# ABSTRACT

Title of Thesis: INVESTIGATING A COOPERATIVE SYSTEM OF SENSING AND TRANSMITTING HAPTIC FEEDBACK OF SOFT TISSUE FOR ROBOTIC SURGICAL APPLICATIONS

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Robotic-Assisted Surgery (RAS) improves upon traditional minimally invasive (MIS) and open surgical techniques by maintaining the benefits of MIS while also providing surgeons with a wider range of motion, increased depth perception, and control for tremors. However, an inherent limitation of the technology is that surgeons performing RAS must rely solely on visual feedback and lose the sense of touch. This creates a steep learning curve for the technique. Previous literature and results from our own survey (n = 15) of robotic surgeons suggested that the introduction of haptic feedback to RAS will improve overall patient outcomes as well as decrease error rates and operating times for surgeons. To address this, we proposed a proof-of-concept addition to RAS systems that relays the firmness of soft tissue to surgeons. We constructed a probe containing a force-sensitive resistor (FSR) to collect information on silicone samples of known varying firmness that mimic soft tissue. From the FSR, currents were generated and amplified into a solenoid actuator. By pressing on the actuator, the user feels a force corresponding to the firmness of the silicone. Preliminary testing of the unified feedback system indicated that users were able to successfully distinguish between varying silicone firmnesses with a 38.89% average accuracy. Future testing will need to be done with participants to further evaluate the system's effectiveness and mitigate preliminary testing errors.

# INVESTIGATING A COOPERATIVE SYSTEM OF SENSING AND TRANSMITTING HAPTIC FEEDBACK OF SOFT TISSUE FOR ROBOTIC SURGICAL APPLICATIONS

by

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# Chapter 1: Overview of Research Project

The immense benefits of robotic surgical systems, like the da Vinci, in contrast to traditional surgical techniques have been well-documented since the system's arrival on the market in 2000 [1]. Robotic assisted surgery allows for increased depth-perception and range of motion, improved ergonomics, and reduced error due to control for tremors [2]. While there are benefits over traditional minimally-invasive surgical techniques, robotic surgical systems still have their drawbacks. Chiefly, the current system relies solely on visual feedback and no haptic feedback is translated to the surgeon in order to bridge the divide between surgeon, machine, and the body. This lack of haptic feedback is thought to increase operative times as well as the learning curve for surgeons, while simultaneously increasing risk and recovery time for patients.

Team FEELS set out to create a prototype that works to mitigate this drawback. The purpose of our study is to create a proof-of-concept device that theoretically would integrate with the da Vinci surgical system and provide haptic feedback to the surgeon. Generally, our goals were to be able to sense the firmness of different types of tissue in the body using a sensor. The tissue firmness information from this sensor would be translated to the surgeon via a hand-held feedback accessory. Specifically, we wanted to know: how well can a unified haptic feedback system sense and effectively mimic the firmness of soft tissue in a way that can be easily understood by surgeons utilizing a robotic surgical system?

A unified prototype was developed that relayed firmness information via a sensor to a handheld feedback device. This prototype was subjected to a limited amount of human testing. Our results signify that participants were able to correctly distinguish between different firmnesses with 38.89% accuracy. This lower accuracy is projected to be due to errors and limitations in the testing of human subjects itself and not within the prototype as a whole. Limitations that may explain the lack of accuracy include lack of testing standardization between participants, time gaps between testing firmnesses that were unavoidable due to testing set-up, the bulky size of the handheld apparatus for those with shorter fingers, and finally lack of confidence in participants' responses. Team FEELS is confident that with the proposed updates to our system more accurate and significant findings are likely.

# Chapter 2: Literature Review

## 2.1 *Haptic Feedback*

Haptic feedback can be broadly defined as the simulation of real touch between a human, a robot, and the local or remote environment that exists between them [3]. The primary goal of haptic feedback for robotic surgical systems lies in the creation of a "telepresence," or a transparency between the surgeon operating the system and the surface of the body cavity with which the system is in contact [4]. In theory, this would allow the surgeon to feel as if they are in contact with the body cavity with their own hands, rather than with the arms of the robot. The benefits of this type of feedback for robotic surgical systems include increased manipulation and perception accuracy, decreased completion time, and decreased peak and mean force applied to the body cavity [4].

Haptic feedback mechanisms can be broadly divided into two main strategies – force and tactile feedback [3]. The type of feedback chosen will define the manner in which all other aspects of a feedback system (sensor, relay, and user interface) work collectively. Thus, the choice of which path to take is one that will define the strategy for surgeon transparency.

### 2.1.1 Force Feedback

Force feedback provides a direct measure of the force applied to the tissue in the body cavity by a surgical instrument [3]. This form of relaying information uses the presence of an external force to move the user's hand which will theoretically be interpreted using one's muscle memory of the feelings of tissue in the body [5]. This type of direct force feedback provides physical constraints for the surgeon [3]. While there are many commercially available force sensors in order to accomplish this, there are equally as many drawbacks to using this type of haptic feedback.

Constraints like size, sterilizability, geometry, and cost within the surgical field make it difficult for force feedback to be implemented [3]. The task of implementing force feedback loops on already existing systems is impossible without extensive modification [3]. This type of teleoperation loop can endanger the patient due to unintended oscillations when grounded forces interact with the master console [4]. Finally, even though the arms of the machine itself often operate in multiple dimensions, it is not possible to simulate those degrees of motion on the user [3]. The risk of resistance and interference that force feedback has on the surgeons dexterity as well as the overall incompatibility with the existing system makes force feedback a workable but complicated candidate for a feedback system for robotic surgery [6].

### 2.1.2 Tactile Feedback

While progress has been slower in investigating the possibility of tactile feedback, the difficulty in integrating force feedback has spurred recent research. The goal of tactile feedback is not to provide a direct force reading but to use a variety of techniques to convey the local mechanical properties of tissue, such as compliance, viscosity, or surface texture [3]. All of these metrics are designed to give the surgeon information about the health of the tissue as well as improve delicate procedures such as knot tying [3]. This information can be presented in a

variety of ways including but not limited to visual, auditory, pressure, or vibrotactile methods [4]. While the stability of the system is ensured, the issues of size, geometry, and sterilizability that are present for force feedback are still very much at play with tactile feedback as well [3], [4].

Numerous and varied methods of this type of feedback have been developed. One such system is comprised of an array of pins that are individually actuated to mimic the feeling of the user's fingertip on the body cavity [3]. Another method uses the interface of hemispherical silicone balloons which when inflated provide pneumatic pressure to the user's fingertips [4]. An alternative to balloons exists in the application of a moving platform to convey pressure in the mechanoreceptors of the skin [4]. One study even determined that particle jamming by controlling the vacuum level of a jamming chamber containing granules provided accurate tactile feedback to the user [7]. There are numerous conglomerations of sight, sound, and touch possible to create a tactile feedback system making it the most dynamic and unexplored option when considering haptic feedback for robotic surgical systems.

## 2.2 *Soft Tissue Modeling*

In order to assess the efficacy, reproducibility, and translatability of the finished feedback system, a model must be used in order to relay information about the firmness of various tissues in the body cavity. Firmness specifically is the metric chosen to create a model because opposed to other measures such as the dielectric constant, it provides the most intuitive and valuable feedback about the surgical field, as confirmed by our survey (Section 3.1). This model must accurately reflect not only the properties of human tissue, but the variety and specificity of the tissue as well. Tissue ranges in firmness from the least firm adipose tissue to the most firm tumor tissue or bone. Thus, the modeling material chosen must be variable in firmness but constant in other dimensions such as texture, shape, and size. Unlike soft tissue, the model chosen should be resistant to environmental influences so that the mechanical properties of the model will be preserved and re-use is possible [8]. There are many measurement techniques to verify tissue models that are documented, ranging from extrapolating elastic and storage moduli, displacement, or force. Using a displacement or indentation-based testing procedure has been documented as an effective method for determining the mechanical properties of soft tissue both in vivo and in vitro [9].

## 2.3 *Tissue Mimicking Materials*

There are a myriad of materials available in order to create a tissue mimicking system which replicates the variability and specificity of tissues within the body. The most analogous option, that of real human, porcine, or bovine tissue, was not a viable option due to financial, ethical, practical, and safety concerns [10], [11]. The inability to use real tissue necessitated an exploration of alternate methods. The alternative is to use artificial tissue composed of synthetic material with similar properties. These synthetic materials are overall less expensive, easier to purchase and store, and more durable over time [10], [11].

Materials can be broadly placed in one of two categories, chemically synthesized polymers (CSP) or biopolymers [12]. The biopolymers agar and gelatin as well as the CSP silicone have each been extensively evaluated for potential use in tissue modeling and were all considered when making our choice in tissue model [8]. Agar is easy to prepare and can have a small range in firmness via manipulating concentrations [8]. However, agar is brittle, affected by the environment, and leaks water [8]. Both the lack of durability as well as narrow range of firmness dissuaded us from using agar to mimic tissue. Gelatin has the same properties of agar and additionally takes a long time to make, also dissuading us [8]. Silicone has been proven to be easy to prepare, be resistant to environmental influences, and have properties analogous to tissue ranging from adipose to tumor [8]. The only documented disadvantage is the sticky nature that can arise with softer silicone samples [8].

### 2.3.1 Silicone as a Tissue Mimicking Material

Silicone has been used as a tissue mimicking material in numerous biomedical pursuits including but not limited to needle insertion training, laparoscopic surgical training, breast cancer diagnostic models, and deep tissue injury simulation [8], [12], [13], [14]. Opposed to biopolymers, silicone can have a wide range of mechanical properties, long-term stability, and resistance against evaporation or microbial growth [12]. There are numerous manufacturers of silicone that vary in firmness. The Ecoflex 0030 and 0010 have been shown to demonstrate moduli within published values for biological tissue [14]. Ecoflex 0030 in particular has been shown to be analogous to porcine muscle tissue [14]. This type of silicone has been used in educational practices in order to practice instrument coordination, suture tying, and laparoscopic skills [13]. This type of dry-lab paradigm is imperative for surgical students to learn essential skills in a zero-risk environment where repetitive practice is possible [13]. Silicone is the ideal material for this type of medical simulation due to its variability and durability and thus was the most fitting candidate for our feedback system tissue model.

## 2.4 *Sensors*

### 2.4.1 Limitations to Sensors in the Context of Robotic-Assisted Surgery (RAS)

A successful system for analyzing the consistency of soft tissue requires a sensor that can precisely evaluate anatomical structures [15]. The sensor that would be used must overcome the particulars of a robotic surgical system, namely the sterilizability, space limitation, and integration with the instrument. Steam sterilization through an autoclave method is currently the most common and standardized mechanism to effectively kill all microorganisms and contaminants present on surgical machinery. This method of sterilization would require the sensor to endure a temperature of 121 degrees Celsius at an elevated atmospheric pressure for 15 minutes [15]. The optimal sensor would also need to adhere to the spatial constraints of surgical machines. The laparoscopic arms of the RAS system must fit through a 12 mm diameter insertion port. Any sensor to be installed on the robotic instrument must then have a diameter significantly smaller than 12 mm [16]. The small size required of a sensor that could fit through the small insertion port limits the accurate measurement capabilities of the sensor. This leads to a third consideration: the integration of the sensor into the robotic surgical system itself. As shown in Fig. 1, there are multiple locations that a sensor could be placed on the robotic instrument. A

sensor placed at the mechanical tip (location 4 in Fig. 1) would need to fit through the insertion port, as mentioned previously. Considering this, the sensor could instead be placed at another location on the arm, allowing for a larger sensor that does not have to fit through the small port. However, gravity and friction of the mechanical connections can make measurement with a sensor in another location less accurate. Therefore, it is preferred to use a small sensor that can be placed on the tip of the machine itself. [15].

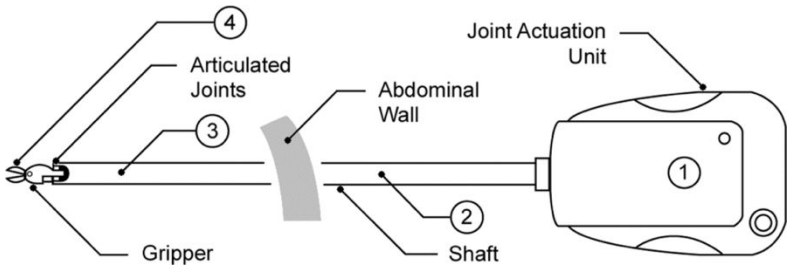



Fig. 1. Four possible locations for sensor placement on a robotic instrument [17]

### 2.4.2 Displacement-Based Sensors

The relatively simple displacement-based sensor detects the displacement of an elastic material such as a linear spring [15]. According to the force-displacement relationship, the force acting on the material can be determined by multiplication of the change in the length of the spring and the stiffness. The main concern with the use of displacement-based sensors for RAS applications is that the sensor output would have to be interpreted using reference stiffness values for various types of tissue, which are not currently available [18]. Liu et al. [19] attempted to address this limitation by creating a force-indentation depth sensor that measures indentation depth and the reaction force of soft tissue. The tissue deformation and corresponding tissue reaction force can then be used to determine tissue stiffness. While the rolling sensor collected accurate data, it is not ideal for surgery in that the spherical indenter may cause shear force that damages underlying tissue. McKinley et al. [20] have also used displacement-based sensing in the context of tactile feedback in RAS, though the sensor they developed is focused on improving autonomous or semi-autonomous procedures rather than measuring differences in tissue firmness.

### 2.4.3 Tactile Sensors

Tactile sensors use force-sensing elements to collect information about stiffness. They respond to contact forces and their spatial distribution in a particular area. Qasaimeh et al. [21] have developed a tactile sensor designed to be mounted on a surgical grasper while preserving the grasper shape. However, this sensor only provided information on grasping force and did not include information about the contact force, which would be helpful to surgeons performing RAS. Further, Pacchierotti et al. [4] have developed a feedback system for the da Vinci Standard robot using a commercially available tactile sensor that was mounted on the distal end of a surgical instrument. While the system allowed the surgeon to feel fingertip contact deformations and vibrations, it was noted that the sensor was too large, could not be sterilized, had exposed

electrical connections, and must be recalibrated to different fingertip sizes. Murayama et al. [22] have also created a system based on a tactile sensor that successfully detected tumors approximately 10 mm in diameter. However, this system is limited by its size, shape, and sensitivity. While tactile sensors are very sensitive, due to these limitations and others such as stray capacity, which causes signal feedback, and hysteresis, which is a lag in sensation feedback, robotic applications tend to utilize force sensors.

### 2.4.4 Vibration-Based Sensors

Other sensors rely on vibration-based sensing, which involves the disruption of a vibrating mechanism at the tip of a sensor when it makes contact with a tissue. As the stiffness of the tissue increases, the amplitude of the resulting oscillation decreases [15]. Baumann et al. used a prototype vibrotactile sensor to successfully differentiate between healthy and diseased human tissue such as carcinoma, healthy mucosa, and carcinomatous-infiltrated mucosa. However, this sensor took several seconds to find the resonance frequency at each measurement, a feature that is not ideal for the time constraints in surgery [23]. For faster measurements, Omata et al. [24] added a piezoelectric transducer to a vibrating tactile sensor. The piezoelectric transducer adapted the sensor's oscillation to a changed resonance frequency immediately after the frequency difference was detected, allowing for rapid identification of mechanical properties of soft tissue without having to scan over the whole frequency range. Yet even this faster vibration-based sensor is not ideal for RAS due to its large size.

### 2.4.5 Force Sensors

The most commonly used type of sensor for RAS applications are force sensors. While they cannot measure slipping forces as tactile sensors can, they are useful for detecting force, which corresponds to tissue firmness. Force sensors often use strain gauges, which measure strain through an attached spring element. The strain gauge measures the electrical signal created by the deformation of the spring element, and the electrical resistance gives information on the force being exerted. Baki et al. [25] developed a miniature force sensor based on strain gauges that can be used for haptic feedback in RAS. Several other systems using force sensors have been developed for similar uses [26], [27], [28]. However, like the sensor developed by Baki et al., they are used mainly for force feedback rather than tactile feedback and thus are not designed for measuring stiffness of soft tissue.

Force sensing also includes piezoelectrics, another promising class of sensors for RAS applications. This type of sensor produces varying voltage levels depending on the force exerted on it [29]. Piezoelectric materials form an electric potential when disrupted by mechanical stress. The realignment of dipoles after the stress results in an electric potential. The measurement of this potential gives information about the nature of the material that is disrupting the piezoelectric sensor [29]. Because of its unique voltage-reliant mechanisms, piezoelectric sensing is reliable and has a larger detection range than most other sensing types [15].

Several sensors involving piezoelectric technology have been developed in the context of RAS [24],[25], [30], [31], 32], but most are intended for force feedback [33], [34]. A system using piezoresistive force sensors developed by Culjat et al. [35] allowed users to distinguish

between up to five different pressure levels corresponding to forces applied at the grasper and was compatible with the da Vinci surgical robotic system. While this is a promising system for tactile feedback, it does not relay information related to tissue firmness and instead focuses on improving the accuracy of grasping tasks. Further, King et al. [36] designed a piezoresistive sensor integrated into the da Vinci surgical robotic system that allowed users to feel pressure from a balloon corresponding to the force distribution applied at the grasper, though further work is needed to prepare the prototype for clinical applications. Commercially available piezoresistive force sensors also have been successfully integrated into RAS tactile feedback systems [37], [38]. The main drawback of piezoelectric technology is sensitivity to temperature and the charge leakages that occur when static forces are measured [7].

Capacitive force sensors are another class of force sensors that have potential for use in RAS. They work based on the principle that capacitance depends on the distance between two conductive elements. Depending on the distance, the voltage and thus electric current can be determined, which allows one to measure force [39]. Paydar et al. [40] and Lee et al. [41] have demonstrated that capacitive force sensors show promise for RAS tactile feedback systems. They are advantageous in that they are highly sensitive and stable and have low temperature dependence. However, they are limited in their ability to measure static forces, hysteresis, and complex control circuitry [42].

A force sensitive resistor (FSR) changes resistance upon application of a force or mechanical stress. Li et al. [43] developed a force sensor using an array of force sensitive resistors that accurately measured tissue stiffness when the robot arm was moved at the depth of 1mm. Further, Schostek et al. [44] have designed a tactile sensor system mounted on a robot arm that uses an FSR sensor to obtain information on tissue shape and consistency. FSR sensors are generally simple, robust, and relatively insensitive to humidity, although they are generally slower and less sensitive to small vibrations unless modifications are made [43].

## *2.5 Feedback Mechanisms*

This section examines different feedback mechanisms that have been explored for robotic surgery.

### 2.5.1. Visual Feedback

Visual feedback is a mode of feedback where the user experiences a visual stimulus to create a feedback loop. Research was conducted in which a feedback loop was created where strain gauges were placed on the instruments such that they measure the amount of applied force [45]. This information was relayed to the user via real time visual force feedback information as seen in Fig. 2 below [45]. Displayed information communicated how much force the user was applying (minimal, ideal or excessive force). The results of having visual feedback were either the same or better in terms of how often the users were able to minimize excessive knot tightening (resulting in breaking the knot) [45].

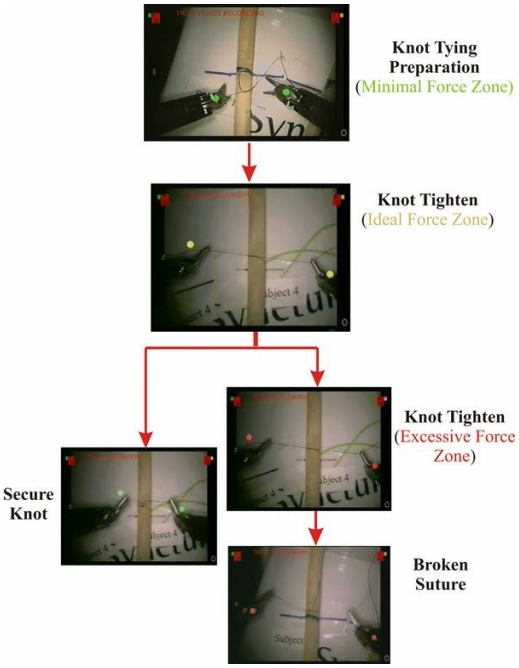



Fig. 2. Visual feedback via color in order to relay force feedback to surgeons during suture tying [45]

The results from this study prove the efficacy of incorporating and providing a feedback mechanism; however, it is important to note how many other visual stimuli the user must be cognizant of when they are using the da Vinci. Fig. 3 shows that there is already a sizable amount of visual information displayed when the machine is in operation, proving to be a possible distracting source if the user were to have an additional visual stimulus they must be aware of [46].

Fig. 3. Image of what a physician is viewing at the console of a da Vinci Xi surgical system [46]

### 2.5.2 Multimodal Haptic Feedback

Multimodal haptic feedback is a feedback mechanism that incorporates multiple modes of feedback simultaneously. There have been a number of studies that have incorporated different forms of feedback together: [47] incorporating tactile, kinesthetic, and vibrotactile feedback, and [48] incorporating force and tactile feedback. The goal of multimodal haptic feedback is to integrate the simultaneous stimulation of mechanoreceptors in the skin (achieved from tactile feedback) and the muscle (achieved from force feedback) such that it can engender a more natural sense of touch [47]. Results of using multimodal haptic feedback show significant improvement in terms of achieving grip forces that are closer to what are more normally frequent than both no feedback and single modal feedback [47].

### 2.5.3 Electromagnetic Actuation

An actuator is defined as a system that can convert, depending on what type it is, a given input energy source into some output mechanical energy [49]. More specifically, electromagnetic actuation is responsible for converting electrical energy into mechanical output through electromagnetic principles. A type of electromagnetic actuation is a linear solenoid as shown in the Fig. 4 below [50].

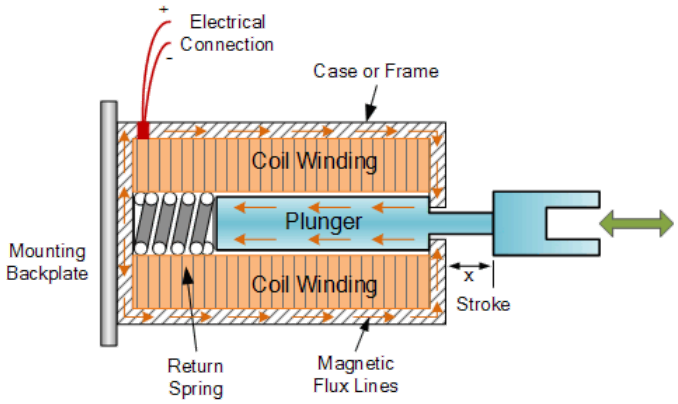



Fig. 4. Image of a basic linear solenoid [50]

As shown in Fig 4., a linear solenoid consists of coil windings that has a plunger nestled in the middle of it. The purpose of the linear solenoid is to actuate the system such that the plunger mechanically moves laterally (turning on and off) [51]. In order to control the movement of the plunger as “on” or “off”, an electric current is applied to the coil of wires such that the solenoid becomes an electromagnet that attracts the plunger to the center of the coil [51]. Additionally, the speed and force that the plunger is moving at may be controlled by the amount of current that is applied to the coil [51].

# Chapter 3: Methodology

Team FEELS approached the research question, *How well can a unified haptic feedback system sense and effectively mimic the firmness of soft tissue in a way that can be easily understood by surgeons utilizing a robotic surgical system?*, as a multi-step process. The team began by focusing on the sensing of a tissue mimicking material. This involved characterizing the material, choosing an appropriate sensor, and calibrating the sensor to the material and system. A different subgroup of the team was focused on developing the theory behind the feedback mechanism that would utilize this sensor information. This involved both designing and testing the circuit which would modulate the current to be running through a magnetically actuated wire coil, and designing the specifications for the wire coil. Multiple iterations of both of these elements led to the final integrated feedback mechanism. The connection between the sensor data and the feedback mechanism was developed through Arduino code. This full system was then integrated with the user interface, which was developed by a third subgroup of the team.

## *3.1 Informing the Research Process*

Task 1 of this project focused on conducting a preliminary survey to confirm the need for tactile feedback in RAS systems as well as inform our prototype, especially the surgeon's interface with the feedback mechanism.

### 3.1.1 Determining Sample Size

The sample for this initial survey consisted of surgeons in the D.C., Maryland, and Virginia area who have used the da Vinci robot in their practice. Using the "Find a surgeon" feature on the da Vinci Surgery website, the team searched for the number of da Vinci surgeons within a 100 mile radius, which was approximately 340. The sample for a population of this size with a 95% confidence ratio and 5% margin of error would require a sample size of about 180. However, Team FEELS recognized that it is not realistic to expect 180 surgeons to respond given the nature of their busy schedules, so the team referred back to sample sizes used in literature.

Previous studies examined in the literature review used samples of 6 medical students, 9 nonsurgeons, or 20 human subjects (10 surgeons, 10 nonsurgeons) [2], [52], [53]. The highest surgeon sample size in these studies was 10 [52]. As such, the team decided on a minimum sample size of 10 surgeons, but aimed for a 20 surgeon sample.

### 3.1.2 Sample Composition and Recruitment

The team looked to include surgeons with a range of experience with robotic-assisted surgery in the sample. The high learning curve for these machines [54] suggests that surgeons who have performed robotic assisted surgery for a longer period of time do not benefit from tactile feedback as much as novices. Consequently, for a more complete sample, it was vital to include both experts and novices in the study, as a surgeon's level of experience could be a determining factor in whether tactile feedback would provide any benefits to the surgeon. For a complete sample, the team recruited surgeons from a variety of specialties, including cardiac,

colorectal, general, gynecologic, head and neck, thoracic, and urologic surgery, in which the da Vinci robot is used [55].

A list of surgeons using RAS systems in the DC metro area was generated using the da Vinci Surgery website as well as recommendations from surgical colleagues. Surgeons were recruited via email to take the 5-10 minute survey on the confidential surveying tool Qualtrics.

### 3.1.3 Survey Design and Results

After reading a brief description of Team FEELS's research and a description of confidentiality, surgeons (n=15) selected a bubble indicating their consent. The surgeons were not compensated. No identifying information was collected from the surgeon and responses remained anonymous. A complete copy of the survey can be found in Appendix A.

The first set of questions provided background information about the surgeon specialty and experience. These responses were used to provide context to later responses. For example, there is evidence that the integration of tactile feedback in RAS would be more helpful to novice surgeons, as more experienced surgeons have learned to compensate for the lack of feedback [54]. These questions asked the surgeon to specify their specialization, to specify how long they have been practicing surgery (including intern year of residency) (0-5 years, 6-10 years, or 11+ years), how long they have been using RAS systems (0-5 years, 6-10 years, or 11+ years), and which robotic system and model they use.

Surgeons were recruited from a variety of specialties, with the majority in a specialty related to gynecology (n=8) or urology (n=4). The breakdown of surgical specialties of those surveyed is summarized in Fig. 5. All surgeons surveyed had been in surgical practice for either 6-10 years (n=3) or 11+ years (n=12; Fig. 6). Surgeons surveyed ranged from novice to experts at using RAS systems in their practice, using RAS systems for 0-5 years (n=2), 6-10 years (n=9), or 11+ years (n=4; Fig. 7). All of the surgeons surveyed used one of the two most recent models of the da Vinci system from Intuitive Surgical. 12 surgeons used the da Vinci Si model which was released in 2009 and 3 surgeons used the da Vinci Xi model which was released in 2014.

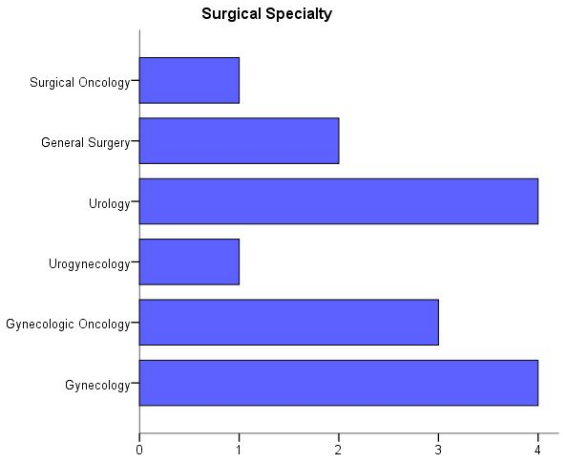



Fig. 5. Surgical Specialties of Surgeons Surveyed (n=15)

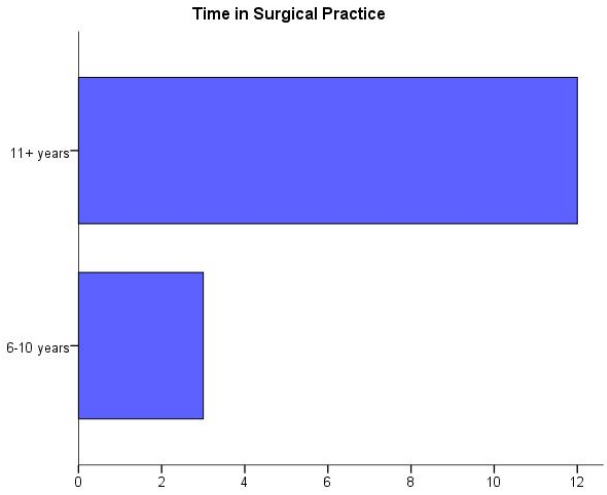



Fig. 6. Time in Surgical Practice of Surgeons Surveyed (n=15)

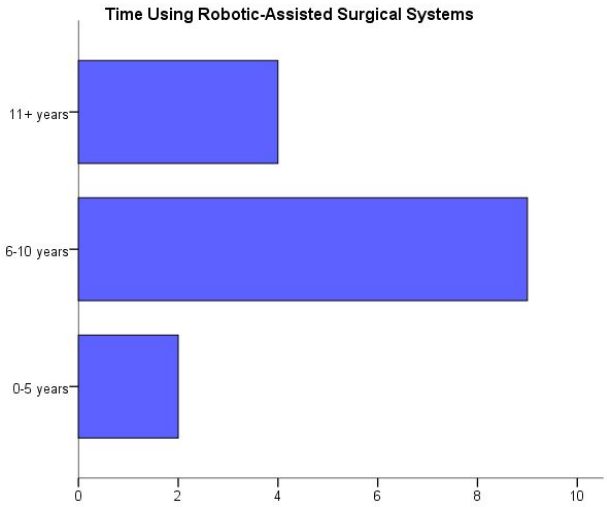



Fig. 7. Time Using Robotic-Assisted Surgical Systems in their Practice (n=15)

The next set of questions asked surgeons for their opinions on the helpfulness of introducing tactile feedback to robotic surgical systems. Surgeons were asked whether they felt tactile feedback would be helpful and whether firmness would be the best measure of soft tissue. 80% of surgeons surveyed (n=12) believed the introduction of tactile feedback to RAS systems would be helpful. 6.67% of surgeons (n=1) felt that the effects of introducing tactile feedback to RAS systems would be negligible. 13.33% of surgeons (n=2) felt that introducing tactile feedback would create adverse effects (Fig. 8). These surgeons elaborated that this change might be distracting or too dramatic a change. 86.67% of surgeons (n=13) agreed with our literature review that firmness would be the best measure of soft tissue information and 13.33% (n=2)

disagreed (Fig. 9). The surgeons that disagreed suggested force feedback measures instead such as the tension on tissues or force applied during suturing. Force feedback measures the force applied by the surgeon as opposed to tactile feedback which provides touch information. Given feedback from the surgeons, our team decided to move forward with creating a tactile feedback system as opposed to a force feedback system. These results were used to verify the direction of our project: (1) tactile feedback would be a helpful addition to RAS systems and (2) firmness would be the most helpful measure to transmit.

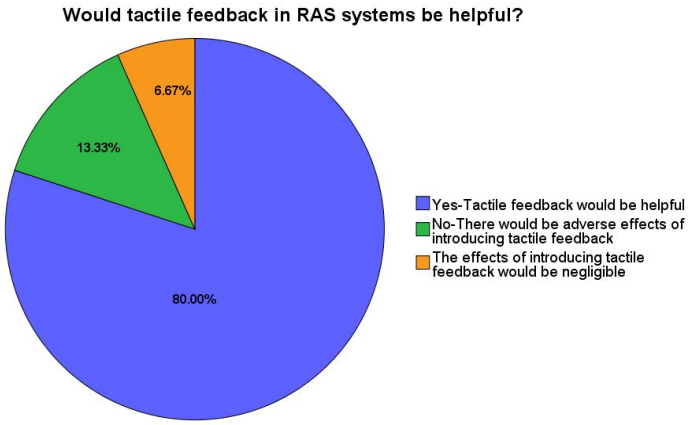



Fig. 8. Surgeon responses to the question of *Would tactile feedback be a helpful addition to RAS systems?* (n=15)

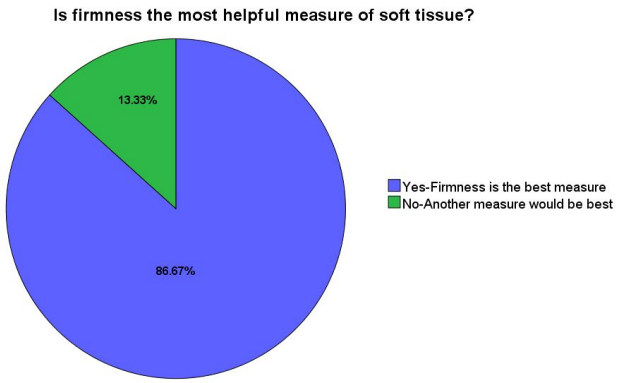



Fig. 9. Surgeon responses to the question of *Would firmness be the best measure of soft tissue to transmit to an operating surgeon?* (n=15)

The last series of questions was used to inform the research design. Surgeons were asked whether they would prefer feedback to be continuously provided or have a choice as to when to receive feedback and where on the body it would be helpful to provide this tactile feedback. 60% of surgeons surveyed (n=9) preferred having control over when to receive feedback and 40% of

surgeons (n=6) preferred continuous feedback (Fig. 10). Based on the majority, we designed our prototype so that surgeons would be able to choose when to receive this feedback.

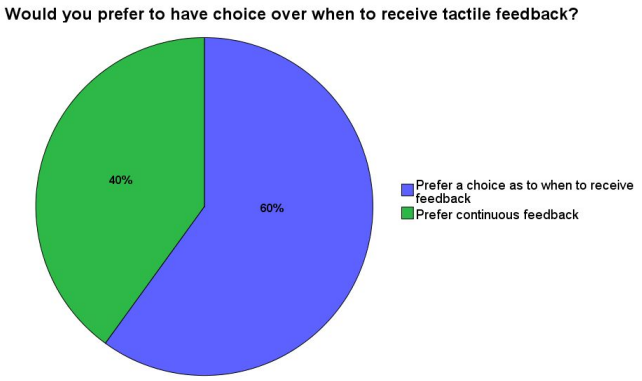



Fig. 10. Surgeon responses to the question of *Would you prefer to have control over when you receive tactile feedback or have it be continuously provided?* (n=15)

We also asked surgeons where on the body they would like to receive this tactile feedback information. As demonstrated in Fig. 11a, the surgeon grips the hand control of the surgeon console using his/her thumb and middle finger. The pointer finger, ring finger, and pinky are not gripping anything to operate the surgeon console. The palm and wrist are also left free. We used this information to generate the possible placements for our device. On the survey, surgeons were shown Fig. 11b and asked to rank locations A-E on a scale of 0 (least helpful) to 10 (most helpful) for placement of the device. Descriptive statistics for the ratings of each location are listed in Table 1. Surgeons overwhelmingly supported receiving feedback at Location B (min=8, max=10, mean=9.80). This location is the thumb and middle finger that grip the hand control of the surgeon console. However, due to the size of our prototype, we were unable to develop the feedback mechanism to provide information at Location B. Our device was too large. Future research should work towards miniaturizing and modifying our prototype to provide tactile feedback at Location B. We developed a feedback mechanism that would sit at Location A where the user would feel the mechanism with their fingers at Location C.

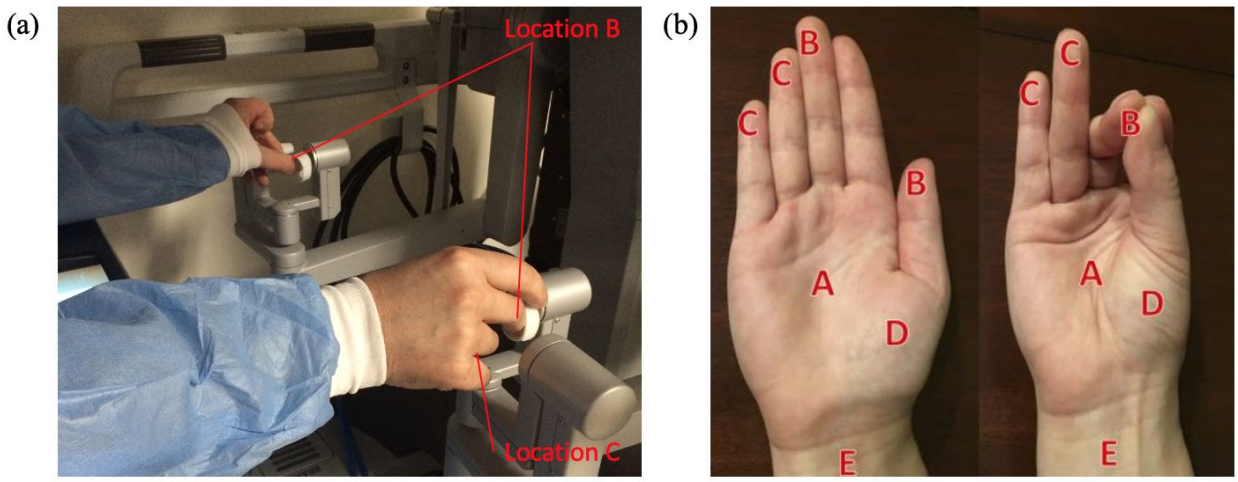



Fig. 11. (a) da Vinci surgeon console hand controls annotated with potential locations for placement of the feedback mechanism, (b) Image shown to surgeons taking survey to demonstrate potential locations for tactile feedback

Table 1. Descriptive statistics for potential locations to receive tactile feedback

| Location | minimum | maximum | mean | std deviation |
|---|---|---|---|---|
| Central Palm (A) | 0 | 5 | 1.27 | 1.870 |
| Fingers at Location B | 8 | 10 | 9.80 | 0.561 |
| Fingers at Location C | 0 | 8 | 2.27 | 3.011 |
| Palm at Location D | 0 | 7 | 2.27 | 2.492 |
| Wrist (E) | 0 | 8 | 1.87 | 2.642 |
| Other | 0 | 6 | 0.67 | 1.799 |

n=15

Surgeons were also asked at which hand they would prefer to receive tactile feedback. 80% of surgeons (n=12) would prefer to receive feedback at both hands, 6.67% (n=1) preferred the dominant hand only, 6.67% (n=1) preferred the non-dominant hand only, and 6.67% (n=1) did not have a preference for which hand, but wanted to receive feedback at only one hand. These results are summarized in Fig. 12.

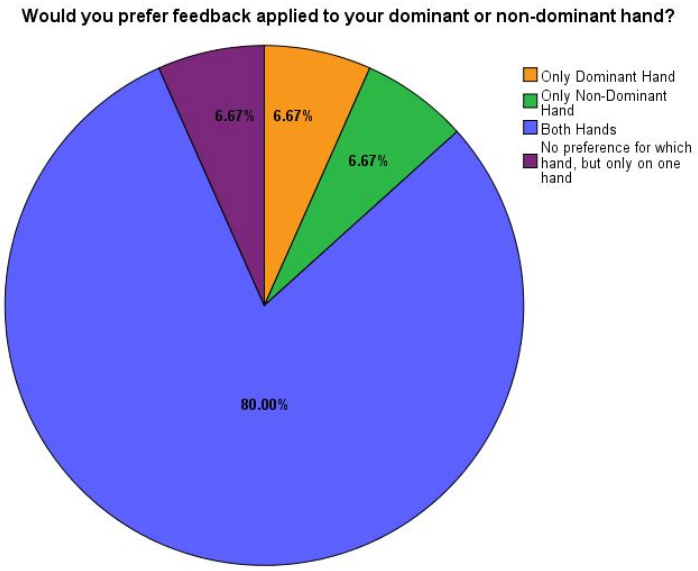



Fig. 12. Surgeon responses to the question of *Would you prefer to receive tactile feedback at your dominant or non-dominant hand?* (n=15)

### 3.1.4 Survey Analysis

Previous literature suggests that surgeons who have been using RAS systems for longer periods of time have learned to compensate for the lack of tactile feedback [11]. Therefore, we expected surgeons who have more recently begun using RAS systems to feel tactile feedback would be more helpful than those surgeons who have learned to compensate for this loss. Correlational analyses were run to determine if time in surgical practice or time using RAS systems was correlated with the surgeon's evaluation of whether tactile feedback would be helpful in RAS systems. This was not significant (time in surgical practice: $r=-.238$, $p>.392$; time using RAS systems: $r=.103$, $p>.715$). A chi-square test of independence was run to determine if there was a relation between time in surgical practice or time using RAS systems and the surgeon's evaluation of firmness as the best measure of soft tissue, which were both not significant (time in surgical practice: $\chi^2(1)=.577$, $p>.448$; time using RAS systems: $\chi^2(2)$, $p>.124$). None of these statistical tests were significant, which is likely due to our small sample size (n=15) and the uneven distribution of novice/expert surgeons. These results are included in Table 2. While the statistical analyses were not significant, by looking at descriptive statistics we can see that surgeons who had been in practice for 6-10 years as opposed to 11+ years all answered that (1) tactile feedback would be helpful and (2) firmness would be the best measure of soft tissue (Fig. 13). This gives some indication that newer surgeons might benefit more from tactile feedback. Surprisingly, the results for surgeons new to using RAS systems were more mixed (Fig. 14). We had expected to see surgeons newer to RAS evaluating tactile feedback as more helpful.

Table 2. Statistical analyses to evaluate if time in surgical practice or time using RAS systems was related to the surgeon's evaluation of tactile feedback as helpful and firmness as the best measure of soft tissue

| | **Would tactile feedback be helpful in RAS systems?** | | **Is firmness the best measure of soft tissue?** | | |
|---|---|---|---|---|---|
| | *Pearson's r* | *p value* | $\chi^2$ | *df* | *p value* |
| **Time in Surgical Practice** | -.238 | .392 | .577 | 1 | .448 |
| **Time Using RAS Systems** | .103 | .715 | 4.183 | 2 | .124 |

n=15

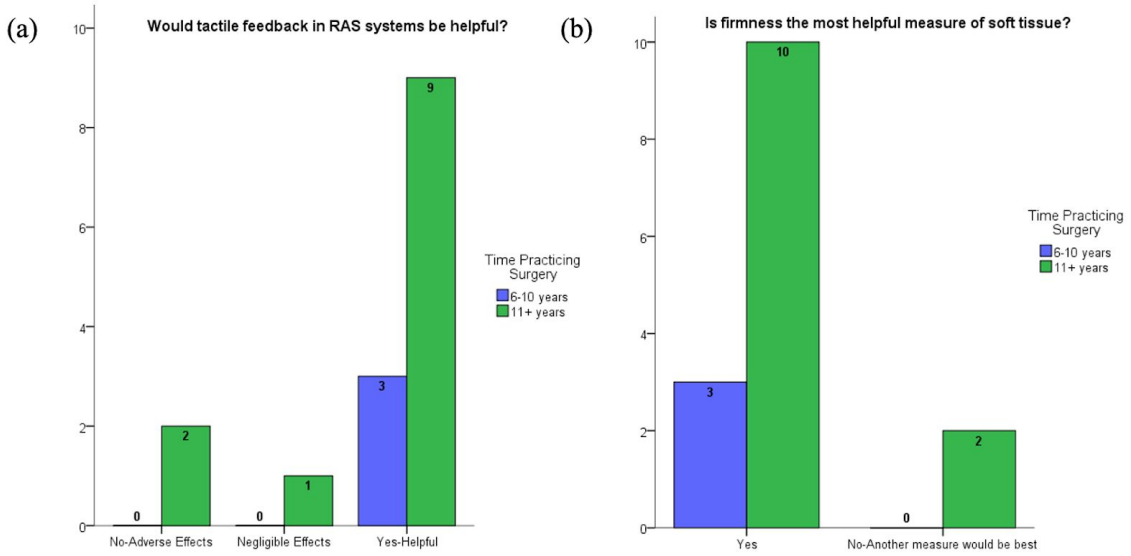



Fig. 13. (a) Surgeon's evaluation of whether tactile feedback would be helpful according to time in surgical practice (b) Surgeon's evaluation of firmness as the best measure of soft tissue according to time in surgical practice (n=15)

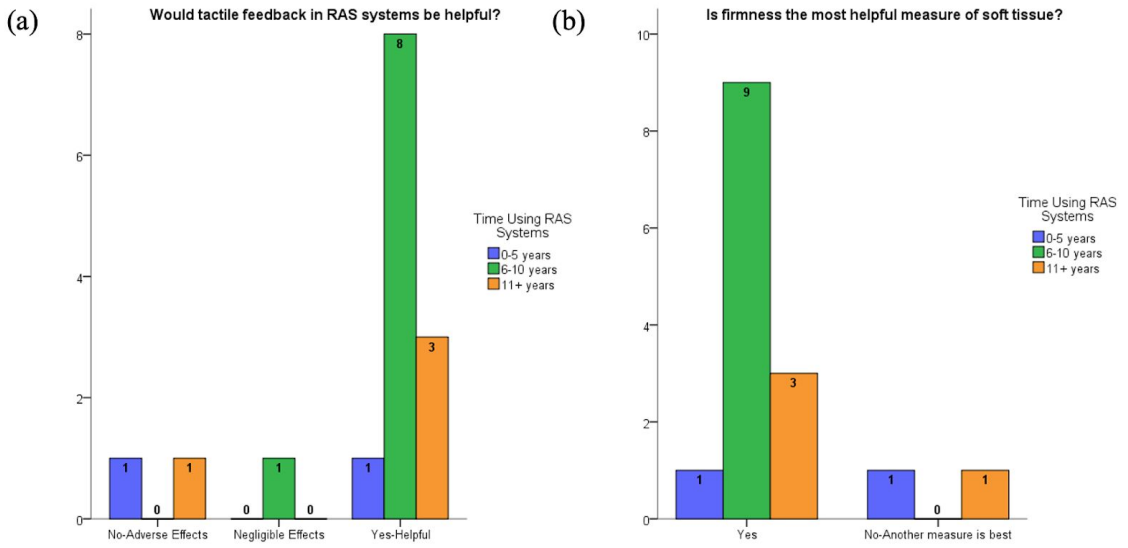



Fig. 14. a) Surgeon's evaluation of whether tactile feedback would be helpful according to time using Robotic-Assisted Surgical systems (b) Surgeon's evaluation of firmness as the best measure of soft tissue according to time using RAS systems (n=15)

Interestingly, surgical specialty was significantly correlated with responses to the question of whether firmness is the best measure of soft tissue (r=.614, p<.015; Table 3). Surgeons practicing surgical oncology (n=1), urology (n=4), gynecologic urology (n=3), and gynecology (n=4) as well as one of the surgeons practicing general surgery (n=1) all felt firmness was the best measure. The surgeon practicing urogynecology (n=1) and one of the surgeons (n=1) practicing general surgery did not think firmness was the best measure. This is summarized in Fig. 15. However, surgical specialty was not significantly correlated with whether the surgeon felt the addition of tactile feedback would be helpful to RAS systems (Fig. 15).

Table 3. Correlation matrix of surgical specialty and surgeon's evaluation of tactile feedback as helpful and firmness as the most helpful measure

| | **Surgical Specialty** | |
|---|---|---|
| | *r* | *p* |
| Would tactile feedback in RAS systems be helpful? | .026 | .927 |
| Is firmness the most helpful measure of soft tissue? | .614 | .015* |

n=15, * p<.05

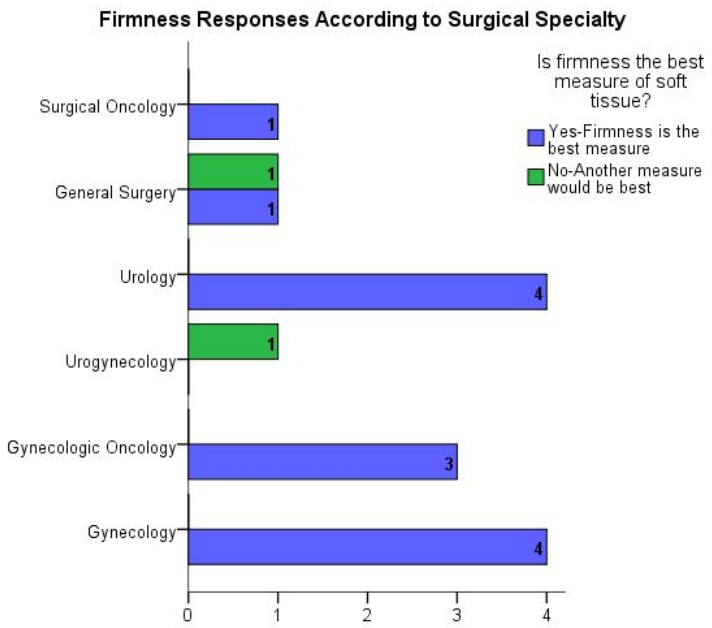



Fig. 15. Surgeon's evaluations of whether firmness is the best measure of soft tissue according to surgical specialty (n=15)

## *3.2 Sensor*

### 3.2.1 Tissue Modeling

*Choosing Tissue Modeling Material*

In order to verify our eventual integrated system, a material that modeled the variability and specificity of tissue within the body had to first be chosen. Initially, both reagent-grade agar powder from Carolina Biological Supply and four variations of EcoFlex Super Soft Shore Platinum Silicone Rubber from Reynolds Advanced Materials were purchased. However, due to the flimsy and easily degradable nature of the agar, silicone was chosen as the sole tissue modeling material for our project moving forward.

Initially, the silicone product was purchased in 00-10, 00-20, 00-30, 00-50, and fast-dry 00-35 variations. The fast-dry 00-35 was removed from our options due to the difficulty in working with such a fast drying substance with the materials we had. These tissue models will be referred to as 10, 20, 30, and 50, hereafter for simplicity. Tissue models were made using 1 oz medicine cups as molds in order to ensure consistency over the shape and size of each model, and silicone was prepared per instructions from the manufacturer and poured into the molds. Molds were allowed to set for 24 hours and then were removed from the medicine cups so that they could be ready for use. Silicone molds do not have a shelf-life and our models could be used repeatedly for the duration of our project without compromising the integrity of the model.

*Data on Silicone Firmness*

Silicone types 10, 20, 30, and 50 were subjected to displacement based testing via a box and probe apparatus. Weights of 7.66, 15.21, 22.86, 30.43, 38.03, 74.5, and 95.42 grams respectively were placed on top of the probe and silicone model. These weights were composed

of 5 bolts, a medium weight, and a large weight that were calculated using a balance within our laboratory. Each weight per silicone type was repeated in triplicate on three different models of the same firmness of silicone. This data was averaged which resulted in 7 final data points per silicone type. The obtained and averaged data points can be seen below in Fig. 16 and data on linear fit of this data can be seen in Table 4.

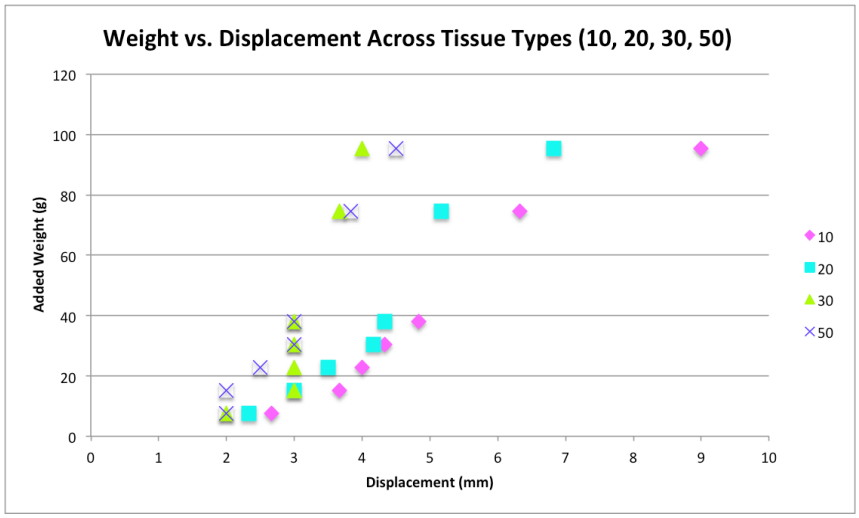



Fig. 16. Added weight versus displacement over silicone types 10, 20, 30, and 50

Table 4. Values from Fig. 16 graph on differences in tissue type slope and $R^2$ values over various weights and displacements

| Tissue Model Type | Slope of Weight vs. Displacement Trendline | $R^2$ Value of Linear Displacement Trendline |
|---|---|---|
| 10 | 15.124 | 0.95858 |
| 20 | 21.164 | 0.94436 |
| 30 | 46.328 | 0.8113 |
| 50 | 34.247 | 0.9639 |

*Box and Probe Design*

In order to estimate firmness values for each type of silicone, a box and probe system was designed to place a repeatable weight on the tissue. Once the weight was added to the probe, as displayed in Fig. 17, the deflection of the probe into the silicone was measured.

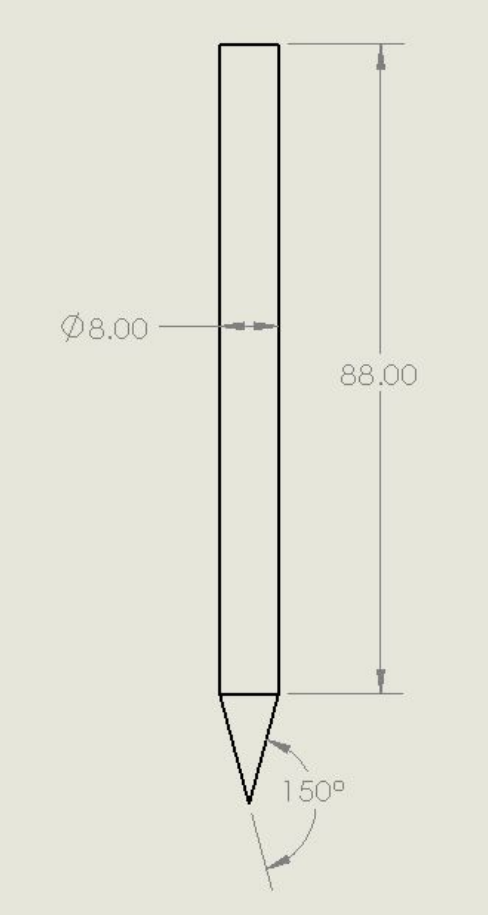



Fig. 17. Technical drawing of probe

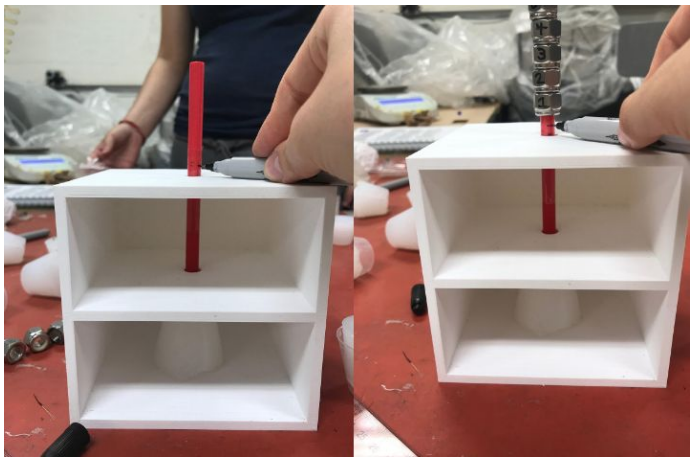


Fig. 18. Box and probe system in action

*Choosing 10, 20, and 50*

By using a displacement-based method of testing the silicone tissue models, we were able to narrow our options to the EcoFlex Super Soft Shore Platinum Silicone Rubber in 10, 20, and 50 varieties. The 30-silicone qualitatively felt similar in firmness to the 50 but was inconsistent in displacement based testing. Further, it was found to have the least linear relationship out of all silicone varieties as shown via $R^2$ values in Table 4. Therefore, the tissue types 10, 20, and 50 were the models that were consistently used throughout the remainder of our research and experimentation. These types were also used consistently in reference to each other to provide standards for varying tissue firmness over three different firmnesses.

*Tissue Firmness Extrapolation Protocol*

The protocol procedures can be found in Appendix B. Data was collected via the box and probe system detailed in Section 2.1.2.1. Data was taken by measuring the distance between the "before weight added" mark and "after weight added mark." These marks were made using a sharpie after weight was added to the probe as detailed in Fig. 18. The distance between each mark was measured via a standard ruler and recorded in a spreadsheet. Each measurement was taken in triplicate per silicone type. This procedure was repeated for seven separate weights and each triplicate data set was averaged to give seven distinct data points per silicone type.

### 3.2.2 Sensor Calibration

The team began by choosing a sensor appropriate for testing. After assessing the information found in the literature review, the team chose to proceed with a sensor based on applied force and varying resistance. The final sensor chosen was a force sensitive resistor and can be seen below in Fig. 19, prior to connection with its circuit. This sensor varied its output voltage based on the amount of force applied. It should be noted that though consideration was placed into utilizing a sensor that could be integrated into surgical situations, the team recognized the increased difficulty that would place on testing and fabrication. The team chose to move forward initially with a sensor that could not be utilized in surgery due its larger size, exposed electrical components, and inability to withstand sterilization. This choice was made synchronously with the choice to create a proof-of-concept prototype, as the team prioritized the development of a full working prototype over advancement of only one aspect of the prototype. Further research would involve updating this sensor to one that could be applied to the surgical environment, which is discussed in later chapters.

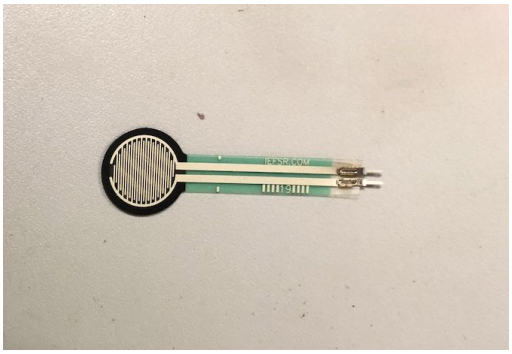


Fig. 19. Final sensor (Force Sensitive Resistor) chosen for testing, prior to connection with circuit

The primary goal of sensor calibration was to obtain a characteristic curve of the sensor wherein weight applied to the sensor correlated to the voltage output of the sensor. The team began this process by collecting small weights of the same size that incrementally could be added onto the top of the sensor. The sensor was placed on a flat table, and each weight was added individually and stacked on the one prior. It should be noted that the weights were hexagonal in shape with a hollow center, which initially caused concern from the team in terms of equal loading of the sensor. However, testing showed relative consistency in the results and similarities among the weights was considered desirable enough to move past this initial concern. The sensor was connected to an Arduino for data capture through a circuit that was specified on the sensor specification page, which can be found below in Fig. 20. A simple Arduino script was created that would take in the sensor data acquisition, convert the data to a voltage output read within the range of 0 to 5 volts, and read out that value onto the screen. The value was then recorded once the readings settled, which was typically a few seconds after the additional weight was added (Table 5 and Fig. 21).

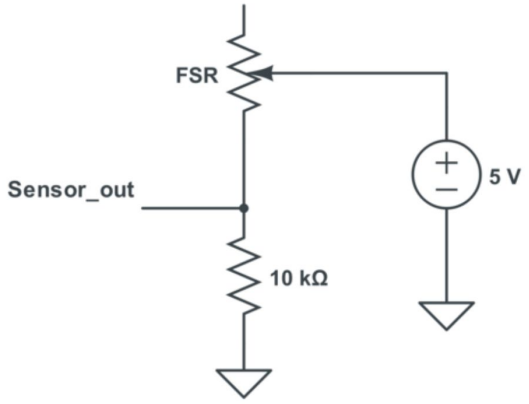



Fig. 20. Sensor circuit diagram as prescribed by sensor instruction

Table 5. Obtained sensor data with the experimental methods described above

| Mass (kg) | Reading (V) |
|---|---|
| 0.00951 | 0.00 |
| 0.18407 | 0.43 |
| 0.35836 | 0.81 |
| 0.53271 | 1.05 |
| 0.70737 | 1.18 |
| 0.88195 | 1.30 |
| 1.03082 | 1.35 |

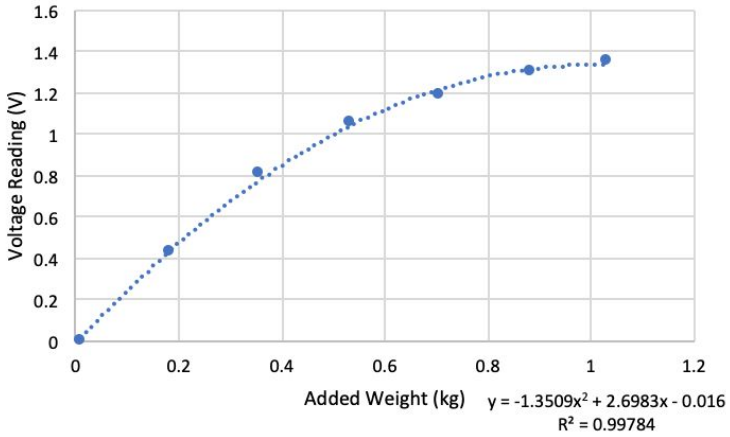



Fig. 21. Obtained sensor characteristic curve with the experimental methods described above

Once the data was plotted and analyzed, the team determined that a parabolic fit was more appropriate. The $R^2$ value of this fit produced a result of 0.997, indicating that the sensor reacted to a linear addition in weight with a decreasing difference in voltage output. However, the team desired a result in the linear range for simplicity and ease of analysis; therefore, the team chose to limit the full data set and utilize only the first few data points to create a final characteristic curve. The resulting curve can be found below in Fig. 22. This result indicated a linear fit with an $R^2$ value of 0.985, and a slope of approximately 2 wherein the voltage output changed twice as much as the added weight input. Though the fit of this set was not as strong as the parabolic fit of the initial curve, the team determined that this was still sufficient for use. Therefore, the team chose to move forward with testing the silicone with applied weights in this narrowed range of the sensor. Moreover, this stage of testing determined and confirmed the working weight range of the sensor.

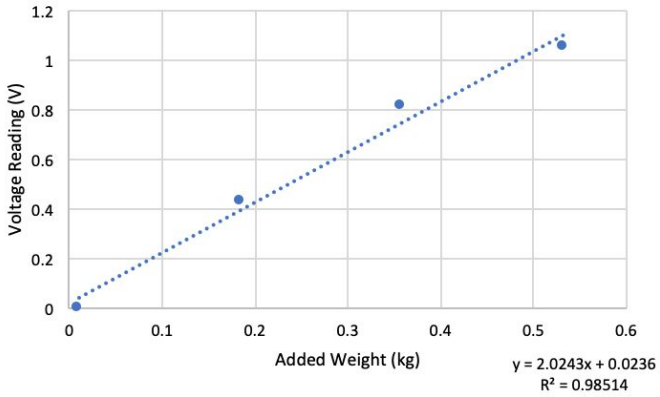



Fig. 22. Narrowed sensor characteristic curve to linear region with the experimental methods described above

Using weights within the sensitive region of the sensor, a range of displacement values was experimentally gathered. A box was created that would stabilize the probe and allow for the probe to consistently interact with the silicone at the same position. This box design was nearly

identical to the one found in a latter section describing the final sensor measuring silicone design. For each type of silicone, a weight of 514 grams was placed on the probe. The approximate displacement of the probe was measured at the top of the box for each type of silicone, and a displacement of 8 mm was selected. The displacement was chosen so that the probe did not travel so far into the silicone that it reached the surface on which the silicone was resting, but also that the force was within the sensitive range for the sensor for all three types of silicone. The probe was also created to have a narrowing tip to facilitate deformation without being too sharp that any tearing of the silicone would occur.

### 3.2.3 Testing of Silicone with Sensor

To gather sensor data, a small box was used to keep the probe upright and to house the silicone. This design can be seen below in Fig. 23 and Fig. 24. The sensor was affixed to the top of the probe with tape, and the probe was pressed down such that the top of the probe was flush with the top of the box. This mechanism of pushing the probe to the top of the box was refined numerous times, since standardizing the approach for each trial was essential. The team chose this design since it ensured the same displacement each time sensor data was gathered. Using these methods, sensor voltage ranges for each type of silicone were gathered. The deformation of the silicone by the probe can also be observed in Fig. 24. It should be noted that this image utilized a black block to compress the probe, which was done for ease in capturing the image. However, testing utilized the palm of the hand to compress the probe. When the added force on the top of the probe was removed and the probe lifted from the silicone, no residual deformation was observed. The team ensured that the silicone samples did not degrade over time of testing and no deformation was observed. This step was taken to ensure that the silicone samples were standardized and did not produce any unexpected results due to overuse.

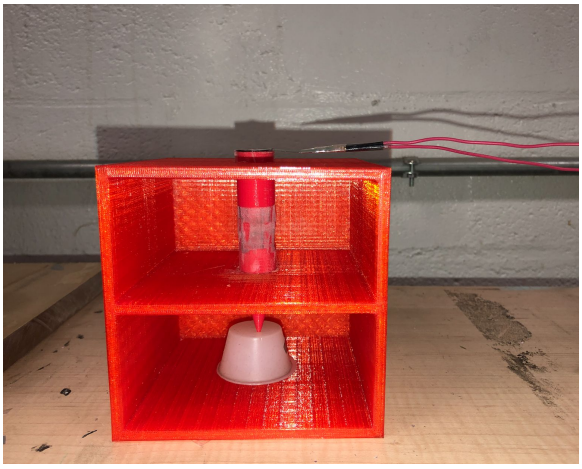


Fig. 23. Design of sensor to silicone testing box, prior to any added force for displacement

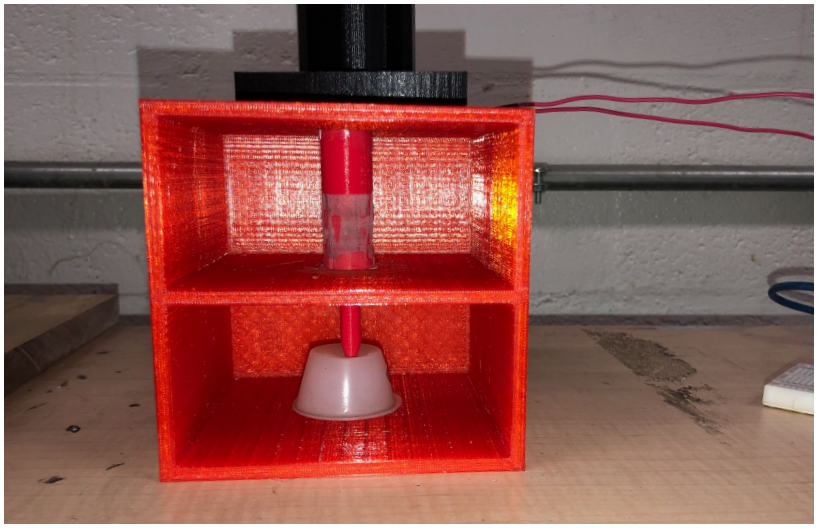


Fig. 24. Design of sensor to silicone testing box, after force has been applied to cause deformation in the silicone

Generally, the obtained voltage outputs were linearly spaced as expected. This linear spacing and significant gaps between the outputs allowed the team to set a system wherein the system could distinguish between the samples. The input was integrated into the Arduino software such that any input between 0.05 to 0.3 corresponded to the least firm sample (10), between 0.31 and 0.55 corresponded to the sample of medium firmness (20), and between 0.56 and 1 corresponded to the most firm sample (50).

These values were determined after conducting testing on each silicone type and its respective sensor output voltage. The results of these tests are displayed in Fig. 25. Each silicone type was tested with n=10 and the results were promising in that there was a clear delineation with the exception of some outlier readings for each silicone type.

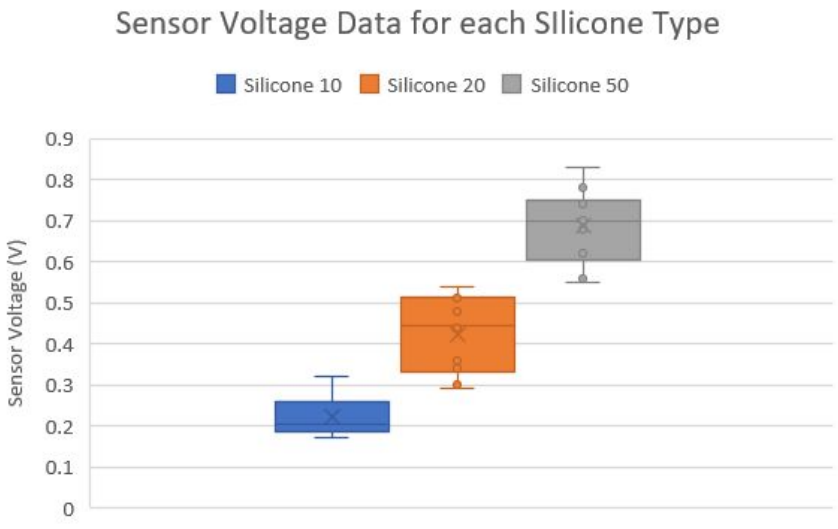



Fig. 25. Voltage values obtained from each silicone type (n=10)

This encompassed all of the possible readings without including any input that was erroneous. This was done since the sensor would produce outputs of 0 or well over 1 without regard to the sample during some trials. These unexpected outputs were mostly eliminated after a few design modifications were made, which will be discussed in a later section. A schematic of this theory for setting the output can be seen in Fig. 26. so that the feedback mechanism corresponded to the sensor reading. The output of the Arduino code was an arbitrary number that corresponded to a magnet-to-coil interaction which resembled a feeling of the silicone, which will be discussed in further detail in a later section. This output value was singular, therefore a full range of input values would correspond to a single type of output. This was done since the sensor had inherent variability wherein a single sample could output a range of values.

| 0.05 – 0.30 | 0.31 – 0.55 | 0.56 – 1.00 |
|---|---|---|
| Output 10 Firmness | Output 20 Firmness | Output 50 Firmness |

Fig. 26. Theory for assigning output based on input

The final code utilized for integration can be found in Fig. 27, wherein the sensor reading can be found in the “if” statements and the coil output can be found in the “analogWrite” statements.

```
const int PIEZO_PIN = A0; // Piezo output

void setup()
{
  Serial.begin(9600);
  pinMode(9, OUTPUT);
  pinMode(4, INPUT);
}

void loop()
{
  if(digitalRead(4)==HIGH){
    // Read Piezo ADC value in, and convert it to a voltage
    float piezoADC = analogRead(PIEZO_PIN);
    float piezoV = piezoADC / 1023.0 * 5.0;
    Serial.println(piezoV); // Print the voltage.

    if ( piezoV >=0.02 && piezoV<=0.3 ) {
      analogWrite(9, 80);
      Serial.println("low");
    }

    else if ( piezoV >=0.31 && piezoV<=0.55 ) {
      analogWrite(9, 85);
      Serial.println("medium");
    }


   else {
     analogWrite(9,0);
     Serial.println("not on");
   }
  }
  delay(100);

}
```

Fig. 27. Final Arduino code utilized for sensor reading and system integration

The sensor remained attached to the same circuit as above; however, a button feature was added to the circuit, as seen in Fig. 28 and Fig. 29. The team chose to add this element so that the feedback could be turned on and off as the user desired. Therefore, when the user is ready to apply the force to the probe on the silicone, the button should be pressured and the output on the solenoid will be determined and provided as discussed above. However, when the sensor is resting and no force is being applied, the button will not be pressed and no feedback will be provided. This feature is meant to represent the desire of survey responses for feedback only when it is requested by the user.

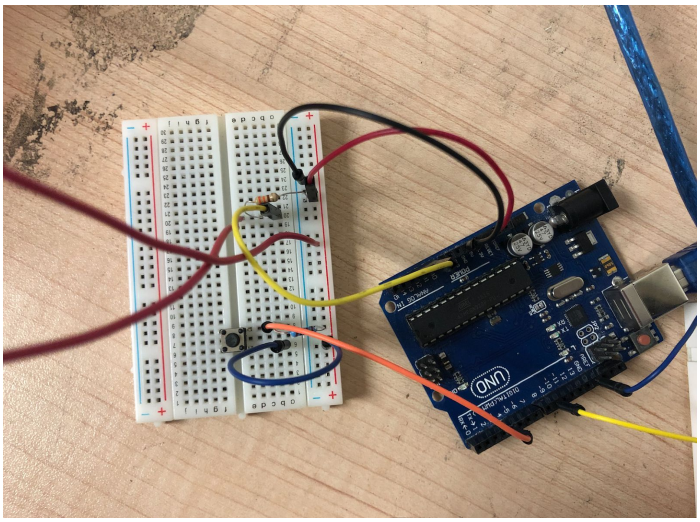


Fig. 28. Circuit for reading of data from the sensor, with the addition of a button for data acquisition

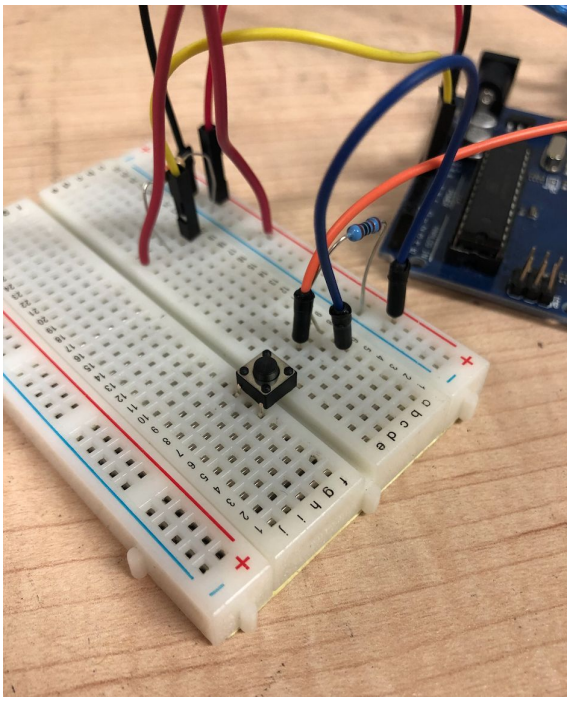


Fig. 29. The simple button addition to the sensor circuit

Overall, this setup was sufficient for movement into the subject testing piece of the protocol. However, some improvement areas to standardize the amount of displacement and pressure applied were foreseen that could help in producing more consistent and accurate results. These will be analyzed further in the discussion chapter, but were not pursued due to time constraints.

### 3.2.4 Design Improvements for Final Design

The team was looking to optimize the testing procedure, and one of the primary issues came with moving the silicone. Though the 50 and 20 samples did not present much difficulty, the 10 sample was quite sticky, a problem that was seen in literature and was predicted to occur. This made moving the sample tedious, adding unnecessary time. To improve this, circular pieces of plastic were cut and placed on the bottom of each sample. This allowed for the samples to slide with ease and avoid sticking to the users hand. Further, these were placed on all of the samples to ensure standardization and can be seen below in Fig. 30. In addition, it can be seen through the image that no visual cues such as color or porosity could differentiate the samples.

Fig. 30. Left to right: 10, 20, 50, visually indistinguishable and of the same dimensions

Another essential modification came with the probe utilized within the testing box. The first probe was small in diameter and had a duller tip. This is the top red probe in Fig. 31. This probe was sufficient for initial testing, yet led to significant issues. Initial testing frequently led to an output of 0 from the sensor, even when force was being applied. However, it could not be determined when the sensor would give an accurate reading or 0, as the team felt that the trials were nearly identical in procedure. After troubleshooting and a long process of elimination, it was determined that the cause of this issue was the diameter of the probe. Since this diameter was smaller than the diameter of the sensor, some of the sensor was experiencing no force. Since subject testing was reliant on accurate readings from the sensor, the team was resolved to correct this problem. Further, the probe was often sliding within the sections of the box and getting caught, causing the need for constant resetting. Therefore, a larger diameter of the barrel in comparison to the diameter of the tip was designed.

The next iteration of the probe involved this larger diameter of the probe itself in addition to a larger diameter of the top portion for the sensor. This version can be seen in the middle of the image below as the black colored probe. This top could fully contact the sensor without any overlay. However, testing revealed the same issue wherein the sensor produced a 0 output. The team determined that contact between the top of the sensor overlay and the box was negating the effect of the silicone deforming. This also led to inaccuracies in the result. Therefore, a third iteration was designed.

The only difference made for this iteration was removing the top overlay. The team ensured that the entire sensor was in contact with the probe, but that the probe would never contact the top surface of the box. The overall length of the probe was maintained to ensure the

same deformation length in the silicone, and therefore preserve the previously obtained results. Testing of this iteration, seen below as the bottom orange probe, produced results consistently between trials as desired. This iteration was kept for final subject testing. The color difference was due solely to PLA loaded when 3D printing and not due to any specifications of the team.

Fig. 31. Multiple iterations of the sensor probe for the testing box

## *3.3 Feedback System*

### 3.3.1 Circuit for Magnetic Actuation

*Overview of Goals*

The actuation device of our feedback system relies on a solenoid, which is discussed within the literature review. When pressing on a firm object, the object provides a large amount of resistance to the applied force. Conversely, a less firm object provides less resistance when one pushes against it. This is the principle we seek to emulate in our actuation device. By increasing the current through the coil around a stack of magnets, the magnetic field within the coil increases, thus the magnetic force that pushes the magnets upward is greater. This means that when more current is applied, it takes a greater amount of force to push the magnets down because they provide a greater resistive force. The design of our actuation device needs a relatively high current to produce a noticeable magnetic force. However, the magnitude of the

current that the Arduino microcontroller produces is minimal in comparison to the amount of current we need to feel a significant resistive force. This required us to design a circuit that amplifies the current generated by the Arduino before it enters the coil of our solenoid. Our circuit went through several iterations, which we describe in detail in this section, with the ultimate goal to increase the amount of current through the solenoid substantially.

*First Iteration of Circuit*

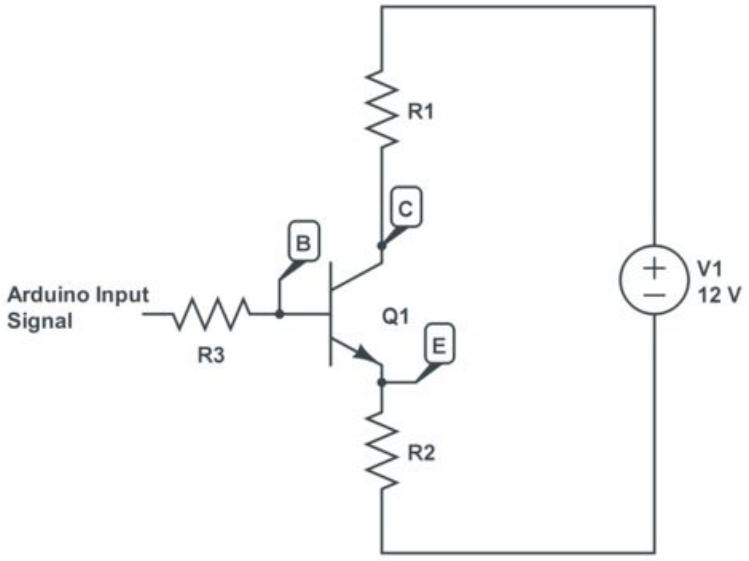
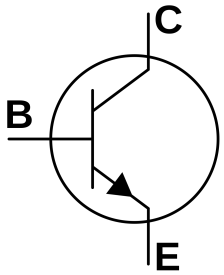



Fig. 32. First iteration of circuit for magnetic actuation.

In our initial design (Fig. 32), we relied solely on an NPN Bipolar Junction Transistor (BJT), which is a semiconductor device commonly used to amplify current. Specifically, the collector (C) and emitter (E) currents increase as the base (B) current increases. We also used an external power source, V1, to provide a much larger current supply than the Arduino would be able to.




$$IC = \ * IB = ((+1)/) * IE \ where \approx 200$$

Fig. 33. NPN Bipolar Junction Transistor (BJT).

By changing the voltage of the base and keeping the resistance constant, we expected to increase the current of the base (V = IR). Because of the large beta ( ) value, a small change in the base current would produce a large change in emitter current (Fig. 33). However, we found

that the current going through the coil was not varying as much as we expected and the solenoid was not providing any feedback.

*Second Iteration of Circuit*

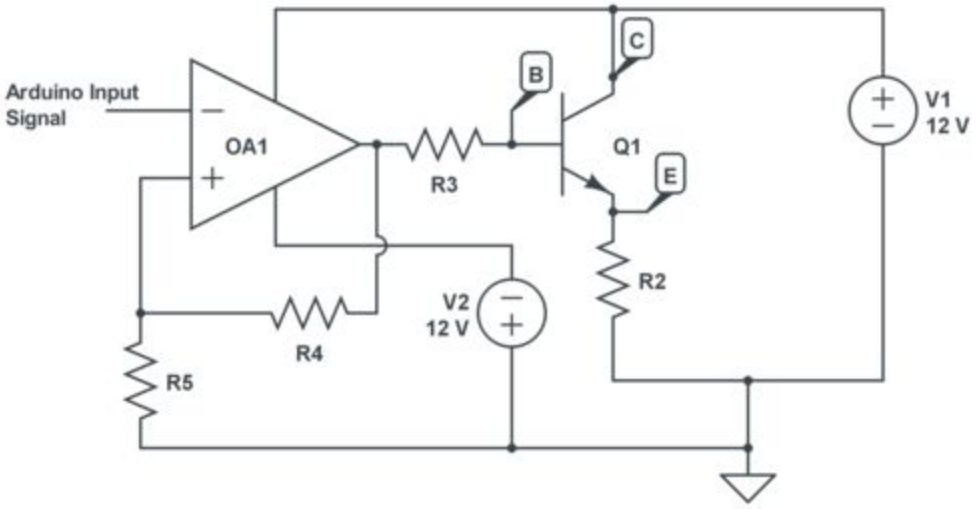



Fig. 34. Second iteration of circuit for magnetic actuation

We then sought to use both an operational amplifier (op amp), to further increase the base voltage, and a BJT (Fig. 34).

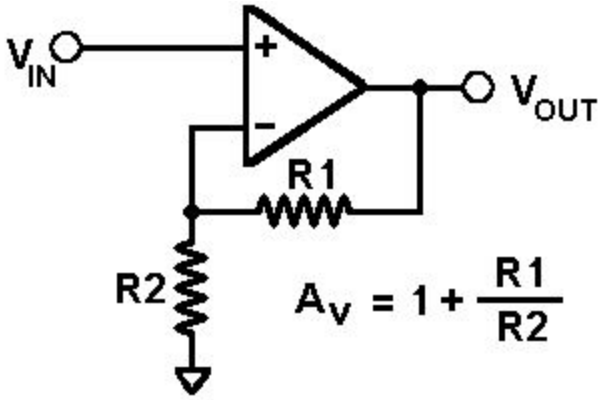



Fig. 35. Non-inverting amplifier using operational amplifier

By using an op amp, the voltage from the Arduino would be magnified, and in theory, create a greater base current while keeping the resistance constant (Fig. 35). With this design, we expected the op amp to widen the range of currents that the coil would be able to experience. However, because the operational amplifier is designed to amplify voltage and not current, we found the operational amplifier to behave suboptimally when trying to increase the base current, which did not allow us to adequately amplify the coil's current.

*Third Iteration of Circuit*

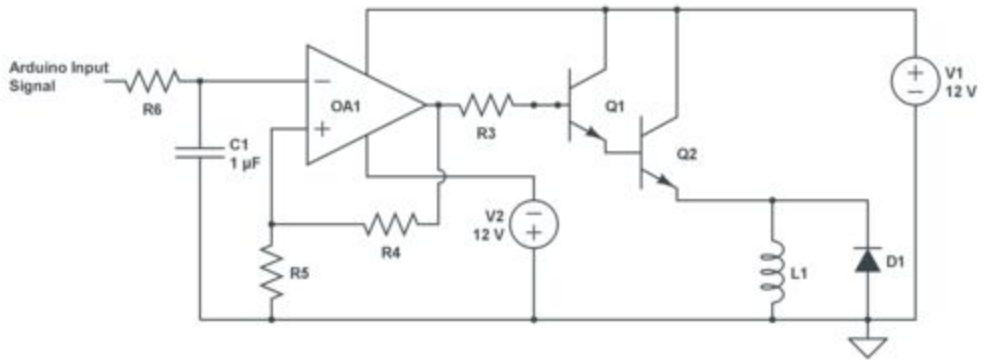



Fig. 36. Third iteration of circuit for magnetic actuation

In the next phase of our design process, we still relied on BJTs to amplify current and op amps to amplify voltage, but we added several components to our circuit (Fig. 36). The output signal of an Arduino microcontroller is a pulse width modulation (PWM) signal, which means that instead of outputting a constant DC voltage, the Arduino outputs a square wave with a particular duty cycle. If the maximum voltage the Arduino can produce is 5V, then to output 2.5V, the Arduino outputs 5V for half of the time within a cycle and 0V for the other half of the time. While the voltage values switch back and forth so quickly that a multimeter would measure the voltage of the output to be 2.5V, this operation was not ideal for our magnetic actuation device. By adding an RC filter before the op amp, we could smooth out the signal, so it became closer to a constant DC signal, which would be a better input for the main component of our circuit. The next change we made was that we added a cascade component, which is a two-stage amplifier with one transistor feeding into another to amplify current more effectively. Finally, we added a diode in parallel with the magnetic actuator to prevent high currents from flowing in the wrong direction and damaging other components of the circuit. Because the cascade component is able to produce extremely high currents, we ended up burning many of the transistors, especially before adding the diode, because they were trying to draw too much current. We were still not getting the coil current that we were expecting to get and the cascade component did not work as expected. However, the beginning of the circuit finally began producing the expected waveforms.

*Final Circuit Design*

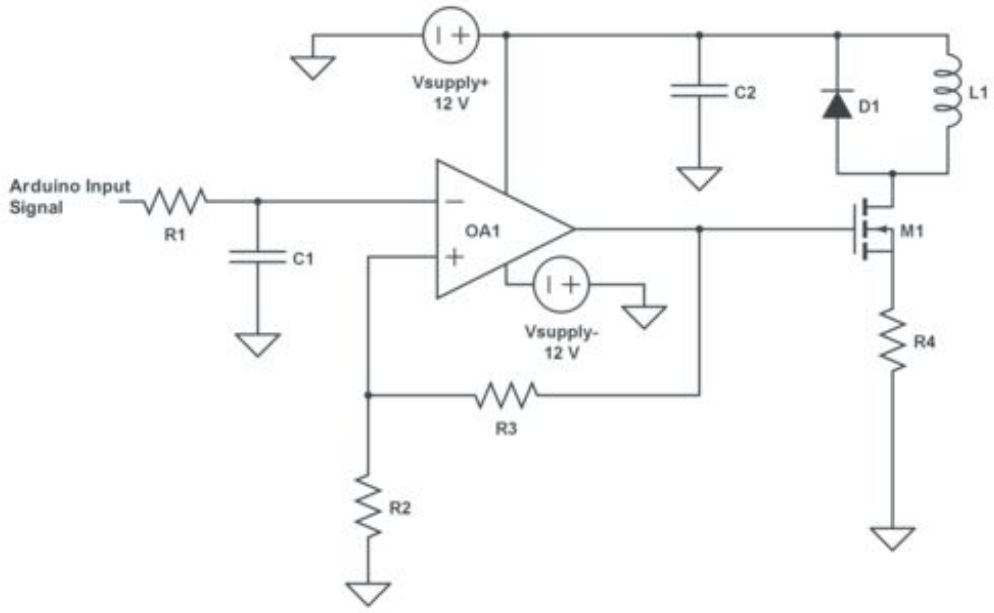
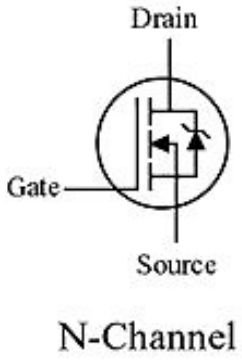



Fig. 37. Final iteration of circuit for magnetic actuation

After working with BJTs unsuccessfully, we decided to work with an N-type Metal Oxide Semiconductor Field Effect Transistor (MOSFET) (Fig. 37), which is another type of transistor widely used for switching and amplifying signals. Unlike BJTs, MOSFETs increase the source current as the gate voltage increases (Fig. 38).




$$i_D = \frac{1}{2} k_n' \left( \frac{W}{L} \right) \left( v_{GS} - V_{TH} \right)^2$$

Fig. 38. N-channel Metal Oxide Semiconductor Field Effect Transistor (MOSFET)

Initially, we worked with a standard MOSFET, which, like the BJT, did not magnify the source current as we expected. We then switched to working with logic-level MOSFETs, which are designed to turn on with 5V. This allowed us to get into the operating range of the MOSFET much faster and let us have a larger range of active gate voltages. Having made these final changes, we were finally producing the currents that we expected to see. Additionally, once we

did testing, we saw that varying the duty cycle of the Arduino signal produced a linear relationship with the current produced from the MOSFET (Fig. 39). We also found that this varying current produced varying solenoid strengths that were distinguishable by touch.

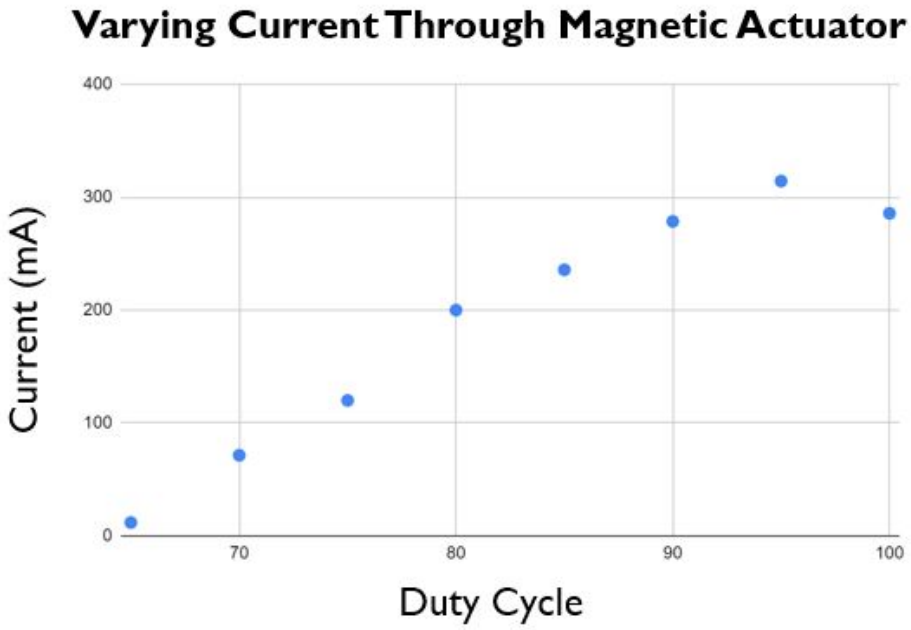



Fig. 39. Current through magnetic actuator for various duty cycle inputs

### 3.3.2 Wire Coil for Magnetic Actuation

Using an approximation for the average size of a human hand, the coil holder was 3-D printed from PLA, a common material for 3D printing. Multiple iterations of the size of this holder were developed until a final design was chosen. This coil holder is wound with multiple layers of enamel coated copper wire. The coil was initially wound by hand. However, the team switched to a coil winding machine, displayed in Fig. 40, as coiling by hand was a tedious and highly time consuming process. Further, consistency in layers created by the machine was higher than when being coiled by hand. Therefore, this machine made the winding process much more efficient and allowed for a more uniform placement of wire, thereby increasing the amount of coils placed.


Fig. 40. Mechanism obtained for easier and more standardized coiling of the wire.

The iterations of the coil holder are shown in Fig. 41. The first iteration can be seen in the middle and was printed in yellow PLA. The second iteration can be seen on the left, printed in black PLA. The final iteration can be seen on the right, printed in clear PLA. Choice of PLA color was arbitrary and use of color above is simply as a descriptor.

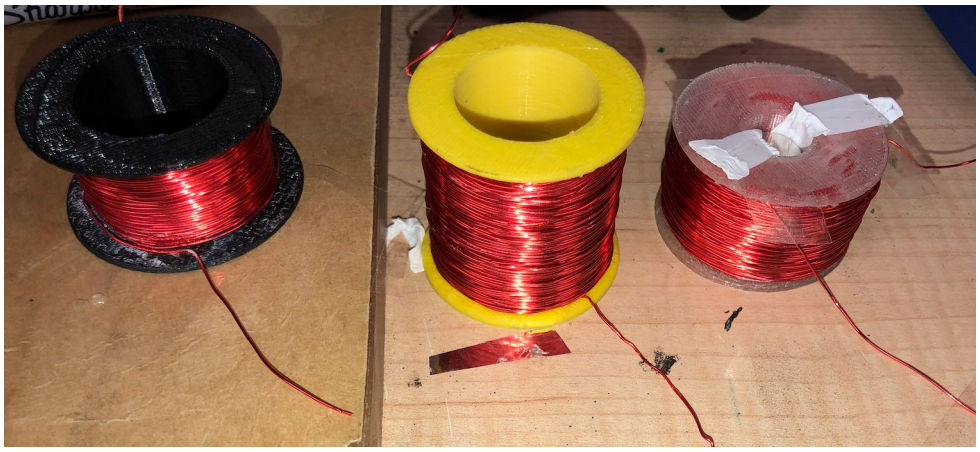


Fig. 41. Multiple iterations of the wire coil for different magnets and designs.

The first iteration used a 1-inch diameter magnet, but was too tall to comfortably fit in a user's hand. The model was then shortened and widened, to accomodate more layers of wires. It was deemed necessary to increase the width with the decreased height, since the same amount of current would need to be accomodated. When the magnets changed to a smaller diameter for purposes of the circuit efficiency, the overall bounding box of the coil holder stayed constant.

Rather, the inner diameter decreased. As a result, more layers of wire could be added to the coil holder. To stop the magnets from exiting the coil holder completely when current was applied, a small piece of teflon tape was used to constrain the magnet's vertical motion. The teflon tape had the added benefit of not causing appreciable friction on the magnets against the coil holder. This strip of teflon tape can be seen in the rightmost iteration in Fig. 41. The CAD drawings of the iterations can be visualized below, with iteration 1 in Fig. 42, iteration 2 in Fig. 43, and iteration 3 in Fig. 44.

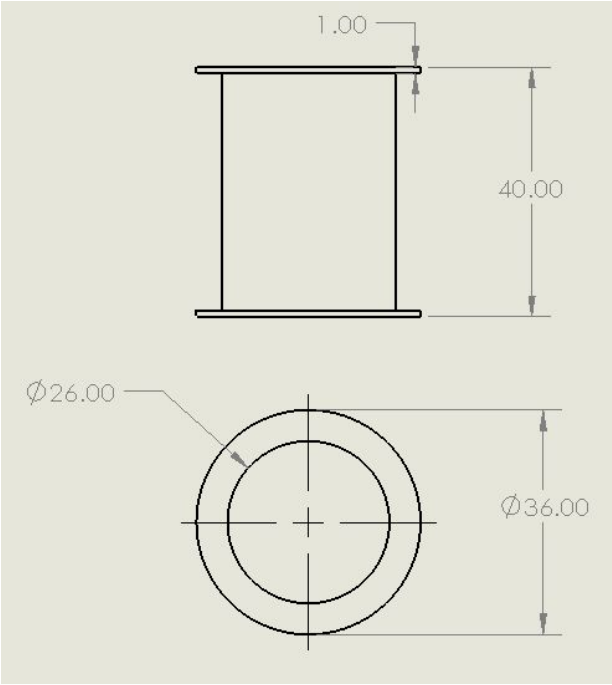



Fig. 42. Iteration 1 of the wire coil holder (dimensions in mm)

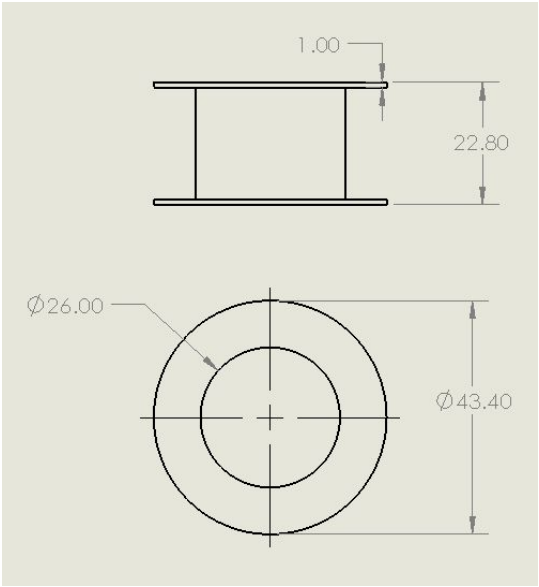



Fig. 43. Iteration 2 of the wire coil holder (dimensions in mm)

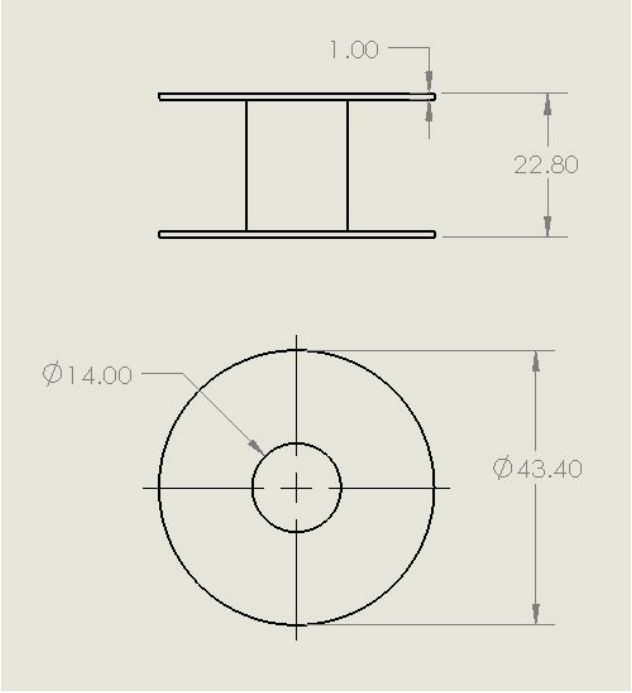



Fig. 44. Iteration 3, the final design, of the wire coil holder (dimensions in mm)

## *3.4. Integration of System and Human Interface*

### 3.4.1 Final Stage of Tissue Mimicking

As mimicking the feel of tissue was the primary goal of the research project, the team was careful in choosing the outer elements of the user interface with the system. The magnetically actuated coil was able to produce different forces to differentiate between samples; however, the sensory feeling of magnets was not similar enough to tissue to truly mimic its properties. Therefore, the team chose to utilize silicone in this aspect of the system as well, since it was already determined to be a proper simulation for physiological tissue. Further, the brand of silicone chosen by the team is commercially marketed for use with human skin. This left the team confident that the material would also not pose a risk to testing participants or future users of the system. To accomplish the goal of tissue mimicking, the silicone was chosen to encapsulate the magnetic coil and inner magnets. For sizing and shaping purposes, multiple iterations of molds were tested. These molds were created in a computer aided design software (CREO Parametric) and 3D printed with PLA. The first iteration of the mold was semicircular in shape and had minimal thickness. The extra width added by the semicircle would place the overall dimensions too large to fit in a human palm, so a new shape was chosen for the next model. Further, the thickness of the resulting silicone posed a risk of easy tearing during use, so a thicker mold was tested in the next iteration.

The second mold employed a cylindrical shape with a slightly greater thickness around the rounded edges and an even greater thickness for the top of the cylinder. This was chosen since the top of the silicone would be the primary point of contact for the user and most prone to wear and tear with repeated use. It was determined that this shape was better equipped to encapsulate the magnets and coil while not extending past the edges of the palm. However, the team decided to limit the thickness of the top to match that of the cylinder walls, as the increased thickness of the top could have potentially limited the user's ability to feel small differences in magnetic force. These alterations were employed for the final iteration, which also was specified for the final sizes of the coil and the magnets. These molds and resulting silicone cases can be seen in Fig. 45.

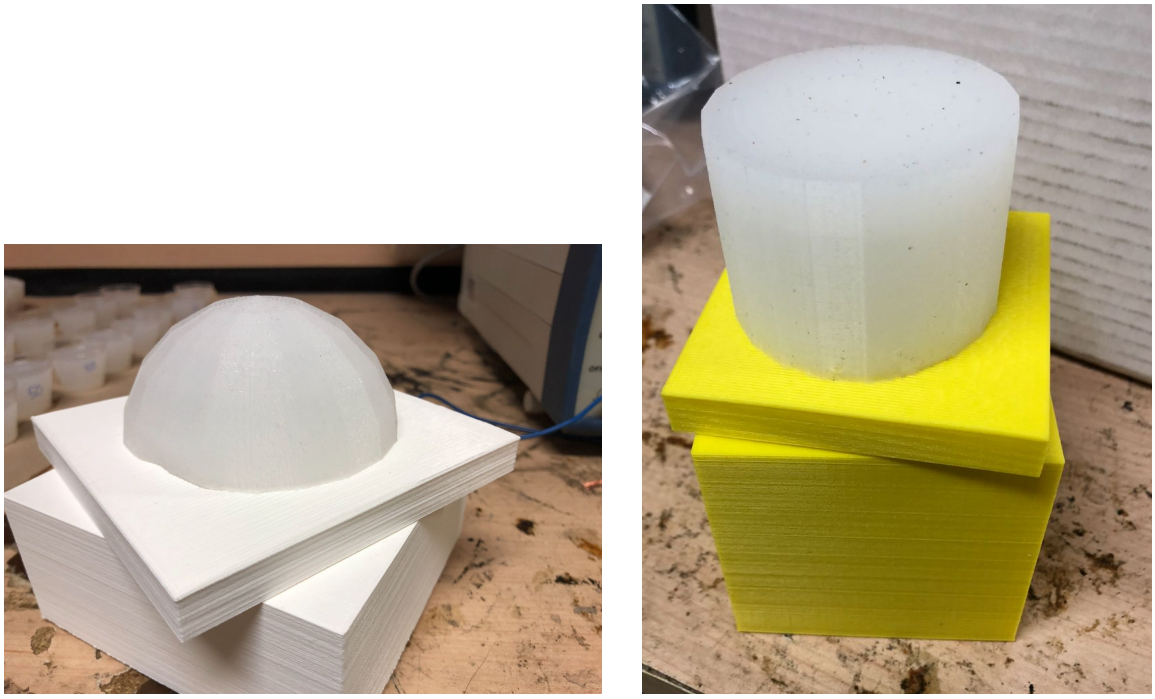


Fig. 45. (left) First design of silicone case, (right) Second iteration of silicone case with thicker top boundary

### 3.4.2 Development of Human Interface

The design of the human interface at the hand of the surgeon was based upon feedback from the initial surgeon survey. This interfacing element which would house the feedback mechanism needed to be accessible to the surgeon without inhibiting the surgeon's ability to perform other required tasks. It was determined that the interface would be placed on the palm of the surgeon and strapped onto the hand so that it would maintain its position. Based on the survey, we created the system so that surgeons would have control over when they receive the feedback by choosing to place their fingers on the feedback mechanism. The design of this element can be seen below in Fig. 46. This design included straps made of elastic and the above mentioned silicone case. To create a flat and stable base for the magnetic coil, a plastic cutting board was chosen. This plastic piece was cut down to a small square shape with rounded edges, which contacted the user's hand below the coil. The flexibility of the plastic allowed for the user's hand to still move without restriction, while the sturdiness of the plastic allowed for support of the coil.

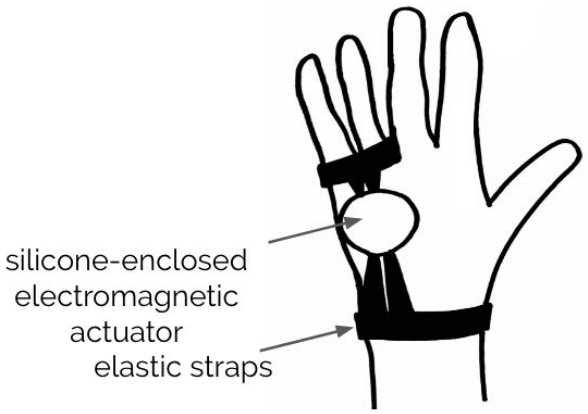



Fig. 46. Design of user interface hand-piece

Fabrication of this interface component was done in multiple steps with two iterations. Elastic and velcro were sewn together using a sewing machine. The first iteration involved using ¼" elastic; however, the team transitioned to a wider elastic as it provided more support and was easier to use in the manufacturing process. The final iteration used a 1" elastic around the wrist and ½" elastic as straps. The 1" elastic was sewn to velcro to allow for the user to adjust the wrist strap size to their own wrist size. A combination of stretchable elastic and velcro were used so that the interface size was adjustable. However, the size of the electromagnetic actuator may have made the device too large for a user with a relatively small hand. The next piece of fabrication involved cutting the plastic cutting board down to the appropriate size and adding holes to the edges where the elastic could thread through. After a second round of sewing where everything was attached, the magnetic coil was placed onto the cutting board and tape was used to secure it. The final step involved placing the silicone case over the coil and magnets, and attaching the silicone to the plastic with super glue. The final prototype can be seen below in Fig. 47. As of note, the final prototype was larger and heavier than the team desired. Future prototyping would involve reducing the size of the coil so that the hand piece could be both smaller and lighter overall.

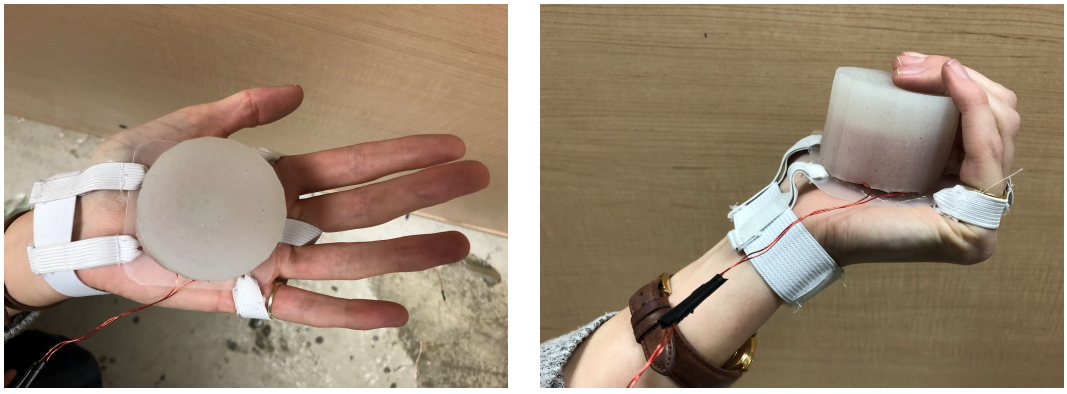


Fig. 47. Prototype of the human interface utilized for human subject testing

### 3.4.3 Fitting of System to Participant Blinded Study

Once all of the individual elements of the comprehensive system including the sensor with probe and testing box, circuit for magnetic actuating, and magnetic actuator coils, were completed, they needed to be integrated. This step of integration included both the previously mentioned methods of relay code for data transfer and physical alteration of the materials. The circuit and button reading in the sensor data and the circuit modulating the magnetic actuator were connected to the same Arduino for attachment. Further, the physical coil attached to the circuit needed a few alterations beyond sizing prior to final human participant testing. During preliminary prototyping and testing, the coil was closely attached to the breadboard with little to no lead wire for separation. However, for the testing participants to be removed from the electrical component of the system and its details, a larger distance separation needed to be developed. The scope of testing involved blinding the participant to the testing through the utilization of cardboard folders and being seated at the opposite side of a table. Therefore, the wires attaching the coil that would be felt by the user's hand and the circuit run by the testing team needed a minimum of four feet between them. To accomplish this specification, additional wire length was soldered to the existing coil. This step introduces the potential for device failure or breaking; however, the team deemed the time and resourcing involved in wiring a new coil with longer leads less essential than other pressing tasks. Testing of output values after this alteration did not indicate any immediate system failures.

Another alteration made to this coil was the addition of electrical tape to the length of the wire. Although the wire chosen by the team was insulated and posed no significant risk to the team or users, it was determined that increased safety felt by any person unfamiliar with electrical safety was important. The team chose to wrap the wire from the distal end of the wire at the hand piece utilized by users to halfway down the wire, wherein the participant saw only wrapped wire and any unwrapped wire was on the side of the table nearest the tester. This tape alteration was also determined to not affect the output of the system.

## *3.5 Testing of Final Device*

After integration of the full system, a protocol was developed to test the efficacy of the combined system. Participants were fitted with the feedback mechanism component of the device, and a member of the research team applied the sensing component to silicone samples of varying firmnesses. The overall goal of this testing was for the firmness of the silicone sample to be correctly sensed and transmitted to the feedback mechanism and for the participant to correctly identify said firmness.

### 3.5.1 Participants

All protocols and recruitment methods were approved by the University of Maryland Institutional Review Board. Participants (n=6) were recruited to test our prototype through online flyers distributed to student organizations. Participants were students at the University of Maryland. Participation criteria included being at least 18 years old, having full range of motion/feeling in arms, hands, and fingers, and no allergies to silicone, plastic, or elastic. They were compensated $10 for their time. Due to unforeseen circumstances (the COVID-19

pandemic), our team was unable to continue testing beyond 6 participants. Future directions of the project would include testing with more subjects.

### 3.5.2 Protocol Design

Three protocols were generated, each with the same trial types in a randomized order. Phase 1 of the protocol consisted of differentiating between two randomized silicone samples. With three different silicone firmnesses (10, 20, 50), there were 9 possible Phase 1 trial types. Three blocks were created, each with a randomized order of the 9 trial types. Each protocol included all three Phase 1 blocks in a randomized order. Phase 2 of the testing protocol consisted of ranking all three samples from softest to firmest. There were 6 possible orders and therefore 6 trial types. Phase 2 of each protocol consisted of a randomized presentation of these 6 trial types.

The three protocols were rotated through the participants to ensure there was no ordering effect of trial types. Each protocol was used for 2 participants. Protocol number was not correlated with overall accuracy ($r=.557$, $p>.251$). The protocols are included in Appendix C.

### 3.5.3 Methods

Two members of the research team were present at each 30-minute testing session. One research team member (researcher 1) prompted the participant through the study and recorded the participant's answers on a confidential Qualtrics survey that was linked to a participant ID. The Qualtrics data collection survey is included in Appendix D. In addition to the participant, researcher 1 was also blind to which sample was being presented to alleviate any risk for biased reporting. The other member of the research team (researcher 2) was responsible for presenting the samples behind a screen. The screen was used so that participants and the other researcher were blind to which silicone sample was being presented.

At the beginning of the 30-minute testing session, participants were consented into the study and any questions were answered by a member of the research team. At this point, researcher 1 asked for the participant's dominant hand preference and measured the width and length of that dominant hand. We were interested in whether hand size was associated with how comfortable the device was to wear.

Participants were then fitted with our prototype and moved through a brief familiarization period. During this time, researcher 2 presented the participants with each sample behind the screen and informed the participant of the firmness ranking of the sample (most, middle, or least firm; corresponding with 10, 20, and 50 silicone). The participant was asked if they were able to feel a difference between the samples and the process was repeated up to two times until they stated they felt a difference between the samples.

The goal of Phase 1 of the testing protocol was to determine if participants can differentiate between silicone samples of different firmnesses or recognize if two silicone samples are the same firmness using our device. Participants were presented with the first silicone sample (Sample A) for about 3 seconds or until they indicated they were ready for the next sample. Immediately following, participants were presented with the second silicone sample (Sample B) for 3 seconds or until they indicated they were done. The participant was then asked

the question, “Which sample was firmer?” Response choices were: Sample A, Sample B, or They were of equal firmness (Fig. 48). If participants were unsure, they were prompted to make their best guess. This was repeated for three blocks of 9 trials each. Each block contained all 9 trial types. Researcher 1 recorded the participants’ responses on the Qualtrics data collection survey.


Fig. 48. Item for recording participant responses to Phase 1 trials

The goal of Phase 2 of the testing protocol was to test if participants could determine relative firmness while using our device. In this second phase, each trial consisted of a random order of the 10, 20, and 50 silicone. Participants were presented with all three silicone samples for about 3 seconds each or until the participant indicated they were ready to move on. The participant was then asked to rank the silicone samples from softest to firmest with 1 being softest and 3 being firmest (Fig. 49). The participant was presented with all six trial type combinations in a randomized order. Researcher 1 recorded the participants’ responses on the Qualtrics data collection survey.

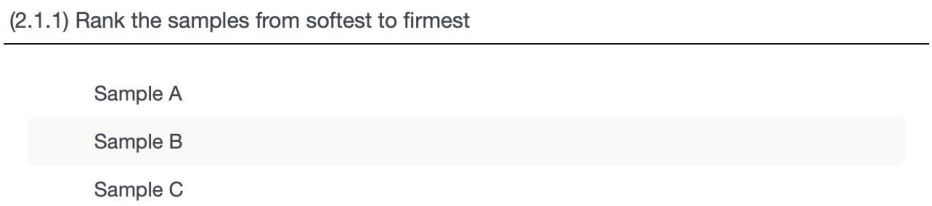



Fig. 49. Item for recording participant responses to Phase 2 trials

At the end of the 30-minute testing session, participants were ask to input their responses to questions on the Qualtrics survey asking about ease of use of the device, their level of comfort while wearing the device, how confident they were with their responses, their familiarity with similar devices, and any suggestions for improvement. These items are included in Fig. 50. At this point, researcher 1 stepped away to reduce reactivity in responses.


Fig. 50. Follow-up items measuring confidence, comfort, and ease of use rankings.

# Chapter 4: Results

All results reported in this chapter were gathered from data obtained during the human participant testing protocol outlined in Section 3.5. Results are reported according to Phase 1, Phase 2, and overall accuracy with a brief discussion of constraints related to overall accuracy. We then discuss the results from post-test questions concerning confidence in using the device and comfort and ease of use.

## *4.1 Accuracy*

### 4.1.1 Phase 1

Accuracy on Phase 1 trials was calculated as correctly identifying which sample was firmer or if the samples were of the same firmness. Average accuracy on Phase 1 trials was 38.89%. A breakdown of accuracy according to trial type is in Table 6. In Phase 1 trials, participants especially struggled to correctly answer when silicone samples had the same firmness, with an accuracy of 24.07%. Of these trial types, they performed particularly poorly when they were presented with two 20-silicone samples, with an accuracy of 11.11%. Anecdotally, we suspect that participants often doubted themselves when the correct response was the same firmness. Many participants asked again throughout the testing if the samples having the same firmness was a correct response. Participants performed notably best on trials where they first presented with 50-silicone and then 10-silicone, with an average accuracy of 72.22%. This is possibly due to 50 being the maximum firmness and 10 being the minimum firmness, making it easy to differentiate between the two. Participants' ease with this trial type makes their average accuracy on trials where sample A was firmer 50%. On trials where sample B was firmer, the average accuracy was 42.59%.

Table 6. Phase 1 accuracy by trial type

| Trial Type | Average % Accuracy | # Trials per Participant |
|---|---|---|
| Phase 1 Overall | 38.89% | 27 |
| Same Firmness | 24.07% | 9 |
| 10-10 | 27.78% | 3 |
| 20-20 | 11.11% | 3 |
| 50-50 | 33.33% | 3 |
| Sample A Firmer | 50.00% | 9 |
| 20-10 | 38.89% | 3 |
| 50-10 | 72.22% | 3 |
| 50-20 | 38.89% | 3 |
| Sample B Firmer | 42.59% | 9 |
| 10-20 | 38.89% | 3 |
| 10-50 | 44.44% | 3 |
| 20-50 | 44.44% | 3 |

n=6

We also looked at whether accuracy improved over the course of Phase 1 as participants adjusted to the system. To do this, we calculated average accuracy for each of the three blocks in Phase 1. The average accuracy in Block 1 was 38.89%, in Block 2 it was 35.19%, and in Block 3

it was 42.59% (Table 7). Average accuracy slightly improved from Block 1 to 3, but dipped in Block 2.

Table 7. Phase 1 accuracy by block

| Block Number | Average % Accuracy |
|---|---|
| Phase 1 Overall | 38.89% |
| Block 1 | 38.89% |
| Block 2 | 35.19% |
| Block 3 | 42.59% |

n=6

We plotted each participant's accuracy over time to see if this change in average accuracy over time reflects an overall trend (Fig. 51). While there were individual differences, there does not appear to be an obvious overall trend in percent accuracy over time. Future research should give participants more time to be acclimated to the system as well as perform more trials in order to see a more positive overall trend in accuracy over time.

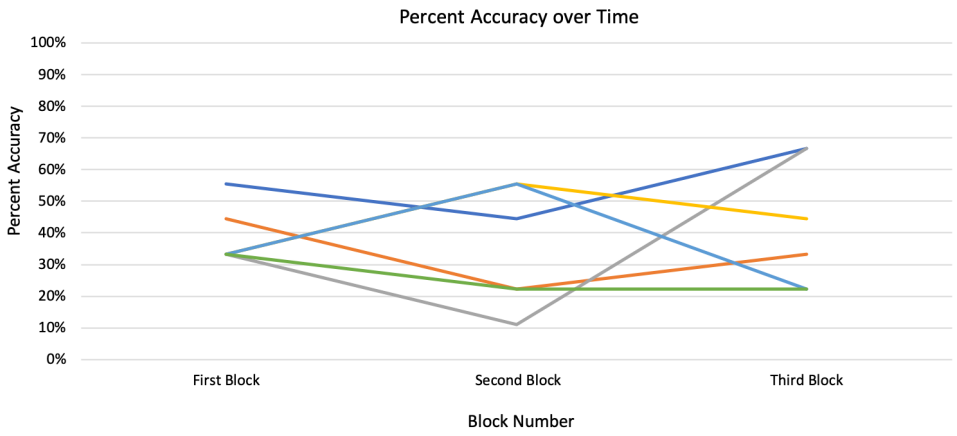



Fig. 51. Each participant's Phase 1 accuracy plotted over time

### 4.1.2 Phase 2

Accuracy on Phase 2 trials was calculated as correct identification of the sample in the correct order. Because participants were told that samples would not be repeated within each trial and this method of accuracy operationalization, accuracy scores were either 0%, 33.33%, or 100%, it was not possible to receive a 66.67% percent accuracy in this phase. Additionally, participants only completed one test of each trial type during Phase 2. Overall accuracy on Phase 2 trials was 37.96%. The team looked at average accuracy by Phase 2 trial type and while there are differences between trials, they do not appear to follow any overall trend (Table 8).

Table 8. Phase 2 accuracy by trial type

| Trial Type | Average % Accuracy | # Trials per Participant |
|---|---|---|
| Phase 2 Overall | 37.96% | 6 |
| 10 - 20 - 50 | 16.67% | 1 |
| 10 - 50 - 20 | 44.44% | 1 |
| 20 - 10 - 50 | 50.00% | 1 |
| 20 - 50 - 10 | 50.00% | 1 |
| 50 - 10 - 20 | 16.67% | 1 |
| 50 - 20 - 10 | 50.00% | 1 |

n=6

### 4.1.3 Overall

Average accuracy overall was 38.89%. Participant hand width was significantly correlated with overall accuracy (r=-.945, p<.005). Hand length was marginally related to overall accuracy (r=-.806, p>.053). This suggests that participants with a larger hand struggled more with the task. This is a possible design flaw that should be revised in future research.

## *4.2 Post-Study Questions*

### 4.2.1 Confidence

Participants were asked to rank how confident they were in their responses on a 5-point Likert scale (1=Not at all confident, 5=Very confident). The majority of participants (n=4) rated themselves as neither unconfident or confident ("Neutral"; 3). Other participants (n=2) ranked themselves as "Not very confident" (2). These results are summarized in Fig. 52.

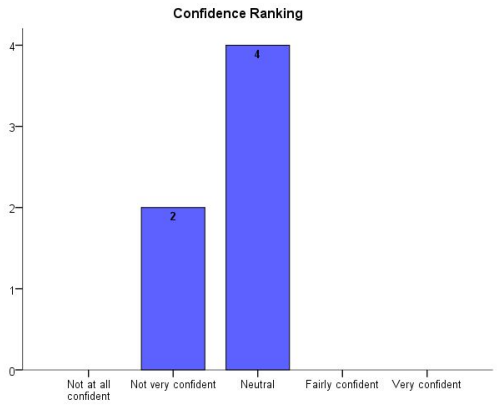



Fig. 52. Participant confidence rankings.

### 4.2.2 Comfort

Participants ranked how comfortable the device was to wear on a 5-point Likert scale (1=Not at all comfortable, 5=Very comfortable). 50% of participants (n=3) ranked the device as "Not very comfortable" (2) and the other 50% of participants (n=3) ranked the device as neither comfortable or uncomfortable ("Neutral"; 3). Comfort rankings are summarized in Fig. 53.

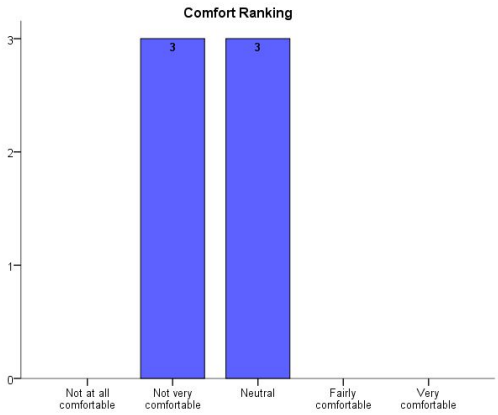



Fig. 53. Participant comfort rankings.

### 4.2.3 Ease of Use

Participants were also asked to rank how easy the device was to use on a 5-point Likert scale (1=Very difficult to use, 5=Very easy to use). Interestingly, participants were equally split between the responses for "Fairly difficult to use" (n=3; 2) and "Fairly easy to use" (n=3; 4). Rankings for comfort and ease of use were perfectly correlated ($r=1$, $p<.00$). Ease of use is summarized in Fig. 54.

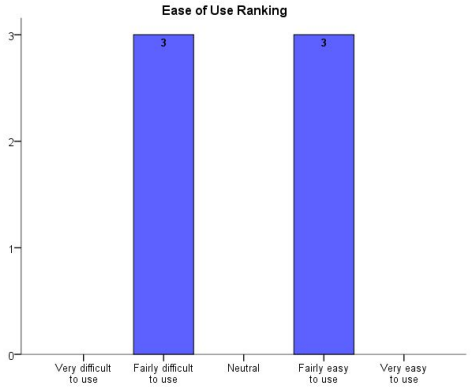



Fig. 54. Participant ease of use rankings.

### 4.2.4 Correlations

Average accuracy in Phase 1, Phase 2, or overall was not significantly correlated with confidence, comfort, or ease of use rankings (Table 9).

Table 9. Correlation matrix of average accuracy and confidence, comfort, and ease of use rankings.

| | **Average Overall Accuracy** | | **Average Phase 1 Accuracy** | | **Average Phase 2 Accuracy** | |
|---|---|---|---|---|---|---|
| | *r* | *p* | *r* | *p* | *r* | *p* |
| **Confidence Ranking** | -.464 | .354 | -.141 | .789 | -.441 | .381 |
| **Comfort Ranking** | -.606 | .202 | -.733 | .097 | -.062 | .907 |
| **Ease of Use Ranking** | -.606 | .202 | -.733 | .097 | -.062 | .907 |

n=6

Hand width or length was not significantly correlated with confidence, comfort, or ease of use rankings (Table 10). While not statistically significant, hand width was marginally associated with comfort and ease of use rankings (both r=.761, p>.079).

Table 10. Correlation matrix of hand width and length with confidence, comfort, and ease of use rankings.

| | **Hand width** | | **Hand length** | |
|---|---|---|---|---|
| | *r* | *p* | *r* | *p* |
| **Confidence Ranking** | .263 | .615 | .578 | .230 |
| **Comfort Ranking** | .761 | .079 | .157 | .766 |
| **Ease of Use Ranking** | .761 | .079 | .157 | .766 |

n=6

While many of these results were nonsignificant, it is important to note that with additional testing, it is possible that values trending towards significance could reach that threshold with more participants.

# Chapter 5: Discussion

As outlined in the above section, the final device our team developed showed promise; however, the results of the participant testing did not necessarily support the objectives of the project. The team believes that a primary cause of the low overall accuracy could be due to testing procedures rather than the device itself. Every effort was made by the team to develop testing protocols and measures that would accurately assess the device. However, the team's experience in designing and conducting device testing leaves room for improvement. Due to testing taking place during a later stage of the overall process and unforeseen circumstances such as restrictions on research during the COVID-19 pandemic, the team was not able to complete a second iteration of testing to address and correct these issues. Here we discuss possible problems with the device itself that could have led to lower accuracy than expected, as well as proposed modifications to testing and the device.

## 5.1 Areas for Improvement in Testing

There are several areas for improvement in the testing process. First, the materials used in testing did not allow for a quick change of the silicone samples. Initial testing designs involved a turntable style box, wherein the samples could be quickly and easily switched. However, time and scheduling restrictions did not allow for this to be implemented. Therefore, each silicone sample was placed by hand for each stimulus presentation while the researcher also held the probe in place. This method led to a gap in reading between the two samples of up to approximately 20-30 seconds. Participant feedback indicates that it was difficult to remember what the first sample felt like by the time the second sample was presented. Further, this gap in reading time between two samples would not be indicative of true surgical conditions, as the surgeon could easily switch between samples.

A second potential area for error involved the lack of standardization of the sensing component of the system. While utilizing the box and probe to measure the firmness, it was necessary for the same pressure and displacement to be applied in order for the sensor to read in the correct range for each type of silicone. However, because the standardization of pressure was up to the researcher presenting the samples, this could have varied between participants and between trials. It should be noted that the displacement of the probe to the top of the box was the same in each case, yet this was not enough to ensure the same force during each application. Therefore, for example, if too much pressure was applied during sensing of the 10 sample, it would be possible that the device relayed the firmness of the 20 sample and the participant would have received incorrect information. This error should be attributed to the setup of the box and probe along with the testing protocol, rather than the device itself. Future testing would involve the development of a secondary device to apply the same pressure during each trial to minimize this error.

This leads into another potential source of error: training and acclimation level of the participant. At the beginning of testing for each participant, they were given the feedback for each sample separately and the testing members of the team confirm that they can feel a difference between the samples. The feedback for each sample was only experienced once, unless the participant requested another round. Since many trials occurred after a single round of

training, it may have been wise to re-train in the middle of testing or after each set. Further, there may have been inaccuracies, as mentioned above, during the training phase of testing, which may have skewed all of the data from that participant.

The final area within the testing protocol that could be improved was overall standardization between participants and team members conducting the testing. A significant amount of time was placed into standardizing the questioning and format of the front-end of the participant trial; however, the same time and consideration was not placed into the back-end of the testing. Specifically, the questioning language and surveys for participants were highly standardized. Additionally, the same research team member prompted each participant throughout testing. However, procedures for the team member responsible for presenting the samples were not as standardized. This includes measures such as how long feedback was given for through the coil, when the button was pushed to begin the sensor reading, and how the silicone samples should be switched if it was a same-type trial. This lack of standardization on the back-end was an oversight of the team and may have significantly impacted the results.

### 5.2 Device-Related Areas for Improvement

While there were areas in which the testing procedure could be improved, we also recognize areas for improvement in the device design. One of the primary concerns of the team prior to testing was the size of the hand piece interface. If a user had shorter fingers, it may be difficult for them to fully reach the magnets and feel the change in resistance. We did receive feedback that it was harder to reach the magnets relative to the large size of the silicone encasement. The size of the piece that was placed on the palm was also larger than the team hoped for, but this was due to the requirements of the solenoid. Interestingly, results indicated that accuracy decreased with increased hand width ($r=-.945$, $p<.005$). This could be due to problems with trying to create a "one-size-fits-all" device. It may have been better to manufacture two sizes, one with shorter lengths of elastic and one with longer. This could also improve overall comfort and ease of use.

Following testing, participants had the opportunity to leave comments on their experience. Many stated that it was difficult to tell the difference when the 20 firmness sample was involved. This may be due to the fact that the 10 and 50 samples were the extremes, and the difference in resistance from the magnets was only slightly different between the samples. This is to say that the magnitude of difference between the 10 firmness silicone and the 20 firmness silicone, or the 20 and the 50, was small and could be difficult to distinguish for the user. The team chose these values to best fit what the silicone felt like qualitatively, as all of the samples were relatively soft. However, this may have made distinguishing the difference more difficult for inexperienced users.

### 5.3 Proposed Modifications

From the experience the team gained during the testing phase and through team analysis, we propose multiple modifications to the original configuration. These modifications would allow for a more accurate characterization of the device and its ability to provide useful haptic feedback to users. The team is hopeful that testing under these new conditions would lead to results demonstrating a statistical significance in identifying each sample's firmness by haptic

feedback alone. This round of proposed testing would also include a larger sample size of participants to gather a more comprehensive data set and minimize single user effects. It should be noted that due to time constraints, it will not be possible for the team to conduct this testing.

The first update would involve the development of a new box used for the sample presentation. Ideally, all three samples would be presented by using either a rotating disk or sliding rule that could easily be moved by the tester. This would minimize the time between samples and standardize the changing of the samples within the confines of testing. It was initially the plan of the team to implement this system for testing. However, the complexities of developing the device itself required more time and team members than originally planned, therefore limiting the resources available for development of testing.

A second modification to this piece of testing would involve development of a system to consistently apply the same pressure and displacement to the sensor and sample. Utilizing the palm of the hand as a means to compress the probe and sensor did not provide enough precision to ensure consistency. While the exact same reading could not be ensured with each attempt due to lack of precision of the sensor, this system would control for the reading to always remain within the desired range. Further, the ranges could be redetermined and set based on this system rather than the testing of a team member. The team envisioned a system consisting of a 3D-printed block that would hit the top of the box when displaced the correct amount. However, reading errors of zero were seen when utilizing this system. The team proposed that this may be due to the hollow nature of 3D-printed parts. Time constraints did not allow for testing of other blocks or systems prior to the formal study; therefore, the team had to move forward with utilizing the palm of the hand.

A third modification would involve more thorough training of participants with the equipment and more extensive familiarization period. A protocol could be implemented that would ensure the user was comfortable with the device and identifying the difference in firmness between the samples prior to the rounds of testing to collect data. This would ensure that the participants felt a difference between silicone samples before beginning actual data collection. This additional step would be similar to that of training surgeons with the device prior to utilizing it for formal tissue determinations.

The final proposed modification is the only change that would alter the device. This would involve changing the current values assigned to each sample's firmness. The arbitrary values chosen were done so as to mimic as closely as possible the real feel of the silicone. However, the differences in the silicones were so slight that the assigned differences in magnetic resistance may not have been great enough for the user to reliably feel through the silicone case. If the firmest sample was assigned a higher current, the magnets would resist compression to a higher degree. The user may then have an easier time identifying each sample, since the difference between least, middle, and most firm would be increased. However, this may lead to a decrease in accuracy of the device, since the feedback given to the user would no longer feel as soft as the tissue within the body. This tradeoff would be an important consideration for future research.

# Chapter 6: Conclusion

## *6.1 Summary of Findings*

This project sought to devise a way to convey tactile feedback of soft tissue firmness to a user in a robotic surgical setting. The investigation was originally guided by a survey of 15 surgeons who use robotic assisted surgical systems. 80% of surgeons surveyed indicated that the addition of tactile feedback to RAS systems would be helpful. Additionally, 86.7% of those surveyed felt that firmness would be the most helpful measure of soft tissue to relay using our system. Based on this feedback, the team moved forward with designing a system that used a force sensitive resistor to measure the firmnesses of 3 different silicone samples and an electromagnetic actuator, which varied the force exerted on the user's fingers according to the current applied, to provide feedback. With the entire system in place, the team proceeded to recruit participants to test the integrated feedback mechanism. Due to time limitations and circumstances such as research restrictions due to the COVID-19 pandemic, the team was only able to test the device with 6 participants. The participants had varying degrees of success in determining the firmness of silicone samples. The average accuracy overall was 38.89%. The team suspects that this lower accuracy is primarily due to problems with the testing protocol and not the device itself. Proposed modifications to the testing protocol to improve accuracy were discussed.

## *6.2 Proposed Future Work*

Based on the work done in this project, there are many potential avenues to pursue with the goal of integrating tactile feedback of soft tissue firmness in robotic assisted surgical systems. The first areas would be the testing and design modifications of the system this team devised. These modifications are explained in Chapter 5. Prior to any upgrades to make the system applicable to the surgical environment, confirming device accuracy with these updated testing measured should be completed.

The next steps of future work should focus on the initial goals of the project that were above the scope and time available for work. These primarily focus on the system being utilized under the heightened constraints of surgical situations. Using real tissue rather than the silicone imitation used in this study would be a significant improvement. Though silicone is a good initial model, real tissue would provide the most accurate demonstration of this device determining tissue firmness. Using more sophisticated sensors as well as those better suited for measuring soft tissue firmness would allow for better data collection and, by extension, more accurate feedback. Furthermore, if this system were to be implemented in a robotic surgical system, the sensor would have to be attached to one of the probes used in the body. Therefore, miniaturization and sterilization of the sensor would need to be possible.

Considerations would have to be made to accomodate the practical restrictions of working in a surgical environment. Changes such as making the wearable device sterilizable and small enough to be comfortable to wear while operating are critical aspects of the device. The

device could also be modified so that the primary placement follows the data we collected from the surgeon survey: the thumb and middle finger (Fig. 11, Location B). We were unable to develop the prototype to be placed here because of manufacturing constraints. Another key element that would need to be studied and accommodated for would include complete encapsulation of all electronic components, as none can be exposed during surgery. Further, the durability of the device would need to be greatly increased. The team faced issues during testing including the sensor tearing and separating from the attached wires. These could not be faced during surgery, as this would compromise patient safety. Therefore, new materials and cases would need to be studied to ensure the integrity of the device over repeated use.

# Glossary

**Adipose Tissue**: connective tissue made up of adipocytes, otherwise known as body fat

**Arduino**: physical programmable circuit board (often referred to as a microcontroller) and a piece of software used to write and upload computer code to the physical board

**Bipolar junction transistor (BJT)**: electronic component commonly used to amplify current within a circuit

**Cascade amplifier**: amplifier consisting of one transistor feeding into another in series to amplify current within a circuit

**Diode**: two-terminal electronic component that conducts current primarily in one direction

**Duty cycle**: fraction of one period in which a signal or system is active for a device that operates operates intermittently rather than continuously

**Force feedback**: a direct measure of the force applied to an object

**Force sensitive resistor (FSR)**: material whose resistance changes when a force, pressure or mechanical stress is applied

**Haptic feedback**: the simulation of real touch between a human, a robot, and the local or remote environment that exists between them

**Hysteresis**: a phenomenon in which the value of a property lags behind changes in the effect that is causing this property

**Laparoscopic arms**: robotic arms attached to a laparoscope which come into contact with the human body during surgery

**Metal Oxide Semiconductor Field Effect Transistor (MOSFET)**: electronic component widely used for switching and amplifying signals

**Operational amplifier (Op Amp)**: electronic component used to perform a mathematical operation on input voltage, typically amplifying voltage within a circuit

**Piezoelectrics**: an electric charge that accumulates in solid materials in response to applied mechanical stress

**Polylactic acid (PLA)**: an inexpensive thermoplastic commonly used as material for 3D printing

**Pulse width modulation (PWM)**: method of chopping an electrical signal into discrete parts such that the average value of the voltage fed to the load is controlled by turning the signal on and off at a fast rate

**RAS / RAS system / Robotic-Assisted Surgical system**: minimally invasive surgical technique involving a robotic surgeon console and patient cart with robotic arms

**Semiconductor**: a solid substance that has a conductivity, making it an essential component of most electronic circuits

**Silicone**: a synthetic polymer made from alternating silicon and oxygen atoms that can be used to create plastics and rubbers

**Solenoid**: a cylindrical coil of wire acting as a magnet when carrying electric current

**Tactile feedback**: a variety of techniques to convey the local mechanical properties of objects such as compliance, viscosity, or surface texture

**Transistor**: a semiconductor device with three connections used to amplify or switch electronic signals and electrical power

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# Appendix A
Surgeon Survey

**Informed Consent**

**Welcome to Team FEELS' Research Survey**

**Who are we?**
We are Team FEELS (tactile FEEdback to improve Less invasive Surgeries), an interdisciplinary undergraduate research team formed through the Gemstone Honors Program at the University of Maryland.

**What are we studying?**
Our team is interested in developing a tactile feedback system that can be incorporated into robotic-assisted surgical systems. Current robotic-assisted surgical systems force surgeons to rely solely on visual feedback. The implementation of tactile, or cutaneous, feedback would allow a surgeon to receive information about soft tissue that is otherwise not possible with the technique. This would be accomplished through a three part system: tactile information acquisition through a sensor, relay of soft tissue data through an Arduino microcontroller, and a novel feedback mechanism for the surgeon that would mimic mechanical properties of soft tissue in the surgical field. The ultimate goal is complete transparency in which an operating surgeon would feel as if he/she was interacting with the surgical field. This would make the technique more intuitive, thereby decreasing the learning curve and making the benefits of the technique more widespread.

**Why do we need your input?**
Because our research is centered around prototyping a tool for surgeons like you who use robotic surgical techniques, we wanted to go straight to the source and collect your input on the best way to go about creating this system. This survey will be used to inform future components of our methodology, namely our novel feedback mechanism. We appreciate any input you have as this product is being created for surgeons such as yourself.

**Will any identifying information be collected? Are my responses confidential?**
Please be assured that your responses will be kept completely confidential and no identifying information will be collected. This study has been approved by the University of

Maryland's IRB Board.

This survey should take you around 5-10 minutes to complete. Your participation in this research is voluntary. You have the right to withdraw at any point during the questionnaire, for any reason, and without any prejudice. If you would like to contact the research team with any questions about the research, please email us at teamfeels.gemstone@gmail.com.

By clicking the button below, you acknowledge that your participation in the study is voluntary, you are 18 years of age, and that you are aware that you may choose to terminate your participation in the study at any time and for any reason.

Please note that this survey will be best displayed on a laptop or desktop computer. Some features may be less compatible for use on a mobile device.

---

- ○ I consent, begin the study
- ○ I do not consent, I do not wish to participate

**Background Information**

**This first set of questions will ask you about your surgical specialty and experience.**

What is your surgical specialization?

How long have you been practicing surgery (including intern year of residency)?

- ○ 0-5 years
- ○ 6-10 years
- ○ 11+ years

How long have you been using robotic assisted surgical systems in your practice?

- ○ 0-5 years
- ○ 6-10 years

- ○ 11+ years

Which robotic system do you use in your practice?

- ○ the da Vinci robot from Intuitive Surgical
- ○ Other

Which model of the da Vinci robot do you use most regularly in your practice?

- ○ da Vinci S
- ○ da Vinci Si
- ○ da Vinci Xi

## Location

**This next set of questions asks about your opinion when it comes to the implementation of tactile feedback in robotic surgical systems such as the da Vinci robot.**

Do you think the implementation of tactile feedback to transmit soft tissue properties to the operating surgeon would be helpful when performing robotic-assisted surgery?

- ○ Yes, tactile feedback would be helpful
- ○ No, tactile feedback would create adverse effects
- ○ There would be a negligible effect

What would be adverse about receiving tactile feedback?

Based on our literature review, our research team determined that firmness would be the most helpful measure of soft tissue to transmit to an operating surgeon. Do you think that firmness is the better measure or is there a different measure that would be more helpful?

- ○ Yes, transmitting information about soft tissue firmness would be the most helpful

- ○ No, a different measure would be more helpful

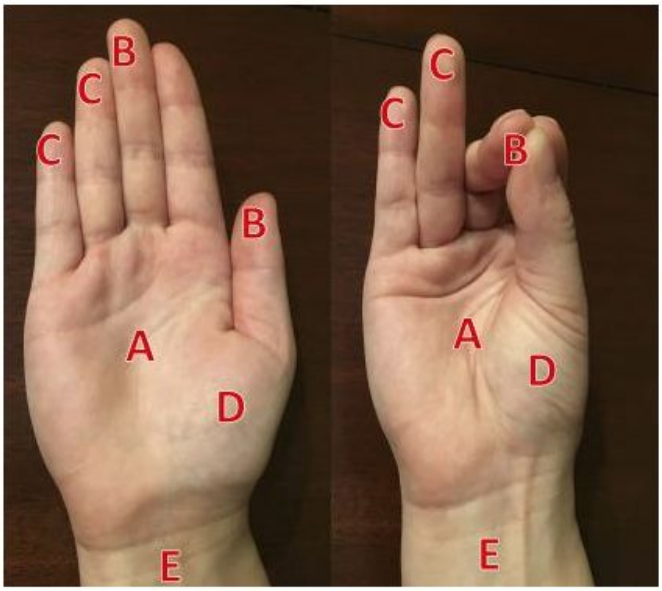
What measure would be more helpful to an operating surgeon?

Would you prefer to have control over when you receive said tactile feedback, or would you prefer for the feedback to be continuously provided while operating?

- ○ Choose when to receive tactile feedback
- ○ Have tactile feedback be continuously provided

## Location

**The following series of questions will you ask you to identify where on the body you would find it most helpful to receive tactile feedback.**




Please rate the following locations from 0 (least helpful) to 10 (most helpful) to receive tactile feedback.

Refer to the diagram above for a visual aid. Please note these locations were selected with the master control of the surgeon console of the da Vinci robot in mind.

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Central Palm at Location A | | | | | | | | | | | |
| Fingers at Location B | | | | | | | | | | | |
| Fingers at Location C | | | | | | | | | | | |
| Palm at Location D | | | | | | | | | | | |
| Wrist at Location E | | | | | | | | | | | |
| Other Location (Specify in next question) | | | | | | | | | | | |

If you feel a different location would be more helpful, please elaborate here.

Would you prefer feedback applied to your dominant or non-dominant hand?

- ○ Only Dominant
- ○ Only Non-Dominant
- ○ Both
- ○ Either (but just on one hand)

**Additional Comments**

**Do you have any additional suggestions/comments to improve our research?**

**THANK YOU**

We wanted to thank you again for taking the time to fill out this survey. Your responses are

valuable to us and will help us shape our future research. Again, if you have any questions, please feel free to reach out to us at teamfeels.gemstone@gmail.com. If you would like to stay up to date on our progress you can go to our website at https://teamfeels.weebly.com

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# Appendix B

Tissue Firmness Extrapolation Protocol

Materials:

- 3D printed probe and box
- 5 screw tops
- 1 medium weight
- 1 large weight
- Scale (g)
- Thin sharpie
- Silicone molds (10, 20, 30, & 50)
- Tape
- Recording notebook
- Ruler

Procedures:

1. Before starting testing, the mass of each screw top, medium and large weight, and the probe itself was taken and each mass recorded in the data spreadsheet. Screw tops were then labeled to differentiate them by mass for consistency.
2. Silicone mold of choice (10, 20, 30, or 50) was then placed underneath the circular opening in the 3D printed box.
3. Clear tape was wrapped tightly around the 3D printed probe.
4. Probe was placed inside the circular opening so that its tip is resting upon the silicone mold.
5. A thin Sharpie was placed level to the top of the box and a line was drawn onto the tape on the probe. This line represents the "before weight added" starting point.
6. Screw top 1 was placed on the probe, the Sharpie was again held level to the top of the box, and another line was drawn on the tape covering the probe.
7. The probe was then removed from the box apparatus and the screw top was removed from the probe. The tape with Sharpie lines was taken off of the probe and placed in the lab notebook. The distance between these lines was taken with a ruler and recorded in the data spreadsheet.
8. This was repeated three times for screw top 1.
9. In between the change in weight, from just screw top 1 to both screw top 1 and 2, and every addition in weight after this, the silicone mold should be shifted slightly in the box apparatus so that the probe touches a new point on the surface of the mold.
10. The procedure for screw top 1 was repeated for each addition in weight until there were 5 screw tops. The procedure was also repeated for the medium and large weights which did not include the addition of a screw top.

# Appendix C

Trial Types for Participant Testing

| Protocol 1<br>Phase 1 | | |
|---|---|---|
| **Trial Type** | **First Sample** | **Second Sample** |
| E | 20-Silicone | 20-Silicone |
| I | 50-Silicone | 50-Silicone |
| A | 10-Silicone | 10-Silicone |
| B | 10-Silicone | 20-Silicone |
| G | 50-Silicone | 10-Silicone |
| F | 20-Silicone | 50-Silicone |
| C | 10-Silicone | 50-Silicone |
| H | 50-Silicone | 20-Silicone |
| D | 20-Silicone | 10-Silicone |
| I | 50-Silicone | 50-Silicone |
| H | 50-Silicone | 20-Silicone |
| C | 10-Silicone | 50-Silicone |
| G | 50-Silicone | 10-Silicone |
| F | 20-Silicone | 50-Silicone |
| B | 10-Silicone | 20-Silicone |
| A | 10-Silicone | 10-Silicone |
| D | 20-Silicone | 10-Silicone |
| E | 20-Silicone | 20-Silicone |
| F | 20-Silicone | 50-Silicone |
| I | 50-Silicone | 50-Silicone |
| A | 10-Silicone | 10-Silicone |
| H | 50-Silicone | 20-Silicone |
| G | 50-Silicone | 10-Silicone |
| D | 20-Silicone | 10-Silicone |
| B | 10-Silicone | 20-Silicone |
| E | 20-Silicone | 20-Silicone |
| C | 10-Silicone | 50-Silicone |

| Phase 2 | | | |
|---|---|---|---|
| **Trial Type** | **First Sample** | **Second Sample** | **Third Sample** |
| F | 50-Silicone | 20-Silicone | 10-Silicone |
| C | 20-Silicone | 10-Silicone | 50-Silicone |
| A | 10-Silicone | 20-Silicone | 50-Silicone |
| D | 20-Silicone | 50-Silicone | 10-Silicone |
| E | 50-Silicone | 10-Silicone | 20-Silicone |
| B | 10-Silicone | 50-Silicone | 20-Silicone |

| Protocol 2<br>Phase 1 | | |
|---|---|---|
| **Trial Type** | **First Sample** | **Second Sample** |
| F | 20-Silicone | 50-Silicone |
| I | 50-Silicone | 50-Silicone |
| A | 10-Silicone | 10-Silicone |
| H | 50-Silicone | 20-Silicone |
| G | 50-Silicone | 10-Silicone |
| D | 20-Silicone | 10-Silicone |
| B | 10-Silicone | 20-Silicone |
| E | 20-Silicone | 20-Silicone |
| C | 10-Silicone | 50-Silicone |
| I | 50-Silicone | 50-Silicone |
| H | 50-Silicone | 20-Silicone |
| C | 10-Silicone | 50-Silicone |
| G | 50-Silicone | 10-Silicone |
| F | 20-Silicone | 50-Silicone |
| B | 10-Silicone | 20-Silicone |
| A | 10-Silicone | 10-Silicone |
| D | 20-Silicone | 10-Silicone |
| E | 20-Silicone | 20-Silicone |
| E | 20-Silicone | 20-Silicone |
| I | 50-Silicone | 50-Silicone |
| A | 10-Silicone | 10-Silicone |
| B | 10-Silicone | 20-Silicone |
| G | 50-Silicone | 10-Silicone |
| F | 20-Silicone | 50-Silicone |
| C | 10-Silicone | 50-Silicone |
| H | 50-Silicone | 20-Silicone |
| D | 20-Silicone | 10-Silicone |

| Phase 2 | | | |
|---|---|---|---|
| **Trial Type** | **First Sample** | **Second Sample** | **Third Sample** |
| F | 50-Silicone | 20-Silicone | 10-Silicone |
| A | 10-Silicone | 20-Silicone | 50-Silicone |
| E | 50-Silicone | 10-Silicone | 20-Silicone |
| B | 10-Silicone | 50-Silicone | 20-Silicone |
| C | 20-Silicone | 10-Silicone | 50-Silicone |
| D | 20-Silicone | 50-Silicone | 10-Silicone |

| Protocol 3<br>Phase 1 | | |
|---|---|---|
| **Trial Type** | **First Sample** | **Second Sample** |
| E | 20-Silicone | 20-Silicone |
| I | 50-Silicone | 50-Silicone |
| A | 10-Silicone | 10-Silicone |
| B | 10-Silicone | 20-Silicone |
| G | 50-Silicone | 10-Silicone |
| F | 20-Silicone | 50-Silicone |
| C | 10-Silicone | 50-Silicone |
| H | 50-Silicone | 20-Silicone |
| D | 20-Silicone | 10-Silicone |
| F | 20-Silicone | 50-Silicone |
| I | 50-Silicone | 50-Silicone |
| A | 10-Silicone | 10-Silicone |
| H | 50-Silicone | 20-Silicone |
| G | 50-Silicone | 10-Silicone |
| D | 20-Silicone | 10-Silicone |
| B | 10-Silicone | 20-Silicone |
| E | 20-Silicone | 20-Silicone |
| C | 10-Silicone | 50-Silicone |
| I | 50-Silicone | 50-Silicone |
| H | 50-Silicone | 20-Silicone |
| C | 10-Silicone | 50-Silicone |
| G | 50-Silicone | 10-Silicone |
| F | 20-Silicone | 50-Silicone |
| B | 10-Silicone | 20-Silicone |
| A | 10-Silicone | 10-Silicone |
| D | 20-Silicone | 10-Silicone |
| E | 20-Silicone | 20-Silicone |

| Phase 2 | | | |
|---|---|---|---|
| **Trial Type** | **First Sample** | **Second Sample** | **Third Sample** |
| B | 10-Silicone | 50-Silicone | 20-Silicone |
| E | 50-Silicone | 10-Silicone | 20-Silicone |
| D | 20-Silicone | 50-Silicone | 10-Silicone |
| C | 20-Silicone | 10-Silicone | 50-Silicone |
| A | 10-Silicone | 20-Silicone | 50-Silicone |
| F | 50-Silicone | 20-Silicone | 10-Silicone |

# Appendix D

Qualtrics Data Entry

**Participant Information: Filled out by researcher**

Subject ID

Protocol Number

- Protocol 1
- Protocol 2
- Protocol 3

Handedness

- Right handed
- Left handed
- Other

Hand Used

- Right
- Left

Hand length (bottom of hand to top of middle finger)

Hand width (base of thumb to base of pinky)

**Phase 1-Block 1**

(1.1.1) Which sample was firmer?

- ○ Sample A
- ○ Sample B
- ○ They had equal firmness

(1.1.2) Which sample was firmer?

- ○ Sample A
- ○ Sample B
- ○ They had equal firmness

(1.1.3) Which sample was firmer?

- ○ Sample A
- ○ Sample B
- ○ They had equal firmness

(1.1.4) Which sample was firmer?

- ○ Sample A
- ○ Sample B
- ○ They had equal firmness

(1.1.5) Which sample was firmer?

- ○ Sample A
- ○ Sample B
- ○ They had equal firmness

(1.1.6) Which sample was firmer?

- ○ Sample A
- ○ Sample B
- ○ They had equal firmness

(1.1.7) Which sample was firmer?

- ○ Sample A
- ○ Sample B
- ○ They had equal firmness

(1.1.8) Which sample was firmer?

- ○ Sample A
- ○ Sample B
- ○ They had equal firmness

(1.1.9) Which sample was firmer?

- ○ Sample A
- ○ Sample B
- ○ They had equal firmness

**Phase 1-Block 2**

(1.2.1) Which sample was firmer?

- ○ Sample A
- ○ Sample B
- ○ They had equal firmness

(1.2.2) Which sample was firmer?

- ○ Sample A
- ○ Sample B
- ○ They had equal firmness

(1.2.3) Which sample was firmer?

- ○ Sample A
- ○ Sample B
- ○ They had equal firmness

(1.2.4) Which sample was firmer?

- ○ Sample A
- ○ Sample B
- ○ They had equal firmness

(1.2.5) Which sample was firmer?

- ○ Sample A
- ○ Sample B
- ○ They had equal firmness

(1.2.6) Which sample was firmer?

- ○ Sample A
- ○ Sample B
- ○ They had equal firmness

(1.2.7) Which sample was firmer?

- ○ Sample A
- ○ Sample B
- ○ They had equal firmness

(1.2.8) Which sample was firmer?

- ○ Sample A
- ○ Sample B
- ○ They had equal firmness

(1.2.9) Which sample was firmer?

- ○ Sample A
- ○ Sample B
- ○ They had equal firmness

**Phase 1-Block 3**

(1.3.1) Which sample was firmer?

- ○ Sample A
- ○ Sample B
- ○ They had equal firmness

(1.3.2) Which sample was firmer?

- ○ Sample A
- ○ Sample B
- ○ They had equal firmness

(1.3.3) Which sample was firmer?

- ○ Sample A

- ○ Sample B
- ○ They had equal firmness

(1.3.4) Which sample was firmer?

- ○ Sample A
- ○ Sample B
- ○ They had equal firmness

(1.3.5) Which sample was firmer?

- ○ Sample A
- ○ Sample B
- ○ They had equal firmness

(1.3.6) Which sample was firmer?

- ○ Sample A
- ○ Sample B
- ○ They had equal firmness

(1.3.7) Which sample was firmer?

- ○ Sample A
- ○ Sample B
- ○ They had equal firmness

(1.3.8) Which sample was firmer?

- ○ Sample A
- ○ Sample B
- ○ They had equal firmness

(1.3.9) Which sample was firmer?

- ○ Sample A
- ○ Sample B
- ○ They had equal firmness

**Phase 2**

(2.1.1) Rank the samples from softest to firmest

Sample A

Sample B

Sample C

(2.1.2) Rank the samples from softest to firmest

Sample A

Sample B

Sample C

(2.1.3) Rank the samples from softest to firmest

Sample A

Sample B

Sample C

(2.1.4) Rank the samples from softest to firmest

Sample A

Sample B

Sample C

(2.1.5) Rank the samples from softest to firmest

Sample A

Sample B

Sample C

(2.1.6) Rank the samples from softest to firmest

Sample A

Sample B

Sample C

**Follow up: Filled out by participant**

Thank you so much for participating in our study. People like you are what makes this research possible. Please answer the questions below about ease of use of our product.

| | Not at all | Not very | Fairly | Very |
|---|---|---|---|---|

| | confident | confident | Neutral | confident | confident |
|---|---|---|---|---|---|
| How confident were you in your rankings throughout this study? | ○ | ○ | ○ | ○ | ○ |

| | Not at all comfortable | Not very comfortable | Neutral | Fairly comfortable | Very comfortable |
|---|---|---|---|---|---|
| How comfortable was this device to wear? | ○ | ○ | ○ | ○ | ○ |

| | Very difficult to use | Fairly difficult to use | Neutral | Fairly easy to use | Very easy to use |
|---|---|---|---|---|---|
| How easy was this device to use? | ○ | ○ | ○ | ○ | ○ |

Have you ever used a similar haptic feedback mechanism and/or robotic surgical system?

○ No

○ Yes, please elaborate

Any additional feedback for us?

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