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PRESSURE SENSING DURING CAST APPLICATION FOR A DISTAL RADIUS FRACTURE

BME 200/300 Design, Fall 2015

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Abstract

Although casting is often viewed as a benign treatment, complications are known to arise in proper placement of these devices. Trial and error is the typical method for medical students and residents learning casting techniques and often direct oversight is lacking. In this work, a system was designed featuring a sleek pressure sensing sleeve to measure the location and magnitude of force applied during cast application to a fracture model arm in combination with a virtual 3D model of the arm to display the information. With this system, medical students will be able to observe how their applied forces affect the setting of a fracture and make appropriate adjustments according to real-time feedback.

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1 Introduction

1.1 Motivation

Because distal radius fractures are common, it is important for medical students to learn proper casting techniques for this frequent treatment. Currently medical students are learning how to cast by observing professionals and practicing trial and error procedures. It is important that casts be applied with uniform pressure to immobilize the fracture, but not too much so that the cast becomes too tight leading to complications. The judgement of this distinction comes with experience, rather than being quantifiable. In addition, no data exists which quantifies the amount of force needed to properly set a bone. Instead this is also done using tactile sensation and practice. Medical students may be unfamiliar with the appropriate amount of pressure to apply when they first begin casting and could benefit greatly from a teaching tool. Ideally this tool would be a pressure sensing sleeve worn over an upper extremity fracture model. The student would be able to practice the entire reduction and casting procedure while the sleeve senses the pressure being applied to it. The information collected by the sleeve device would be displayed with a three-dimensional sensor map onto a computer-aided design (CAD) model of the model arm, giving the student real-time visual feedback. This would allow for technique adjustments to be made as needed.

1.2 Current Methods and Existing Devices

The Colles Fracture Reduction and Casting Technique Trainer by Sawbones allows users to practice traditional roll on casting and removal techniques. Users practice manual reduction with similar forces as are required with a live patient [3]. This tool includes a universal bed rail clamp for users to practice in space and at an angle realistic to treating a patient [3]. This model requires fluoroscopic visualization in order to check the alignment of the break, determined by how well internal pins line up [3]. While this model looks and feels like a real arm with a distal radius fracture, it does not function as any kind of pressure sensor nor does it give the user visualization of where and how much pressure they are applying.

1.2.1 Previous BME Design Course Work

Multiple Biomedical Engineering design teams have worked on this project over the the last few year. Before the Colles Fracture Reduction and Casting Technique Trainer was on the market, teams worked towards creating a model that encompassed modeling the fracture, monitoring alignment, measuring applied pressure, and gathering skin temperature data [15]. The 2013 team built a Platsil arm model with a PVC based mechanical structure, and used a Tekscan pressure mapping system [15]. This team’s work had a semi-realistic feel but their pressure mapping system was very expensive, not user friendly, and displayed as a model of a foot. The 2014 team also built a Platsil arm model but their mechanical structure was based on a wooden dowel [16].

Their pressure sensors were contained within a sleeve, but they were bumpy and did not feel like a realistic arm [16]. They also did not include any form of visual feedback but instead logged pressure data throughout the process and then analyzed it once the process was complete.

1.3 Problem Statement

Bone fractures are one of the most commonly occurring injuries in the United States [18], yet fewer and fewer physicians are being adequately trained in casting procedures [14]. Current teaching methods for medical students are heavily focused on trial and error. Often direct oversight is lacking in the teaching of these techniques. A pre-existing professional distal radius fracture model, the Colles Fracture Reduction and Casting Technique Trainer, allows students to practice the tactile sensation of manual reduction and check success of alignment using fluoroscopic visualization [3]. However, this model lacks applied pressure sensing and mapping capabilities. A device is needed to sense the pressure applied in specific areas of concern and provide immediate feedback to the user via a visual interface.

2 Background

Distal radius fractures are one of the most common types of fractures and are predominantly associated with children and elderly persons. These breaks occur in the wrist approximately 2.54 cm from the distal end of the bone and can develop in various ways and levels of severity. Fractures account for 3.4% of annual emergency department visits [18] and are usually due to falling onto an extended arm [1]. In elderly patients this fracture accounts for 18% of breaks and is common in those suffering from osteoporosis, a condition which causes bones to become brittle [2]. Distal radius fractures are commonly treated by applying casts, a noninvasive procedure in which the limb is immobilized. Casting requires realigning the bone fragments in the wrist and wrapping the arm with layers of stockinet, webril, and plaster or fiberglass to provide external stability of the arm for proper healing[2].

2.1 Physiology

Although casting is a basic medical practice, complications can arise during the procedure and care must be taken to assure that the cast is applied properly. Significant casting complications are uncommon but can be very severe [20]. Improper cast application can lead to an array of further medical conditions such as abrasions, compartment syndrome, severe skin infections, and malunion [6]. Compartment syndrome is a very severe condition caused by a combination of swelling of damaged tissue and tight casts which leads to built up pressure, a lack of blood flow, and permanent damage to muscles and nerves [6]. Very serious cases of compartment syndrome can lead to amputation of the affected limb [6]. Skin infections can arise due to skin abrasions from friction between the cast and the arm. Some of these are very severe and include necrotizing fasciitis and toxic shock syndrome, both of which can lead to permanent damage, and very rarely, death [7]. Another type of complication is malunion which occurs when the fracture has been improperly set during casting causing it to heal with a deformity in the bone [8].

2.2 Wearable Electronics

The field of electronic textiles (e-textiles) is an increasingly popular field for its capabilities of combining electronics with wearable devices. This approach is ideal for our project, due to the essential circuitry and fabric components.

One type of custom sensor functions by reporting different voltage values when resistance changes due to applied force. This is accomplished via layering of conductive and piezoresistive fabrics. The piezoresistive fabric decreases resistance when pressed, therefore decreasing the total resistance of the circuit and allowing greater total voltage out readings [22]. Conductive layers on either side of the resistive layer conduct current in and out of the sensor. It is important for the piezoresistive layer to extend over a larger surface area than the conductive layers in order to prevent the conductive layers from touching [22]. From there, current travels throughout the circuit along the conductive thread, where it feeds into an input device, such as a LilyPad Arduino.

2.3 Data Acquisition and Display

The initial data acquisition device we decided to use was a microcontroller in the form of a LilyPad Arduino. The LilyPad Arduino is designed to integrate with e-textiles via input and output pins that are sewn into the circuit with conductive thread [22]. It requires an FTDI breakout board and mini USB cable for coding and serial communication with the computer [22].

For immediate applied pressure feedback and visualization we decided to use LabVIEW. LabVIEW has a sensor mapping VI that can be used to view real-time data on a CAD model which can display an accurate image of our model arm. The display provides the student a precise visual on how applied pressure corresponds to specific regions of the arm.

The 3D CAD model was researched and attempted via three different programs. The first option we tried was through Rob Swader and the Wisconsin Institute for Discovery with the NextEngine Desktop 3D Scanner. This program would have required hours of precise scanning and integration of those scans into one image. Next the 3D motion capture system located in the Badger Athletic Performance Center was used with the help of Mikel Stiffler. With this program we collected many data points in space but we were unable to render the image in a program compatible with LabVIEW. In the end we decided on the 123D Catch IOS Application because of its versatility, user-friendly nature, and compatibility with LabVIEW.

2.4 Client Information

Dr. Matthew Halanski, MD is an orthopedic surgeon at the University of Wisconsin School of Medicine and Public Health. He specializes in pediatric surgery with interests in spinal and lower extremity deformities, as well as limiting patient morbidity by studying alternatives to invasive procedures.

2.5 Design Specifications

The main design components Dr. Halanski wanted us to focus on over the course of the semester were creating a removable pressure sensing device that monitors pressure during the casting process (especially at locations of 3 point molding) as well as visually displaying the pressure applied to the arm. Previous BME design groups have tackled this project but have been unable to effectively create a realistic arm model and display the data in a usable teaching manner. In past semesters, teams were not only asked to create a pressure sensing system but they were also asked to monitor alignment and temperature along with creating their own arm model. This semester Dr. Halanski wanted us to focus solely on monitoring pressure and he provided us with a model arm that our device was to be fitted to. It was also noted that finding exact pressure values was not as important as seeing changes in pressure. Our prototype is to function as a teaching model for medical students and should be durable and able to be reused through many iterations of the casting process. Please see the complete Product Design Specifications attached in the appendix.

3 Preliminary Designs

There were two major components of our preliminary design: sensors and attachment device. The sensor category would be how applied pressure data is collected. As these function independently, we made our deliberations for each component separately. Our final choices for each design category would then determine the method for attaching and integrating the two components.

3.1 Sensors

Three different sensors fulfilled the main requirements of the design: FlexiForce sensors, Softpot Membrane Potentiometers, and custom sensors fabricated using conductive materials. In particular, the sensor options were thin, and had capabilities for appropriate pressure ranges. The device must be sleek and have limited protrusions in order to maintain the lifelike feel of the arm model, so the sensors we considered for our sleeve were relatively flat so as to be unobtrusive during for tactile sensation of bone reduction.

3.1.1 FlexiForce Sensor

The FlexiForce Sensor by TekScan (Figure 1) is a small, piezoresistive sensor which is able to accurately read point loads up to 445N. The sensor does not change resistance when flexed. This is an ideal feature for sensors which will be bent around an irregular surface such as the Colles fracture model. FlexiForce sensors have a standard sensing area of 0.95 cm^2 with a thickness of 0.2 mm. There are varying lengths of attached leads from approximately 5 cm to 20 cm [4]. These sensors are commonly used for force feedback in physical therapy and CPR manikins, both of which have similar applications to the pressure sensing sleeve.

The drawbacks to this sensor include the small sensing area, as many would need to be applied to our model to cover a given sensing area.

Figure 1. FlexiForce Sensor. This image displays the small round sensing area of the FlexiForce Sensor with the attached flexible leads [4].

3.1.2 Softpot Membrane Potentiometer

The Softpot membrane potentiometer (Figure 4) has a large resistance range (100Ω-10000Ω) and sensing area (40.64 cm^2). It has a thickness of 0.5 mm so it would not interfere with the casting process [5]. The membrane potentiometer is manufactured with an adhesive backing which would allow the sensor to attach easily to the sleeve. This would also inhibit movement of the sensors during the casting procedures. However, the Softpot Potentiometer has a small sensing range and cannot accurately measure the large forces that are applied during reduction and casting.

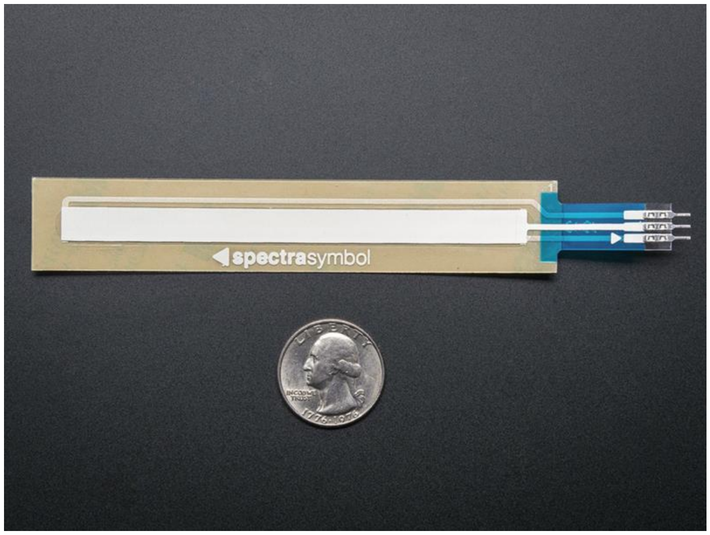


Figure 2. Softpot Membrane Potentiometer with quarter shown for size. The sensing area is the central, white strip which runs the entire length of the potentiometer [11].

3.1.3 Conductive Thread and Materials

Conductive, resistive, and insulating materials can be layered to construct custom sensors which are connected via conductive thread. Conductive thread comes in various resistances and has the capability to carry a current, meaning the thread could be used to sew a circuit directly onto the sleeve. This would eliminate typical wires from the design, leading to fewer protrusions and greater customizability (Figure 3). The sensors could be highly customizable, both in size and placement on the attachment device. The biggest challenge for this approach would be the fabrication skills required to design and fabricate our own circuitry. As the sensors are not professionally manufactured, each individual sensor would also have different characteristics and sensing ranges based upon the size, resistance, and bend at resting conformation.

Figure 3. Conductive thread sewn into material and connected to wires using a zigzag stitch [10].

3.2 Attachment Devices

Method of attachment is also an important design consideration since the sensors must be securely affixed to the arm to accurately measure the applied pressure; however, attaching the sensors directly to arm itself would permanently alter the arm model. This necessitates the existence of a barrier between the sensing layer and arm surface. Two types of design alternatives emerged: pre-existing, professional compression sleeves (Figure 4) and homemade sleeves (Figure 5).

3.2.1 Professional Compression Sleeve

A pre-made sleeve would be ideal for its professional patterning and fabrication. Assuming the dimensions of the Sawbones arm model are compatible with standard sizing, the sleeve would conform exactly to the arm and require little alteration. This option is evidently more expensive. The pre-existing compression sleeve could be stretched over the arm and roll up or down for removal or application [12], however this would likely disturb the sensing layer. A possible solution would be to cut a seam along the side of the wrist into which velcro, a zipper, or fasteners could be sewn. With this additional seam, the sleeve would have a more adjustable fit and be easier to apply to and remove from the model arm. A variety of sleeve lengths are available; a glove which extends past the elbow would increase the anchorage of the fabric during the setting process [12].

Figure 4. Existing Edema Compression Glove. [12]

3.2.2 Homemade Sleeve

A custom sleeve patterned to the Sawbones model could also be fabricated. This would allow for more material options and may simplify the waterproofing process, depending on the inherent water resistance of the materials used. The custom sleeve would be specific to the Sawbones model dimensions. The circumference at the smallest point (wrist) is 19 cm and the circumference at the largest point (bicep) is 37.5 cm. A custom sleeve should have a minimum length of approximately 28 cm in order to cover the forearm (Figure 5). As before, the custom design could either be sewn as an intact sleeve or be fitted with a seam and fastening device to allow for easy removal and application.

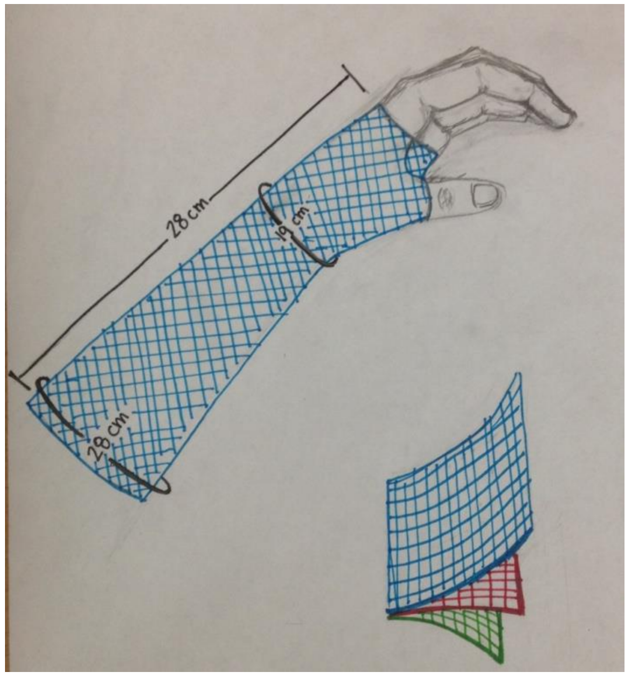


Figure 5. Sketch of Custom Compression Glove. The dimensions of the custom sleeve would be roughly 28 cm long, with a circumference of 19 cm at the wrist and 28 cm at the end of the forearm. The blue, outer layer would be protective; the middle, red layer would be the sensing layer, and the green layer the sleeve.

4 Preliminary Design Evaluation

As sensors and attachment methods are separately functioning components of the design to be considered independently and then integrated, the team created two design matrices. There are specific categories for each matrix, in accordance with the component being evaluated.

4.1 Design Matrices

Pressure Sensors	Flexiforce 	conductive thread 	SoftPot Membrane Potentiometer 
Feel (25)	(5/5) 25	(4/5) 20	(5/5) 25
Feasibility (20)	(4/5) 16	(3/5) 12	(4/5) 16
Sensitivity (15)	(5/5) 15	(5/5) 15	(4/5) 10
Durability (10)	(4/5) 8	(4/5) 8	(4/5) 8

Safety (10)	(5/5) 10	(4/5) 8	(5/5) 10
Fit (10)	(4/5) 8	(5/5) 10	(3/5) 6
Accuracy (5)	(5/5) 5	(3/5) 3	(4/5) 4
Cost (5)	(3/5) 3	(5/5) 5	(4/5) 4
Total: 100	90/100	81/100	83/100

Table 1. Pressure Sensor Design Matrix.

Feel is the most significant category since the sleeve should not alter the realistic feeling of the arm. The FlexiForce sensors and the SoftPot Potentiometers won out in this category because both sensors are are very thin and flexible. These qualities would provide a smooth feel without intruding on the motions involved in casting. The conductive thread originally did not score well because we believed that the sensors would be too thick due to the multiple layers of neoprene. However, after further research we discovered that 0.5mm neoprene was available. We found that the thread and neoprene had a more realistic feel.

Feasibility is also an important factor because we have to work based on the tools that are available to us and that do not require advanced training outside of the team's skill sets. The FlexiForce sensors and the SoftPot Potentiometers were the top scorers in the feasibility category because they came already fabricated and did not require much extra work to incorporate them into the design. The only issue with these sensors is that we would have a very difficult time attaching them to the sleeve. The SoftPot sensors come with an adhesive backing which would allow for easier attachment but it would be difficult to come up with a way to ensure that they stayed on the sleeve. The FlexiForce sensors came with no adhesive backing so they would be especially difficult to attach to the arm. The conductive thread sensors are very difficult to fabricate because it involves a large amount of sewing which none of us are very proficient in. Also, we would have to fabricate our own sensors rather than using pre-made ones.

Sensitivity relates to the sensor's ability to notice changes in force applied to it. If the sensor does not pick up on the pressure applied to it, there will be no feedback. The FlexiForce sensors and the conductive thread scored the highest in this category because the FlexiForce can sense up to 445 N [4] and the conductive thread sensors are very customizable to a wide range of forces. The SoftPot Potentiometers have a small sensing range that would not be suitable for the casting procedures [5].

Since the device will be put through the casting process numerous times, it must be durable and able to withstand moisture and repeated compressive forces. All of the proposed sensors are flexible which will allow them to withstand the forces present in the casting procedures.

Safety is an important aspect of every design. In this design we want to make sure all electrical components are contained and do not pose a threat to the user. The SoftPot and the Flexiforce are both factory fabricated sensors that have been designed to prevent short circuits. However, the conductive thread will short circuit if it touches any other conductive thread or fabric. If the threads touch they could potentially start a fire or shock the user. This is why the conductive thread sensor is ranked below the SoftPot and FlexiForce sensors.

Fit is another category that must be considered. The sensors will be fixated to the arm and compressed during casting, so they need to be able to move with the arm and not wrinkle when bent. While the FlexiForce and SoftPot sensors are both flexible, the conductive thread is much more so. The thread has the capability to be sewn directly to the sleeve providing maximum fit to the arm.

Accuracy is not extremely important because the client is more concerned with measuring the changes in force rather than the absolute values. The FlexiForce sensors won in this category because they have the largest range of resistance and could detect very small changes in force allowing for the most accurate force readings. The SoftPot sensors scored lower because they had a smaller resistance range. Finally the conductive thread was scored the lowest because it would be the most difficult to interpret actual readings from the sensors.

Cost must also be accounted for but is not a primary issue for this project as all of the sensors are relatively inexpensive and we have been given a $1,000 budget. The conductive thread was the cheapest option at $2.95 for 9.144 m of thread.
Overall the FlexiForce sensors scored the highest, however, we decided to go with the conductive thread. After further research into the conductive thread, we discovered that this would be the best option for our project because it is the most customizable and would provide the best results.

Method of attachment	Compression Sleeve- Intact	Compression Sleeve- Velcro	Custom Sleeve- Complete Glove	Custom Sleeve- Velcro
Functionality (25)	(2/5) 10	(4/5) 20	(3/5) 15	(4/5) 20
Bulkiness (20)	(5/5) 20	(4/5) 16	(4/5) 16	(4/5) 16
Removability (20)	(3/5) 12	(5/5) 20	(3/5) 12	(5/5) 20
Feasibility (15)	(5/5) 15	(4/5) 12	(2/5) 6	(3/5) 9
Durability (10)	(4/5) 8	(4/5) 8	(3/5) 6	(3/5) 6
Safety (5)	(5/5) 5	(5/5) 5	(5/5) 5	(5/5) 5
Cost (5)	(5/5) 5	(5/5) 5	(4/5) 4	(4/5) 4

Aesthetics (5)	(5/5) 5	(5/5) 5	(4/5) 4	(4/5) 4
Total: 100	80/100	91/100	68/100	84/100

Table 2. Attachment Device Design Matrix.

An attachment device should be functional, according to our design specifications. The main purpose of the sleeve is to affix the sensing element to the model and allow it to function. If the device did perform well in this category, it should not be chosen as our device. Thus the intact professional sleeve scored the lowest due to its anticipated extreme tightness to the arm, leading to difficulties sewing on our sensing layer and to likely disturbances during removal of the sleeve. The custom intact glove also scored low for this reason, but would be slightly more adjustable due to patterning specific to our model. Each of the modified options, both professional and custom, should be similar in their functionality as they are easily accessible for integration with the sensors.

Bulkiness was key for the attachment device, similar to the the importance of feel for the sensing component. A pre-existing compression sleeve would be most sleek in design, due to the professional patterning and thus scored the highest. A modified professional sleeve would be slightly less tight to the arm due to the bulkiness of the velcro. The custom sleeve options would not be professionally patterned and would likely be more ill-fitting than the pre-existing option.

For the attachment device component of our design, removability is an essential feature. Our device cannot be permanently affixed to the arm model in order to allow standard use of the model. Both an intact professional compression sleeve and an intact custom sleeve received the lowest scores as they would need to be rolled or tugged on and off the model. In addition to being difficult due to the rubber skin surface of the model arm, this would likely disturb the sensing layer attached to the sleeve layer. The modified professional compression sleeve and modified custom sleeve both scored well because the additional seam and velcro could be outfitted with an additional seam and velcro along the side which would greatly increase removability.

The professional compression sleeve is the most feasible option, as it would be purchased and arrive in the state we needed. A modified professional sleeve is also quite feasible because the seam can be easily cut and the velcro added with minimal sewing expertise. Between the two custom patterned options, the velcro-modified version is the most feasible as adjustments to the pattern and fit would be possible without a complete remake. The intact, custom sleeve would need to be fabricated from scratch and then significantly cut and resewn if the pattern needed adjustments.

Durability of attachment device was important for our overall sleeve unit to stand up to multiple iterations of the reduction and casting procedure. Professionally manufactured sleeves would be most secure due to their established fabrication procedures and professional stitching. Especially if sewn improperly, there is a risk the custom sleeves could wear out out with time.

While safety is always a key component of any design evaluation, we had no concerns related to this category for any of our design options. Therefore, each attachment received a perfect score.

Cost is not a very important category because all of our options are relatively inexpensive and we were given a large budget. The manufactured compression gloves would be cheaper than purchasing fabric and fabricating our own sleeve.

Our project should be aesthetically pleasing, but this is not as important as how well it functions. The pre-made compression gloves would look the nicest because it would be professionally fabricated whereas the custom sleeves would have to be sewn. No member of the team is proficient with a sewing machine which would have made fabrication of a custom sleeve very difficult. If we had sown the sleeve by hand, the final product would have had flaws and would not have been as pleasing to the eye.

Overall, the Compression Sleeve with Velcro scored the highest. However, after analyzing more options, we modified the sleeve to include a zipper rather than velcro for increased removability and sleekness.

4.2 Proposed Final Design

Because the majority of our reservations with regards to the conductive materials approach stemmed from inexperience with the field of e-textiles, we conducted further research to evaluate the feasibility of this option. Additional sources indicated that fewer layers would be needed to complete a single sensor than we originally thought. The functional layers would consist of a central piezoresistive layer which decreases in resistance with applied force, covered on either side by a layer of conductive material to carry current. The outermost non-conductive layers would serve to protect the sensors.

To test these layers, the team fabricated several sample sensors to test the validity of this approach. When attached to a circuit with a light bulb and power source, pressure applied to the sensor caused an increase in bulb brightness as it should with decreasing resistance. The sensors functioned well using both insulated wire and conductive thread. The relative flatness of the fabric layers and sensitivity of our test sensors indicated that conductive materials approach was our best option for satisfying the design specifications.

Due to the complexity required for each individual sensor, as well the number of conductive thread lines required for each unit, the team narrowed the focus to three sensing regions most important for reduction and casting of a distal radius fracture. These regions included the lower forearm and back of the hand on the dorsal side of the forearm and the wrist just below the area of the break on the Sawbones model. To better accommodate these new sensing areas, increase increased security, and add professional aesthetic, the team used an invisible zipper to modify the edema glove. Using conductive thread lines sewn into the edema glove, 12 custom fabric sensors, and a microcontroller optimized for use with e-textiles, the Arduino LilyPad, the entire circuit would be able to be mounted directly onto the arm model. From there the data would be displayed using the LabVIEW Sensor Mapping Express VI.

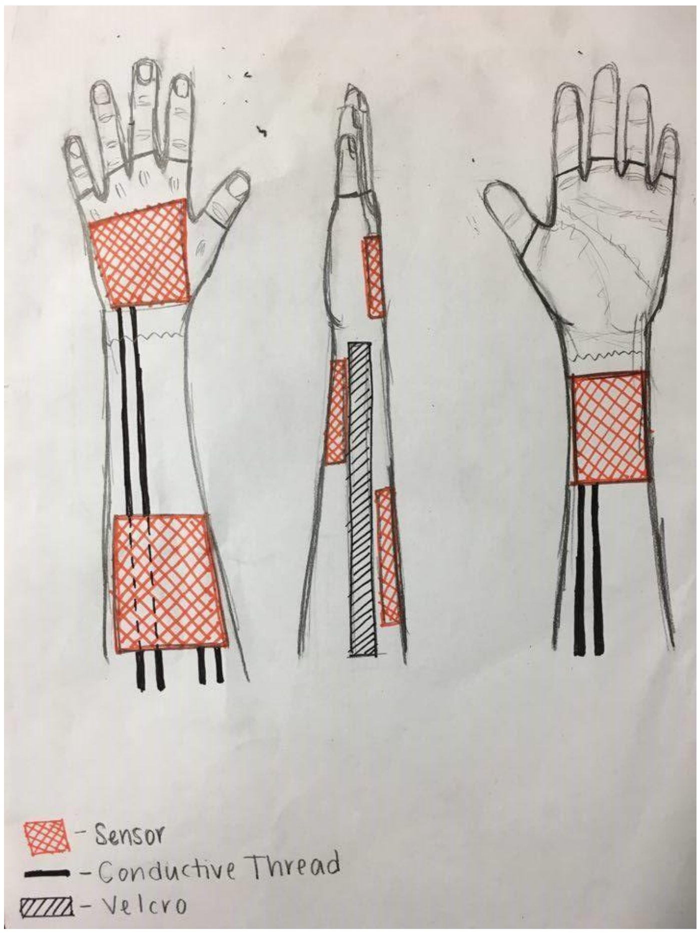


Figure 7. Sketch of preliminary prototype including updated sensing areas, a velcro seam, and conductive thread lines to and from each sensing area.

5 Fabrication and Development Process

5.1 Materials

The base of the pressure-sensing sleeve is a shoulder length compression glove made of lycra and spandex material. The glove is professionally fabricated and used to control edema; the level of compression as well as the size and length made it an appropriate fit for the model arm used by the client.

Functional sensors were affixed to the sleeve and featured layers of conductive, piezoresistive, and nonconductive materials. Ripstop is a highly conductive knit fabric with a surface resistivity of <0.02 ohm/sq. This material was chosen because it is easily sewn and is commonly used in e-textiles. Velostat is a piezoresistive material; it varies in resistance based on its mechanical strain. For example, applying force to the material causes resistance to decrease. It has a volume resistivity of <500 ohm-cm and a surface resistivity of <31,000 ohm/sq.cm. Neoprene was used as a non-conductive material. As a synthetic rubber it is a reliable insulator and has the additional benefit of being water resistant. The thickness of the neoprene used was 0.5mm in order to keep the depth of the sleeve as small as possible.

Using standard wires to power and read data from the sensors would have resulted in a bulky, cumbersome final product. Instead, conductive thread was sewn directly into the sleeve. This particular type is spun from stainless steel fiber and, unlike typical thread, does not have a nylon core. This means, although difficult, it is possible to solder as needed. This thread is also particularly “toothy” meaning it grabs to fabric easily and is, therefore, easy to work with.

Please see complete list of materials and budget attached in Appendix A.

5.2 Methods

5.2.1 Sewing

We began the process of fabrication by mapping out the locations of the sensors onto the sleeve and drawing a line pattern for the paths of the conductive thread. The zipper was then sewn into the sleeve and we attached the sensors by hand sewing them into their mapped locations.

For the sewing of the conductive thread lines and the zipper we contacted Paige Goodings. She machine sewed the threads using a specialized knit stitch that allowed for the conductive thread to be sewn under the edema glove and the sensors. This stitch prevented potential short circuits by blocking the conductive thread from touching other threads and from coming into contact with the conductive fabric of the other sensors.

Figure 8. Knit stitch off conductive thread on underside of edema glove

After the conductive threads and the zipper was sewn onto the arm, the sensors could then be sewn onto the sleeve. The sensors had to be hand sewn onto the sleeve to ensure that the layers of fabric and Velostat remained in place. The hand sewing also protected the Velostat from being accidentally sewn through. This would have changed the resistance values measured across the sensor because the thread would have applied a force that would have skewed our results. The sensors were fabricated by sewing one layer of conductive fabric directly onto the edema glove and another layer onto the piece of neoprene. Velostat was placed between these two pieces and the neoprene was hand stitched onto the edema glove. Finally, conductive thread from the machine sewed lines was sewn through the tabs of the conductive fabric and the neoprene creating a complete sensor.

5.2.2 3D CAD Model

In order to visually display data on the Sawbone model arm, an accurate 3D image of the model was required. To create our model, we used an iPhone app called 123D Catch. Pictures of the arm were taken at multiple angles in a 360° rotation in order to get a full image. The initial image (Figure 9) was then able to be cleaned up in a compatible program called Meshmixer (Figure 10).

Figure 9. 123D Catch Image

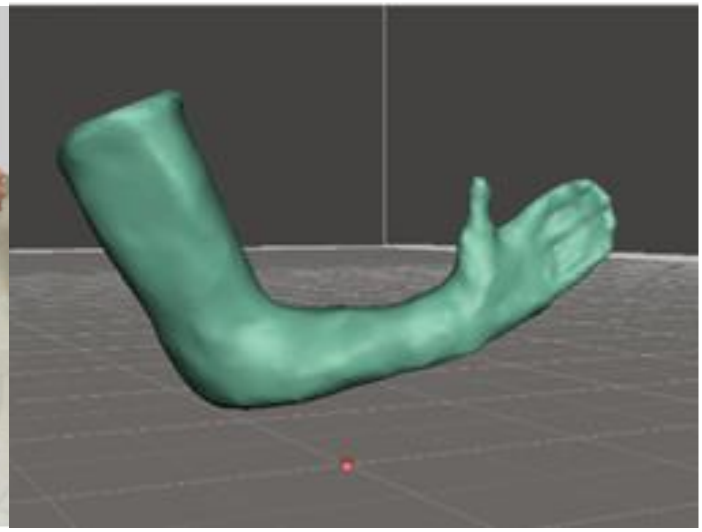


Figure 10. Refined version of model arm in Meshmixer

5.2.3 Circuitry and Programming

The circuit we created was based off of the circuit used by the Fall 2013 Fracture Model design group. It consists of resistors in series with the pressure sensor. The resistor is connected to ground, the pressure sensor is connected to the power source outputting 5V and voltage is read between the resistor and sensor. The basic setup for one sensor can be found in Figure 11. Because we have twelve pressure sensors, this set up was duplicated twelve times. The program we chose to display our data (voltages) sets a single base range for all of the sensors and because our sensors are custom, the base ranges vary for each sensor. To account for this, we chose resistors for each pressure sensor that would cause them all to have a resting voltage of roughly 2V.

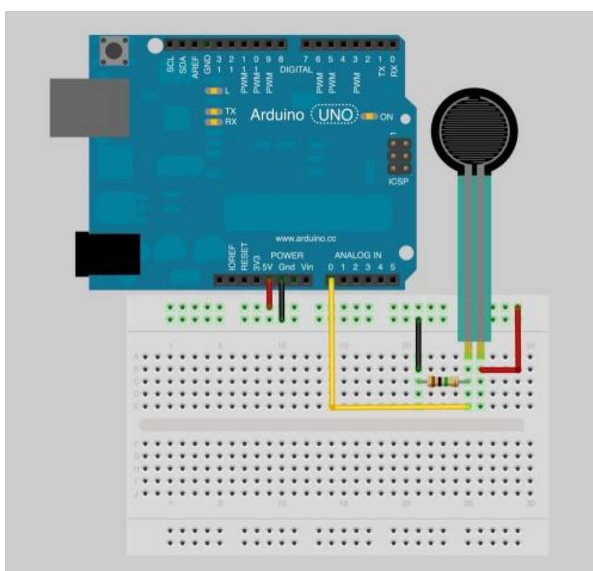


Figure 11. Basic Circuit Setup [19]

An Arduino MEGA 2560 was programmed to read output voltage between each of the twelve resistor/sensor pairs (Figure 12). We chose to use the MEGA because it has sixteen analog pins and we needed twelve analog pins to support the number of resistors in our design.

Figure 12. Arduino Mega. This image shows an Arduino Mega, the microprocessor used in this prototype. [17]

The Arduino code is able to communicate with another programming language, LabVIEW. LabVIEW is able to process and display data in real time. Our client stressed the importance of visually displaying pressure applied to the arm in certain locations. To address this, LabVIEW has a Sensor Mapping Express Virtual Instrument (VI) that can display real-world data on a 3D image [21]. The 3D CAD model of the Sawbones arm was able to be uploaded directly into the VI as a STL and then free sensors were placed on the image in accordance with the pressure sensor positions on the actual prototype (Figure 13).

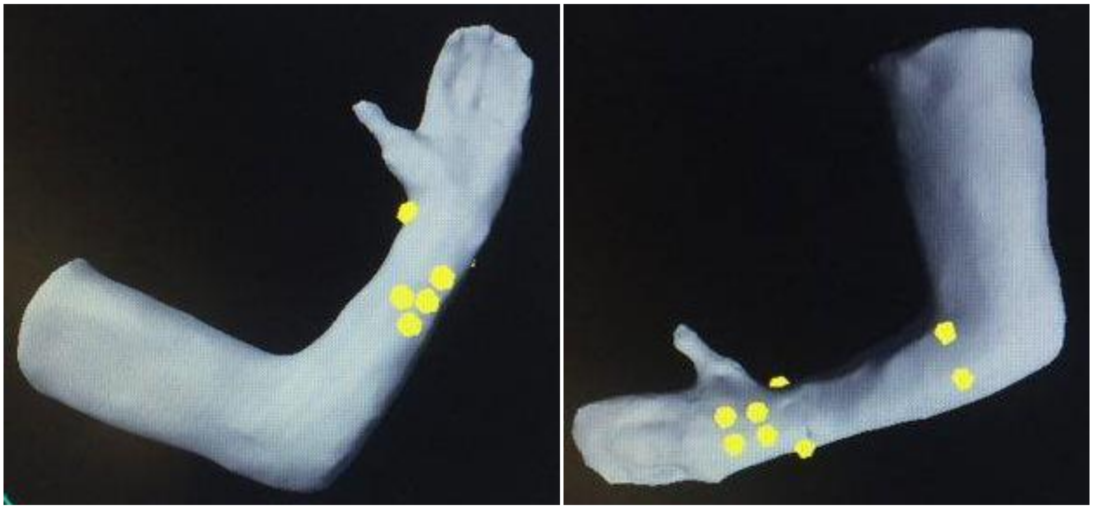


Figure 13. These images display the 3D Sawbone CAD model with pressure sensor locations.

When pressure is applied to the sensors on the prototype, the corresponding locations on the model arm change color based on the amount of voltage being read in which corresponds to force applied (Figure 13). To send the correct voltage readings to their assigned locations on the arm model, the voltage data from the Arduino was broken up into twelve parts and sent to an array. The array of data was then sent to the the Sensor Mapping Express VI and this process is repeated constantly, bringing in new voltage values each time.

5.3 Final Prototype

Figures 14, 15, and 16: These images show the final product at multiple angles in order to display all of the sensors and the interior conductive thread.

As shown in the final prototype images, the conductive thread lines are sewn to the very end of the glove, instead of leading directly to the microcontroller. Including the lines from each resistor to the analog pins, as well as the input and the output lines, three separate conductive lines would be needed per sensor. The team determined that this forced the addition of at least four barrier layers, two per each additional line: one actual barrier, one to be sewn into. As this is beyond our fabrication and time limitations for the current semester, we chose to use an external circuit box, with wires leading from the base of the model where the conductive thread lines end. The thread is converted to wire using double or triple mating pieces, depending on the mapping of the threads from sensors in a given area. Because of the switch the the Arduino Mega, which is not meant to be integrated with e-textiles, the addition of wire was already necessary in some length to convert from conductive thread to wire to be placed in the Mega pins.

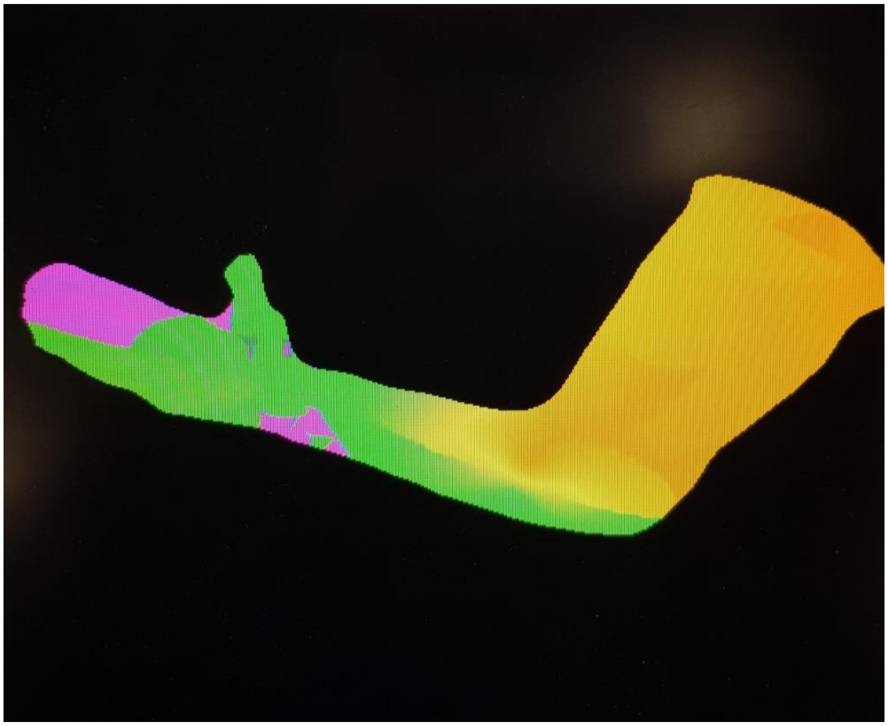


Figure 17. This figure shows how LabVIEW displays different colors in relation to pressure data assigned to specific areas of the arm.

5.4 Testing

5.4.1 Number of Velostat Layers Required per Sensor Size

The original fabrication plan for the sensors included sensors with only a single layer of Velostat which was found to be too sensitive to variations in pressure because they reached their maximum output voltage when applying very little pressure. To address this issue, we conducted testing on each of the three sensor sizes with various layerings of Velostat. Initially, we placed masses of 10, 100, 200, 500, and 1,000 grams in the center of a sensor comprised of a single layer of Velostat. Voltage output was read for each mass. We performed this test three times and averaged the data. After the first trial was completed, a second layer of Velostat was added to the sensor and the same test was conducted again. The small sensors were tested up to five layers of Velostat and the medium and large sensors were tested up to six layers.

5.4.2 Sensor Sensitivity to Bending

The sensors will be subjected to bending when they are sewn to the sleeve and when pressure is applied them. Because of this, it is important to make sure that the sensors will still have accurate readings when subjected to such motions. A bending test was performed to determine if multiple iterations of bending would have significant effect on sensor readings. A sensor with a single layer of Velostat was created and connected to a HP E3631A power supply outputting 2V.

An initial voltage reading was taken and then the sensor was bent twenty times and another reading was taken. The test consisted of twenty trials with bends in different directions each time, resulting in 400 total bends.

5.4.3 Location of Mass Applied to Sensor as Related to Voltage Output Readings

In theory, the sensors should read the same voltage at any point pressure is exerted on it. A certain mass applied to the upper left corner of the sensor should output the same voltage as that same mass applied to the lower left corner of the sensor. To test this theory, a 100 gram mass was placed at five different locations on a medium sized sensor (Figure 18). Ten voltage values were read at each location and readings were averaged. Testing was conducted with the sensor in series with a 22 ohm resistor powered by a LilyPad Arduino 328 Main Board outputting 5V.

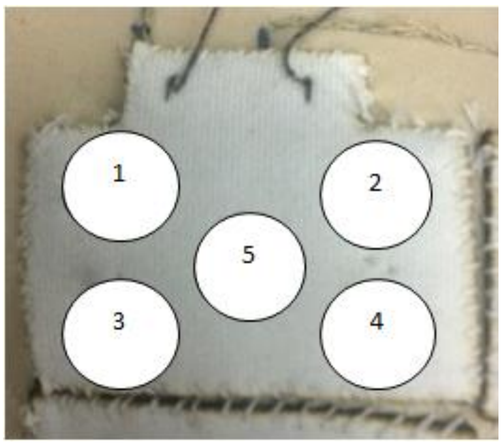


Figure 18. Locations of applied mass on a medium sized sensor

5.4.4 Sensor Calibration

Using masses of 10, 100, 200, 500, and 1000 grams, a calibration curve was created to determine the relationship between force and voltage of the sensors. Because masses over 1000 grams were not available, the upper limit of the curve was estimated by applying body weight to the sensor and recording this as the maximum voltage output. Mass in grams was converted to force in Newtons by utilizing the conversion factor of 1g:0.0098N.

6 Results

6.1 Number of Velostat Layers Required per Sensor Size

To organize the collected data, we used MATLAB to create bar graphs that relate the number of Velostat layers to the voltage output due to the specified masses (Figure 19).

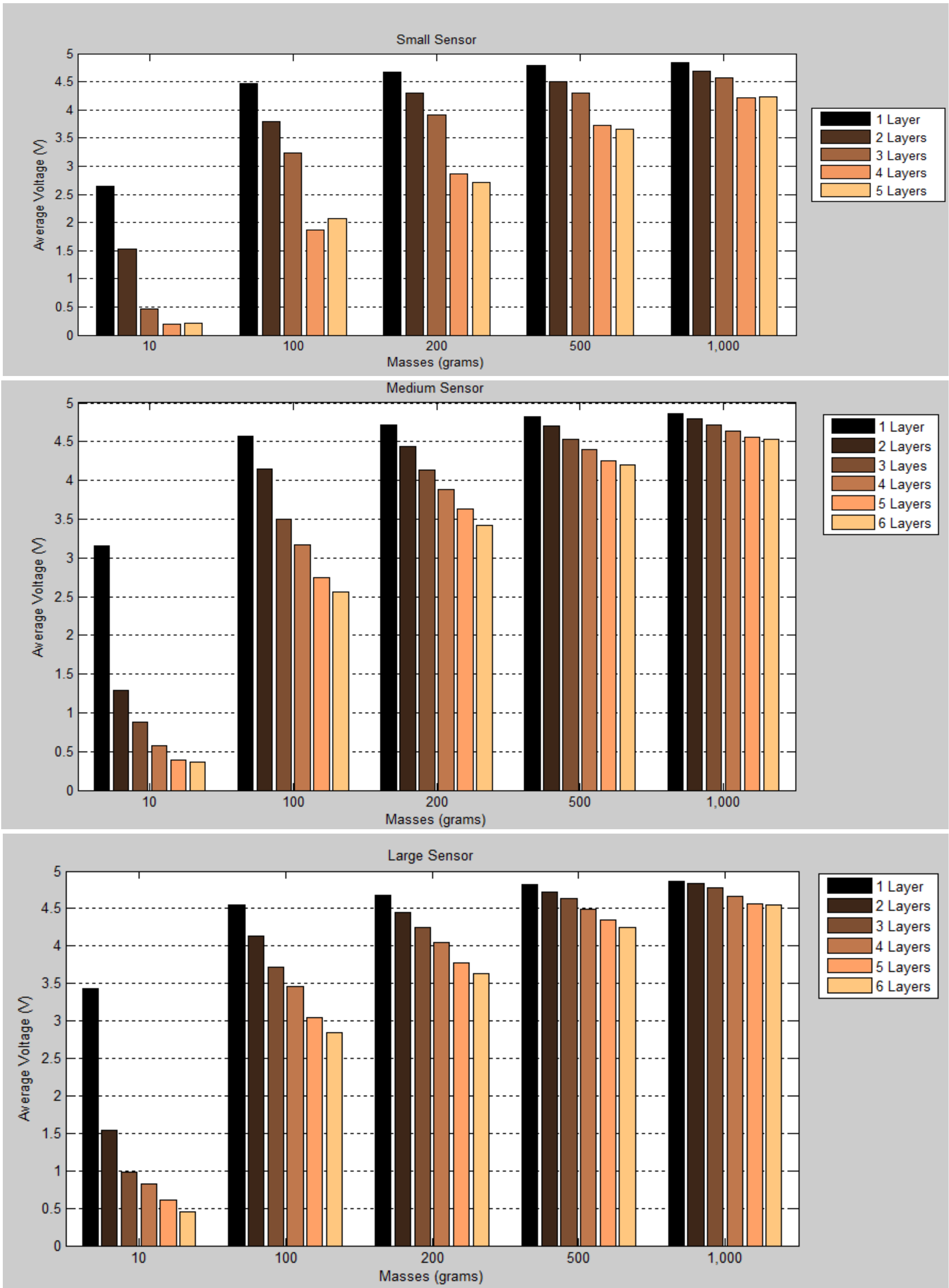


Figure 19. Effects of Differing Layers of Velostat on Voltage Reading. Voltages were measured using a LilyPad Arduino 328 Main Board and a circuit with a 1 kohm resistor in parallel with the pressure sensor.

All of the graphs share a common trend of decreasing in voltage when additional layers of Velostat are added to the sensors. The small sensor did not vary significantly between four and five layers of Velostat and the medium and large sensors did not vary much from five to six layers. Once the voltage values began to respond similarly to the masses it was concluded that there would be no more significant changes in how the layers would affect readings. The final sensor design consists of four layers of Velostat in the small sensors and six layers of Velostat in both the medium and large sensors.

6.2 Sensor Sensitivity to Bending

A one sample t-test of the voltage readings from the bending test was conducted in R. This test is suitable because our data is normal and we are concerned with the mean value. The null hypothesis states that there is no significant change in voltage after the sensor experiences bending. A 95% confidence interval was used with an alpha value of 0.05. The calculated p-value of the data was 0.4344 which is greater than the alpha value and leads to failing to reject the null. Because the null was not rejected, it can be concluded that the voltage readings do not differ significantly from 2V and that bending does not affect the readings of the sensors.

6.3 Location of Mass Applied to Sensor as Related to Voltage Output Readings

Data taken from each of the five locations on the sensor was averaged in MATLAB and converted into a scatter plot (Figure 20).

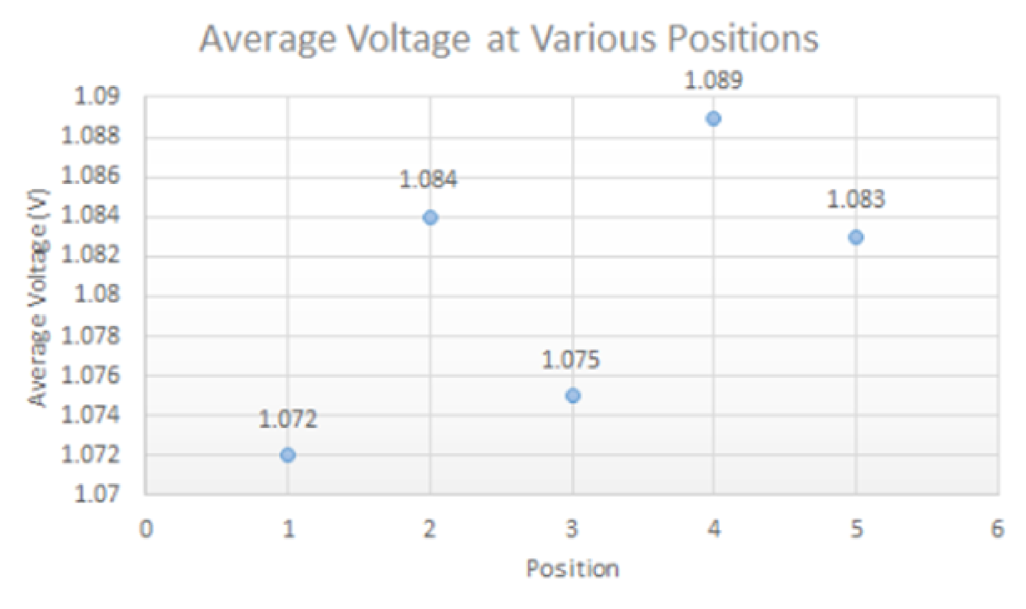
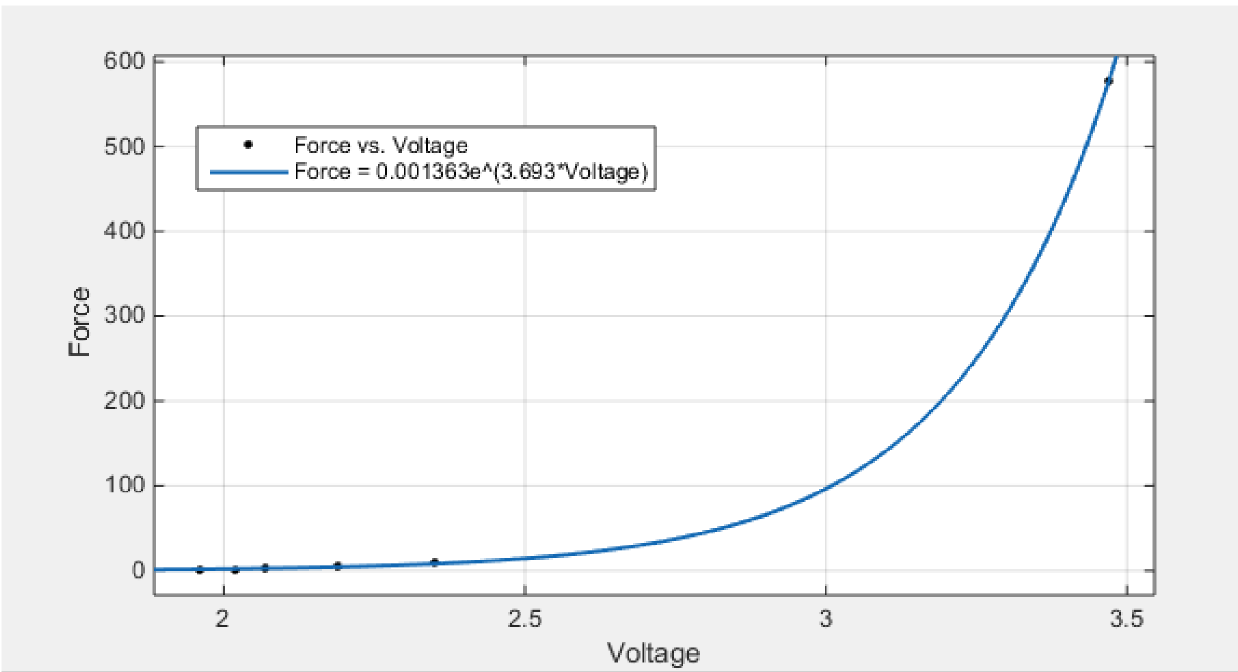


Figure 20. Voltages at differing locations on sensor. Graph compares the average voltage readings taken from each of the five location on a medium sized sensor subjected to 100 grams.

The highest voltage was recorded on the upper left section of the sensor and the lowest voltage was recorded in the lower right corner. The data has a range of .017V and a standard deviation of .007V. Since we are more concerned with voltage ranges when using the prototype we have concluded that the differences are not significant enough to hinder our data since they are within a tight range.

6.4 Sensor Calibration

To obtain a visual of the data, MATLAB was used to create a plot of force versus voltage (Figure 21).



The curve has an exponential fit with a maximum voltage output occurring at 3.47V. The relationship between force and voltage is described in Equation 1

$$Force = .001363e^{3.693*Voltage} \qquad \text{(Eqn. 1)}$$

Given Equation 1 we are able to determine how much force is put on the arm for a given voltage output (x)

7 Discussion

After finding that neither bending nor location of applied force significantly affects the resistance of the sensors, it is safe to conclude that this device can be used to quantify force ranges at which casting is done correctly. Using the voltage to force calibration curve, adjustments can be made to the visual feedback; the color ramp can be adjusted to reflect the established force application range. In addition to the immediate feedback, force should be recorded over time for future analysis.

8 Conclusion

Medical students learn to cast by trial and error and observing others. When too much pressure is applied during casting complications may arise. The final design provides visual feedback of the force applied to pressure sensors at locations of three point molding. The custom sensors that we created appear to be durable and yield consistent readings. One downfall of the design is that each sensor varies from the others and this causes different readings. If the sensors are shifted drastically on the arm, the readings of each sensor may vary due to different positioning. Ideally the sleeve is placed on the arm in the exact same position every time. To ensure this, simple markings should be placed on both the sleeve as well as the arm which align when the sensors are placed correctly.

8.1 Future Work

Our original design featured a microcontroller optimized for e-textile applications, but due to the capabilities of current commercial microcontrollers, specifically the limited number of analog pins on e-textile options, we switched to a higher level Arduino which could accommodate our needs. In the future, the microcontroller portion of the circuit would be selected or manufactured to only include with relevant analog, digital, and ground pins, while still maintaining compatibility with conductive thread and materials. Additional sensing components could also be incorporated into this prototype. Skin temperature sensing and bone alignment sensing would be very useful additions to this learning tool to expand upon the types of information necessary for proper casting. In the future it would be beneficial to have Dr. Halanski or another medical professional practice setting our model so that an accurate pressure sensing scale can be created.

9 Acknowledgements

We would like to recognize and thank all of the individuals who have helped and advised us throughout the semester. A special thanks to our client, Dr. Halanski, for giving us our design and working with us throughout the semester. We appreciated his enthusiasm and creative mind. We would like to thank Catherine Finedore for answering our questions about conductive thread and sharing some of her e-textile projects with us. We would also like to thank Paige Goodings for taking the time to sew the conductive thread lines and the zipper onto the sleeve. The team would also like to thank Sam Lines for helping us understand and work out our Arduino/LabVIEW communication. Dr. Yen and Dr. Nimunkar also helped clear up some questions we had about electronics and programming. Lastly, we thank Dr. Puccinelli for his guidance and for providing us with useful resources and suggestions.

10 References

(1) Nellans, K., Kowalski, E., & Chung, K. (2012). The Epidemiology of Distal Radius Fractures. *Hand Clinics*, 28(2), 113-125.
(2) AAOS (2013). Distal Radius Fractures (Broken Wrist). Retrieved from http://orthoinfo.aaos.org/topic.cfm?topic=a00412
(3) Sawbones (2013). Colles Fracture Reduction and Casting Technique Trainer. Retrieved from http://www.sawbones.com/Catalog/Skills%20Training/Fracture%20Reduction%20and%20Casting/1530#
(4) Tekscan (2015). Force Sensors. Retrieved from https://www.tekscan.com/product-group/embedded-sensing/force-sensors
(5) Spectra Symbol (2015). SoftPot Datasheets. Retrieved from http://www.spectrasymbol.com/potentiometer/softpot/softpot-datasheet
(6) Benjamin, C. (2014). Compartment Syndrome. D. Zieve (Ed.), *A.D.A.M. Medical Encyclopedia.*
(7) Delasobera, Elizabeth (2011). Serious Infectious Complications Related to Extremity Cast/Splint Placement in Children. Retrieved from http://www.medscape.com/viewarticle/746890_2
(8) Brown, Jennifer (2014). Cast Care. Retrieved from http://www.emedicinehealth.com/cast_care/page7_em.htm
(9) The Royal Children's Hospital Melbourne. Retrieved from http://www.rch.org.au/clinicalguide/guideline_index/fractures/Distal_radius_and_or_ulna_metaphyseal_fractures_Emergency_Department_setting/
(10) How to Get What You Want, Machine-sewable Hard/Soft Connections. Retrieved from http://www.kobakant.at/DIY/?p=1272
(11) Adafruit. Retrieved from http://www.adafruit.com/search?q=softpot&b=1
(12) Patterson Medical. Retrieved from http://www.pattersonmedical.com/app.aspx?cmd=get_subsections&id=57942
(13) National Instruments. Connect Sensor Data to 3D Models. Retrieved from http://www.ni.com/white-paper/7335/en/
(14) Halanski, M., Noonan, K. (2008) Cast and Splint Immobilization: Complications. *Journal of the American Academy of Orthopedic Surgeons,* 30-40.
(15) Moehling, T., Haug, L., Dunn, C., Schultz, M.(2014) Development of an Upper Extremity Fracture Model. BME Design.
(16) Maciolek, K., Marshall, H., Beene, K., Bautista, G. (2013) Development of an Upper Extremity Fracture Model. BME Design.
(17) Arduino (2015). Arduino Mega. Retrieved from https://www.arduino.cc/en/Main/arduinoBoardMega

(18) McCaig, L., & Burt, C. (2006). National Hospital Ambulatory Medical Care Survey. ICPSR Data Holdings.
(19) Dee, Jordan (2013). Flexiforce Pressure Sensor (25lbs) Quick Start Guide. Retrieved from https://www.sparkfun.com/tutorials/389
(20) Place, R., Delasobera, E., Howell, J., & Davis, J. (2011). Serious Infectious Complications Related to Extremity Cast/Splint Placement in Children. *Emergency Medicine, 41*(1), 47-50.
(21) National Instruments (2013). Mapping Data Using the Sensor Mapping Express VI. Retrieved from http://zone.ni.com/reference/en-XX/help/371361K-01/lvhowto/mapping_using_express_vi/
(22) LilyPad Arduino. LilyPad Arduino Main Board. Retrieved from http://lilypadarduino.org/?p=128

11 Appendix A

11.1 Materials List

Product	Quantity	Product #	Price	Type	Dimensions	Website
Ripstop Conductive Fabric	3 Sheets	10056	$11.95	N/A	12"x13"	https://www.sparkfun.com
Velostat Resistive Fabric	4 sheets	1361	$3.95	N/A	11"x11"	https://www.adafruit.com
Neoprene Fabric	7 sheets	NEOPRENE-L-0.5mm-White/White	$90.51	L Foam Neoprene	49"x89" (0.5 mm thickness)	http://www.rockywoods.com
LilyPad Arduino 328 Main Board	1	9266	$19.95	N/A	N/A	https://www.sparkfun.com/
Rolyan Shoulder Length Compression Glove	1	929323	$12.45	Large, Open Finger Glove, Left	10"	https://www.healthproductsforyou.com

LilyPad FTDI Basic Breakout - 5V	1	10275	$14.95	N/A	N/A	https://www.sparkfun.com/products/10275
SparkFun USB Mini-B Cable - 6'	1	11301	$3.95	N/A	6'	https://www.sparkfun.com
3-Pin Connector with Header	2	CON-243	$1.00	N/A	N/A	www.allelectronics.com
2-Pin Connector with Header	9	CON-232	$0.75	N/A	N/A	www.allelectronics.com
1K Ohm Resistor	12	291-1K	$0.07	N/A	N/A	www.allelectronics.com
Conductive Thread Bobbin - 30ft (Stainless Steel)	5	10867	$2.95	Stainless Steel	30’	https://www.sparkfun.com

12 Appendix B

12.1 Gantt Chart

	August	September				October				November					December	
Task	30	6	13	20	27	4	11	18	25	1	8	15	22	29	6	13
Project R&D																
Preliminary Research	X	X	X	X												
Brainstorming			X	X	X	X										
Choose Design						X	X									
Order Materials							X	X	X	X	X					
Fabrication																
Model Arm								X	X	X	X					
Sew Individual Sensors												X	X	X	X	
Attach Zipper to Sleeve														X		
Sew Sensors onto Sleeve														X	X	
Create Circuit											X	X				
Write Arduino Code									X	X	X	X				
LabView Programming											X	X	X	X	X	
Testing																
Circuit												X	X			
Sensor Testing										X	X	X	X	X		
Sensor Calibration															X	
LabView Sensing Ranges														X	X	
Product Revision													X	X	X	
Final Product															X	
Deliverables																
Progress Reports		X	X	X	X	X	X	X	X	X	X	X	X	X		
Preliminary Presentation				X	X											
Preliminary Deliverables					X	X										
Final Deliverables															X	
Poster															X	
Meetings																
Advisor	X	X	X	X	X	X	X	X	X	X		X		X		
Client		X	X	X				X				X				
Team	X	X	X	X	X	X	X	X	X	X	X	X		X	X	
Website																
Udpate	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
Colored Cells: Projected Timeline																
X: Completed Tasks																

13 Appendix C

13.1 Arduino Code

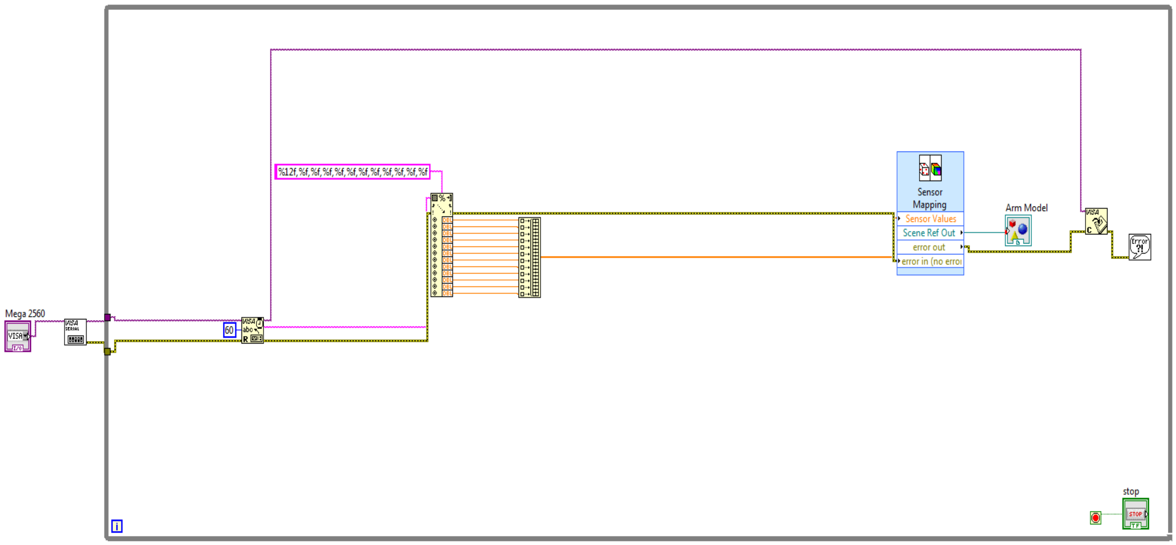
```
void setup() {
  // initialize serial communication at 9600 bits per second:
  Serial.begin(9600);
}
// the loop routine runs over and over again forever:
void loop() {
  // read the input on analog pin 0:
  int sensor1Value = analogRead(A0);
  // Convert the analog reading (which goes from 0 - 1023) to a voltage (0 - 5V):
  float voltage1 = sensor1Value * (5.0 / 1023);

  int sensor2Value = analogRead(A1);
  // Convert the analog reading (which goes from 0 - 1023) to a voltage (0 - 5V):
  float voltage2 = sensor2Value * (5.0 / 1023);
```

```
int sensor3Value = analogRead(A2);
// Convert the analog reading (which goes from 0 - 1023) to a voltage (0 - 5V):
float voltage3 = sensor3Value * (5.0 / 1023);

int sensor4Value = analogRead(A3);
// Convert the analog reading (which goes from 0 - 1023) to a voltage (0 - 5V):
float voltage4 = sensor4Value * (5.0 / 1023);

int sensor5Value = analogRead(A4);
// Convert the analog reading (which goes from 0 - 1023) to a voltage (0 - 5V):
float voltage5 = sensor5Value * (5.0 / 1023);
// print out the value you read:

int sensor6Value = analogRead(A5);
// Convert the analog reading (which goes from 0 - 1023) to a voltage (0 - 5V):
float voltage6 = sensor6Value * (5.0 / 1023);

int sensor7Value = analogRead(A6);
// Convert the analog reading (which goes from 0 - 1023) to a voltage (0 - 5V):
float voltage7 = sensor7Value * (5.0 / 1023);

int sensor8Value = analogRead(A7);
// Convert the analog reading (which goes from 0 - 1023) to a voltage (0 - 5V):
float voltage8 = sensor8Value * (5.0 / 1023);

int sensor9Value = analogRead(A8);
// Convert the analog reading (which goes from 0 - 1023) to a voltage (0 - 5V):
float voltage9 = sensor9Value * (5.0 / 1023);

int sensor10Value = analogRead(A9);
// Convert the analog reading (which goes from 0 - 1023) to a voltage (0 - 5V):
float voltage10 = sensor10Value * (5.0 / 1023);
// print out the value you read:

int sensor11Value = analogRead(A10);
// Convert the analog reading (which goes from 0 - 1023) to a voltage (0 - 5V):
float voltage11 = sensor11Value * (5.0 / 1023);
// print out the value you read:
```

```
  int sensor12Value = analogRead(A11);
  // Convert the analog reading (which goes from 0 - 1023) to a voltage (0 - 5V):
  float voltage12 = sensor12Value * (5.0 / 1023);

  Serial.println(voltage1);
  Serial.print(",");
  Serial.println(voltage2);
  Serial.print(",");
  Serial.print(voltage3);
  Serial.print(",");
  Serial.print(voltage4);
  Serial.print(",");
  Serial.print(voltage5);
  Serial.print(",");
  Serial.print(voltage6);
  Serial.print(",");
  Serial.print(voltage7);
  Serial.print(",");
  Serial.print(voltage8);
  Serial.print(",");
  Serial.print(voltage9);
  Serial.print(",");
  Serial.print(voltage10);
  Serial.print(",");
  Serial.print(voltage11);
  Serial.print(",");
  Serial.println(voltage12);
}
```

14 Appendix D

14.1 LabVIEW Code



15 Appendix E

15.1 PDS

Product Design Specifications - September 18, 2015

Title: *Pressure Monitoring During Cast Application for a Distal Radius Fracture*

Team: Hannah Lider - lider@wisc.edu (Leader)
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Alexandra Hadyka - hadyka@wisc.edu (BPAG)

Function: Casting is becoming a lost art in medicine, yet many children and adults need casts applied. While this appears to be a benign treatment, complications are known to exist in the placement and removal of these devices. Typically medical students and residents learn these techniques by trial and error. Often direct oversight is lacking in the teaching of these techniques. The client would like a supplement to an already existing fracture model arm that can aid medical students in learning how to appropriately apply casts for distal radius fractures. The device will sense pressure applied to specified areas of the arm/hand and give immediate feedback to the user via a visual interface.

Client Requirements:
Create an easily removable pressure monitoring device for a fracture model arm
Monitor pressure at specified locations
Visually display applied pressure

Design Requirements
1. Physical and Operational Characteristics
Performance Requirements: Pressure sensing device must be sufficiently affixed to the model arm such that sensors are not moving during the procedure. Display must then give immediate visual and quantitative feedback of applied pressure to specified areas on the hand, wrist, and forearm
Safety: The product must not harm the model arm or the user.
Accuracy and Reliability: Not a great amount of sensitivity is necessary on the lower threshold of pressure, but the device should be able to measure when an excessive and potentially dangerous amount of force is being applied (upwards of 700 N).
Operating Environment: Device will be used in a medical classroom setting as well as hospitals and will be subjected to a range of pressures. Should be able to withstand maximum human grip strength forces of up to 700 N and 25 kN/m of torque.
Ergonomics: Should mimic the feel of an actual arm
Size: The device must cover the model sawbone arm that has a circumference of 19 cm at the smallest point (the wrist) and a circumference of 37.5 cm at the largest point (the bicep). Its length should fall between 25.4 and 30.5 cm.
Materials: Device should use materials which will not be damaged by the plaster or fiberglass materials used in the casting process. Materials should be relatively flat to keep a realistic feel. Materials must not damage the arm model with regular use.
Aesthetics, Appearance, and Finish: Device should have a smooth feel and appearance with limited protrusions. Display of feedback should be visually descriptive and given on a laptop or tablet.

2. Production Characteristics
Quantity: One complete device is necessary for Dr. Halanski's purposes.
Target Product Cost: The total cost of the device should be less than $1000.

3. Miscellaneous

Customer: After practicing with this product, medical students should have knowledge of the proper pressure to apply during the casting process.

Patient Related Concerns: The device is to be used on a teaching model, not an actual patient. However, it must be assured that the device accomplishes given requirements to make sufficient teaching possible.

Competition: There are currently no pressure sensing devices on the market that assist in the teaching of cast application. Medical students traditionally learn how to apply appropriate amounts of pressure during casting by observing and doing.