bladder** (Manu, 2006) (Fu, 2013)	
	Average volume	80 mL
	Palpable range	40 mL-100 mL
	Internal pressure	1.5 mmHg-5.5 mmHg
	Elastic modulus	11.52 kPa
	Composition	Urine is typically 95% water, 5% solutes
	Shape	Balloon-shaped and tapers down to urethra
	Colon (Yildiz, 2006)	
	Length	33.32 cm

	Diameter	28.39 mm
	Elastic modulus	1.83 MPa
	Shape	Cylindrical, straight, and tubular
	Gut	
	Volume	480 mL
	Shape	Rounded and full
Imitate the abdominal skin, fat, and muscle (Tran, 2014)	Skin thickness	0.5 mm-1.5 mm
	Skin elastic modulus	0.10 MPa
	Rectus abdominis thickness	0.5 mm
	Rectus abdominis elastic modulus	3 kPa
Abnormal conditions	Bladder stones	1 cm-2 cm diameter
	Constipation	40-60 mm diameter (double normal colon)
	Liver mass (Baba, 2007)	Up to 15 cm diameter
	Overweight, excess adipose	Approximately 2-4 inches thicker epidermal layer
	Mid-abdominal masses	Average 3-4 inches in diameter

4.3. Conceptual Designs

In order for the design team to determine how the devices would accomplish the functions, a functions and means table was created. As the materials used in the project were most imperative to achieving the goals of the MQP, this table describes only the material means. Brainstorming means that could accomplish each function was the first step towards creating conceptual designs. The material means to achieve the following functions are detailed in Table 12.

Table 12: Material functions and means

Functions	**Means**					
Upper structural support	HDPE	Lexan	Wire	Air- hardened clay	Wicker	Synthetic skeleton
Height support	Wood	Metal	Plastic			
Base support	Wood	Metal	Plastic	None		
Skin, muscle, & fascia layers	Elastic fabric	Polyester fiberfill sheet	Silicone	Ace bandage	Latex	Suede
Skin, muscle, & fascia connector	Velcro strips	Elastic thread	Thread	Cloth ties	Pegs	Buttons
Abdominal filler	Polyester fiberfill bulk	Air	Cotton	Bags of liquid		
Bladder shell	Latex	Silicone				
Bladder filling	Water	Silicone	Air	Gel		
Colon filling	Play-Doh	Flour	Air-dry clay	Model Magic	Sand	
Colon shell	Latex sheeting	Silicone	Penrose drain	Polyethylene wrap		
Abnormal Conditions	Polystyrene	Closed-cell polyurethane foam rubber	Dried clay	Rocks and pebbles	Plastic pieces	

As well as considering the possible materials that could accomplish the functions, structural means were considered. Both soft tissue and hard tissue structural means were brainstormed to create the optimal structure that satisfies the functions of the project to create a device with the structural specifications and anatomical accuracy of a beagle. Table 13 describes the means brainstormed for soft tissue structures, while Table 14 depicts the means for the hard tissue structures of the device.

Table 13: Soft tissue structural functions and means

Functions	**Means**			
Skin, muscle, & fascia layers	Layers sewed together	Layers separate and unattached	Velcro layers together	Segmented packets of layers
Colon	Single-layered	Double-layered	Triple-layered	
Bladder	Single-layered	Double-layered	Triple-layered	
Abdominal filler & filler space	Free form	Segmented	Layered	

Table 14: Hard tissue structural functions and means

Functions	**Means**			
Rib Cage	Disk-shaped	Rib-shaped	Conical	Cylindrical
Pelvis	Circular	Y-shaped	Disk-shaped	
Supports	Four legs	Two legs	Cylindrical	Rectangular prisms
Spine	Cylindrical	Branching ribs	Rectangular prism	Cut-out cylinder

After brainstorming to create the functions-means tables based off of the needs and device specifications, conceptual designs were created. The designs that accurately addressed the needs of the device are described in the following sections. While each conceptual design had benefits and drawbacks, they all worked to fulfill the functions and meet the specifications outlined in Table 11. These conceptual designs detail both the soft tissue and hard tissue aspects of the device, and when combined, would create an upright beagle model.

4.3.1. Hard Tissue Conceptual Designs

4.3.1.1. Conceptual Design I

The first conceptual design would use HDPE pipe as the upper structural support. The design, cut from two different diameters of HDPE pipe into the shape, formed the backbone, depicted in Figure 4. It would be supported by two rods of HDPE pipe and secured down into a plastic base. The epidermal layers would be attached to the plastic upper support using pegs. The epidermal layers would contain holes to fit over pegs drilled into the upper plastic back. The bladder would be attached at one end at the back of the abdominal region. The colon would be attached at both ends to the back of the abdomen and towards the middle of the palpable region. Internal organs would be accessible through the removal of the epidermal layers using pegs. Elastic threads would be used to sew the epidermal layers together into one, easily removable layer. The benefits and drawbacks are outlined in Table 15.

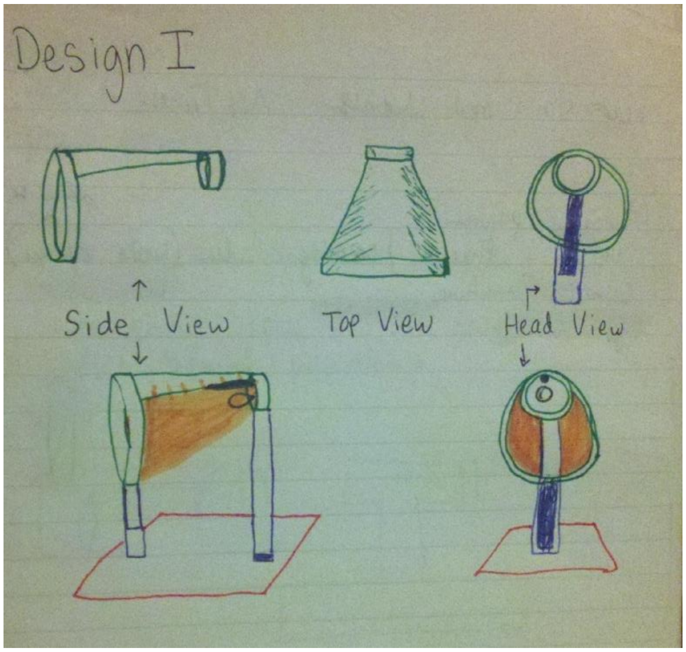


Figure 4: Conceptual design I

Table 15: Benefits and drawbacks of conceptual design I

Conceptual Design I	
Benefits	**Drawbacks**
• Material compatibility of plastic legs and base • Elastic thread will provide elastic response • Inexpensive: HDPE, plastic base, elastic thread • Shape of structure guides soft tissue to form as shape of canine	• Difficulty with seamlessly connecting the two diameters of HDPE pipe and supports • Shape of conical spine is not easy to machine • Using one rod per end does not simulate dog legs; more unstable • Base adds weight

4.3.1.2. Conceptual Design II

The second conceptual design would have a metal wire frame that functions as the upper structural support and the legs. It would have two metal rods welded on either end to give the frame support. The metal rods would be attached to a plastic base. The epidermal layers would be attached to the metal support using elastic threads tied to the wire. The bladder would be attached at one end at the back of the abdominal region. The colon would be attached at both ends to the back of the abdomen and towards the middle of the palpable region. The metal rods that serve as ribs would allow easy attachment of the soft tissue layers to the device through elastic thread. Figure 5 depicts the second conceptual design, and Table 16 describes the benefits and drawbacks of this design.

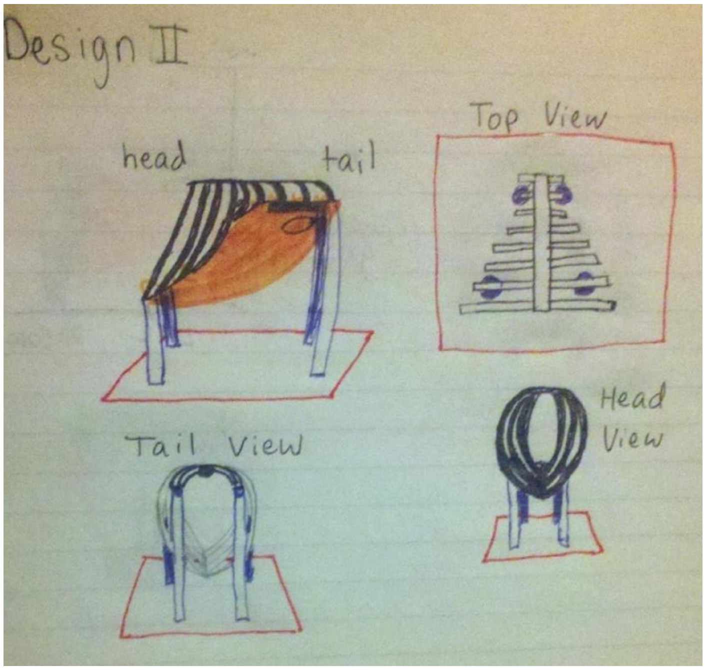


Figure 5: Conceptual design II

Table 16: Benefits and drawbacks of conceptual design II

Conceptual Design II	
Benefits	**Drawbacks**
• Customizable shape • Using two rod per end does simulate dog legs • Inexpensive: plastic, elastic thread	• Metal wire frame difficult to machine • Not easily reproducible • Time consuming to make • Expensive: metal

4.3.1.3. Conceptual Design III

The third design would have a structural framework based off of a HDPE 25-gallon bucket. The bucket would have the top and bottom rings cut off, leaving a uniform, hollow cylinder. The cylinder would be cut into the shape depicted in Figure 6. There would be two plastic legs that would be plastic-welded to the HDPE rings on either end. The epidermal layers would be attached to the bucket using Velcro®. It would have one attachment point at the back of the abdominal cavity and another on the rib aspect of the device. The colon would have two attachment points, one at the back of the abdominal cavity and the other towards the upper-middle portion of the palpable region. Utilizing Velcro® as the attachment point for the soft tissue to the hard tissue interface allows for frequent and seamless removability of layers from the device. These means of attachment may be used in any of the conceptual designs to aid in fitting the soft tissue around the hard tissue. Table 17 describes the benefits and drawbacks of Conceptual Design III.

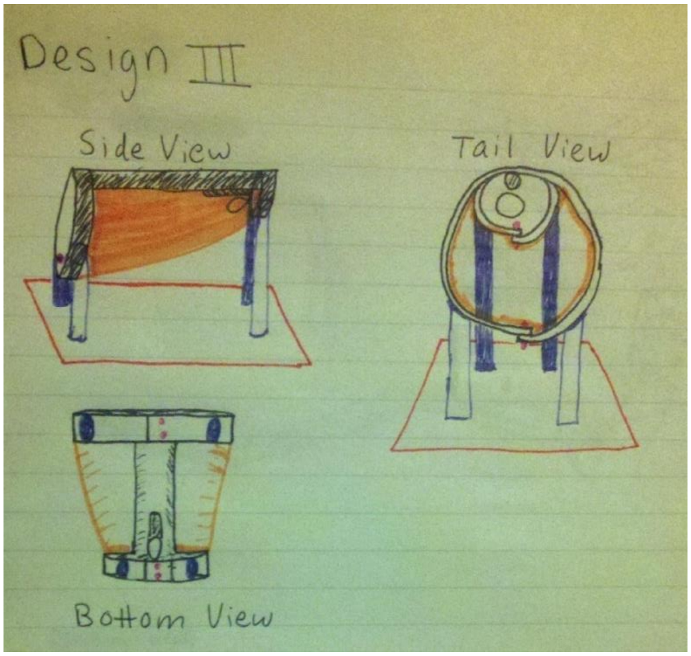


Figure 6: Conceptual design III

Table 17: Benefits and drawbacks of conceptual design III

Conceptual Design III	
Benefits	**Drawbacks**
• Customizable bucket diameters • Cheap: bucket, Velcro® • Most inexpensive model • Fairly easy to reproduce • Four supports give device stability and accurate to canine anatomy	• Bucket section may not be durable • Structure may not endure loads without bending • Difficult to attach legs to HDPE bucket

4.3.1.4. Conceptual Design IV

The upper structural support would be a synthetic canine skeleton depicted in Figure 7. Its base support would be plastic. The layer that represents the skin, muscle, and fascia would have multiple layers. The epidermal layer compilation would be attached to the upper structural support using elastic thread. The abdomen would be filled with polyester fiberfill bulk. The bladder would be attached at one end to the back of the abdomen. The colon would be attached at both ends to the back of the abdomen and towards the middle of the palpable region. Table 18 describes the benefits and drawbacks of Conceptual Design IV.

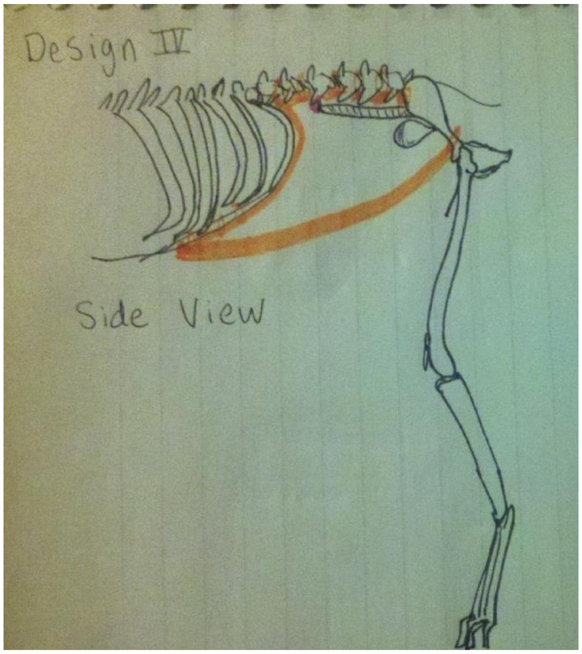


Figure 7: Conceptual design IV

Table 18: Benefits and drawbacks of conceptual design IV

Conceptual Design IV	
Benefits	**Drawbacks**
• Realistic structure • Inexpensive: plastic, elastic thread • Anatomically correct	• Difficult to machine • Not easily reproducible • Expensive • Not structurally stable

These four hard tissue designs represent the wide variety of alternative designs. Research to confirm the benefits and drawbacks of different materials and manufacturing methods allowed for educated selection of the most suitable materials and device assembly. The materials have a wide range of costs, which was also factored into the material selection of the final device. The final device aimed to cost less than $200, be feasible to produce, and functional to meet the client’s needs. The hard tissue aspect of the device had to be feasible to produce in the sense that parts are easily available to order and work with, and the final design is easy to construct and assemble with basic manufacturing tools and techniques. The chosen design was also determined and produced given the available time and resources for this MQP.

4.3.2. Soft Tissue Conceptual Designs

4.3.2.1. Epidermal Conceptual Designs

The epidermal layers consist of skin, muscle, adipose, and fascia. Conceptual designs of different combinations of these four layers were created by the design team to determine the most optimal combination of layers based on the functions of the device. The most important function for this aspect of the device was that it felt realistic. The exact anatomy of all four layers was not necessary to accomplish the goals of the device, but ultimately, multiple layers were combined for the final device. Table 19 depicts the iterations of epidermal conceptual designs the design team compiled.

Table 19: Epidermal layers conceptual designs

Design	Materials	Benefits	Drawbacks
1	**Skin**: Suede **Muscle**: Elastic bandage (cotton & polyester) **Adipose & Fascia**: Polyester fiberfill sheet	• Suede has optimal thinness and is pliable • Polyester and elastic bandage are inexpensive	• Suede is not elastic • Elastic bandage will not provide support • Suede is expensive
2	**Skin**: Soft elastic fabric (polyester) **Muscle**: Elastic bands **Adipose & Fascia**: Neoprene foam sheet	• Soft elastic fabric is durable and behaves elastically • Entire conceptual design is inexpensive • Elastic bands side by side create structure similar to muscle (bundle of fibers)	• Elastic bands are not durable when stretched too much • Elastic bands may not be compatible with fiberfill sheet (ripping & wear)
3	**Skin**: Latex layer covered with polyester fabric **Muscle**: Latex strip **Adipose & Fascia**: Polyester loose batting	• Latex is very elastic • Latex strip gives support • Loose batting is moldable to necessary thickness • Inexpensive design	• Latex feels too synthetic & does not act like biological tissue to touch • Latex allergies make design unsafe • Questionable durability
4	**Skin**: Fleece (polyethylene terephthalate)	• Fleece has an accurate feel • Nylon gives support to internal organs	• Fleece is not elastic and may be too thick

	Muscle: None **Adipose & Fascia**: Polyester loose batting and nylon stockings	- Loose batting gives more control over thickness - Inexpensive design	- No support for internal organs without muscle layer - Lacks durability

Although each conceptual design consists of a mixture of layers for the skin, adipose, fascia, or muscle, the best materials from each conceptual design were taken and combined to create the final design. Specific benefits and drawbacks to each material were researched and studied to determine the optimal materials that fit the functions and objectives of the project. Samples of materials that were inexpensive were purchased to assist in choosing and eliminating materials to work towards the final design as well.

4.3.2.2. Bladder Conceptual Designs

In a canine's anatomy, the bladder attaches at the rear end of the abdominal cavity below the colon. The bladder is balloon-shaped and tapers down towards the back to the urethra. It is typically filled with varying volumes of liquid and has the ability to feel fairly mobile during palpation. This anatomy was considered during the conceptual design phase for the bladder. Important objectives of the device for the bladder were realistic feel and anatomically correctness. Durability was another important objective specifically for the bladder because it would most likely be filled with liquid. If the material of the bladder was not durable, it could potentially ruin the device by breaking and releasing liquid into the abdominal cavity. Table 20 depicts the iterations of bladder conceptual designs compiled by the team.

Table 20: Bladder conceptual designs

Design	Materials	Benefits	Drawbacks
1	**Lining**: Latex balloon **Filling**: Water	- Latex balloon has necessary elasticity - Inexpensive design	- Latex balloon lacks durability and may get stiff over time - Water may not be viscous enough - Not realistic mobility of bladder
2	**Lining**: Silicone molded shell **Filling**: Molasses/syrup with higher	- Silicone can be shaped to exact structure of bladder - Thicker silicone structure is durable - Feels more realistic	- Liquid food product is not durable and composition may change over time

	viscosity than water		• Potential for destroying device if there is a leak or break • Not realistic mobility of bladder • Expensive design
3	**Lining**: Latex condom **Filling**: Water-based lubricant	• Latex condom is durable • Lubrication of condom and added water-based lubricant creates a preserved and mobile structure • Viscosity of fluid is more realistic • Shape of latex condom filled with liquid anatomically correct to bladder • Latex condom has proper elasticity	• Lubricant could dry out • Latex condom breaking could destroy device with filled liquid • More expensive design
4	**Lining**: Latex liner **Filling**: Air	• Latex liner has elasticity • Durable design • Inexpensive • No chance of destroying device is tear or break occurs in the latex	• Latex liner could dry out • Latex liner might not have anatomically correct shape of bladder • Air does not have the same feel as a liquid-filled structure

The benefits and drawbacks of each bladder conceptual design were based on team discussion, research, and trial and error experience. Although each design has numerous drawbacks, the drawbacks were weighed against the benefits to determine the most optimal design. Samples of materials that were inexpensive were purchased to assist in choosing and eliminating materials to determine the final design as well.

4.3.2.3. Colon Conceptual Designs

In a canine's anatomy, the colon runs parallel to the spine and attaches to the rear end of the abdomen to deposit into the rectum. When palpated, stool is soft and malleable when pressure is applied from the fingers. The lining of the colon is imperceptible to palpation; it is the stool that may be palpated. The colon is palpable with stool and impalpable without stool. When palpated, it can be plucked similar to a guitar string, springing back into its original orientation. The design team kept the properties and behavior of the colon when brainstorming conceptual designs. These conceptual designs are described below in Table 21.

Table 21: Colon conceptual designs

Design	Materials	Benefits	Drawbacks
1	**Lining**: Silicone molded shell **Filling**: Small-grain sand	• Silicone could be molded to accurate shape and thickness • Sand composition will not change over time • Sand is inexpensive	• Silicone is expensive • Sand may not have correct consistency • Sand may leak and destroy the device
2	**Lining**: Penrose drain (latex) **Filling**: Non-drying clay	• Clay has accurate consistency • Penrose drain is accurate shape • Clay can be shaped and molded to be anatomically correct	• Clay could harden over time • Penrose drain latex could dry out and break over time • Difficult to control amount of clay in Penrose drain
3	**Lining**: Polyvinylidene chloride (plastic wrap) **Filling**: Flour	• Inexpensive design • Accuracy of shape and size can be controlled with plastic wrap • Flour composition will not change over time	• Flour may not be correct consistency • Flour may leak and destroy device • Plastic wrap is not durable or easy to permanently seal

The benefits and drawbacks of each colon conceptual design were based on team discussion and research. Although each design has numerous drawbacks, the drawbacks were weighed against the benefits to determine the most optimal design. Samples of materials that were inexpensive were purchased to assist in choosing and eliminating materials to determine the final design as well.

These soft tissue designs represent the preliminary ideas the design team had for the construction of the device. While many materials were researched, it was difficult to make a final decision on these materials until a few chosen designs had been constructed and tested against the functions and objectives of the device. The designs chosen for construction were the ones that met many of the objectives of the device based on the benefits and drawbacks. These chosen designs ultimately were the alternative designs that the team chose from to decide upon the final design for the device. Research to confirm the benefits and drawbacks of different materials and ease of constructing allowed for educated selection of the most suitable materials and device assembly. Most of the soft tissue design materials are fairly inexpensive and available in bulk, although some materials, such as silicone (SmoothOn) are very expensive in bulk and difficult to acquire. The final device aimed to cost less than $200 overall, be feasible to produce, and functional to meet the client's needs. The soft tissue aspects of the device must be feasible to produce in the sense that parts are easily available to order in bulk and work with, and the final design is easy to construct and intuitive to assemble. The chosen design was also determined and produced given the available time and resources for this MQP.

4.4. Alternative Designs

4.4.1. Alternative Hard Tissue Designs

The hard tissue aspect of the device had to be determined before the soft tissue because the soft tissue was supported by and oriented around the hard tissue design. The hard tissue design was the foundation of the device, and moving forward with the project required a design that supported the addition of soft tissue alternative designs. The most important objectives required by the hard tissue design were durability, reproducibility, and portability. This design also had to be reusable, and this included adding and subtracting different iterations of soft tissue designs to one device. Another objective that was important to consider was the how realistic the design was to the skeletal structure of a beagle.

4.4.1.1. Conical Design

The conical design was modeled after a cone and a computer-aided design model completed in SolidWorks© is shown below in Figure 8.

Figure 8: Conical design

The design utilizes a tapering, conical spine that connects the ring that serves as the ribs of the body to the ring that acts as a pelvis. Both the cylindrical ribs and the conical spine would be fabricated from a flexible, lightweight plastic, such as high-density polyethylene. The cylindrical rings serving as the pelvis and ribcage are designed to be hollow to anatomically mimic these structures in a live canine. These parts would either be bonded or screwed to the conical spine. The supports of this design are two rectangular prisms of different heights that are fixed to each ring. The materials used to simulate the soft tissue of the device would be wrapped around the conical spine and fixed to each cylindrical end to create an abdomen-shaped region. The conical-shaped spine guides the shape and structure of the soft tissue materials to simulate the roundness and curvature of a canine abdomen. The structural supports are minimalistic, therefore reducing the cost of materials needed for this design and allowing the device to remain fairly lightweight.

Anticipated difficulties with this design included the ability to fabricate plastics using the given dimensions, such as the conical spinal column. This may increase the cost of the design and the required time and tools to produce it. This design also lacked the structural support necessary for the hard tissue base of the device. Without the addition of the soft tissue materials, this structure may remain stable, but when these materials are included and palpated, the structure would have less stability with only two points of contact with the ground. The design team determined that a more stable, three-point or four-point base of the device would serve better in the final design. For these reasons, the conical design was ultimately deemed unfeasible.

This design will affect the experience of the veterinary student by providing a realistic structure of a canine abdomen that tapers to the pelvis. Although the spine, pelvis, and rib cage pieces of the design are realistic, the supports may hinder palpation. The rear support does not simulate the gap where the two legs of a canine would meet at the pelvis. This could obstruct the palpable area from the student, and it is not realistic to canine anatomy. The stability of the design may also affect a student’s experience with the device. Tipping or swaying during palpation does not create a realistic experience, and it may also prevent the student from focusing on the task of learning. A one or two-handed palpation approach should be attainable to perform on the device, and the conical design may not support the proper learning experience.

4.4.1.2. Rib Design

The rib design was modeled to more closely resemble the rib cage of a canine and a computer-aided design model completed in SolidWorks© is shown below in Figure 9.

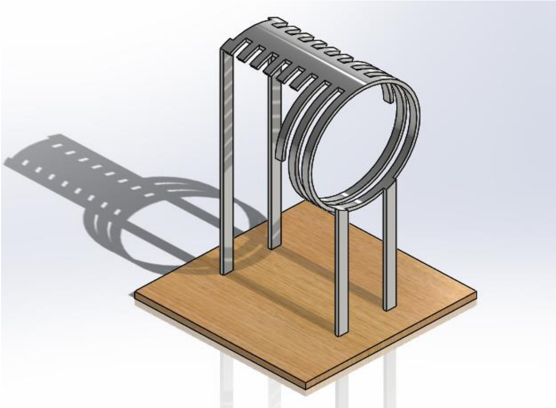


Figure 9: Rib Design

This design includes a rib cage ring, but not a pelvis ring. To create the spinal and rib structures, a cylindrical-shaped, rigid, lightweight plastic would be cut to the shape shown in Figure 9, resembling the skeletal structure of a canine. This design utilizes a single piece of plastic to achieve the cut and shape necessary for anatomical resemblance to a canine's skeletal structure. There would be four supports on this design, composed of either wood or a rigid plastic. These supports would be cut into rectangular prisms to raise the body the appropriate height from the base. Two supports would be fixed to each opposite end of the abdomen piece. The materials used to simulate the soft tissue of the device would be wrapped around the protruding pieces from the spine and fixed to each end to create an abdomen-shaped region. The purpose of the rib design is to guide the shape and structure of the soft tissue materials to simulate the roundness and curvature of a canine abdomen. This better simulates the skeletal structures underlying the soft tissue materials. This design uses less material than the conical design and provides more structural stability, as there are four supports instead of two. The supports are also attached to a wooden base to increase stability and weight of the device.

Figure 10: Rib cage of a canine

Anticipated difficulties with this design included the time and detail necessary to replicate the skeletal shape shown in Figure 10 out of a piece of plastic. While this design may be more anatomically correct, it may not be necessary for the device to accomplish the determined functions. Initially, the design team believed constructing individual rib-shaped pieces was important for the device to feel realistic. After several interviews with the client, the team discovered palpation of the ribs was less important to the function of the device. This assisted in moving forward with designs that were simpler and easier to reproduce. These designs were still able to simulate the transition of the palpable abdominal soft tissue to the impalpable region where the ribcage begins. The most critical parts of the device are the soft tissue materials, and the rib design may spend too much time and too many resources on creating an unnecessarily detailed design. A basic static analysis of this structure's rib pieces also allowed the team to determine the structure to lack the function of durability. If forces are constantly being applied on each individual rib piece from the soft materials fixated on these pieces, they will bend and wear over time, and this could lead to failure of the device. While failure of the device would not be catastrophic, it would not satisfy one of the most important functions of durability. This design would also be more difficult to replicate and reproduce. The wooden base also hinders the lightweight and portability functions of the device, so the design team decided a base platform should not be included in the final design.

4.4.1.3. Straight-Back Spine Design

The straight-back spine design was modeled to be a design that would be easiest to fabricate and manufacture, and a computer-aided design model completed in SolidWorks© is shown below in Figure 11.

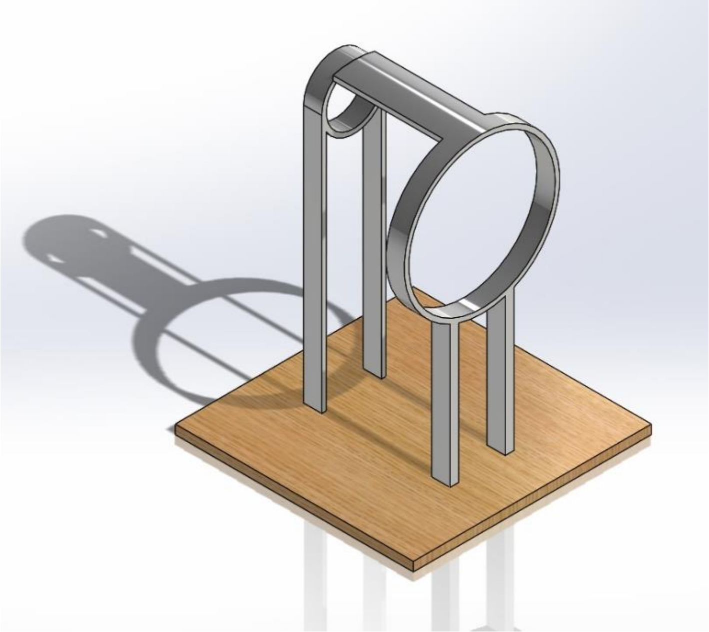


Figure 11: Straight-back spine design

The rib cage consists of a larger diameter ring that would be made out of a lightweight, rigid plastic. This cylinder of plastic would be used for both the rib cage ring and the spine piece that connects to the pelvis part of the model. Both the spine and rib cage would be attached and fabricated from a single, cylindrical piece of plastic to create a more rigid and durable structure. The pelvis ring would also be composed of the same type of plastic of a cylinder with a smaller diameter of approximately 4 inches, and this piece would be attached to the spine either through melting the plastics together or fixing them together with screws. Protruding from both the rib and pelvic rings would be the four leg supports. These supports would either consist of wood or the same plastic as the body pieces, and they would be cut into rectangular prisms at the correct height. The supports would be fixed to the pelvic and rib rings, and they would protrude down to a wooden base. The bottom of these supports would be fixed to the wooden base as well. This design is fairly simple, simulates the appropriate anatomical structures, and it is structurally stable. The weight of the wooden base prevents the device from being lifted up during palpation to mimic the weight of a mid-sized canine.

Although this design is simple, it would be more difficult to fabricate and manufacture. Fixing or melting plastic pieces together requires certain tools and skills that may be difficult to replicate for ten different devices. This form of connecting the base structure together may also cause the device to be less structurally durable. These pieces do not fit together well or easily, and this prevents the device from remaining as stable as possible over a long period of time. As time progresses and the device is subjected to constant wear, the seams where the device is fixed or melted together may eventually fail. This will not accomplish the design team's objective of a device that is durable and long lasting. The wooden base also hinders the lightweight and portability functions of the device, so the design team decided a base platform should not be included in the final design.

4.4.2. Alternative Soft Tissue Designs

The soft tissue aspect of the device was determined once the hard tissue design had been chosen. Even though this was the logical order of the project, the final design selection of both the hard and soft tissue aspects is described after the alternative designs section. The soft tissue was the substance of the device, and it determined the overall success of the device by accomplishing the objectives of being realistic, accurate, durable, and reproducible. It was necessary that the materials used in the soft tissue aspect were realistic to each biological tissue the material was representing. The three main tissues and organs necessary to represent in this device were the epidermal layers, the bladder, and the colon.

4.4.2.1. Epidermal Alternative Designs

The first epidermal alternative design was composed of latex sheeting, and varying thicknesses of latex are shown below in Figure 12.

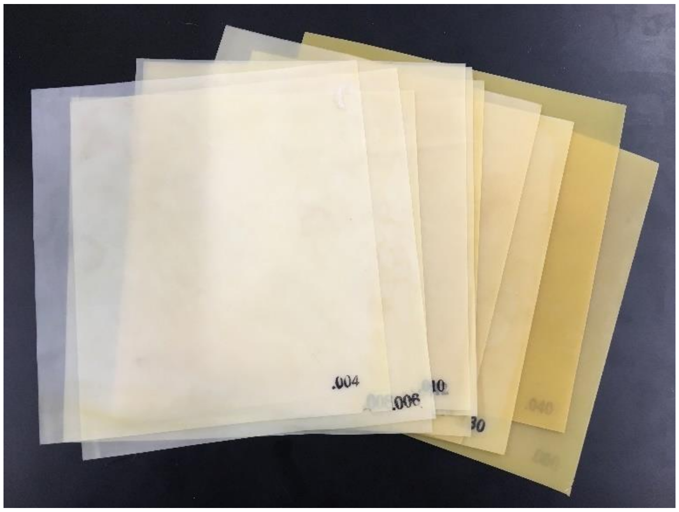


Figure 12: Latex sheeting of various thicknesses

An appropriate chosen thickness of a latex sheet would closely simulate the elasticity of skin. This material would be wrapped around the abdominal region, cut, and sewed together to create a taut outer layer. Latex would have the stiffness to hold the abdominal filling and organs within the device, but it is also elastic enough to stretch and move with palpation of the device. The elastic modulus of this material could easily be tested and measured to determine if it matches the elastic modulus of skin. Drawbacks to this design were that latex sheeting is reasonably expensive, latex crinkles and does not form to the abdomen unless stretched very tight, and this design has potential to be unsafe for those with latex allergies. Although latex is appropriately elastic, it might not feel realistic and accurate to represent skin and epidermal layers.

The second epidermal alternative design was composed of neoprene sheeting, and a representative image is shown below in Figure 13.

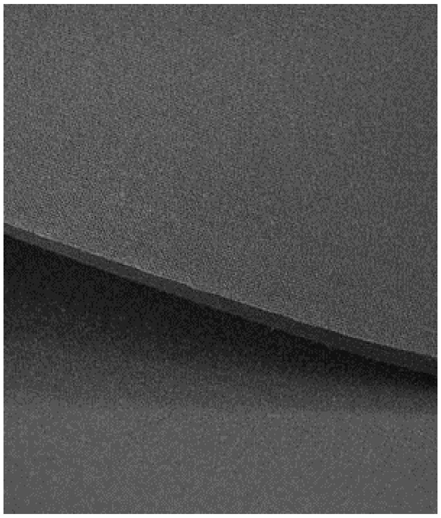


Figure 13: Neoprene sheeting thickness

A specific thickness of a neoprene sheet would simulate multiple outer layers of a canine epidermis. Neoprene is spongier and thicker than latex, and it has the ability to simulate the adipose and muscle layers as well as the skin. Neoprene is elastic, compressible, and resists degradation, therefore fulfilling the objective of durability. This material would be wrapped around the abdominal region, cut, and fixed together to create a taut outer layer. Drawbacks to this design were that neoprene sheeting is more expensive than latex sheeting, and it is thicker and heavier than originally expected. It might be difficult to palpate organs through a thick, stiff outer layer of neoprene. Although neoprene has a slightly elastic quality, it might not feel realistic and accurate to represent skin and epidermal layers. The texture of neoprene is also not accurate to how the abdomen of a canine feels.

The third epidermal alternative design was composed of a polyester-fleece fabric as shown below in Figure 14.

Figure 14: Polyester-fleece fabric

A polyester-fleece fabric can be purchased for less than $10/yard at any craft store. The dimensions could be easily cut and altered to create the appropriate size to wrap around the abdominal region and fixate together. Polyester-fleece is soft, slightly elastic, and has an appropriate thickness. This material is closely accurate to the abdominal region of skin and fur on a canine. A drawback of this material was that it is not resilient or durable; this material can easily be ripped or fall apart. This fabric is also not elastic enough to stretch and move with palpation. Ultimately, all three of these alternative designs were deemed inappropriate for the device, and they were not chosen as the final design.

4.4.2.2. Colon Alternative Designs

The colon must lie parallel with the spine at the rear of the palpable area. The stool within the colon is palpable, while the colon tissue is not, especially when it does not contain stool. The colon is cylindrical and the stool can be pressed and shaped. The very first alternative design for the colon the design team created is shown below in Figure 15.

Figure 15: Colon Alternative Design 1

This design consisted of flour wrapped in plastic wrap, or polyvinyl chloride. Any amount of flour could be added to the design to create the desired dimensions of the colon. Plastic wrap is also elastic enough to stretch and mold to the flour shapes during palpation. At approximately 0.45 GPa, plastic wrap is over four times stiffer than skin (Modulus of Elasticity, n.d.). A drawback to this design was that flour is not the correct consistency to simulate stool. Plastic wrap is also difficult to seal the structure with the correct size and thickness to create a repeatable design. Although an appropriate place to start, this design did not meet many of the objectives necessary to be successful.

The second alternative design for the colon was a Penrose drain filled with water and molding clay, and this is shown below in Figure 16.

Figure 16: Penrose drain and modeling clay

This design was accurate to the shape and size of the colon, and the consistency of the molding clay and water created a very desirable texture for the stool. When palpated alone, this design was very realistic, but once this design was placed under layers of fabric and cotton-polyester batting, it was difficult to palpate. The diameter of this design was also much smaller than the dimension specifications for the colon. The water also caused some of the clay to become dry and crack, creating an undesirable texture. Although this design was not chosen due to the drawbacks, the Penrose drain was a material that the design team decided to proceed with using in alternative designs. A Penrose drain is simply a soft latex tube.

The third alternative design for the colon was a Penrose drain filled with clay that hardens, and this is shown below in Figure 17.

Figure 17: Penrose drain and air-hardening clay

This design was similar to the second colon alternative design with minor modifications. The ends were sealed shut with knots, and a different clay was used inside the Penrose drain. The Penrose drain was filled with clay that hardens to create a colon with a larger diameter, but this diameter was still too small compared to the specification of approximately 30mm. In addition, clay that hardens ultimately did not supply the most accurate texture of stool. This design was too stiff and difficult to palpate. Due to the lack of accuracy and realistic feel, this alternative design was not chosen as the final design.

4.4.2.3. Bladder Alternative Designs

The bladder is balloon-shaped, tapering back to attach at the rear of the canine at the pelvis. When palpated, the bladder is mobile and slips between the fingers when palpated. The first alternative design for the bladder was a latex balloon filled with water as shown below in Figure 18.

Figure 18: Latex balloon filled with water

This design was simple, and it was the first bladder the design team created. This design is very inexpensive, and varying volumes of water may be used to fill the balloon to the desirable bladder volume specifications with ease. Although this design accomplished a few of the objectives, it was not accurate to the feel of a bladder. Even though balloons are elastic, they are not as mobile as a palpable bladder. This design was not durable either. The first bladder alternative design was an appropriate starting point for the bladder, but it did not meet enough of the objectives to be successful.

The second alternative design for the bladder was a silicone-based “liquid rubber” molded into a sphere. Silicone was chosen as an alternative design because it is a rubbery plastic that had the potential to simulate a biological bladder. This material could also be shaped and molded into the desired structure. The design team hypothesized that liquid rubber might be used to create human palpation models. This alternative design is shown below in Figure 19.

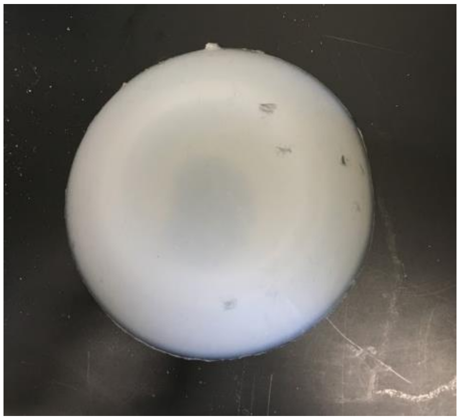


Figure 19: Silicone sphere

This second alternative design for the bladder is more complex and expensive to make, however it can be shaped to the specifications for the bladder. This design would be durable and accurate because the silicone molding material is thick, elastic, and resilient. This bladder design does not meet the objective of reproducibility, nor is it accurate to the texture and mobility of a palpable bladder. Therefore, this alternative design was deemed inappropriate for the device and was not chosen as the final design.

4.5. Design Concept Modeling, Feasibility Studies

To fulfill the goals of this project given the budget and time constraints, decisions were made based on the feasibility of each idea and design throughout the different stages of creating the final model. The first stage of the design process was determining the hard tissue foundation of the device. Section 4.4.1 depicts three hard tissue alternative designs that do not include the final design. The final design constructed from polyvinyl chloride (PVC) was chosen based primarily on the feasibility of manufacturing the device. This was based on client interviews and project assistance by the manufacturing knowledge of Thomas Partington, a machinist in the WPI machine shop. Mr. Partington is a lab manager of the Unit Operations Laboratory at WPI, and his expertise has been to provide machine shop services to students and faculty at this institution for many years. The PVC hard tissue design was created as a compromise between the ideas of the design team and professional opinion of the machinist. His professional expertise has stemmed from experience working with many different materials and machining procedures. Mr. Partington assisted the design team in understanding the importance of how materials work together and fit together, the expenses of ordering parts, and the time necessary for certain machining methods. To satisfy the objective of reproducibility, the process of purchasing, machining, and assembling the design must be cost effective, time efficient, and straightforward. A design that was arduous, expensive, or requires complex machining methods and machinery was not a successful design for this project. The final hard tissue design exceeded the wants and needs of the client, and it was created from parts that were easy to access, machine, and manufacture, as well as it remained within the budget.

After choosing the hard tissue final design, the design team had to determine the final design and materials for the soft tissue aspect of the device. The material options for the epidermal layers fell within a wide price range. The materials used in the final model were chosen based on a compromise between the material properties and the cost of the materials. When deciding on methods and materials for the organs used in the final model, decisions were made based on the feasibility of their manufacturability. The creation of the bladder required numerous trials with different materials. Overall, the final device exceeds the needs and wants of the client while meeting the budget and time expectations.

4.5.1. Optimization

The optimal design was based on an erect, adult male beagle. The design needed to provide support for the palpable organs as well as simulate the anatomical structure of a beagle.

Organ material choices were based on availability, price, and realistic feel. The first organ selection was for the skin, muscle, and fascia layers as this is what students learning to palpate feel first. These layers dictate how realistic the device initially feels. These layers should simulate the abdominal region of skin and muscle on a canine. This can be described as the short and soft fur, the mobility of the skin sliding over fat and muscle layers, and the appropriate thickness of these layers. The abdominal filler was selected based on its resistance to applied pressure. It does not act as a liquid but can be easily maneuvered around to feel internal organs through it. The colon was selected based on how closely its reaction to applied pressure matched that of a live animal's colon. It should not have much resistance to being pinched, but it should not move caudally or cranially. When pulled down and released, it should lightly spring back into place. It should also feel smooth. The bladder was selected based on if it had fluid pressure similar to that of a half-full bladder. It should be slightly more resistant to being squeezed. If squeezed tightly, it should slip out of the hands. It may rotate in 360 degrees, but it is restricted by its attachment at the back of the pelvis. It should have a smooth surface and the filler should feel like a liquid. The final weight of the abdominal cavity was 4 lbs. The structural support weighed 16 lbs. It provides support and structure for the abdominal cavity.

4.6. Final Design Selection

4.6.1. Hard Tissue Design Selection

The final design of the hard tissue aspect of the device was created from polyvinyl chloride (PVC) piping and connectors fastened together with stainless steel screws. The PVC created the four legs, shoulders, a pelvis, and spinal supports of the device. Two circular ribs were cut from Lexan sheets to create ribs that were slid onto the PVC spine and secured with a non-marring flat point set screw for adjustments. The computer-aided design model completed in SolidWorks© of the final design and the machined prototype are shown in Figures 20 and 21. The decision process of the hard tissue skeletal support of the device was determined through a number of variables. These included research of materials and plastics done by the design team, the anatomy of a canine skeleton, and the assistance of professionals both in the veterinary field and in the manufacturing field.

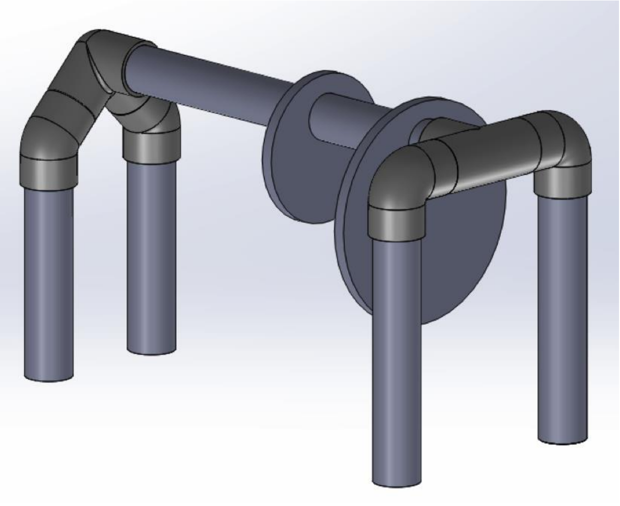


Figure 20: SolidWorks© model of hard tissue

Figure 21: Final hard tissue prototype

The design team met with Thomas Partington of the Worcester Polytechnic Institute machine shop multiple times to discuss design ideas. The team showed him alternative designs and ways to manufacture these designs were discussed. Mr. Partington assisted with instruction of materials, best fit design for the materials, and a final design that included all wants and needs of the design team based on the functions, specifications, and revised client statement. Polyvinyl chloride (PVC) was chosen for the final design hard tissue structure because it fits the needs of the device. PVC is a lightweight plastic, and this allows the device to be portable for carrying it to classrooms and laboratories. It is also a durable, as the plastic is corrosion resistant, and this accomplishes the design team's goal of a device that is long lasting. PVC also achieves cost effectiveness because PVC piping and connectors can be purchased in bulk for reasonable prices. The cost of all necessary PVC parts for one device was approximately $25. This plastic is also easy to process and machine to the design's specifications. It is a mechanically stable and rigid material. PVC is a versatile material that can be purchased in bulk as piping and assembled to create a design using connectors and other fixation methods. The specifications of the PVC materials used in the hard tissue final design are described in Table 22 below.

Table 22: Hard tissue design specifications

Item	**Number Per Device**	**Length (inches)**	**Pipe Diameter (inches)**	**Outer Diameter (inches)**	**Additional Features**
45 Degree Elbow	2	1.25 socket depth	For 1.5 pipe size	2.25	Female unthreaded socket ends
90 Degree Elbow	2	1.28 socket depth	For 1.5 pipe size	2.25	Female unthreaded socket ends
Side Outlet Elbow	1	1.31 socket depth	For 1.5 pipe size	2.25	Female unthreaded socket ends
Tee	1	1.31 socket depth	For 1.5 pipe size	2.25	Female unthreaded socket ends
Short Legs	2	10.25	1.5	1.9	Hollow pipe
Long Legs	2	12.75	1.5	1.9	Hollow pipe
Spine	1	19.75	X	1.875	Rod

While the majority of the hard tissue final design was composed of PVC, this was not the only material used. Stainless steels screws and polycarbonate sheets were also included in the final design. Lexan™ polycarbonate was a material chosen for the final design with the assistance of Mr. Partington. Lexan was interfaced with the PVC and served as the rib cage of the body of the canine. Lexan is an amorphous thermoplastic that is versatile, tough, and durable. The Lexan ribs were used to section off a palpable area and give the device a more accurate abdomen.

Although most products were ordered, the polycarbonate, otherwise known as Lexan™, was not ordered. Existing scrap polycarbonate material was used to create the ribs of the final design, and this material was not ultimately included in the cost of the device. The cost of ordering Lexan sheets was calculated into the cost of the hard tissue device shown in the table below. The product information on the hard tissue design as well as the cost per device is shown in Table 23.

Table 23: Hard tissue design product information and cost

McMaster Carr #	Item	# Req'd Per Dog	Unit Price ($)	Cost of One Device
4880K35	45-degree elbow	2	1.64	3.28
4880K25	90-degree elbow	2	1.16	2.32
4880K634	Side outlet elbow	1	3.16	3.16
4880K45	Tee	1	1.54	1.54
48925K95	PVC Pipe 5ft long	1.5	7.12	10.68
8745K25	PVC Round 5ft long	0.5 foot	7.99/ft.	4.00
91771A539	¼-20 screws pkg/50	10	0.13	1.13
8560K265	Lexan (Cast Acrylic) 12"x12"x1/2"	1	30.24	X
8560K274	Lexan (Cast Acrylic) 6"x6"x1/2"	1	8.46	X
8745K22	PVC End Cap 1ft long	8/12 foot	5.33	3.56
6448K106	Rubber inner stoppers	4	1.25	5.00
The Home Depot Model # 55141	Sand	8 lbs.	3.98 / 50lbs	0.64
92313A574	Cup Point Set Screw	2	0.39	0.77
Total without Lexan cost ($38.70)				**$36.08**

The PVC was purchased in multiples of 5-foot pipes. These were cut to the dimensions of the long and short legs and the spine. Using a lathe, the ends were turned down so that a press-fit into the fittings would be possible. Sand was compacted in each of the legs and held in place using rubber caps on the bottom of the pipe, and a rubber stopper in the inner pipe. In between each pipe and fitting seal, a solid PVC pipe with a diameter of 1-⅞ inches was inserted. A hole was drilled through the fitting, hollow PVC pipe, and solid PVC round. An 18-1 stainless steel flat head Phillips machine screw (¼ inch-20 thread, ⅝ inch length) was screwed in to secure the fitting. The final model was 15 inches high and 23 inches long, and according to the specifications, the overall height of a beagle is approximately 16 inches. The length of the device is not as important as the length of the palpable region, which was adjusted to 6 inches to meet specifications.

Lexan™ was used to create a smaller diameter rib in the form of 6-inch and 9-inch diameter rounds, 0.6 inches wide. These Lexan™ rounds had 2-inch holes cut to the size of the PVC pipe outer diameter near the top of each round. This allowed them to slide onto the spinal section of the PVC piping for to create the appropriate palpable region of 6 inches from the pelvis to the rib. A threaded hole was drilled into the side of each round, and a non-marring flat point set screw was used to fix it in position on the PVC pipe. The Lexan© rounds and PVC piping cut to specifications are shown in Figs. 22 and 23 below.

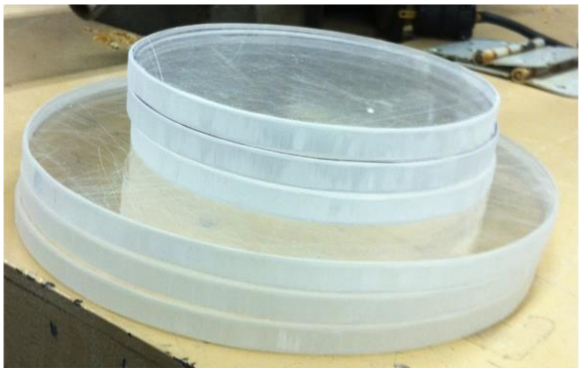


Figure 22: Lexan™ rounds

Figure 23: PVC cut pipes for final design

4.6.2. Soft Tissue Design Selection

The decision process of the soft tissue component of the device was predominantly determined through an iterative trial and error process of comparing materials and designs to each other against the objectives of the device. The material or design that best fit the objectives and the needs of the client was chosen for use in the final device. The choices made about each design were then validated by the team and client. Mechanical testing experiments were conducted to ensure the chosen materials fit the objective of durability and that the materials were as realistic as possible compared to the representative biological tissue of an animal. These materials underwent uniaxial mechanical testing to determine the elastic modulus of each material to compare it to the equivalent in an animal. For example, the 100% polyester panne velvet fabric was mechanically tested and the elastic modulus of the material was compared to the elastic modulus of the abdominal skin of a porcine. The mechanical testing is further described in Section 5.

The ultimate decisions were based on sense of touch and feel because the most important objectives had to satisfy the tactile sense. The purpose of this device was to most accurately simulate the movement, weight, consistency, and feel of a live canine's abdomen. This was mainly accomplished by utilizing the client's knowledge of veterinary abdominal palpation. Once the final design for the hard tissue component had been determined and a prototype of the structure created, the design team began to test different iterations of soft tissue designs and materials. The team first researched materials online that might have been suitable for each different aspect of the soft tissue component of the device. As mentioned previously, these included skin, fat, muscle, fascia, a colon, a bladder, and abdominal filler. Aside from these main components of the abdomen, other materials were necessary to simulate an enlarged liver, a constipated colon, a bladder with stones, and a mid-abdominal mass. Some of the final devices were also altered to contain more layers of fat to simulate an overweight canine to make palpation even more difficult for students using the device.

Through online research and local material stores, the design team purchased an assortment of materials to work with to create the soft tissue component of the device. An array of fabrics of varying textures and thicknesses were purchased for the skin, fat, and muscle layers. Latex Penrose drains, various clays, and baby powder were purchased to create a colon. Latex balloons, other latex products, silicone mold-making kits, and lubricants were purchased for the design of the bladder. Batting and foams were purchased for abdominal fillers, and stress balls and other various objects were purchased for foreign bodies. These materials became the alternative designs.

The team began by assembling the first prototype using the PVC design constructed from the machine shop. The materials were temporarily fixed to the device to create the palpable area using duct tape, zip ties, and pipe cleaners. An example of these assemblies is shown in the Figures 24 and 25 below.

Figure 24: Attachment of temporary alternative designs

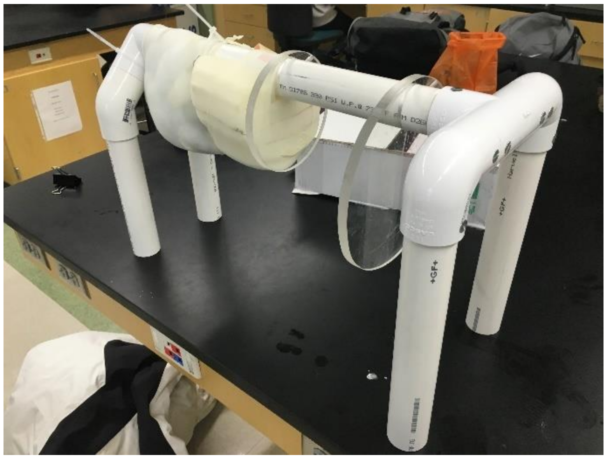


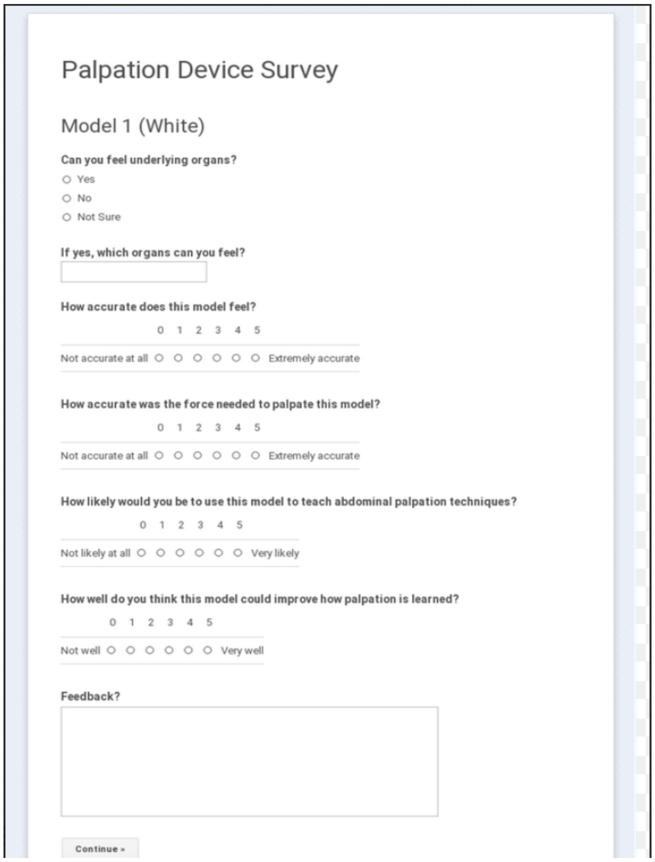
Figure 25: Iterations of alternative designs

Each week, the team assembled a new iteration of the prototype and the client assessed the device. The comments and suggestions were collected from the client and used to modify the device to work towards a device that simulates an abdomen accurate to that of a live canine. Each alternative soft tissue design for a specific aspect of the abdomen was substituted in to the hard tissue final design and combined with other soft tissue designs. More specifically, each colon alternative design was temporarily attached to the hard tissue model and combined with alternatives designs for the bladder, abdominal filler, epidermal layers, and abnormal conditions. Through the first several weeks, one device was modified each week to work towards the final design. Once some alternative designs were determined to best fit the objectives for the final device and the client had deemed the prototype accurate enough, three more models were made with slight modifications in the type of organs and epidermal layers on the device. Once this step was completed, there were four different prototypes of the device. Each one had the same hard tissue component, but the soft tissue components varied and included different combinations of the alternative designs for each organ. These models were compared against each other to determine the designs that were most accurate and realistic. Table 24 below describes the soft tissue alternative designs within each model.

Table 24: Soft tissue alternative prototypes for testing

Prototype	Skin	Fat	Abdominal Filler	Colon	Bladder
1	White 100% polyester panne velvet fabric	Cotton sheets	Medium amount of polyester loose batting	Alt. design 2	Final design (1 layer of latex condom)
2	Black alt. design 3	None	Large amount of polyester loose batting	Alt. design 2	Final design (1 layer of latex condom)
3	Brown 100% polyester panne velvet fabric	Thin foam pad	Medium amount of polyester loose batting	Final design	Final design (1 layer of latex condom)
4	Black 100% polyester fabric (Non-panne & inelastic)	None	Large amount of polyester loose batting	Final design	Final design (1 layer of latex condom)

These four different prototypes were then tested by veterinary students and professionals at the Cummings School of Veterinary Medicine at Tufts University. The devices were set up and labeled 1 through 4. The veterinary students and professionals then palpated each different prototype, and completed a survey as they consecutively palpated each prototype. The final results of this survey were collected using an online survey. Figure 26 is an example of the survey that was conducted. An image of a veterinarian palpating a prototype is depicted in Figure 27.



Palpation Device Survey

Model 1 (White)

Can you feel underlying organs?

○ Yes
○ No
○ Not Sure

If yes, which organs can you feel?

How accurate does this model feel?

	0	1	2	3	4	5	
Not accurate at all	○	○	○	○	○	○	Extremely accurate

How accurate was the force needed to palpate this model?

	0	1	2	3	4	5	
Not accurate at all	○	○	○	○	○	○	Extremely accurate

How likely would you be to use this model to teach abdominal palpation techniques?

	0	1	2	3	4	5	
Not likely at all	○	○	○	○	○	○	Very likely

How well do you think this model could improve how palpation is learned?

	0	1	2	3	4	5	
Not well	○	○	○	○	○	○	Very well

Feedback?

Figure 26 Tufts survey #1:

Figure 27: Palpation device feedback at Tufts University

The results of the opinions of twelve veterinary students and professionals were collected, giving the design team professional feedback to determine which alternative designs best met the objectives. The results of this survey are shown below in Table 25. This table allowed the team to proceed with the best design to take input from the survey and improve feature of this design. Accuracy was assessed through a 1 through 5 rating of the overall accuracy of the device to a live canine. The objective of a realistic feel was assessed by determining the percentage of veterinary students and professionals that could feel the organs through the different layers. General comments and feedback was collected to determine potential improvements for the device and ways to assess the other objectives, such as durability and reusability. An observation of the state of the prototypes after the palpation of twelve subjects allowed the team to further assess the objectives of durability and reusability.

Table 25: Feedback from Veterinarian Survey

Prototype	Feels presence of underlying organs	Accuracy of model out of 5 (5 being most accurate)	Usefulness of model	General consensus from comments
1	42.9% yes	2 out of 5	1 out of 5	Too thick and soft; overweight dog
2	91.8% yes	4 out of 5	3.5 out of 5	Too easy to feel organs; need more force
3	90.9% yes	4 out of 5	4 out of 5	Too easy to feel organs; colon too small
4	54.5% yes	2 out of 5	0.5 out of 5	Required a lot of pressure to palpate; organs could be more pronounced

This survey allowed the design team to determine that the amount of epidermal layers and padding used in the device greatly affects the objectives. Foam padding for fat was too thick, while no padding made palpation too easy and unrealistic. While the presence of underlying organs was originally believed to be a good thing, feedback allowed the design team to understand that the organs may be too pronounced in prototypes 2 and 3. From the survey results, the design team proceeded forward by making necessary adjustments. The bladder pronouncement and durability was improved by adding another layer of a second latex condom. The colon diameter was increased by adding more molding clay to the Penrose drain. The epidermal layers were altered and improved by removing a single large foam pad layer and utilizing thin cotton batting sheets and smaller cuts of foam pads.

A series of decision matrices were also used to support the decisions the team made in choosing materials and methods for the final design, shown in Tables 26, 27, and 28. Separate decision matrices were performed for the skeletal-foundation, the epidermal layers, and the organs, in particular the bladder. The scale used for this matrix was from 1-3 and was used to describe the extent to which the material or strategy met the criteria, 1 being slight extent, 2 being some extent, and 3 being great extent. These decision matrix ratings were solely based on research, the outcomes of the cost calculations, the knowledge of the design team, the expertise of the client and a machinist, and the feedback from the survey of veterinary students and professionals. All mechanical testing for realistic material properties and durability was done separately and is described in Section 5.

Table 26: Hard tissue decision matrix

	Realistic/Accurate	Easy to Machine	Reproducible	Within Budget	Total
Conical	1	1	1	2	5
Rib	3	1	1	2	7
Straight Spine	2	2	1	2	7
PVC Pipe	**3**	**3**	**3**	**3**	**12**

Table 27: Bladder decision matrix

	Realistic/Accurate	Reproducible	Durable	Within Budget	Total
Balloon	2	3	2	3	10
Latex Condom	**3**	**3**	**2**	**3**	**11**
Ecoflex Smooth-on®	3	1	3	1	8

Table 28: Epidermal layers decision matrix

	Desired Elastic Properties	Realistic/ Accurate	Within Budget	Reproducible	Total
Foam Sheeting	**3**	**3**	**3**	**3**	**12**
Latex Sheeting	3	1	1	2	7
Cotton Batting Sheeting	1	2	3	3	9

The decision matrices above helped determine the materials, while the iterative process of the design team working with the client and the survey results from Tufts allowed the team to work towards the final design. A decision matrix was not used for the colon alternative designs because the logical flow towards the optimal design only compared different material stools and not the design as a whole.

The final design of the soft tissue aspect of the device consisted of many components. These components were built around the hard tissue component, and the skeleton design was how the soft tissue was connected. These components chosen for the final soft tissue design were realistic to each biological tissue the material was representing. The three main tissues and organs that created the soft tissue design were the epidermal layers, the bladder, and the colon. The organs were protected and surrounded by an abdominal filler of varying densities. The abnormal conditions and organs were added to the design as the last step. The deconstructed final design is depicted in Figure 28 to show the internal organs.

Figure 28: Deconstructed final design

The bladder and colon were the two organs necessary to make the device accurate to palpation of a canine. The bladder was made from a material more elastic than the alternative design of the balloon and more mobile than the silicone molding material. The design team research balloon-like products that have more durability, elasticity, and mobility than classic latex balloons. The best suitable option based on these criteria was a latex, lubricated condom. After constructing a synthetic bladder using a single condom filled with water-based lubricant mixed with water, and tied and sealed shut with an elastic rubber band, the client assessed and approved of the design. To increase durability and accuracy in anatomically accurate mobility of the bladder design, the team layered another latex condom on with lubricant between the two sheaths. An image of the final design of the bladder is shown in Figure 29.

Figure 29: Bladder final design

The colon alternative designs led the iterative process to the final design. The final design of the colon had modeling clay that does not dry. This clay was used to fill the Penrose drain to the specified thickness of 1.25" and sealed on each end with elastic rubber bands. The molding clay remains soft enough to simulate stool, while the Penrose drain does not hinder the palpation of the clay. The thickness of the clay within the colon is large enough to be palpable as well. An image of the final design of the colon is depicted below in Figure 30.

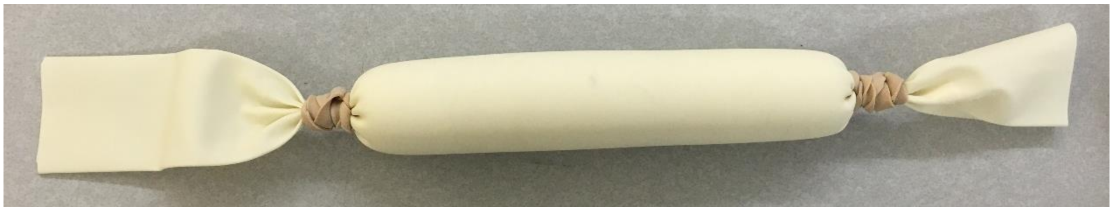


Figure 30: Colon final design

The internal abdominal filling gave support and shape to the abdomen of the device. This filling surrounded and protected the abdominal organs and assisted in tailoring the device to feel as realistic as possible. The design process of choosing the internal abdominal filling was an iterative one as well. The design team tested out different thicknesses and densities of foam padding, polyester batting, and soft fabric fillers and had the client evaluate each iterative design on how realistic it felt through the skin and how accurately it simulated a canine abdomen. The final design chosen utilized a combination of foam padding and polyester batting to protect the internal organs and give structure to the abdomen. A thick foam pad was cut into pieces to fit in the space above the colon and below the bladder as shown in Figure 31. This was used to keep the organs in the proper anatomical area within the abdomen. The rectus abdominis, or the abdominal muscle, was simulated by stretching a strip of latex from the pelvis to the first rib. This also served as a platform for the bladder and abdominal filler to rest on, and this layer can also be seen in Figure 31.

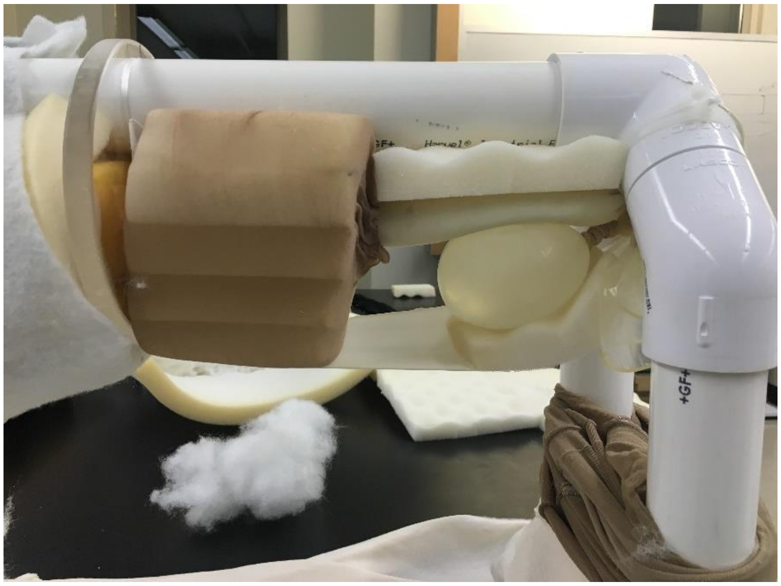


Figure 31: Internal structure and organs of final design

To fill the abdominal space next to the ribs, five thick foam squares of padding were cut and stacked to the shape of the abdomen and covered with a cutout of a nylon stocking. This is shown in Figure 32.

Figure 32: Abdominal filler of final design

The rest of the abdomen was filled with polyester loose batting molded into groups to fill necessary areas. The bladder was surrounded with this, as well as the open space between the foam pads and the organs. These pieces are shown below in Figure 33.

Figure 33: Adipose and abdominal filler of final design

Next, nylon stockings with the legs cut off were used as a fascia layer to cover internal abdominal filling and organs. This layer was pulled to fit over the palpable area and fixed over the first rib. Figure 34 depicts this layer in the process of being pulled over the abdominal padding.

Figure 34: Fascia layers of final design

A second nylon layer was used to give additional support to the abdomen, and this layer was pulled over the first and filled with minimal polyester batting to simulate fat. In addition, the space between the ribs was filled by rolling a thick foam pad into the shape of the ribcage and covered with a polyester fabric and a nylon sheath. Both the second nylon layer and the ribcage filling are shown below in Figure 35.

Figure 35: Adipose layers of final design

The final epidermal layer was composed of a 100% polyester panne velvet fabric. This fabric was cut to shape to fit over the length of the abdomen and ribcage. A strip of Velcro© was used to connect the fabric at the top so it can be easily removed. This fabric was chosen for its elasticity, texture, and thickness. It best simulates the soft and elastic skin of the abdomen of a canine. The final device covered with the final epidermal layer is shown in Figure 36 below. A final step-by-step description of the assembly process is further described in Chapter 6.

Figure 36: Final design

Below is the cost assessment of the soft tissue component of a single device.

Table 29: Soft tissue design product information and cost

Item #	**Item**	**# Req'd Per Dog**	**Unit Price**	**Cost of One Device**
PF12A- 357203	Poly-fill Supreme Fiber	1/5 of a 12oz bag	$6.10	$1.22
2332434-CUT-39	David Textiles Crushed Panne Velvet Fabric (58" W)	1 Yard	$5.00	$5.00
MED-DYND50426_CS	Penrose Drain (18" by 1") box of 50	2 individual Penrose drains	$17.97	$0.72
Hanes-90982	Sheer Energy Control Top Pantyhose (Size B, Medium Support	2	$4.47	$8.94
Trojan-64214	Trojan Magnum Premium Lubricated Latex Condoms, Large Size (12 pack)	2 individual latex condoms	$6.47	$1.08
IDL31-388	ClearGlide™ Ideal Electrical polymer-based lubricant	1/3 of 1-quart bottle	$10.44	$3.48
18834334	Crayola Model Magic Modeling Compound, 2lbs	0.25 lbs.	$24.99	$3.13
10030BULK2	Multipurpose foam (2" thick)	1 (22" W x 22" L)	$5.97	$5.97
Office Playground-1304	Stress Balls (12)	1 ball	$9.99	$0.83
Total				**$30.37**

As the client requested, a total of ten devices were produced as the final product of this MQP. Each of the ten devices is described below in Table 30. The design of each abnormal condition is described as well. Each device has up to two abnormalities and up to three palpable objects or organs.

Table 30: Conditions of all ten devices

Device Number	Bladder Condition	Bladder Design	Colon Condition	Colon Design	Abnormal Condition	Abnormal Design
1	Healthy bladder	Normal design	Healthy colon	Normal design	Small splenic mass	Small stress ball
2	Healthy bladder	Normal design	Healthy colon	Normal design	Large mid-abdominal mass	Large stress ball
3	Small bladder	1/3 less fluid of normal design	Constipated colon	Three medium stress balls within latex sheet	Mid-abdominal mass	Medium stress ball
4	Small bladder	1/3 less fluid of normal design	Constipated colon	Three large stress balls within latex sheet	Mid-abdominal mass	Medium stress ball
5	Small bladder	1/3 less fluid of normal design	Healthy colon	Normal design	Large liver mass	Styrofoam cut-out
6	Large bladder	2/3 more fluid of normal design	Healthy colon	Normal design	Large liver mass	Styrofoam cut-out

7	Medium bladder	Normal design	Healthy colon	Normal design	Overweight	Additional cotton sheet padding between nylon layers
8	Large bladder	2/3 more fluid of normal design	Healthy colon	Normal design	Overweight	Additional cotton sheet padding between nylon layers
9	Bladder stones	Normal design containing small, smooth pebbles	Healthy colon	Normal design		
10	Bladder stones	Normal design containing small, smooth pebbles	Healthy colon	Normal design		

Abnormal conditions were simply integrated into the device as the abdominal filler and organs were in the final design of the original device. Figure 37 shows the final design of the constipated colons. One colon consists of medium-sized stress balls covered in a latex sheet, while the second contains large stress balls covered in a latex sheet.

Figure 37: Constipated colon final designs

In addition to the constipated colon, bladders containing bladder stones were also created. The bladders were created the same way as the healthy bladders, except small, smooth stones were poured into the latex condom with the water and lubricant. These stones are shown in Figure 38. They are small aquarium stones that can be purchased at any store that has a pet aisle. The enlarged liver is also shown in Figure 38 as the object farthest to the left. The enlarged liver was carved out of a Styrofoam block into a triangular, rounded shape. Splenic and mid-abdominal masses were created out of stress balls of varying shapes and sizes, such as the two on the right in Figure 38.

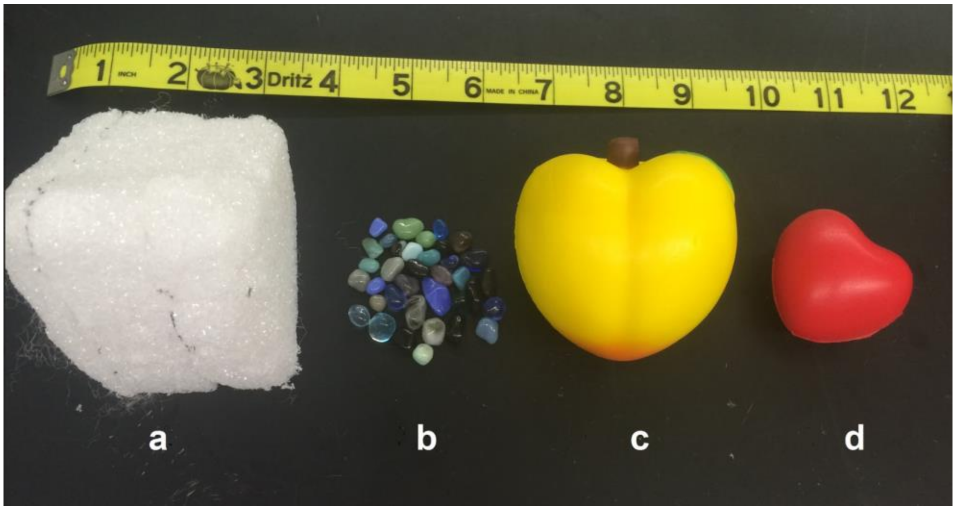


Figure 38: Liver mass, bladder stones, spleen, and mid-abdominal mass

The objects chosen to simulate abnormal conditions in the devices were brainstormed and validated by the design team working with the client. The client described how each abnormal condition feels when it is palpated within a canine, and the design team worked to create a design that could be inserted into the device to simulate each condition. The conditions chosen to be simulated in each device were deemed the most important to learn and prevalent to find in the clinic by the client.

Chapter 5: Final Design Verification

The objective of this MQP is to create a series of ten beagle abdominal palpation training devices to be used in a classroom setting to teach veterinary students diagnostic palpation techniques. The materials chosen for the device must be able to withstand the forces of palpation and must be durable enough to undergo extended use. This entails a device that can withstand at least two years of use in laboratory settings without extensive repairs or replacements. With each veterinary class containing approximately 80 students and duplicates of each device, each device will undergo the palpation from about 40 students during a laboratory palpation session. Each student will use varying levels of force to palpate and a varying amount of palpating gestures on the device. Tests run on various aspects of the device aim to validate that the device can withstand consecutive, repeated palpation and the materials will retain their material properties far beyond the forces required to palpate. This chapter will discuss the results and findings from various tests performed on the final device to ensure compliance with the project's objectives.

As mentioned in the previous chapter, materials for the various aspects of the device were chosen for the final design. These materials were chosen based on the specific criteria, ensuring that they would accomplish the objectives of the device. These materials were chosen because they are realistic to the tactile sense and accurate to the anatomy of a canine as described and validated by the client. To verify that these materials were able to withstand the expected palpation conditions, achieving durability and reusability of the device, different tests were completed. These tests also aimed to verify that the materials were mechanically comparable to their biological tissue counterparts.

5.1. Force of Palpation Testing

The first step in the testing process was to determine the normal abdominal palpation parameters in order to obtain forces the materials should be able to withstand. This was done using force plates and AMTI software. The design team's client, Dr. Stone, performed palpation on a variety of objects on top of the force plate. The objects included layers of the optimal epidermal materials as well as stress balls used as masses in order to mimic the act of palpating a device. The first test performed was one-handed palpation on the bare surface of the force plate. Data was collected using AMTI software of the forces in the x, y, and z direction, as well as the moments about each of these planes. An example of the planes of the force plate is shown in Figure 39 below.

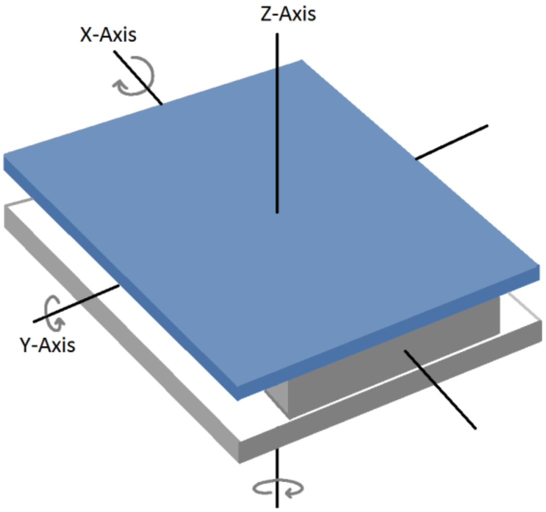


Figure 39: The three axes and moments orientation on a force plate

The force readings in the z-direction from the force plate were graphed against time to produce a force versus time graph of one-handed palpation forces. This can be seen in Figure 40 below. The curve represents the repetitive nature of palpation as the client used his hands to apply repetitive forces to the force plate. During palpation, both the fingers and thumb are used so force measurements for both were taken. The maximum force applied from palpation with the thumb oriented on the top of the force plate and four fingers underneath was found to be 32.8 N. After this control test, a variety of materials were placed on the force plate and palpated by the client. The readings from the forces in the z-direction were analyzed for each scenario seen in the trial description in the table below, and the maximum force applied and the average force applied were taken from each data set. These values are shown in Table 31. The purpose behind the palpation forces testing with the client was to gain an idea of the maximum and average forces exerted by the fingers or hand used in palpation. A variety of objects were used to show the variation that occurs during palpation when an object is palpated through other objects.

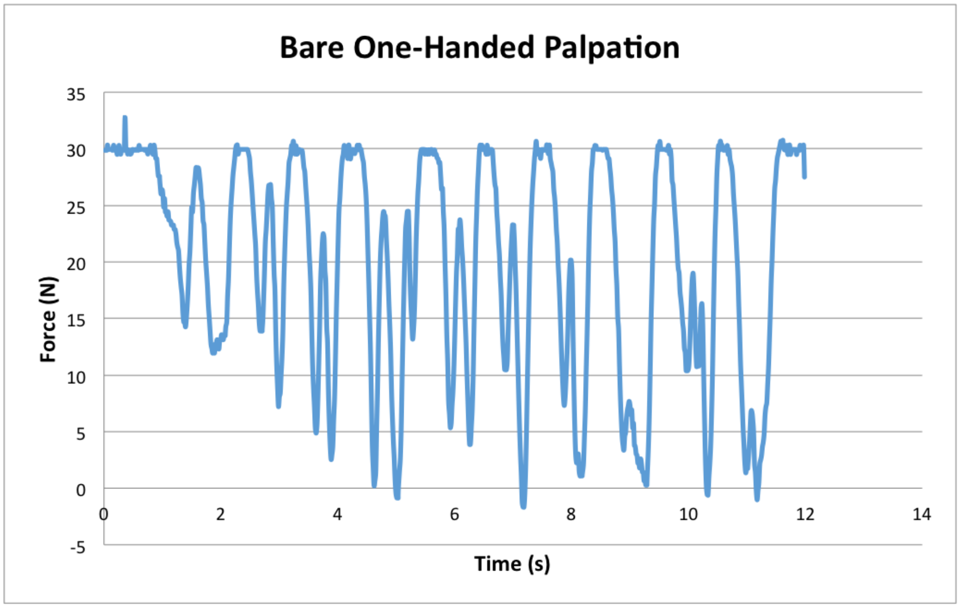


Figure 40: Bare one-handed palpation forces

Table 31: Palpation forces for various scenarios

Trial Number	**Trial Description (On force plate)**	**Maximum Force Applied (N)**	**Average Force Applied (N)**
1	Thumb: Bare	32.76	20.09
2	Thumb: Stress ball	29.10	24.42
3	Thumb: Foam, blanket, stress ball	27.13	6.34
4	Thumb: Foam, blanket, balloon	26.39	9.95
5	Thumb: Balloon	28.33	25.48
6	Four Fingers: Foam Pad, Stress Ball	29.06	18.56
7	Four Fingers: Stress Ball	29.52	27.50

As the team hypothesized, the maximum force applied to the layered materials decreases. This means that the organs palpated within the confines of the device will be subject to a lower force than if they were palpated alone. This decreases the palpation forces the internal organs of the device must withstand, further increasing the reusability and durability of the device. While this data shows the maximum force is decreased when palpating through organs or layers, the average force applied is fairly close to the maximum force when the client was palpating organ-like objects, such as the stress ball and the balloon. This indicates that the client applies a more constant force in the higher range of palpation when palpating specific objects. The maximum applied force used in bare, one-handed palpation was used as a benchmark for mechanical testing maximum force values to validate the durability of the materials used in the device.

5.2. Uniaxial Mechanical Testing

Next, a series of mechanical tests were performed. The materials focused on for mechanical testing were the polyester fabric used for the skin and fur layer, the latex Penrose drain used for the colon, and the latex condom used for the bladder. The goal of the mechanical testing was to determine that these materials used within the device were durable. This was achieved by simulating palpation conditions to determine if the materials could withstand comparable factors and beyond. These mechanical tests were also performed to ensure accuracy of each material in comparison to the equivalent biological tissue within an animal. The elastic modulus of the materials and the biological tissue were compared to validate that these materials were accurate and realistic to those of living tissue, specifically within a canine. In summary, the mechanical testing was used to validate that the soft tissue materials achieved the objectives of durable, reusable, accurate, and realistic.

5.2.1. Epidermal Testing

The first set of mechanical tests were performed on the polyester crushed panne velvet fabric intended to be used for the skin and fur layer. Three rectangular samples at an unloaded size of approximately 60 mm in length, 25 mm in width, and 1 mm in thickness were cyclically loaded in tension using an Instron 5544 and Bluehill software. The sample was loaded into the Instron and applied to a tare load of 5 N. The sample was then stretched at 100 mm/min to a load of 20 N, corresponding to the average palpation force. Once this force was reached, the sample was returned to a 15% strain and cycled 30 times. The purpose of the cyclic loading was to imitate repeated palpation. After the completion of the 30 cycles, the sample was loaded once more to 100 N. All three samples failed before reaching the 100 N end test parameter. The purpose of stretching the fabric to failure after being cyclically loaded was to determine the maximum force the material can withstand after being repeatedly palpated. This maximum force reached by the fabric material was compared with the maximum forces used in palpation to ensure the failure of the material was well above any forces exerted through palpation. While there were no benchmark mechanical values for the polyester crushed panne velvet fabric, the benchmark values used were from the specifications for the mechanical properties of porcine abdominal skin. Values for canine skin were not available. The benchmark for maximum force necessary for the material to be durable was 1.5 times the maximum palpation force, at 32.8 N.

Figure 40 depicts the cyclic loading of the polyester fabric to 30 cycles. The area enclosed by the loading and unloading paths is known as the hysteresis loop. This represents the energy the material loses through heat during the deformation and recovery phases. The graph below shows that polyester does in fact lose some energy to heat as it is cyclically loaded and unloaded. While initially elastic, polyester loses some of its elasticity because the plastic region is entered past the yield point. The material exhibits some plastic behavior and deformity throughout 30 cycles, but most of the energy loss occurs in the first five cycles. After this, the loading and unloading curves follow an almost identical path for the rest of the cycles.

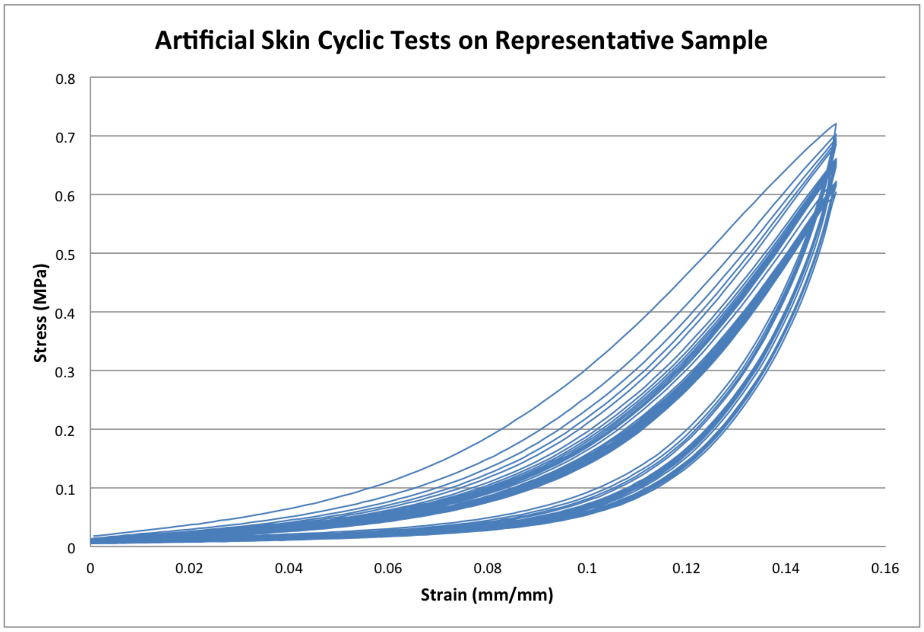


Figure 41: Polyester cyclic loading (30 cycles)

The elastic modulus values were calculated from the initial loading curve of each specimen, and the average in the palpation range was found to be 21.6 MPa. The average elastic modulus of the final loading curve was found to decrease in stiffness at 11.9 MPa. The initial loading curve is shown in Figure 42 below. The modulus was calculated from the second linear region of the elastic curve because this depicts the linear elastic region of the curve in the range of palpation.

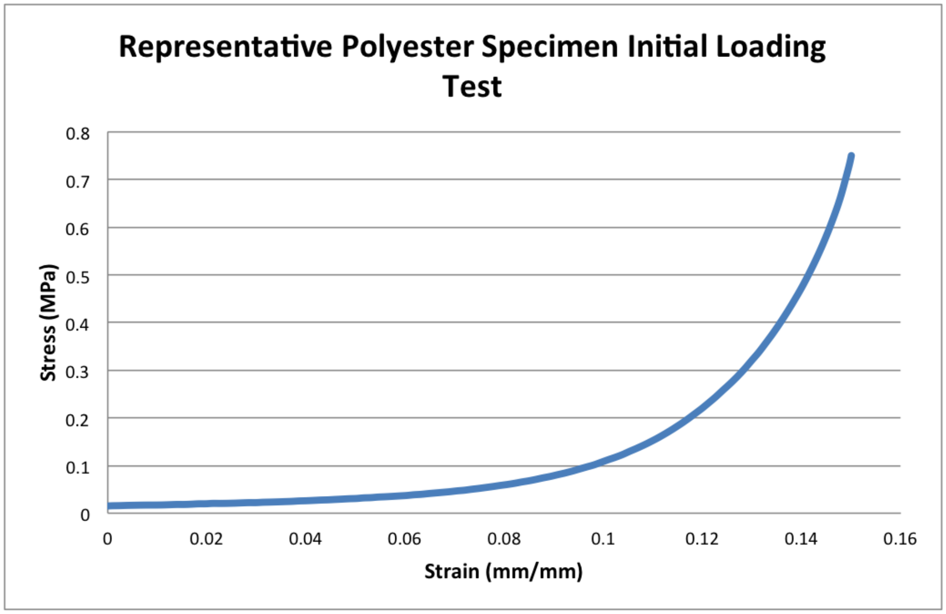


Figure 42: Polyester initial loading

In the final graph for polyester in Figure 43, the final loading curve is shown to failure. After 30 cycles, the sample was pulled to failure which was defined as a 40% drop in stress. The polyester fabric failed at a stress of approximately 1.8 MPa at approximately 40% strain.

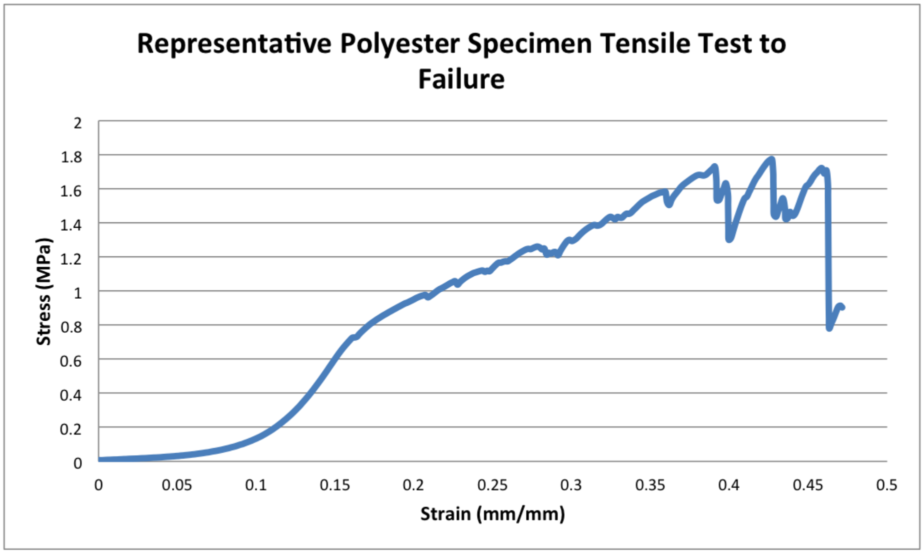


Figure 43: Representative polyester final load curve

The material properties analyzed following the test were the elastic modulus, hysteresis, and maximum force. The elastic modulus was compared to values from the literature of the elastic modulus of porcine skin to ensure the elasticity of the polyester fabric was realistic to that of skin. The hysteresis was visually assessed from each graph to ensure that the material did not lose extensive amounts of energy within 30 cycles. A significant drop from the first cycle to the 30th cycle would have been cause for reevaluation of materials that were more durable.

The maximum force the polyester fabric could withstand was compared to the maximum force of palpation, and should exceed palpation forces by at least 150%. Below in Table 32 is the measurement of the elasticity of the three samples of polyester.

Table 32: Polyester fabric elastic modulus

Sample #	Elastic Modulus of Initial Loading	Elastic Modulus of Final Loading
Sample 1	20.3 MPa	10.0 MPa
Sample 2	21.8 MPa	14.2 MPa
Sample 3	22.8 MPa	11.6 MPa
Average	**21.6 +/- 1.30 MPa**	**11.9 +/- 2.10 MPa**

In Table 33, the elastic modulus averages from initial and final loading are compared to the range from the literature of porcine abdominal skin elastic modulus.

Table 33: Skin elastic modulus comparison

	Skin (Porcine Abdomen)	Polyester Fabric (Before Cyclic Loading)	Polyester Fabric (After Cyclic Loading)
Elastic Modulus	20-60 MPa (Shergold, 2004)	21.6 +/- 1.30 MPa	11.9 +/- 2.10 MPa

In Table 34, the maximum loads the polyester reached before failure are shown. The average maximum load polyester reaches before failure was found to be 52 N. This data was retrieved from the BlueHill software post-test data, and the average was calculated for all three specimen.

Table 34: Polyester maximum load

Sample #	**Maximum Load**
Sample 1	62.0 N
Sample 2	45.59 N
Sample 3	48.3 N
Average	**52.0 +/- 8.80 N**

Table 34 depicts the maximum average load the polyester fabric reached before failure compared to the maximum force of palpation. The polyester fabric maximum load after 30 cycles is at least 1.5 times greater than 32.8 N which is the maximum load of normal palpation.

The mechanical testing validates that polyester fabric achieved the objectives of realistic and durable. The polyester fabric serves as the skin of the canine device, and the initial elastic modulus of this material falls within the elastic modulus range for the skin of a pig's abdomen. While there has been no research done on the mechanical properties of canine skin, the porcine skin abdomen elastic modulus range is large enough to encompass the variability of skin between species. After cyclic loading, the final elastic modulus decreases to below the researched range, but this has been determined acceptable by the team due to the variability of skin between species. A slightly more elastic material is more acceptable than if the material grew too stiff after cyclic loading. After repeated loading at the force and speed of palpation, the polyester fabric was still able to withstand over 1.5 times the maximum load of palpation at an average of 52 N. This material used in the device achieves the desired objective of durability. While validation of materials ultimately came from the client, the mechanical testing and comparisons with skin and palpation forces validated that the polyester fabric was durable through repeated cycling and realistic to the behavior of biological skin.

5.2.2. Colon Testing

The next material tested was the latex Penrose drain used for the colon. Test parameters similar to the fabric testing were used. Three ring samples measuring 1 inch in diameter and approximately 0.75 inches in height were tested. Each sample was loaded into the ring gages of the Instron and a 5 N tare load was applied. The sample was then loaded to a force of 20 N at a crosshead speed of 100 mm/min. Once the sample reached 20 N it was returned to 15% strain and cycled 30 times at 100 mm/min. This was intended to mimic the repeated loading of palpation. After 30 cycles, the sample was stretched to 100 N, which was the end of the test. Each of the samples was able to stretch to 100 N without failure (Edsberg, 1999).

The material properties analyzed following the test were the hysteresis, elastic modulus, and maximum force. Below in Figure 44 is a graph of the cyclic portion of the test.

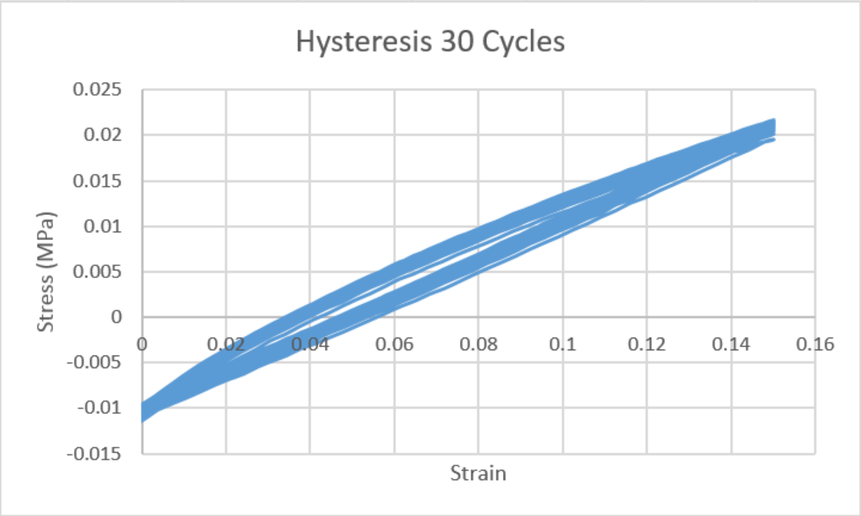


Figure 44: Representative Penrose Drain Hysteresis

This graph displays the hysteresis that took place over the 30 cycles of the test. Next, the elastic modulus of the preload and the final load were compared to see if the Penrose drain maintained its elasticity after being cyclically loaded. Below in Figures 45 and 46 are the preload stress strain curve and the final load stress strain curve respectively.

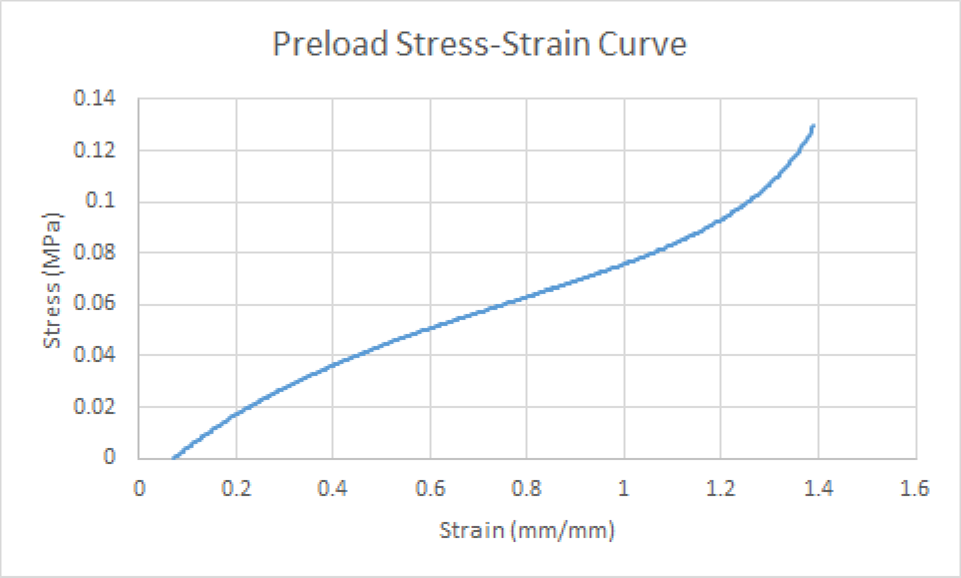


Figure 45: Representative Penrose Drain Preload Stress-Strain Curve

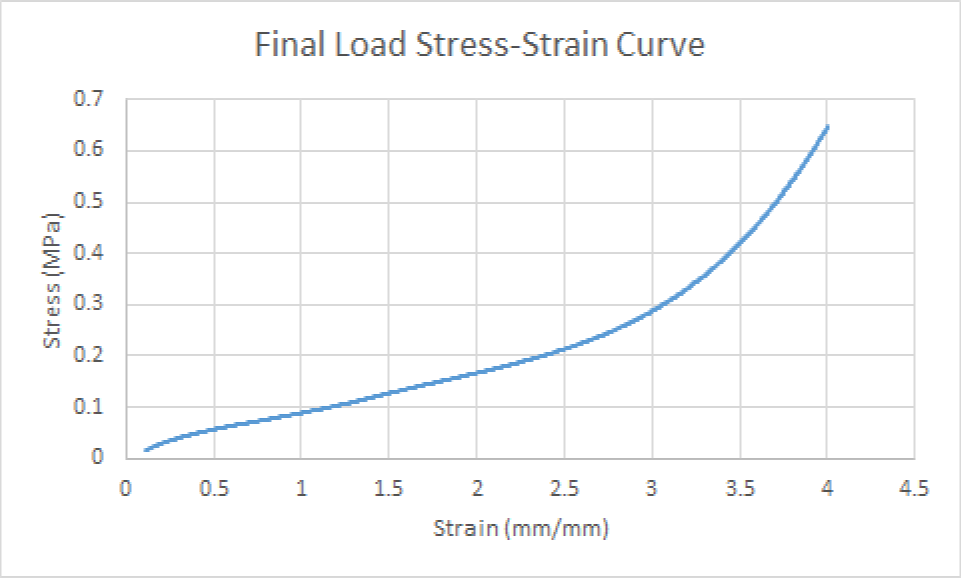


Figure 46: Representative Penrose Drain Final Load Stress-Strain Curve

The material properties analyzed following the test were the elastic modulus and maximum force. The elastic modulus was compared to values from the literature of the elastic modulus of porcine bowel tissue to ensure the elasticity of the Penrose drain was realistic to that of the colon. The hysteresis was visually assessed from each graph to ensure that the material did not lose extensive amounts of energy within 30 cycles. A significant drop from the first cycle to the 30th cycle would have been cause for reevaluation of materials that were more durable. The maximum force the Penrose drain could withstand was compared to the maximum force of palpation, and this should exceed palpation forces by at least 150%. Table 35 below shows the elastic modulus of the preload and final load. This shows the effect of the cyclic loading on the elasticity of the material.

Table 35: Penrose Drain Elastic Modulus

Sample #	Elastic Modulus of Preload	Elastic Modulus of Final Load
Sample 1	0.206 MPa	0.207 MPa
Sample 2	0.145 MPa	0.157 MPa
Sample 3	0.247 MPa	0.253 MPa
Average	**0.199 +/- 0.051 MPa**	**0.206 +/- 0.480 MPa**

In Table 36, the elastic modulus averages from initial and final loading are compared to the range from the literature of porcine bowel tissue elastic modulus.

Table 36: Elastic modulus comparison of bowel tissue

	Bowel Tissue (Porcine)	**Penrose Drain (Before Cyclic Loading)**	**Penrose Drain (After Cyclic Loading)**
Elastic Modulus	1.83 MPa (Christensen, 2015)	0.199 +/- 0.051 MPa	0.206 +/- 0.480 MPa

Table 37 depicts the maximum average load the Penrose drain reached before the end of the test compared to the maximum force of palpation. Initially, the team intended to stretch the Penrose drain until failure, but the maximum load of the final part of the test ended with 100 N. This means the Penrose drain was able to stretch to 100N without failing indicating it will not fail under normal palpation conditions. The Penrose drain maximum load after 30 cycles is just over 3 times greater than the maximum load of normal palpation. This far exceeds the durability needs of this project.

Table 37: Polyester maximum load comparison

	Normal Palpation	**Polyester Fabric (After Cyclic Loading)**
Maximum Load	32.8 N	100 N*

*Stretched to 100 N and did not fail

Although Table 36 does not validate that the Penrose drain achieved the objective of a realistic aspect of the device, there are other reasons why the material was chosen and validated for a final design. The Penrose drain serves as the colon tissue of the canine device, and the initial elastic modulus of this material falls below the elastic modulus range for the bowel tissue of a porcine abdomen. The Penrose drain is significantly more elastic than the bowel tissue of a porcine. While there has been no research done on the mechanical properties of canine bowel tissue, the porcine bowel tissue elastic modulus range leaves room for discussion of errors. According to the *SpringerPlus* paper this value is cited from, the bowel tissue of animals tends to vary considerably in stiffness from species to species. In addition, after numerous client interviews, the Penrose drain was deemed acceptable and most realistic to use as the colon in the device when compared to the preliminary design materials such as plastic wrap. While the mechanical properties of this material are important, it is the stool that is felt during palpation, not the colon lining. Therefore, the mechanical properties of the

Penrose drain and bowel tissue are close enough to validate this material based on how it feels within the device. After cyclic loading, the final elastic modulus only increases very slightly.

Table 37 shows that after repeated loading at the force and speed of palpation, the Penrose drain was still able to withstand over 2 times the maximum load of palpation at an average of 52 N. This material used in the device achieves the desired objective of durability. While validation of materials ultimately came from the client, the mechanical testing and comparisons with bowel tissue and palpation forces validated that the Penrose drain was durable through repeated cycling and realistic to the behavior of biological bowel tissue.

5.2.3. Bladder Testing

Lastly, latex condoms used for the bladder were tested. The condom was cut into rings, each about an inch in width. Three samples total were tested. The prepared samples of latex condoms and Penrose drains cut into rings are shown in Figure 47.

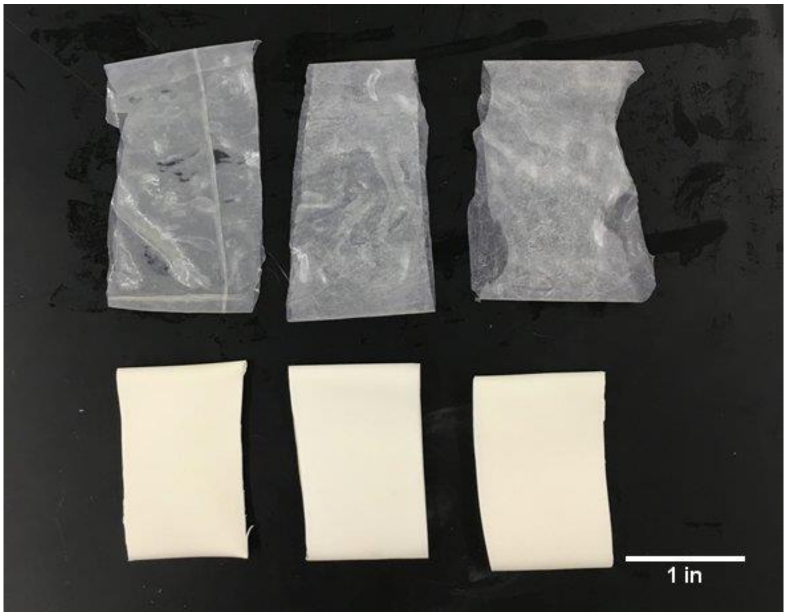


Figure 47: Penrose drain and latex samples

The samples were loaded into the ring grips and applied with a tare load of 2 N before the test began. The test began by stretching the sample at a rate of 100 mm/min to a load of 7 N. Once it reached this load, it was returned to 15% strain and cycled 30 times to mimic the repeated loading during palpation. After 30 cycles, the condom was stretched to 15 N, which completed the test. The force parameters for the condom samples were much less than the parameters used for the polyester fabric and Penrose drain. It was found through trial testing that the condom samples showed a great increase in elongation under minimal loading. While the test parameters were set to loads, the parameter of interest was the elongation of the samples. Once the tests were concluded, the material properties analyzed were the hysteresis, the elasticity, and the maximum elongation. Below in Figure 48 is the hysteresis curve for the 30 cycles of loading.

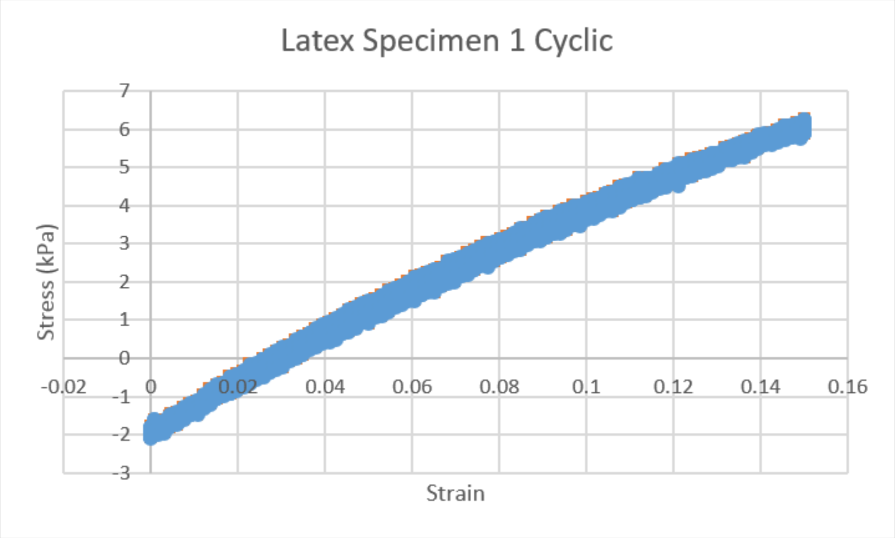


Figure 48: Latex cyclic loading curve

Next, the modulus of the initial load and the final load were compared to understand the effect of the cyclic loading. Figures 49 and 50 below show the stress strain curves for the preload and final load.

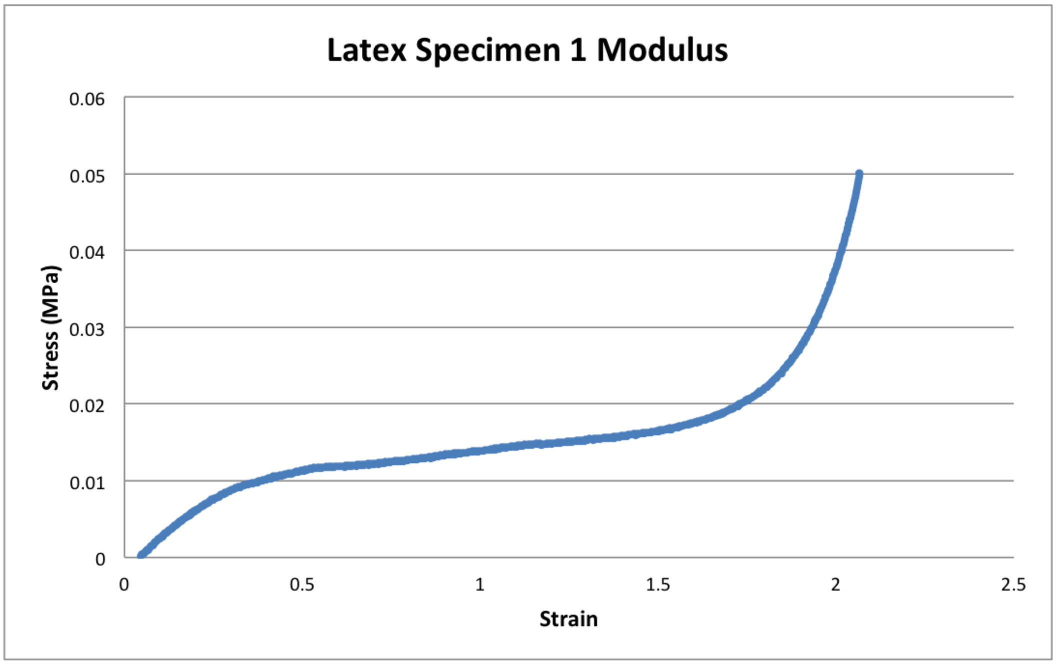


Figure 49: Representative Latex Preload Stress-Strain Curve

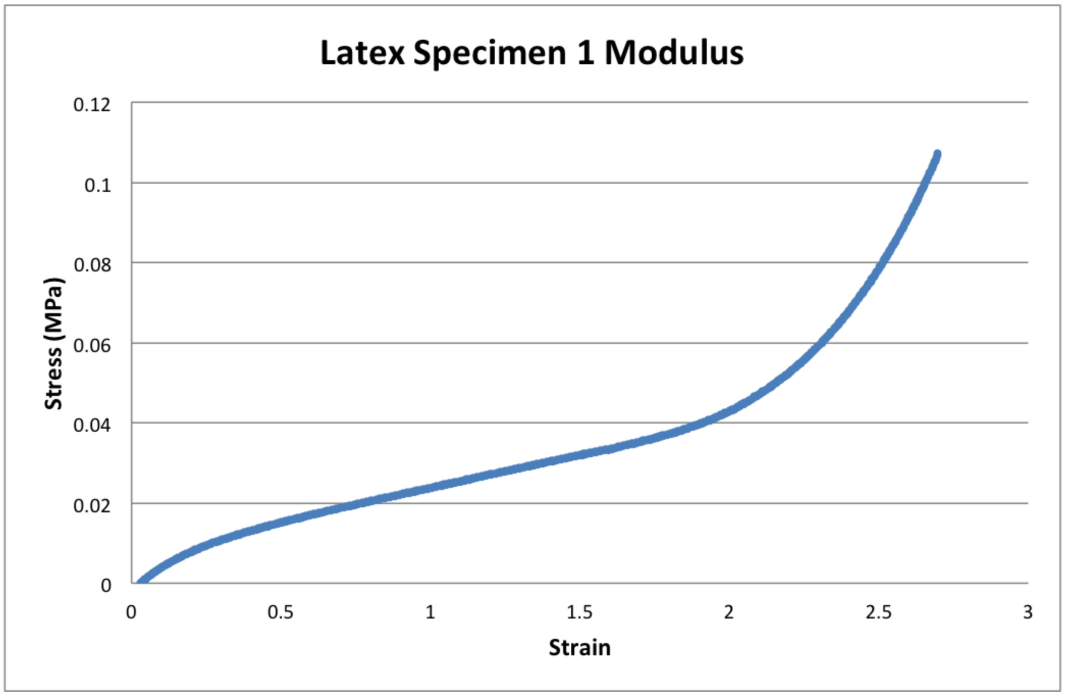


Figure 50: Representative Latex Final Load Stress-Strain Curve

Table 38 below contains the numerical values of the elastic modulus for the initial loading and the final loading.

Table 38: Latex condom initial modulus

Sample #	**Elastic Modulus of Initial Loading**	**Elastic Modulus of Final Loading**
Sample 1	0.033 MPa	0.034 MPa
Sample 2	0.015 MPa	0.053 MPa
Sample 3	0.04 MPa	0.05 MPa
Average	**0.029 +/- 0.013 MPa**	**0.046 +/- 0.010 MPa**

In Table 38, the elastic modulus averages from initial and final loading are compared to the range from the literature of the elastic modulus of bladder tissue.

Table 39: Elastic modulus comparison of bladder tissue

	Bladder (Porcine)	Latex Condom (Before Cyclic Loading)	Latex Condom (After Cyclic Loading)
Elastic Modulus	4-260 kPa (Li, 2014)	29 +/- 13 kPa	46 +/- 10 kPa

Lastly, the extension of the latex condom at the maximum load was analyzed. When palpated, the condom bladder undergoes a maximum extension of approximately 20 mm as determined through preliminary testing. By stretching the samples to a maximum load of 15 N, the team was able to measure the extension the latex condom reached and compared these values to the extension of the material under normal palpation conditions. The table below displays the extension of the samples at the maximum load.

Table 40: Latex condom maximum extension

Sample #	**Extension at Maximum Load**
Sample 1	296.7 mm
Sample 2	265.0 mm
Sample 3	306.4 mm
Average	**289.4 +/- 21.70 mm**

Table 41 depicts the maximum average load the latex condom reached before the end of the test compared to the maximum force of palpation. Initially, the team intended to stretch the latex condom until failure, but due to the elasticity of the latex condom, the final load would never be reached using this test. As mentioned before, extension values were used instead and compared to the extension an organ undergoes during palpation.

Table 41: Latex condom maximum extension comparison

	Normal Palpation	Latex Condom (Extension at Maximum Load)
Maximum Load	~20 mm	289.4 +/- 21.70 mm

*Stretched to 100N and did not fail

Table 39 validates that the latex condom accurately mimics the elastic modulus of canine bladder. The latex condom serves as the bladder tissue of the canine device, and both the initial and final elastic modulus of this material fall within the elastic modulus range for porcine bladder tissue. While there has been no research done on the elastic modulus of a canine bladder, the elastic modulus range of a porcine bladder is large enough to encompass the variability of tissue properties between species. After cyclic loading, the final elastic modulus increases to stay within the range, and this shows that the latex condom becomes slightly more elastic as it is palpated. Table 41 shows that after repeated loading at the force and speed of palpation, the latex condom was still able to withstand nearly 14.5 times the maximum extension of palpation of approximately 20 mm. This material used in the device achieves the desired objective of durability. While validation of materials ultimately came from the client, the mechanical testing and comparisons with bladder tissue and palpation forces validated that the latex condom was durable through repeated cycling and realistic to the behavior of biological bladder tissue.

5.3. Validation Survey

As mentioned in Chapter 4, the design team visited the Cummings School of Veterinary Medicine at Tufts University to have veterinary students and professionals palpate the preliminary devices during the decision making process. A second visit to the veterinary school was used to conduct surveys for design validation of the final devices and for feedback to make minor improvements.

In the second visit, five of the 10 final devices were brought to Tufts and 25 veterinary professionals and students were surveyed after palpating each device. Table 42 below shows the abnormalities present in each of the named devices.

Table 42: Conditions of the 5 devices tested at Tufts

Device Name	**Conditions**		
Hades	Bladder stones	Normal colon	
Ares	Normal bladder	Constipated colon	Mid-abdominal mass
Chaos	Small bladder	Constipated colon	Foreign mid-abdominal body
Apollo	Normal bladder	Normal colon	Liver mass
Atlas	Normal bladder	Normal colon	Splenic mass

The abnormalities present in the five devices were constipation, liver mass, mid-abdominal mass, overweight and bladder stones. A survey was given for each individual device, and the feedback from the 25 professionals and students are displayed in Table 43 below. The participants were asked to palpate the device and indicate whether or not they felt the presence of underlying organs and described what they thought they were feeling. After this, they were given a description of the abnormalities within the device they had just palpated. Once the participant knew this information, they were asked to palpate the device again and rate how accurately the device portrays a live canine with these conditions. There was also space at the end of the survey for general comments and feedback on each individual device.

Table 43: Feedback from veterinarian validation survey

Device	Feels presence of underlying organs	Accuracy of model out of 5 (5 being most accurate)	General consensus from comments
Hades	77.4% yes	4 out of 5	Very hard to feel bladder stones; bladder feels realistic
Ares	100% yes	4 out of 5	Feels very much like a full bladder; colon material is too hard to be feces
Chaos	100% yes	4 out of 5	Nice lumpy feel; very well done
Apollo	93.9% yes	3 out of 5	Liver mass extends too far past ribcage and is too firm and angular
Atlas	100% yes	5 out of 5	Movable mass; confusion if mass was a bladder

A majority of the participants indicated they could feel the presence of underlying organs within each device. After given knowledge of the conditions within each device, a majority of the devices were ranked a 4 out of 5 for how accurately they simulated these conditions in a live canine. Most of the feedback was helpful and indicated for only minor improvements to be made.

At the very end of the survey, participants were asked how well the devices simulate the experience of palpation, whether or not he or she would use the devices in a classroom setting, and if the devices could help someone to learn or teach palpation techniques. A majority of the participants ranked the accuracy of experience of palpating the devices a 4 out of 5, 96% said they would use the devices in a classroom setting, and the average rating for how well the models could help students learn palpation techniques was a 4.3 +/- 0.6 out of 5. The validation survey led to the conclusion that the final devices were realistic, accurate, and suitable for use in a classroom setting.

Chapter 6: Final Design and Validation

6.1. Hard Tissue Design

The final design of the hard tissue aspect of the device was created from polyvinyl chloride (PVC) pipe and connectors fastened together with stainless steel screws. The four legs, shoulders, a pelvis, and spinal supports of the device were formed from PVC pipe. Two circular ribs were cut from Lexan sheets to create ribs that were slid onto the PVC spine and secured with a non-marring flat point set screw for adjustments. The computer-aided design model completed in SolidWorks© of the final design and the machined prototype are shown in Figures 51 and 52. The decision process of the hard tissue skeletal support of the device was determined through a number of variables. These included research of materials and plastics done by the design team, the anatomy of a canine skeleton, and the assistance of professionals both in the veterinary field and in the manufacturing field.

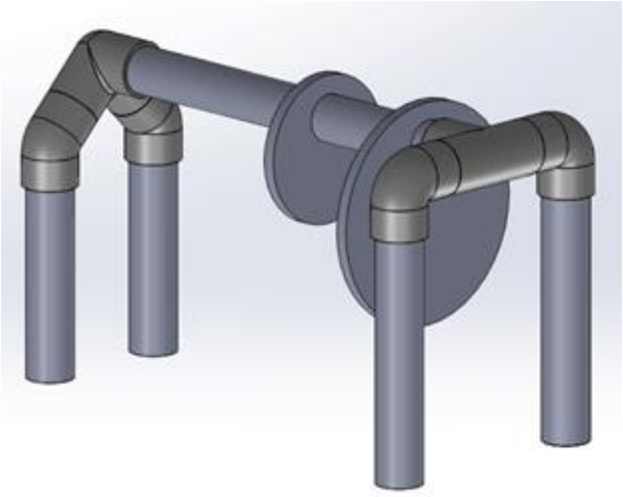


Figure 51: SolidWorks© model of hard tissue

Figure 52: Final hard tissue prototype

The design team met with Thomas Partington of the Worcester Polytechnic Institute machine shop multiple times to discuss design ideas. The team showed him alternative designs and ways to manufacture these designs were discussed. Mr. Partington assisted with selection of materials, best fit design for the materials, and a final design that included all wants and needs of the design team based on the functions, specifications, and revised client statement. Polyvinyl chloride (PVC) was chosen for the final design hard tissue structure because it fits the needs of the device. PVC is a lightweight plastic, and this allows the device to be portable for carrying it to classrooms and laboratories. It is also a durable, as the plastic is corrosion resistant, and this accomplishes the design team's goal of a device that is long lasting. PVC also achieves cost effectiveness because PVC piping and connectors can be purchased in bulk for reasonable prices. The cost of all necessary PVC parts for one device was approximately $25. This plastic is also easy to process and machine to the design's specifications. It is a mechanically stable and rigid material. PVC is a versatile material that can be purchased in bulk as piping and assembled to create a design using connectors and other fixation methods.

While the majority of the hard tissue final design was composed of PVC, this was not the only material used. Stainless steels screws and polycarbonate sheets were also included in the final design. Lexan™ polycarbonate was a material chosen for the final design with the assistance of Mr. Partington. Lexan was interfaced with the PVC and served as the rib cage of the body of the canine. Lexan is an amorphous thermoplastic that is versatile, tough, and durable. The Lexan ribs were used to section off a palpable area and give the device a more accurate abdomen. PVC, screws, and other hard tissue materials were purchased from McMaster-Carr with the specifications in Table 44.

Although most products were ordered, the polycarbonate, otherwise known as Lexan™, was acquired at no cost from the WPI machine shop. Existing scrap polycarbonate material was used to create the ribs of the final design, and this material was not ultimately included in the cost of the device. The cost of ordering Lexan sheets was calculated into the cost of the hard tissue device shown in the table below. The product information on the hard tissue design as well as the cost per device is shown in Table 44.

Table 44: Hard Tissue Product Information and Cost

Item	McMaster Carr #	Number Per Device	Unit Price ($)	Cost of One Device
PVC 45-degree elbow	4880K35	2	1.64	3.28
PVC 90-degree elbow	4880K25	2	1.16	2.32
PVC Side outlet elbow	4880K634	1	3.16	3.16
PVC Tee	4880K45	1	1.54	1.54
PVC Pipe 5ft long	48925K95	1.5	7.12	10.68
PVC Round 5ft long	8745K25	0.5 foot	7.99/ft.	4.00
¼-20 screws pkg/50	91771A539	10	0.13	1.13
Lexan (Cast Acrylic) 12”x12”x1/2”	8560K265	1	30.24	30.24
Lexan (Cast Acrylic) 6”x6”x1/2”	8560K274	1	8.46	8.46
PVC End Cap 1ft	8745K22	8/12 foot	5.33	3.56
Rubber inner stoppers	6448K106	4	1.25	5.00
Sand	The Home Depot Model # 55141	8 lbs.	3.98 / 50lbs	0.64
Cup Point Set Screw	92313A574	2	0.39	0.77
Total without Lexan cost ($38.70)				**36.08**

The PVC pipe has an outer diameter of 1.9 inches and an inner diameter of 1.61 inches. It has a 0.145-inch wall thickness. Each fitting has an outer diameter of 2 ¼ inches and an inner diameter of 1.912 inches with slightly variable socket depths. The solid PVC rod has a diameter of 1 7/8 inches.

The PVC was purchased in multiples of 5-foot pipes. These were cut to the dimensions of the long and short legs and the spine. A horizontal belt saw was used to cut the 5 foot PVC pipe into the lengths presented in Table 45, plus 0.25 inches. In order to preserve materials, one pipe was used for three spine lengths, or two short legs and three long legs. A belt sander was used to shave off the extra PVC pipe so that the length was as close to the lengths presented in Table 45 as possible. A curved blade was used to clean the pipe shavings off the pipe ends. The pipe was then ready to have the ends turned down in the lathe. This resulted in a slightly smaller outer diameter. This allowed for a non-permanent press-fit into the elbow and the tee fittings, without the use of PVC primer and cement. Figure 53 shows the different lengths of PVC pipes.

Figure 53: PVC Pipe for 3 Models

Table 45: PVC Pipe Section Dimensions and Number per Dog

	Final Pipe Length	**Number Per Dog**
Short Legs	10.25”	2
Long Legs	12.75”	2
Spine	19.75”	1

Circular ribs were cut from 0.6-inch wide Lexan™ in two different sizes: 6 inches and 9 inches in diameter, shown in Figure 54. The sharp edges were filed down into rounded edges. Then, one 1.92-inch wide hole was cut 0.5 inches from the outer diameter of the Lexan™ round. This allowed them to slide onto the spinal section of the PVC piping for to create the appropriate 6-inch-long palpable region from the pelvis to the rib. Each round had a threaded hole drilled into the side of the round that connected with the 1.92-inch hole. The Lexan rounds were slid onto the PVC spinal length. The 9-inch diameter round was placed 0.5" from the end of the tee connector. The 6-inch diameter round was placed 8" from the end of the tee connector. This marked out a 10" long palpable area. A ¼" long, 6/25" wide cup point set screw was screwed into each threaded hole to secure the Lexan rounds into place.

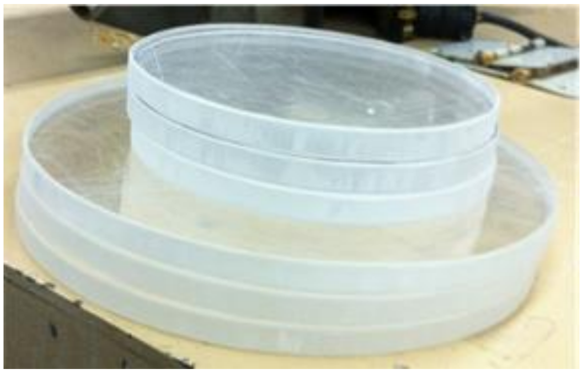


Figure 54: Lexan™ Rounds Used for Ribs

A custom made-PVC end cap, shown in Figure 55 was inserted into the bottom of each leg and glued in place. Approximately 2 lbs. of sand were poured into each leg and compacted using a rubber stopper, shown in Figure 56 that fits into the inner diameter of the pipe. The stoppers were acquired from WPI machine shop stores. The end cap for the bottom of the legs has an outer diameter of 1.91 inches and an inner diameter of 1.57 inches. Each is 1-inch-long with at 1.2-inch lip. The rubber stopper for the inner pipe has a major diameter of 1.60 inches and tapers down to a minor diameter of 1.30 inches. Each is 1-inch long.

Figure 55: Custom-made PVC end caps

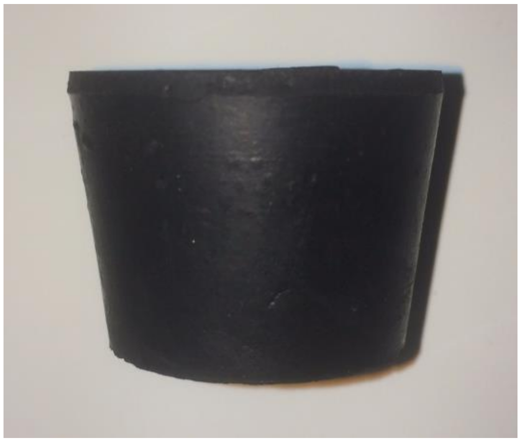


Figure 56: Rubber stopper

18-1 stainless steel flat head Phillips machine screws (¼"-20 thread, ⅝" length) were screwed through the PVC pipe and PVC connector at each joint. One screw was used per joint. The final hard tissue portion of the device was 15 inches high and 23 inches long. According to observations from the visit to Tufts Anatomy Lab, the overall height of a beagle is approximately 16 inches. The length of the device is not as important as the length of the palpable region, which was adjusted to 6 inches to meet specifications.

6.2. Soft Tissue Design

The skin, colon, and bladder are the main components of the soft tissue aspect of the palpation device. The colon was created out of a Penrose latex drain and modeling clay, shown in Figure 57. Penrose drains are commercially available online in different size diameters. The diameter used in the model was 1 inch. Model Magic® that does not dry out was molded into rods large enough to stretch open the Penrose drain diameter to over an inch diameter. The weight of the clay used in each colon was approximately 56 grams, or 0.12 lbs. The palpation colon length was 5 ⅝ inches long. This calculated out to be 9.95 grams per inch. These rods were used to fill the Penrose drain. Once inside the Penrose drain, they were compressed to expand laterally and further stretch the drain's diameter. The ends of the Penrose drain were tied shut with rubber bands.

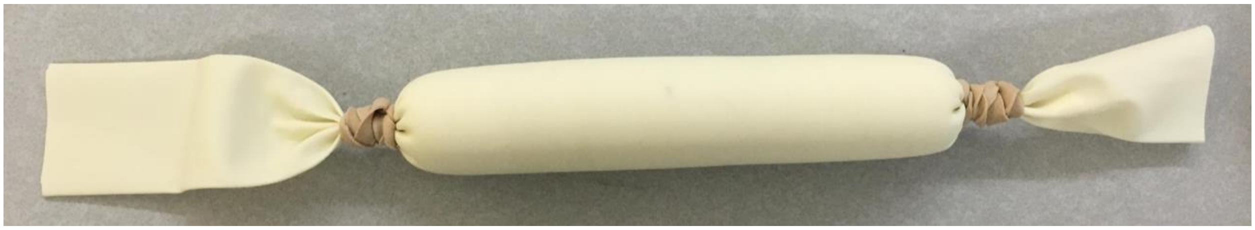


Figure 57: Penrose Drain Colon

The bladder was created with two latex condoms, water, a polymer-based latex-safe lubricant, and rubber bands, shown in Figure 58. One latex condom was filled with water and water-based lubricant until full. Polymer-based lubricant was used over other types of lubricants because it will not degrade the latex condom. This latex condom was tied shut with a knot and the knot was secured by wrapping a rubber band around it until the latex condom was sealed tightly sealed shut. The simulated bladder was then placed inside another latex condom. The outer latex condom was knotted and tied shut with a rubber band as well.

Figure 58: Latex Condom Bladder

The skin was created out of a polyester crushed panne velvet fabric. This fabric has stretch in a single direction. The fabric was aligned so that stretch occurs over the width of the abdomen. The fabric was cut to fit around the back two legs of the device to be wrapped around the palpable area and rear rib. Velcro was used to attach the ends of the fabric along the spine of the device. An image of the skin design completed is shown in Figure 59.

Figure 59: Completed skin construction

The soft tissue of the abdomen was created out of batting, foam pads, and nylon stockings. A foam pad with a thickness of 1 inch was purchased at a craft store. This pad was cut into 5.5-inch by 4.0-inch rectangles and stacked on top of each other. The top foam pad has a 1-inch by 4-inch rectangle cut out of the center to accommodate the shape of the spine. The lower legs of a nylon stocking were cut off to create a stocking of a length of approximately 13 inches. The stack of foam was placed inside the foot end of the nylon stocking. This created the abdominal filler next to the ribcage. The rear end of the abdominal was created by filling the waist area of a nylon stocking with the legs cut off with batting, shown in Figure 60. The nylon stockings were 7 inches high and 5 ⅕ inches wide.

Figure 60: Abdominal filler

A variety of common abdominal conditions were represented. A liver mass was simulated using a block of Styrofoam shaved to approximately 3 inches wide. It was secured against the rear of the back rib. Bladder stones were represented by filling a normal sized bladder with ½ cup of pebbles. The pebbles were acquired from a pet store and are traditionally used as aquarium gravel. Doubling the volume of liquid in the condoms represented a large bladder. 1.5 times the normal volume in a condom was used to represent a medium sized bladder. Mid-abdominal masses were simulated by stress balls of varied shapes. These objects are shown in Figure 61. A constipated colon, shown in Figure 62, was represented by three round stress balls inside a latex sheet, secured with rubber bands. An overweight animal was simulated by filling the abdomen with another thicker layer of foam padding.

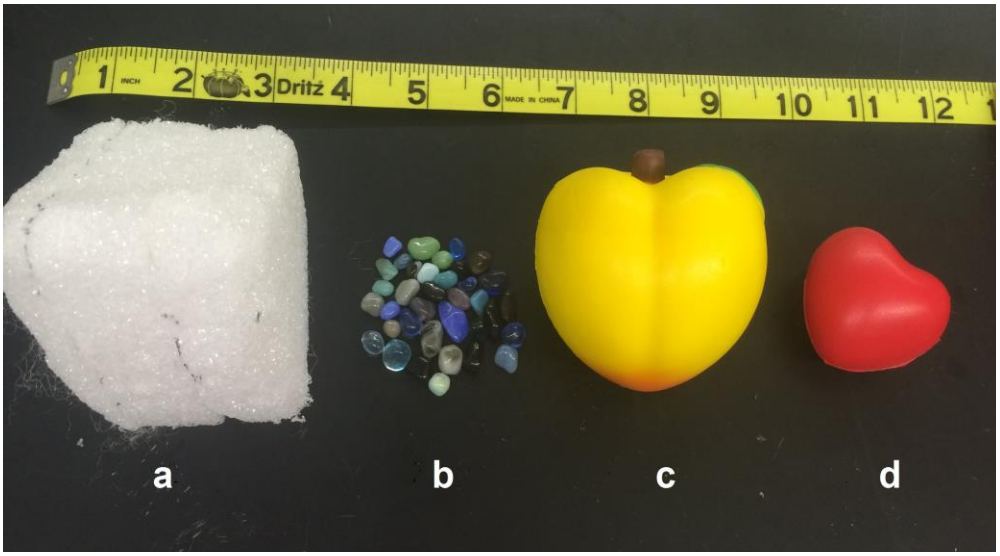


Figure 61: Abnormalities: a) liver mass, b) bladder stones, c) splenic mass d) abdominal mass

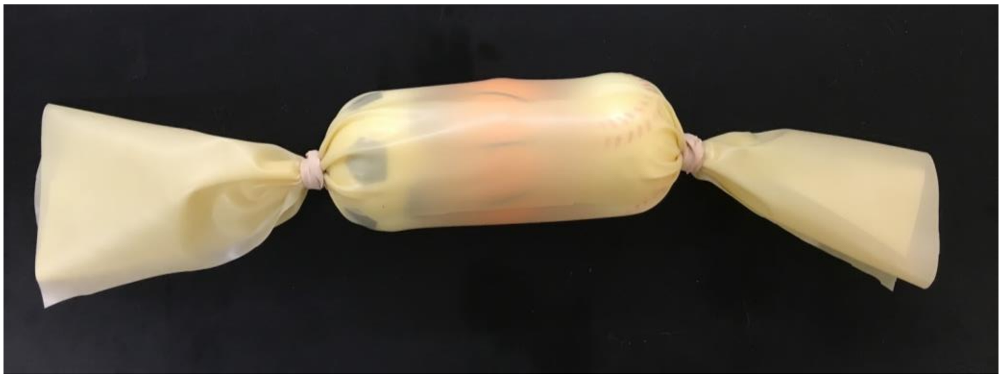


Figure 62: Constipated colon construction

6.3. Construction of Final Design

The front of the abdomen was filled with foam and a cotton-polyester batting. Approximately 20 grams of the cotton-polyester batting was used to fill the empty space in the palpable region, cushion the organs, and give shape to the abdomen. The foam padding used to in the abdominal filler was also cut into small blocks to support the bladder from the bottom and each side. It was also placed above the colon to create space between the colon and the spine. Both the bladder and colon were fixated to the pelvis PVC connector from the rear of the device using zip ties. A Penrose drain cut into a flat rectangle approximately 10 inches long was stretched from the ribcage to the pelvis and fixed with zip ties. These features are shown in Figure 63. The waist of a nylon stocking was then pulled over the entire abdomen to hold the organs and fillers together, shown in Figure 64. A second waist area of a nylon stocking was pulled over the first nylon layer, pictured in Figure 65. In between these two layers, 12 grams of the polyester fiberfill was used to pad the bottom and sides of the abdomen to create an adipose layer. The final layer consisted of a polyester cloth material wrapped around the abdomen from the pelvis to the ribcage, shown in Figure 66. Velcro® strips were hot glued onto this material and used to wrap it securely above the spine piece. The Velcro® allows users to remove this layer easily in the case that a part needs to be replaced.

The device construction is shown in progressive stages in Figure 63 - Figure 68.

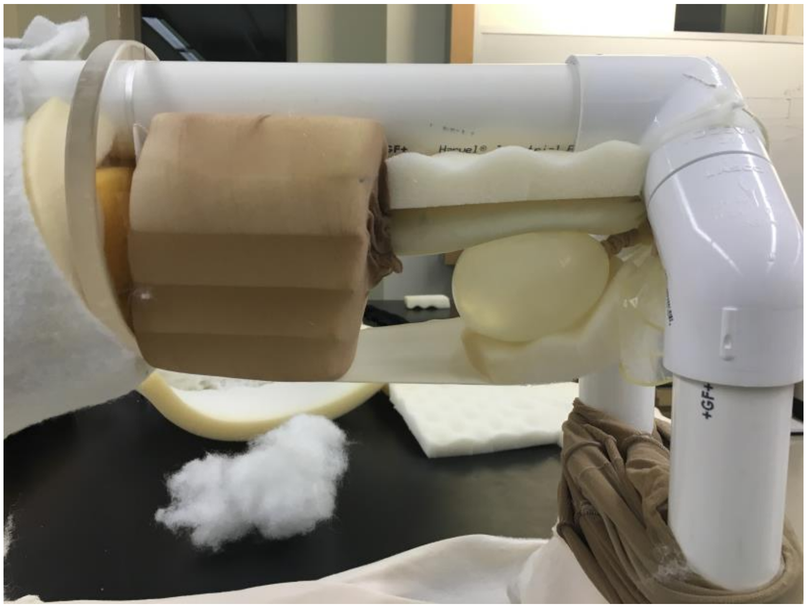


Figure 63: Part 1 of the inner abdomen construction

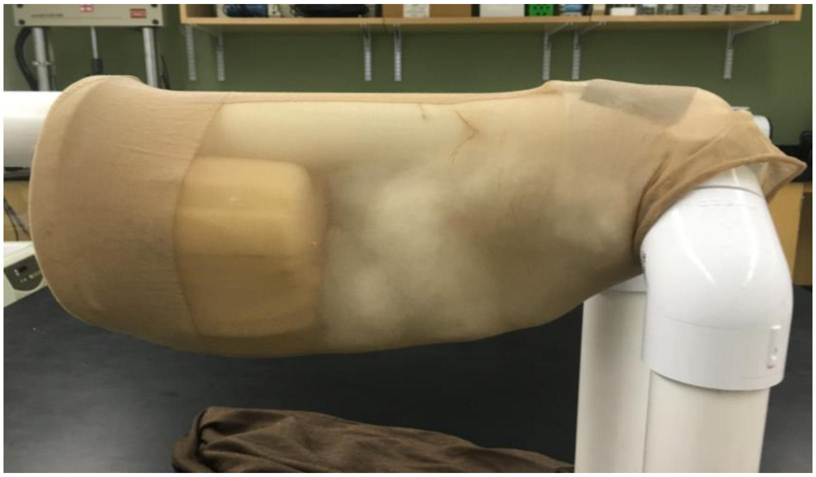


Figure 64: Part 2 of the inner abdomen construction

Figure 65: Part 3 of the inner abdomen construction

Figure 66: Top view of skin layer

Figure 67: Side view of skin layer

Figure 68: Rear view of skin layer

6.4. Experimental Methods Summary

The materials of the soft tissue components of the model were mechanically tested using an Instron 5544. The materials tested included the polyester fabric used to represent the skin and fur layer and two different latex materials used for the colon and bladder. Three samples of each material were tested. The test performed on these materials was a cyclic test in tension. The cycling was intended to mimic an exaggeration of the repeated forces applied to the materials during palpation. Each sample was loaded into the Instron and applied with a tare load. Each sample was then stretched to an initial load that varied based on the material. The polyester fabric and latex Penrose drain were loaded to 20 N while the latex condom was loaded to 7 N. The justification for these initial loads has been explained in Chapter 5. The sample was then returned to 15% strain and cycled 30 times. Once all 30 cycles were complete, the sample was then stretched to a final load or failure. The polyester fabric and latex Penrose drain were set to a load of 100 N while the latex condom was set to a load of 15 N. These final loads were set with the intention for the materials to fail, but the latex condoms and Penrose drains were so mechanically resilient that they did not fail under the loads. In addition, stretching the latex condom to a final load of 100 N was not feasible and beyond the extent of the Instron 5544, so 15 N was chosen based on the high amount of extension the latex condom had to undergo to reach this force.

6.5. Data Analysis Summary

The elastic modulus of the polyester fabric, latex Penrose drain, and the latex condom are outlined in Table 46. These values were important to test the durability of the fabric to ensure that significant changes do not occur after the material has been repeatedly palpated where tensile loads are applied. The loads applied to these materials were higher than what should be experienced in regular palpation. Since the elastic moduli remained relatively similar for each material, it can be stated that the materials would retain their mechanical properties and strength throughout multiple palpations.

Table 46: Elastic Moduli

Material	**Average Elastic Modulus: Before Cyclic Loading**	**Average Elastic Modulus: After Cyclic Loading**
Polyester Fabric (Skin)	21.6 MPa +/- 1.3	11.9 MPa +/- 2.1
Latex Penrose Drain (Colon)	0.199 MPa +/- 0.0513	0.206 MPa +/- 0.480
Latex Condom (Bladder)	0.029 MPa +/- 0.013	0.046 MPa +/- 0.010

The maximum force of palpation was found to be 32.76 N. The average maximum load the polyester fabric could withstand after 30 cycles was found to be 52.0 N +/- 8.80. This is displayed in Table 47 and is approximately double the maximum palpation force. Based on this comparison, the forces that the fabric will be subject to are well below the maximum force it can withstand after repeated use, showing that it is durable and safe to use for palpation.

Table 47: Polyester fabric maximum load

	Normal Palpation	**Polyester Fabric (After Cyclic Loading)**
Force	32.76 N	52 N +/- 8.80

The Penrose drain elastic modulus was used to determine its accuracy, durability, and realism. The elastic modulus was compared to the elastic of porcine bowel tissue, shown in Table 48, to ensure its realism. The modulus was calculated after the material was cycled 30 times and compared to the initial modulus to show the reusability of the Penrose drain. Although the modulus did not fall into the biological tissue range, the client valued the feel of the synthetic stool through the Penrose drain more than the elasticity of the Penrose drain.

Table 48: Penrose drain elastic modulus comparison to biological tissue

	Bowel Tissue (Porcine)	Penrose Drain (Before Cyclic Loading)	Penrose Drain (After Cyclic Loading)
Elastic Modulus	1.83 MPa (Christensen, 2015)	0.199 MPa +/- 0.0513	0.206 MPa +/- 0.480

Durability was tested by finding the maximum load the Penrose drain could withstand. The maximum force applied during palpation is 32.8 N, while the Penrose drain withstood 100 N without failing, displayed in Table 49. This shows the Penrose drain will not fail under normal applied palpation forces.

Table 49: Penrose drain force comparison

	Normal Palpation	Penrose Drain (After Cyclic Loading)
Force	32.76 N	100 N *

*Stretched to 100N and did not fail

Similarly to the Penrose drain, the elastic modulus of the latex condom, shown in Table 50, was found and compared to biological tissue to show that the properties were realistic and accurate. After the cycle was cycled 30 times, the elastic modulus remained within the biological range of a porcine bladder. This shows that the latex condom has realistic properties when compared to a biological bladder.

Table 50: Condom elastic modulus comparison to biological tissue

	Bladder (Porcine)	Latex Condom (Before Cycles)	Latex Condom (After 30 Cycles)
Elastic Modulus	4-260 kPa (Li, 2014)	29 kPa +/- 13	46 kPa +/- 10

In normal palpation, the materials are stretched approximately 20 mm. The average extension at maximum load for the latex condom was 289.4 mm +/- 21.7, displayed in Table 51.

This shows that the condom can stretch beyond 10 time the palpable range, proving it can safely withstand the stretching that occurs in palpation.

Table 51: Latex condom maximum extension comparison

	Normal Palpation	**Latex Condom** **(Extension at Maximum Load*)**
Extension	~20 mm	289.4 mm +/- 21.7

*Stretched to 100N and did not fail

The materials chosen for the soft tissue of this device were mechanically tested to make sure they were realistic, accurate, and durable. They can all be safely used for palpation in this device without being likely to fail.

6.6. Analysis of Survey Data

Two surveys were performed at Tufts' Cummings School of Veterinary Medicine during the design process. The first survey conducted was used to determine the most accurate soft tissue layers in terms of skin, muscle, fat, and fascia to be used for the final devices. The second survey conducted was used to validate how realistic and accurate the final devices are.

6.6.1. Preliminary Survey

For the first survey, four devices with different combinations of layers were brought to Tufts and eleven veterinary professionals were asked questions based on how accurate and realistic each device felt as well as whether or not he or she believed the device was an accurate enough representation that it could be used to teach palpation techniques. These questions are shown in Appendix E. The description of each device is displayed below in Table 52. Each device had similar bladder and colon materials.

Table 52: Description of layers for each device in preliminary survey

Device 1	**Device 2**	**Device 3**	**Device 4**
White fabric	Black suede fabric	Soft black fabric	Brown fabric
Cotton sheeting	Extra batting	Extra batting	Thin foam pad
Medium batting			Medium batting

It was reported for Device 1 that 6 out of 12 respondents could feel internal organs; 5 specifically mentioned the bladder. On a scale of 0-5, this device was ranked an average of 1.54

for accurate feel. On a scale of 0-5, this device was ranked an average of 1.90 for accuracy of force needed to palpate the model. On a scale of 0-5, this device was ranked an average of 1.18 for how likely the surveyor would be to use this device to teach abdominal palpation techniques. On a scale of 0-5, this device was ranked an average of 1.27 for how well the respondent thought the device could be used to teach abdominal palpation. Comments on this device spoke of the outer layers being too thick to palpate, similar to that of an overweight dog. Device 1 is displayed in Figures 69 and 70.

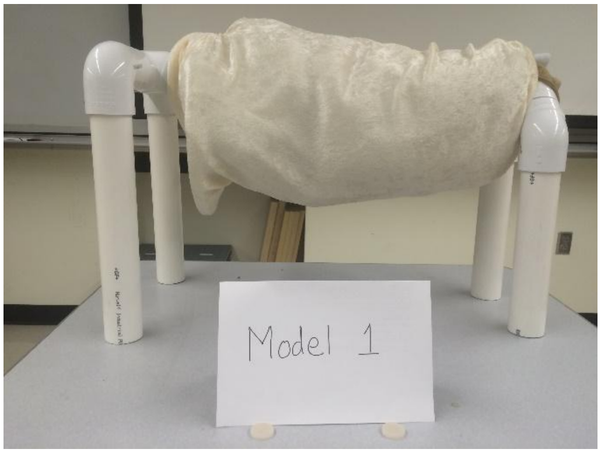


Figure 69: Device 1 with outer layer

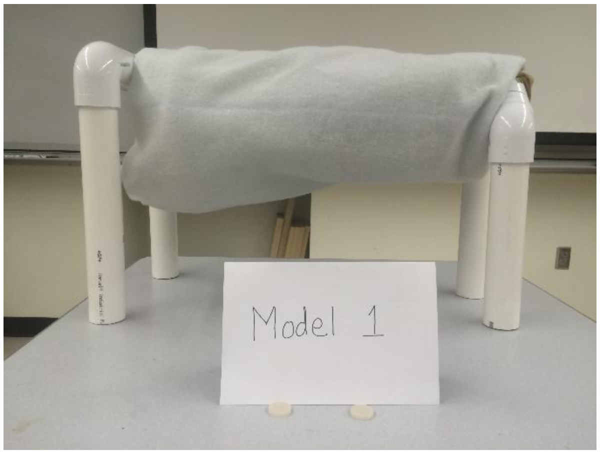


Figure 70: Device 1 without outer layer

It was reported for Device 2 that 9 out of 12 respondents could feel internal organs; 9 specifically mentioned the bladder, and 7 specifically mentioned the colon. On a scale of 0-5, this device was ranked an average of 2.72 for accurate feel, with a majority of 5 respondents ranking it at a 4. On a scale of 0-5, this device was ranked an average of 2.27 for accuracy of force needed to palpate the model. On a scale of 0-5, this device was ranked an average of 2.50 for how likely the surveyor would be to use this device to teach abdominal palpation techniques. On a scale of 0-5, this device was ranked an average of 2.63 for how well the respondent thought the device could be used to teach abdominal palpation, with a majority of

4 ranking it at a 4. This device had comments such as, “the ‘pop’ you get with the bladder is pretty similar to real life” (Survey), and “better than model 1” (Survey). Device 2 is displayed in Figures 71 and 72.

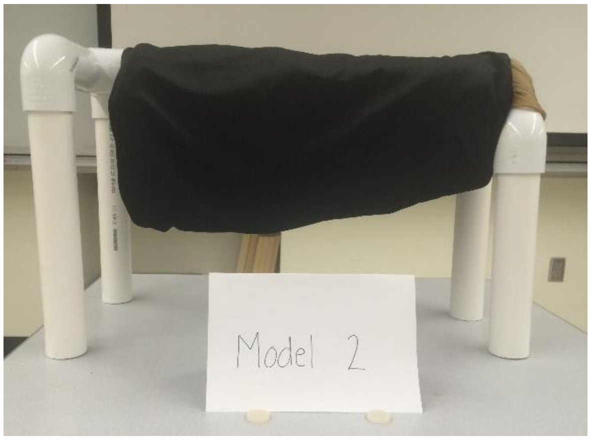


Figure 71: Device 2 with outer layer

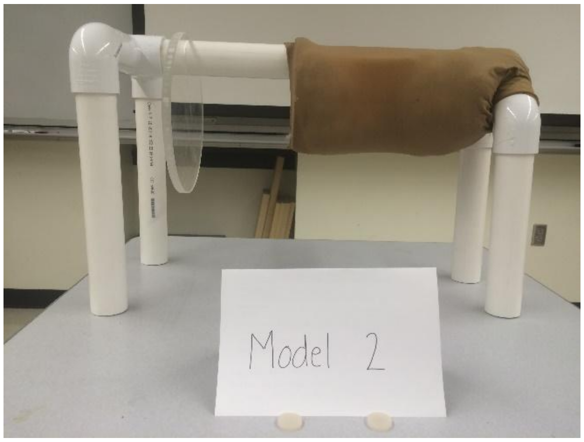


Figure 72: Device 2 without outer layer

It was reported for Device 3 that 11 out of 12 respondents could feel internal organs; 11 specifically mentioned the bladder, and 8 specifically mentioned the colon. On a scale of 0-5, this device was ranked an average of 3.18 for accurate feel, with a majority of 5 respondents ranking it at a 4. On a scale of 0-5, this device was ranked an average of 3.18 for accuracy of force needed to palpate the device, with a majority of 6 respondents ranking it at a 4. On a scale of 0-5, this device was ranked an average of 3.18 for how likely the surveyor would be to use this device to teach abdominal palpation techniques, with a majority of 5 respondents ranking it at a 5. On a scale of 0-5, this device was ranked an average of 3.09 for how well the respondent thought the device could be used to teach abdominal palpation, with a majority of 5 respondents ranking it at a 4. This device had comments such as, “This one is the best so far.

The colon is well palpable. The bladder is a little more difficult" (Survey). Device 3 is displayed in Figures 73 and 74.

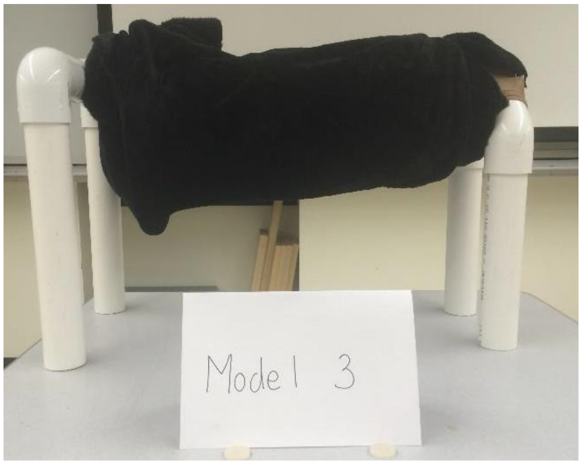


Figure 73: Device 3 with outer layer

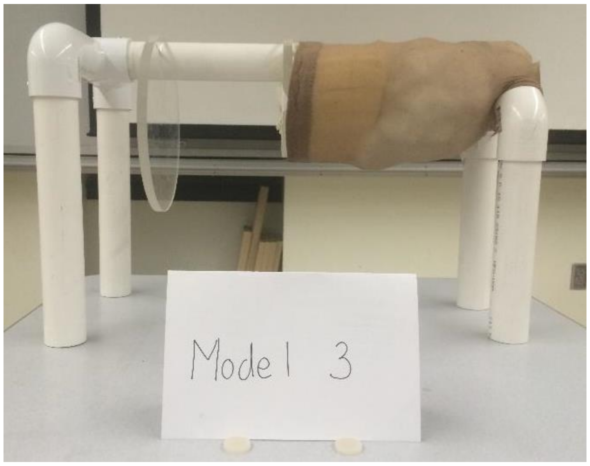


Figure 74: Device 3 without outer layer

It was reported for Device 4 that 6 out of 12 surveyors could feel internal organs; 4 specifically mentioned the bladder, and 4 specifically mentioned the colon. On a scale of 0-5, this device was ranked an average of 1.45 for accurate feel. On a scale of 0-5, this device was ranked an average of 1.55 for accuracy of force needed to palpate the model, with a majority of 6 respondents ranking it at a 2. On a scale of 0-5, this device was ranked an average of 1.09 for how likely the surveyor would be to use this device to teach abdominal palpation techniques. On a scale of 0-5, this device was ranked an average of 1.09 for how well the respondent thought the device could be used to teach abdominal palpation. This device had comments such as, "The abdominal wall is too thick…not very elastic" (Survey), and "Required a lot of pressure" (Survey). Device 4 is displayed in Figures 75 and 76.

Figure 75: Device 4 with outer layer

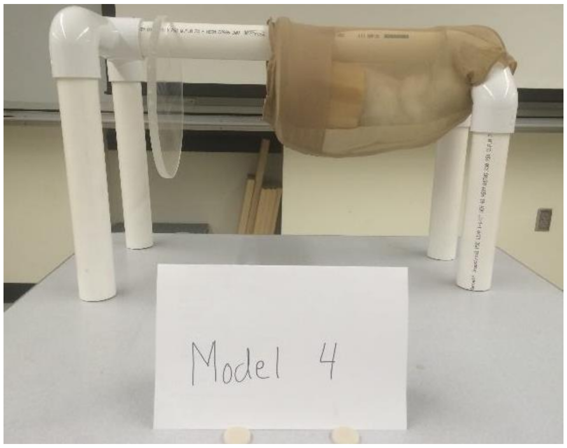


Figure 76: Device 4 without outer layer

The preliminary survey lead to the conclusion that device 3 was the most accurate in terms of how it felt and how palpable the internal organs were. Devices 1 and 4 were the lowest ranking devices based on the same terms. One outstanding comment was that the colon should be larger in the final models. The results of this survey acted as a deciding factor in the soft tissue materials used in the final device and allowed the team to determine the sizes for the colon and bladder. Because it was concluded that Device 3 was the most accurate, it was decided that the soft tissue layers of the final devices would consist of foam and batting for abdominal filler, nylon stockings for fascia, and polyester fabric for skin.

6.6.2. Device Validation Survey

In the second visit to Tufts, the 10 final devices with abnormalities were tested to ensure they were realistic and accurate. Five of the 10 final devices were brought to Tufts and 25 veterinary professionals and students were surveyed. The survey questions and responses are shown in Appendix F. The abnormalities present in the five devices were constipation, liver mass, mid-abdominal mass, overweight and bladder stones. Participants were asked how well the devices simulate the experience of palpation, whether or not he or she would use the devices in a classroom setting, and if the devices could help someone to learn or teach palpation techniques. A majority of the participants ranked the accuracy of experience of palpating the devices a 4 out of 5, 96% said they would use the devices in a classroom setting, and the average rating for how well the models could help students learn palpation techniques was a 4.3 +/- 0.6 out of 5. The validation survey lead to the conclusion that the final devices were realistic, accurate, and suitable for use in a classroom setting.

6.7 Industry Standards

In order to be accredited by the American Veterinary Medical Association (AVMA), a college must meet certain requirements. The requirements related to this device fall under 7. Requirements of an Accredited College of Veterinary Medicine, Standard 9: Curriculum, and Standard 11: Outcomes Assessment. Standard 9 calls for hands-on experience to ensure students' capabilities in diagnostics and interpretation, as well as patient management and care. Students can use these models to simulate an experience with a client in order to practice professional ethics and behaviors. Students must be able to acquire information from patients. Standard 11: Outcomes Assessment mandates that students must have achieved competence in diagnosing patients using problem solving skills. Patient welfare, basic medicine skills, and client communication proficiency are included in the competency requirements. Both standards also call for students to be aware of ethical conduct (Accreditation Policies, 2016).

The ISO mechanical testing standards for uniaxial tensile mechanical testing only apply to certain processes and metallurgical materials that were not used in the scope of this MQP. The ISO standards for mechanical testing were researched by the design team, although none were necessary to fit the mechanical tests of this project to (ISO Standards, n.d.).

This device fulfills and improves upon the criteria described above. The device allows real-time information gathering about the patient's current health state. Students will be faced with determining the health of the device they are palpating, which will require them to use their diagnostic, problem solving, diagnostic, and interpretation skills. They can practice caring for an animal without the possible negative consequences if they make a mistake on a live animal. This device inherently addresses proper ethical conduct requirements since it eliminates the need to use live animals for initial palpation training.

6.8. Impact of Device

The purpose of the following sections is to discuss the impact and implications the device will have on the economy, the environment, society, global markets, ethical concerns, health and safety, manufacturing, and sustainable production.

6.8.1. Economics

This palpation device is the first step towards creating a teaching device that replaces live animals that must be sedated to teach palpation to veterinary students. The device design is filed under a provisional patent with the United States Patent and Trademark Office under

Number 62322472. The lifespan of the devices will most likely match or exceed the lifespan of the canines used for teaching in the laboratory. Housing lab animals incurs other associated costs such as food, shelter, and medical care. Synthetic training models that replace the lab animals currently used for palpation training would reduce these costs. Parts of the device may also be replaced for low expense if something were to malfunction or break. This will decrease the costs needed for anesthetics for the live canines when teaching palpation. This device is also easy to machine and produce with minimal labor. The materials are readily available from craft stores and large scale general retail stores. The device can be created for a cost of $70.62 and it is an investment that will save both time and money compared to the care and costs of using live canines. This device allows professors of veterinary schools to have a practical and cost effective method for teaching students abdominal palpation. The amount of time spent learning palpation can be increased since the students and professors do not need to consider causing an animal discomfort when palpating.

6.8.2. Environmental Impact

The device positively affects the environment by reducing need of anesthetics used on canines to teach preliminary palpation practices. This reduces plastic waste from single-use syringes used to anesthetize the animals. Although the device uses various plastics, it was also designed to be durable and have a lifespan of at least two years. Therefore, excess waste will not be generated by the use of the palpation devices. The hard tissue design of this device was also designed to last even longer than five years, so even if soft tissue materials must eventually be replaced, the waste they will create is minimal and the majority of the device will remain intact. The worn out fabrics and foams could be repurposed for an application that requires less elasticity. The polyester fiberfill batting does not degrade and will only become less dense. As such, its lifespan will also be longer than two years. The only waste products generated from manufacturing include excess polyvinyl chloride and polycarbonate, and these are both recyclable plastic materials. The lack of waste products results from the fact that this device utilizes mostly commercially produced parts. There is no electricity or external resources necessary for the functionality of this device, therefore, the effect this device will have on the natural environment is minimal.

6.8.3. Societal Influence

A device that teaches palpation has only been created for widespread use for human medicine. In almost every medical school across the country, there are simulation labs that include mannequins and models to teach students clinical procedures, and this includes palpation devices. There is no product that is widely used by veterinary schools. This device may create market where animal palpation devices are mass-produced and distributed to veterinary schools across the country. This would prevent the overuse of live canines, saving them from discomfort and the potentially harmful side effects of being anesthetized. This device can also be altered and improved to be a model for other breeds of canines or other small animals.

6.8.4. Political Ramifications

There is currently no global market for animal palpation devices, although the production of this device has the potential to create a market in the future. A market this product could create would only benefit the markets of other countries. This device has the potential to prevent the unethical treatment of canines used in veterinary school laboratories. In addition to this, veterinary schools in other countries have expressed interest in the creation of a palpation training device for students, giving encouraging feedback on the usefulness of this device in the schools (Parkes, 2009). There is currently no controversy about student training devices as long as the devices are synthetic and do not harm animals (Williamson, 2015). We currently do not anticipate negative political ramifications.

6.8.5. Ethical Concerns

This device will create ethical benefits because the canine teaching models will be replaced by synthetic models. The device will also provide a better opportunity for learning palpation in veterinary schools. As one of the primary skills necessary for a veterinarian working in a clinic, the device will provide more enhanced learning for students to feel various conditions they may encounter within the abdomen. The abnormal conditions that will be simulated are a small and large bladder, a bladder with bladder stones, a constipated colon, liver, splenic, and mid-abdominal masses, and an overweight animal. Ten different devices, each with a different abdominal medical condition, will greatly augment the learning of palpation for veterinary students compared to just learning palpation on healthy canines. This also creates an easier and more fulfilling role for the professor of the class because they can present each condition and teach the students each likely scenario with a teaching tool. Often times during palpation a group of canines will be used throughout the whole course of one day of training. This can often times cause the animal stress and cause the abdominals to become tender and painful. By implementing this device during student training, live canines will potentially be used less for palpation training sessions. The students also now have the ability to learn how abnormal abdominal conditions feel. This was not possible previously since palpating an unhealthy animal is unethical.

6.8.6. Health and Safety Issues

The palpation device is safe for nearly all users. The exception includes those allergic to the materials the device contains, specifically latex. While latex is used within the device, it is shielded by external materials so that a user would never come into direct contact with the latex. The device produces no harmful chemical by-products. The device weighs approximately 16 pounds and is a maximum of 11.5 inches wide and 24 inches tall. As long as the device is handled properly and with care, the weight and size of the device will not cause any harm to users who are transporting the device.

6.8.7. Manufacturability

The palpation device is simple to reproduce. The soft tissue aspect of the device can be produced from craft store or household products that may also be ordered online. These materials can easily be found and are manufactured uniformly. These parts are simple to assemble and do not require an excessive amount of time. The hard tissue aspect of the device can be produced using the purchased materials, a saw, a basic tool kit with a screwdriver or drill, and ideally a lathe. The hard tissue aspect is the only part of the device that must be manufactured. Needing a lathe to turn down the edges of the PVC pipe can be solved by using glue instead. This would mean that the pipes were essentially permanently attached. The custom made end caps, or something with a similar function, are only required if sand is used to fill the legs. Making and assembling the hard tissue aspect takes approximately 5 hours per device.

6.8.8. Sustainability

The largest components of the device are composed of polyvinyl chloride and polycarbonate. Both of these materials are general purpose plastics that are long-lasting and durable in moderate environments under minimal stress. Their role in the device is optimal for sustainability of the device as no high stresses are applied to the device under proper use. The bottoms of the legs of the device are capped in rubber to prevent any wear of the PVC against surfaces it rests on. A function of this device was durability, and it has been proven through testing the elastic moduli of materials after cyclic loading that it meets this function. The devices will last through years of use, only requiring small, accessible, and commercially produced replacement parts. The use of the device requires no external energy, and there are no waste products created by the use of the device.

Chapter 7: Discussion

The goal of this project was to create a series of beagle abdominal palpation training devices for veterinary students to use in a classroom setting to learn palpation techniques. In order to achieve this goal, primary objectives were established. The final beagle abdominal palpation training devices had to be realistic, accurate, durable, reusable, portable, and reproducible. To assure these objectives were met, a series of different tests and interviews were performed throughout the duration of the project.

7.1. Reproducible and Portable

To ensure that the devices could be easily reproduced, a few considerations were taken into account. The two main aspects were the design and the material choices. The design of the model had to be easily constructible. For the skeletal foundation of the model, numerous CAD design alternatives were evaluated. With the help of a machinist, the team was able to decide on the most feasible design based on its reproducibility. The reproducibility of the hard tissue component was later put to the test by creating multiple models. Within a week, the team was able to construct four models. This time frame included ordering and receiving materials, machining the individual parts, and constructing the frame. The time calculated to create a single hard tissue aspect of the device was estimated to be approximately 5 hours. The materials used for the model also had to be easily accessible and within the budget. A decision matrix was used to determine the most feasible materials in terms of cost and availability that could be used to manufacture multiple models. It was verified that the models were portable throughout the work done on the models. Between the construction and testing, the models were transported a great deal. Models were easily moved to different locations in the provided laboratory space as well as transferred to Tufts Veterinary School for testing without any difficulty. Each model is approximately 15 inches tall and 24 inches long. The front is 11.5 inches wide. The back is 7 ¾ inches wide. The weight of each device is approximately 16 lbs. making the device easily portable.

7.2. Durable and Reusable

The objective of durability and reusability was assured through a series of mechanical tests. The materials used to mimic the vital soft tissues were cyclically tested using an Instron 5544. These materials included the polyester fabric used to represent the skin and fur layer and two different latex materials used for the colon and bladder. The samples were stretched to a set load, cycled 30 times, and stretched to a final load or failure. The magnitude of the initial and final loadings varied between the different materials tested. The purpose of the cyclic testing was to mimic an exaggeration of the repeated loadings the materials are assumed to undergo during palpation. This test simulated the highest loads under the worst possible conditions for the device to undergo at one time. Each device will be palpated much more than 30 times, but it is unlikely that high tensile loads will be applied to a device 30 consecutive times. During palpation laboratory sessions using these devices, the materials will likely have more time to return to their original state and the forces of palpation will be applied over a larger area.

The parameters of interest for the skin layer were the elasticity and the maximum load. On average, the polyester material showed a modulus of 21.6 MPa during the initial loading and an average modulus of 11.9 MPa during the final loading, following the cyclic loading. These results show that the stiffness of the polyester fabric decreased after the 30 cycles above the palpation range. A paired two sample mean t-test was performed to determine if the modulus of the preload and the modulus of the final load were significantly different. The null hypothesis for this test was that the values were not significantly different. Based on the results of the t-test, the alpha level output was 0.48 while the alpha level chosen was 0.05. Because the alpha output was greater than the chosen alpha level, the null is not rejected. In terms of the t-score, the t critical output of 4.30 is smaller than the t-critical value of 8.97, so again we fail to reject the null. Based on the t-test, it cannot be proven that the values for modulus during the preload and final load are different. The average maximum load the polyester fabric was able to withstand was 52.0 N. During initial testing, it was determined that the maximum force exerted during proper palpation techniques was 32.76 N. The results show that the polyester fabric is able to withstand forces greater than the force applied during use of the device. The difference in values also leaves room for error assuming veterinary students may apply larger forces while learning the proper techniques.

The parameter of interest for the colon material was the elastic modulus. The average modulus of the latex material during the initial loading was 0.199 MPa, while the average modulus of the material during the final loading was 0.206 MPa. This shows that after being repeatedly palpated, the latex Penrose drain used for the colon will not lose elasticity showing it is able to withstand repeated use. The samples also did not fail at 100N, showing that this material will be well able to withstand the forces of palpation.

The parameters of interest for the bladder material were the elastic modulus and the maximum extension. The average modulus of the thin latex material during the initial loading was 0.029 MPa, while the average modulus of the material during the final loading was 0.046 MPa. This shows that after being repeatedly palpated, the thin latex used for the bladder will not lose elasticity. This proves it is able to withstand repeated use for practicing palpation. During the final loading, the material was able to reach an average extension of 289.4 mm. During initial testing it was found that the maximum extension of this material for normal palpation techniques was approximately 20 mm. The bladder material is easily able to surpass this extension value leaving room for error during palpation of the device. This validates the durability of the latex condom for use as the bladder.

7.3. Realistic and Accurate

In order to ensure that the materials used in the final device were realistic and accurate, the values for elastic modulus of the material samples were compared to that of biological tissue. Elastic modulus is important because the material must be able to both stretch and return to its original position the same way biological tissue on a live canine would. The elastic modulus for the Penrose drain did not fall into the range of biological porcine colorectal tissue. However, according to the literature colorectal tissue properties vary significantly between species (Christensen, 2015). Also, the client stated that during palpation, it is the stool inside the colon rather than the colon itself that is felt. Because the feel of the model magic within the Penrose drain is realistic, the final design of the colon is deemed realistic. The average initial modulus for the polyester fabric was 21.6 MPa, which falls into the range of biological porcine skin deeming the polyester fabric realistic. Lastly, the elastic modulus for the latex condom, 29 +/- 13 kPa, fell within the range for biological porcine bladder tissue, 2-260 kPa, deeming the latex condom bladder realistic.

To ensure that the final devices were realistic and accurate enough to be used in a classroom setting for teaching palpation techniques, a series of surveys were performed at Tufts Veterinary School. The first survey conducted was used to determine the most accurate soft tissue layers in terms of skin, muscle, fat, and fascia. Four devices with different combinations of layers were brought to Tufts and eleven veterinary professionals were surveyed and asked questions based on how accurate and realistic each device felt as well as whether or not he or she believed the device was an accurate enough representation that it could be used to teach palpation techniques. It was determined that the device with polyester fabric, foam, nylon stockings, and polyester batting was the most realistic and accurate. For this device, 90.9% of participants could feel the underlying organs, majority of participants ranked the accuracy of the model to be 4 out of 5, and a majority ranked the accuracy of the force needed to palpate the model a 4 out of 5. Overall, the consensus of the feedback was that the use of that device could significantly improve how palpation is taught and learned. Based on these results, the skin, muscle, fat, and fascia layers of the final models were determined. The negative feedback for the other models acted as inspiration for the abnormal conditions for the final devices. The models that received feedback of having too much padding were used to represent an overweight canine abdomen. In the second visit to Tufts, the 10 final devices with abnormalities were tested to ensure they were realistic and accurate. Five of the 10 final models were brought to Tufts and 25 veterinary professionals and students were surveyed. A majority of the participants ranked the accuracy of palpation a 4 out of 5, 96% said they would use the devices in a classroom setting, and the average rating for how well the models could help students learn palpation techniques was a 4.3 +/- 0.6 out of 5. The results prove that the devices meet the objectives realistic and accurate and are suitable for use in a classroom setting.

7.4. Limitations

This device is the first of its kind. While there are existing human devices used to practice abdominal palpation and other medical practices, there are no such devices that exist in veterinary medicine. While this device is a novel one in the field of veterinary medicine, the lack of existing devices was a limitation of the project. Without other devices, there were no test methods or numerical test values to compare to, leaving the team to make their own assumptions based on literature on different devices. Based on the survey feedback, it was determined that the final devices best represent sedated canines. The devices are unable to respond to palpation the same way a live animal would in term of tensing up.

Chapter 8: Conclusions and Recommendations

8.1. Conclusions

The devices, a series of canine palpation training devices for the purpose of teaching, met the objectives within the given time frame of nine months, using the allotted budget of $800 and accessible equipment. The client's needs, wants, and constraints were also met. The devices are capable of performing the necessary functions while meeting the primary and secondary objectives. The primary objectives were that the devices should be realistic, accurate, durable, and reusable, while the secondary objectives were that the devices should be portable as well as reproducible. The functions of the devices were primarily evaluated using mechanical tests and field surveys from students and Doctors of Veterinary Medicine at the Cummings School of Veterinary Medicine at Tufts. The results of these surveys were used to alter and improve the prototypes, resulting in the final devices.

The objective of this project was to create a series of realistic canine abdominal palpation devices for veterinary students to learn abdominal palpation and diagnostic palpation techniques. These devices create a positive alternative to using live animals to learn palpation, as well as additional opportunities for learning various abnormal conditions simulated by the devices. Often times, practicing on live animals can put a great deal of stress on the animal, and by the end of the day the animal is very stiff, fatigued, and uncomfortable. Using these devices allows for more effective training and avoids the need to use live animals to teach veterinary students palpation. This device will be useful in a wide variety of learning settings, and it will be useful for veterinary schools across the country.

Quantitatively, the design team's test results have shown that the palpation devices accurately represent palpation of a live animal with regard to the mechanical properties of biological tissue as well as the dimensions of each biological tissue or organ of a canine. The mechanical properties of the device were measured using mechanical tests and comparing calculated values to those found in the literature. The dimensions, shapes, and sizes were measured with calipers, rulers, and validated with feedback from the client. The devices are haptically and mechanically accurate based on mechanical testing, veterinary professional and student feedback, and according to the client. This means the device has the most realistic feel when being palpated and the best representation when compared to a live animal.

One main roadblock to success was the lack of information about the background information needed to build this device. Human palpation devices have been widely produced and are frequently used in the medical community. However, there is a distinct lack of detail about which materials are used in these devices and the mechanical properties of the materials used. Further research is needed to determine the mechanical properties of canine organs including the skin, fat, and fascia layer, as well as the bladder and colon. If the device is extended to different species, the mechanical properties of these animals' organs should also be investigated and reported. These mechanical properties will allow product developers to select synthetic materials with comparable mechanical properties to animal organs.

8.2. Recommendations

The device could be enhanced and extended with further research and implementation. The material used for the ribs was acquired from the WPI Machine Shop at no cost to the team. It was recycled from a previous project but was not damaged in any way relevant to this project and fulfilled the functions of the ribs satisfactorily. The team recommends that in future production, a different, less expensive material, be chosen to fulfill the functions of the ribs. This material's functions can be equally fulfilled by the less expensive option, such as acrylic or polyacrylamide sheets.

Veterinary students must pay attention to the amount of force they are using during palpation. Using too little force will prevent the student from feeling internal organs, while too much could cause pain or discomfort to the animal. The team recommends that force sensors be implemented to determine how much force is being applied on the device. This was not feasible to do within the scope of this project in terms of cost and time. Depending on how much force is applied, feedback could be given to alert the student as to whether more or less force should be applied. This would incur a higher cost per device, but it would add a valuable functionality to the device, according to the client.

Another option that would add functionality to the device is the implementation of a dynamic bladder. In a clinical setting, animal bladder size and turgidity will rarely be the same from patient to patient, so the students should be able to learn what various size bladders feel like. The volume of the internal bladder could be changed by using a pump and vacuum combination to either add or remove fluid.

This project presents ten different devices, each with its own abdominal condition. This makes it possible for students to palpate each device in succession and compare the conditions of each device with each other. If the application of these devices requires them to be more compact, the team recommends manufacturing one device with interchangeable parts. The outer layers, internal organs, and filler could be changed to simulate a variety of abdominal conditions within one device. The device created by the team was designed with the intent that this could be a potential option using the hard tissue design with some minor alterations.

Based on feedback from veterinary professionals at Tufts, the devices could be improved to incorporate abdominal muscle tension. During palpation, the animals tend to tense up. According to the surveys, the current models are an excellent representation of sedated canines, but implementing a model with tense abdominal muscles could be beneficial.

The team recommends further expansion of the devices in regards to the breeds and species it is used to model since palpation is a diagnostic tool used throughout the span of veterinary medicine. More devices could be manufactured to model other canine breeds as well as different animal species, including but not limited to felines, goats, or horses. These devices would facilitate student education on a wider variety of animals. Additional devices could simulate a larger range of abdominal medical conditions by adding more diagnostic scenarios to the soft tissue design.

Further research should be conducted to determine an optimal way to transport the ten devices. It is possible to disassemble the devices so that they can be transported in a more compact manner. The devices should then include assembly instructions. If they are not disassembled, they can be arranged so that the legs of the device interlock. This would eliminate variability in how assembly procedures are followed. Once at their destination, one or more wheeled racks, depending on their size, could be used to transport the devices from one classroom to another.

The team recommends that a long-term durability study be conducted to determine the actual wear properties of each material. The absence of this study should not prevent the devices from being used in the classroom since they pose a low risk to those using the devices. Usage data, such as the modulus of elasticity at set time points, and when each material begins to break down should be recorded to estimate maintenance and replacement time points for each material.

The creation of these devices can provide an enhanced quality of life for animals. Improving the palpation skills of veterinarians will lead to more accurate diagnoses, and thus, faster and more appropriate treatment plans. The main impact will be on the everyday lives of pets and their caretakers around the world. Hopefully, this project will be further enhanced so that its current capabilities can be extended to facilitate training of veterinary students on a wider breadth of animals and abnormalities.

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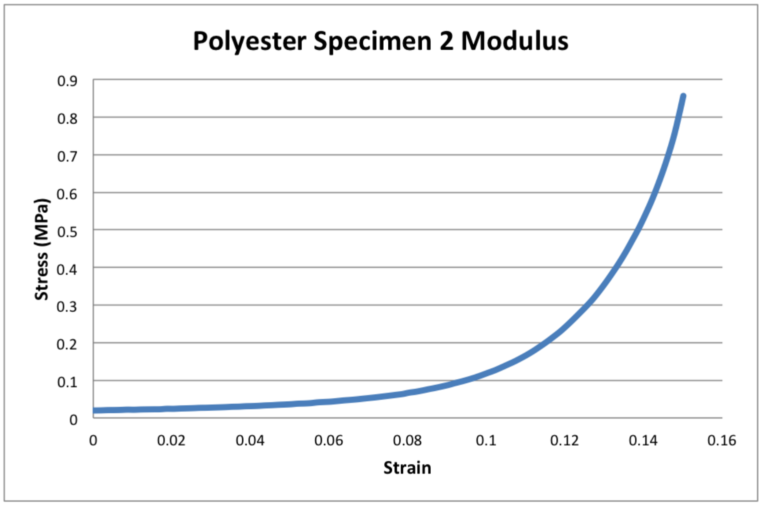
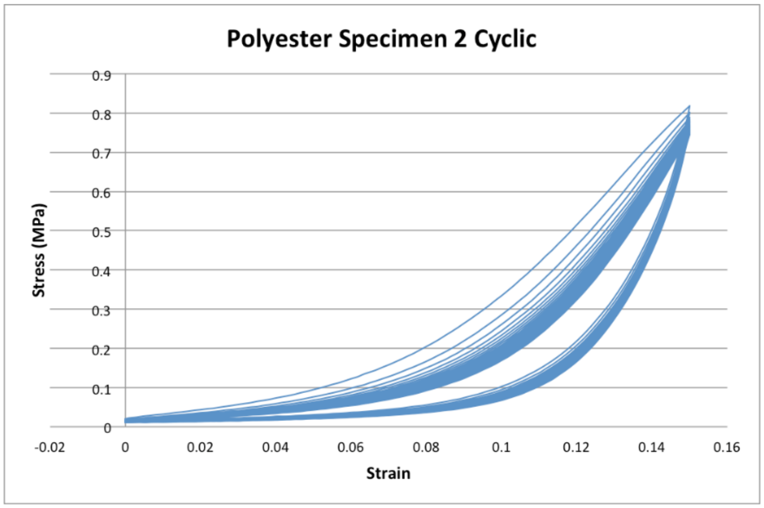
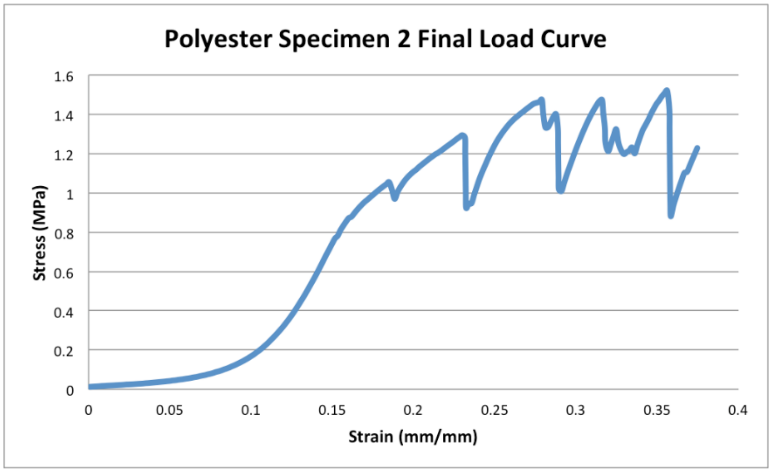
Appendix

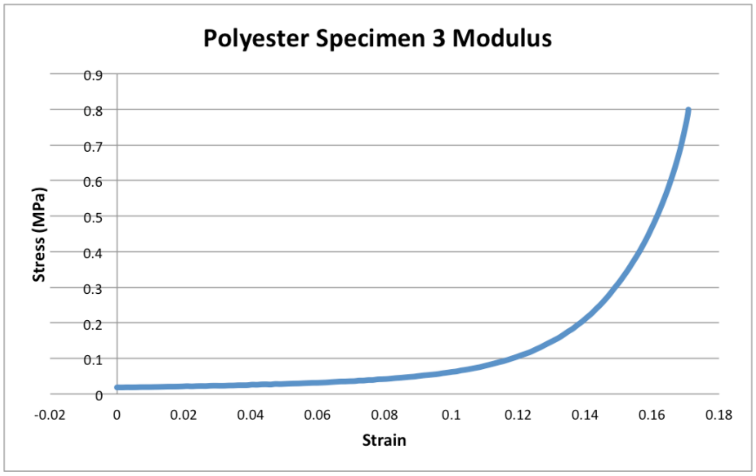
Appendix A: Polyester Specimen 2

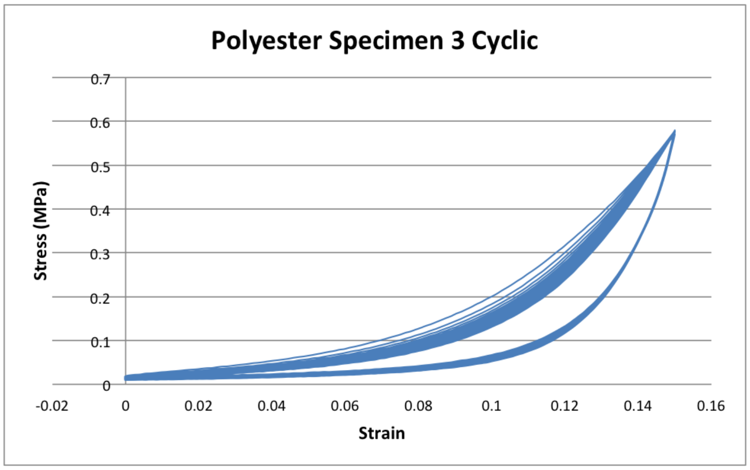


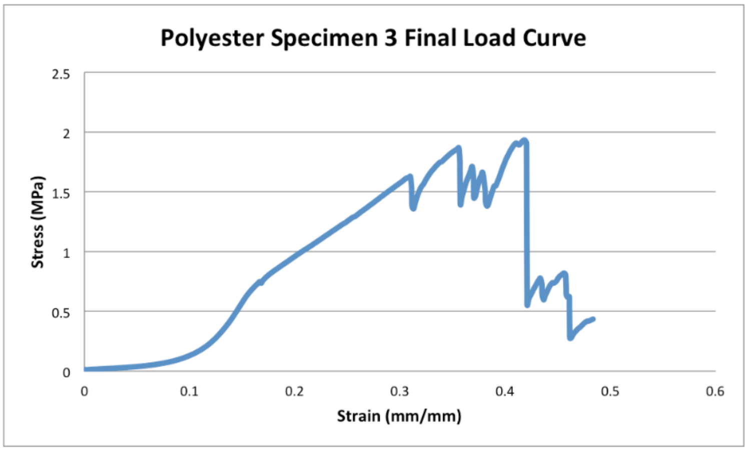




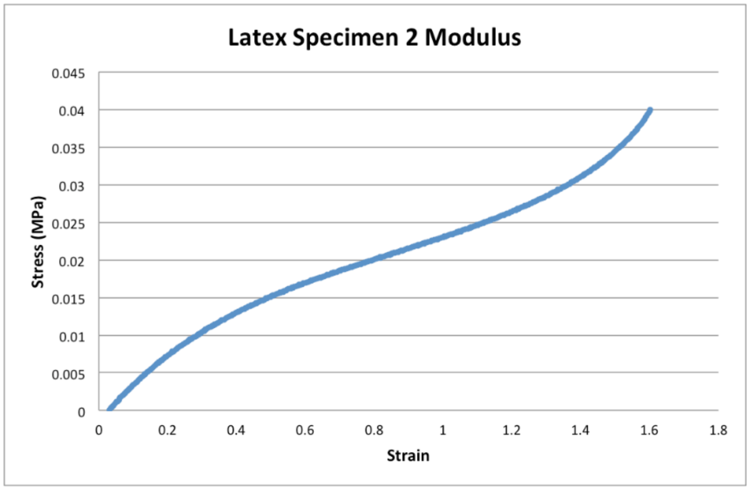
Appendix B: Polyester Specimen 3

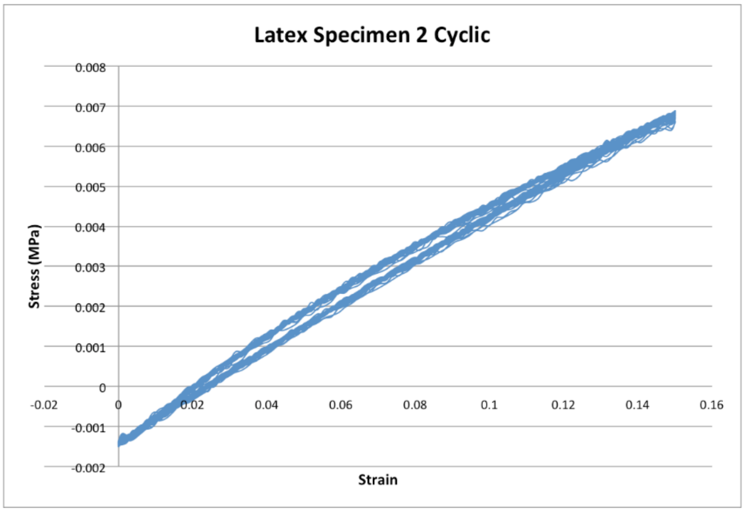


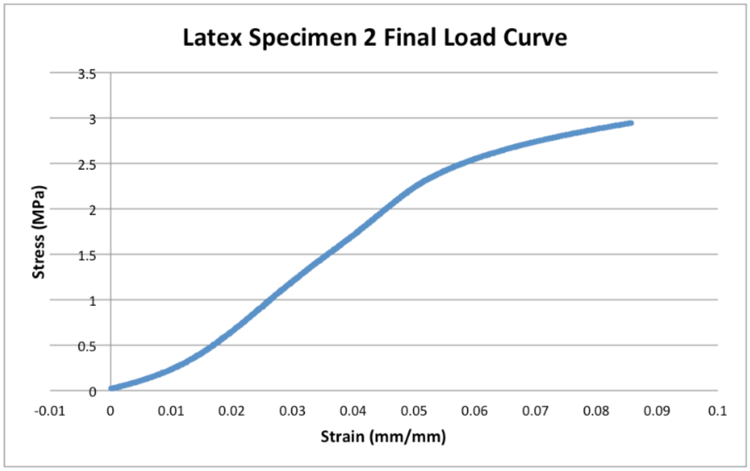




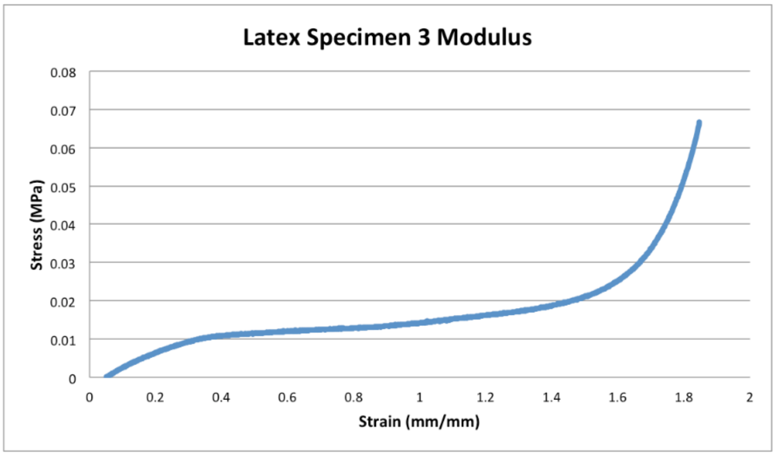
Appendix C: Latex Specimen 2

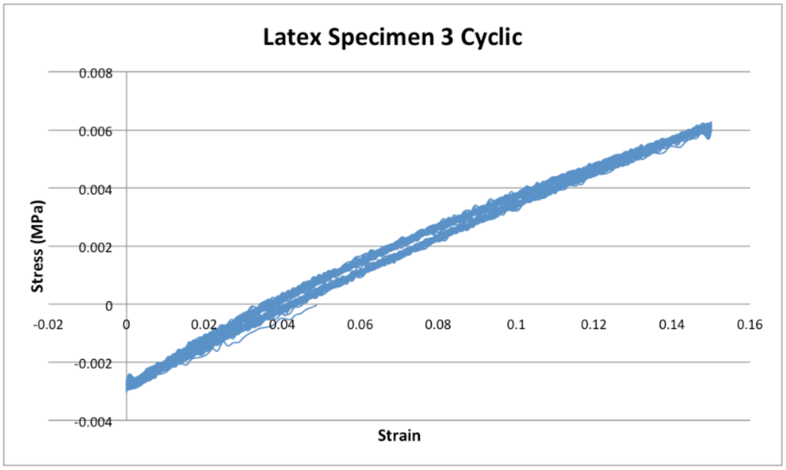


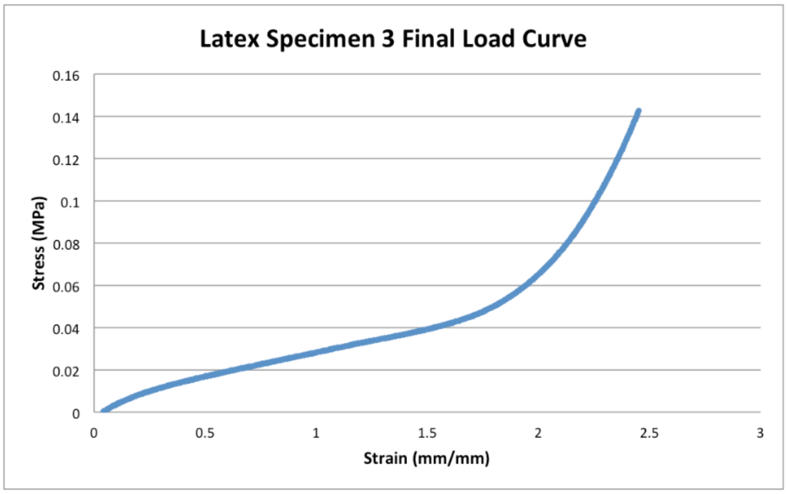




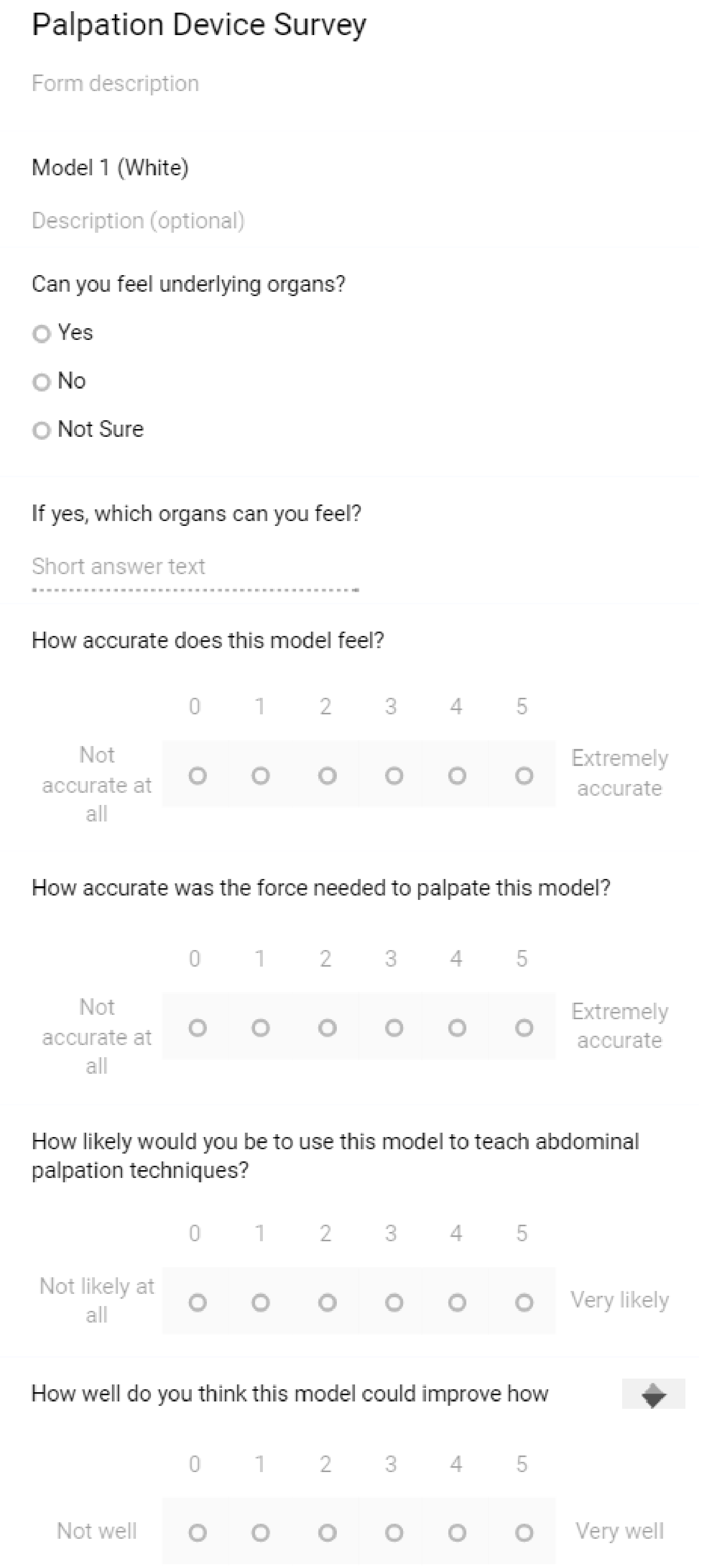
Appendix D: Latex Specimen 3







Appendix E: Tufts Preliminary Survey



Palpation Device Survey

Form description

Model 1 (White)

Description (optional)

Can you feel underlying organs?

○ Yes

○ No

○ Not Sure

If yes, which organs can you feel?

Short answer text

How accurate does this model feel?

	0	1	2	3	4	5	
Not accurate at all	○	○	○	○	○	○	Extremely accurate

How accurate was the force needed to palpate this model?

	0	1	2	3	4	5	
Not accurate at all	○	○	○	○	○	○	Extremely accurate

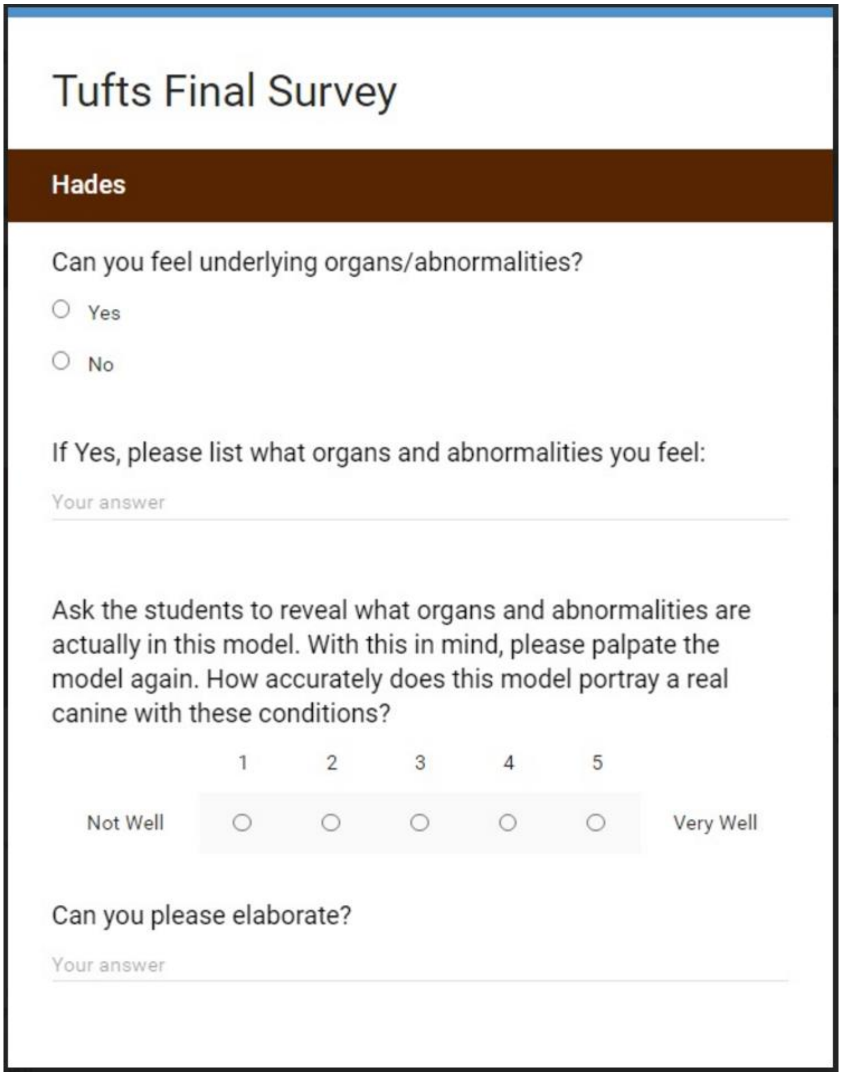
How likely would you be to use this model to teach abdominal palpation techniques?

	0	1	2	3	4	5	
Not likely at all	○	○	○	○	○	○	Very likely

How well do you think this model could improve how

	0	1	2	3	4	5	
Not well	○	○	○	○	○	○	Very well

Appendix F: Tufts Final Validation Survey



Tufts Final Survey

Hades

Can you feel underlying organs/abnormalities?

○ Yes

○ No

If Yes, please list what organs and abnormalities you feel:

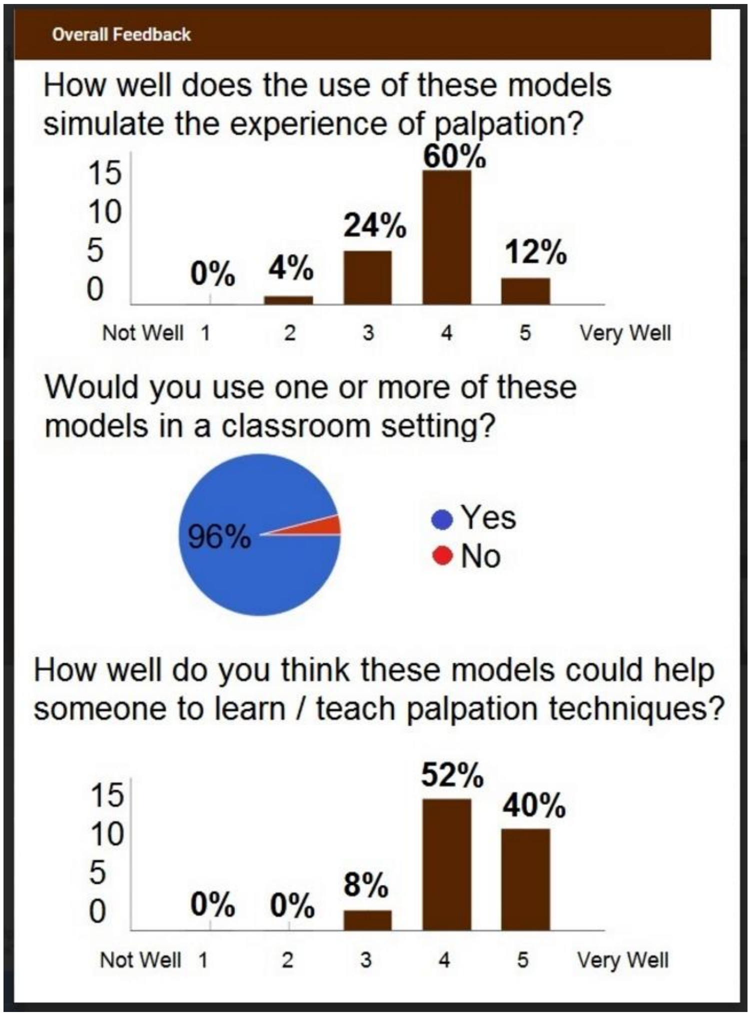
Your answer

Ask the students to reveal what organs and abnormalities are actually in this model. With this in mind, please palpate the model again. How accurately does this model portray a real canine with these conditions?

	1	2	3	4	5	
Not Well	○	○	○	○	○	Very Well

Can you please elaborate?

Your answer



Overall Feedback

How well does the use of these models simulate the experience of palpation?

Would you use one or more of these models in a classroom setting?

How well do you think these models could help someone to learn / teach palpation techniques?