Development of an Upper Extremity Fracture Model

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1. Abstract

Bone fractures to the distal radius and ulna are one of the most common pediatric ailments. Casting is often preferred as the common treatment method for pediatric forearm fractures and is assumed to be safe. However, residents are expected to learn through trial and error or through textbooks. This can result in complications arising from cast application or removal. Therefore, a pediatric fracture simulator is needed to teach proper techniques of cast application, reduction, immobilization, and cast removal. The fracture simulator must provide immediate feedback to the user and monitor fracture reduction, force applied during three-point molding, and temperature of skin surface.

Components for the force, temperature and alignment sensors were evaluated using a design matrix. The final design will include a pressure mapping system and thermistors as well as a complete circuit to indicate alignment. Additional design components include a cut-resistant sleeve to protect sensors, inductive sensors to measure cast saw location relative to skin, and tissue-mimicking materials for skin, soft tissue and bone. Future work includes verifying compatibility of all components and integrating sensors with a simple user interface. Finally, the design will be validated through use by casting experts.

2. Introduction

2.1. Occurrence of Pediatric Fractures

Bone fractures are a common pediatric injury due to the porous developing skeleton of young children. Nearly one-third of all children suffer at least one fracture before the age of 17 [1]. Additionally, forty percent of all pediatric fractures involve the forearm [2]. These fractures represent 9% of all injuries reported to health professionals [1].

Children's bones are often more flexible than adult bones and when impacted, a child's bones tend to bend and only partially break. This is known as a greenstick fracture, as seen in Figure 1A, and is the most common type of distal radial and ulnar fracture in pediatric patients. Such fractures are often treated via casting to immobilize the fracture, as seen in Figure 1B.

Figure 1: A. X-ray of green stick fracture. B. X-ray of properly reduced green stick fracture [3].

2.2.Casting Process

Before the physician begins the casting process, it is important that an x-ray image is taken of the fracture so as to confirm whether or not casting is the best treatment option or if surgery should be considered. In pediatrics, the most common treatment for greenstick fractures is known as reduction to reverse deformity. First, the healthcare provider must correct or restore length, rotation, and angulation of the ulna and radius. This process often requires exaggeration or reversal of mechanism of injury. In pediatric fractures with an intact periosteum, the soft tissues interfere with the convex side of the fracture [4].

Next, the forearm is covered with a stockinette and padding and the bones are aligned using three-point molding (Figure 2). A plaster or fiberglass layer is then applied to maintain the pressure. While plaster is most commonly utilized among pediatric orthopedists due to its ease of molding, fiberglass is much stronger, lighter and more durable.

It is important for the physician applying the cast to mimic the limb they are immobilizing as closely as possible to preserve proper reduction of the fracture [2]. According to Chess et al., casts that successfully maintained reductions had sagittal to coronal ratio (or "cast index") near 0.7 [5]. Therefore, the cast cross section should be an oval rather than a circle [2].

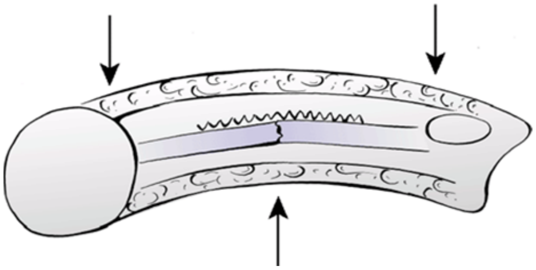


Figure 2: Sketch of three-point molding [3]

Proper reduction of the fracture is confirmed with additional x-rays. Acceptable angulation is less than 15 degrees but more angulation is allowed in younger children and preferred over a surgical option. Rotational alignment is verified by observing minimal distance in bone widths at fracture edges [4].

After four to six weeks, that cast is removed. A cast saw is used to cut two straight lines down either side of the cast by moving the saw in and out with brisk movements. The cast saw contains an oscillating blade that moves about a quarter of an inch and is designed to cut only hard objects. Therefore, it only will cut the cast padding or skin if excess pressure is applied. Once cut, cast spreaders are used to increase the size of the opening created by cast saw. Finally, a blunt tipped scissors is used to cut through the padding and stockinette. Upon complete removal of the cast, the skin should be inspected for any injury [6].

2.3. Dangers of Casting

While casting is often assumed to be a relatively low-risk treatment option for forearm fractures, it has also become a lost art among physicians and medical residents, putting patients at an increased risk of injury. Cast immobilization is frequently overlooked as more and more residents are being trained on newer forms of treatment and surgical techniques. However, despite this shift in training, the conservative treatment of casting still remains to be one of the key forms of treatment for many orthopedic conditions. As most young physicians have come to learn casting techniques – both application and removal – through trial and error, casting has become an area of greater concern for orthopedists across the nation [2]. In fact, in a recent study of about 400 physicians from a large multispecialty, multi-location pediatric group of approximately 400 physicians, casting was the number one cause of litigation, and about 35% of the claims paid an average of $120,000 each [7].

When applying the cast to the immobilized limb, the physician should be concerned about potentially burning the patient's skin from the hot casting materials as well as failing to properly immobilize the limb. If the cast is applied too light, it becomes a rigid tourniquet that restricts proper blood flow to the limb. On the other hand, if the cast is applied too loosely, it will fail to hold the proper reduction and the fracture will heal improperly [2].

Complications with the cast removal process largely revolve around the cast saw and the potential burns and cuts that can result from incorrect cast saw usage. While there are several factors that can contribute to a cast saw burn, the most easily preventable factor is the technique used by the physician when cutting through the cast, further emphasizing the importance of proper training on methods of cast removal. Shuler and Grisafi explain that the cast saw blade should be removed from the cast material after each cut to allow for cooling of the blade. When the blade is not allowed to cool, the average temperature of the blade at any given time during the cast removal is about 41°F higher, putting the patient at an increased risk of obtaining a burn or abrasion [8].

Figure 3: Example of burns and cuts from cast saw [3].

2.4. Client's Current Model

The client currently utilizes a forearm model designed and constructed by a former design team (Figure 4). The model is made primarily of PVC pipes that are connected to a thick wood board measuring about 0.5 m x 0.5 m. The PVC pipes fit together in an L-shape, the tail end of which serves as the forearm and is wrapped in a thin layer of copper foil. This copper layer simulates the skin surface of the forearm. The physicians and training residents apply the casting materials to copper-coated PVC pipe and practice removing the cast with a cast saw, trying their best not to damage the copper in the process. The cast saw (not see in Figure 4) has temperature loggers on its blade that track the temperature of the blade throughout the duration of its use. While this model has proven to be sufficient at recording the cast saw blade temperature and displaying to the user whether they have cut through the copper layer, it fails to teach the user proper fracture alignment techniques, lacks the ability to monitor the amount of force the user applies to the forearm during immobilization, and does not track the temperature of the skin surface (in addition to the temperature of the saw blade).

Figure 4: Photo of client's current forearm model [9].

3. Problem Statement

The focus of this project is to construct a distal radial and ulnar fracture simulator to teach proper techniques of cast application, reduction, immobilization, and cast removal. The fracture simulator must provide immediate feedback to the user and monitors fracture reduction, force applied during three-point molding, and temperature of skin surface.

4. Design Specifications

Since the fracture simulator device will mimic a child's forearm, it should be 18cm in length and 5cm in width. The device must be reusable, easy and safe to transport, as it will be used as a training tool in various hospitals throughout the nation. The device must measure and display saw blade temperature and artificial skin temperature in real time. In addition, the device should measure the forces applied to the arm in real time and display them on a nearby monitor or laptop. The device must clearly indicate a successful fracture reduction, which is characterized by an angulation of less than 15 degrees and displacement of less than 2mm. The device must last at least 10 years when stored at room temperature and effective for training residents in the three point molding technique for fracture reduction as well as cast removal.

5. Design Components

5.1. Force Sensors

5.1.1. Design Options

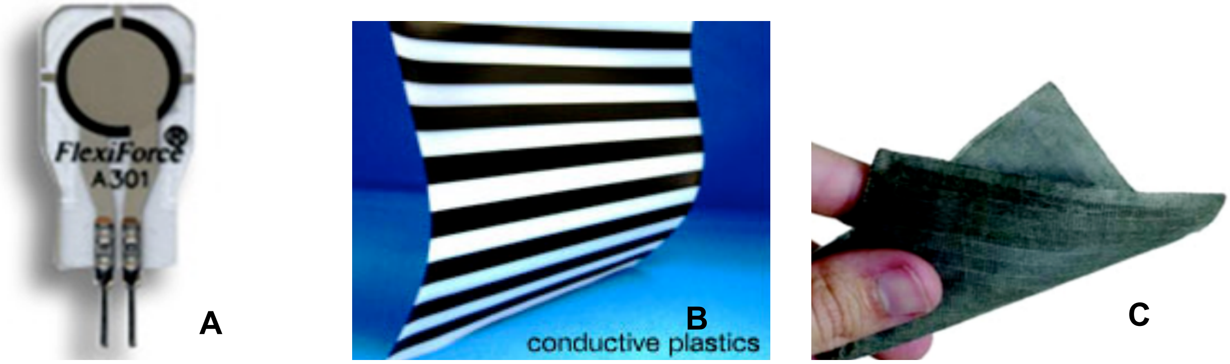
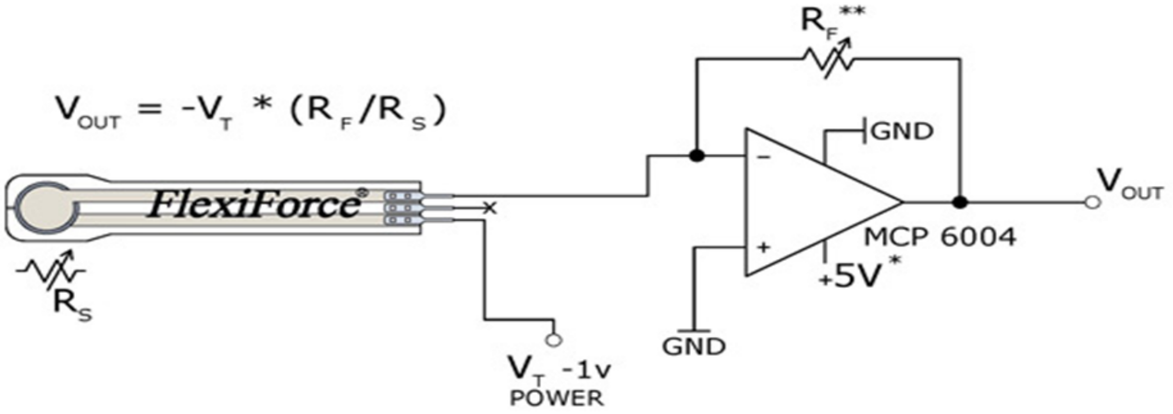


Figure 5: Possible pressure sensors. A) FlexiForce® Sensor [10]. B) Zebra™ Pressure Mapping Sensor [11]. C) TactArray Sensor [12].

The first alternative the team looked at for the pressure mapping required for this project was the use of individual force sensors (Figure 5A). These sensors are printed circuits and are therefore readily available at a low cost (~$15 a piece [10]). As force is applied to the sensor its conductance increases in a linear fashion and using the circuit shown below the force can be quantified as a voltage (Figure 6).



- * Supply Voltages should be constant
- ** Reference Resistance R_F is 1kΩ to 100kΩ
- Sensor Resistance R_S at no load is >5MΩ
- Max recommended current is 2.5mA

Figure 6: Recommended circuit for FlexiForce® Sensors [10]

By setting up several of these sensors in a matrix, it is possible to determine the pressure being applied to certain parts of the arm. This solution, however, would be limited in resolution by the number of sensors used and would require vast amounts of programing and circuit design in order to function properly.

The Zebra™ Pressure Mapping Sensor from SensorTech™ was the second option looked at for this aspect of the project (Figure 5B). This type of sensor is created by overlapping Zebra™ sheet sensors (sheets with parallel strips of piezo resistive material) at right angles (Figure 7). Each point where the strips overlap forms a sensor location capable of independently measuring pressure. This leads to sensors with a maximum spatial resolution of ~6 sensing points/in.^{2} with up to 1024 points. This type of sensor is stretchable and can be thermoformed or machined depending on its use and thickness [11]. SensorTech™ also provides its own DAS (Data Acquisition System) and software for pressure mapping.

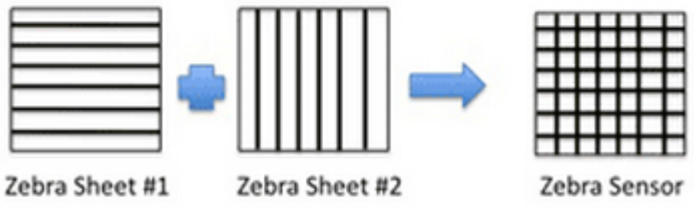


Figure 7: Zebra™ Sensor construction [11]

The last sensor considered for this part of the project was the TactArray line of pressure mapping sensors from Pressure Profile Systems (PPS) (Figure 5C). This type of sensor is built out of a flexible, conductive cloth that can be wrapped or molded in various shapes. They have a maximum resolution of 2mm with up to 10,240 elements. Just like SensorTech™, PPS provides a USB drive and real time visualization & acquisition software. However, the PPS software allows custom 3D scanning in order to show pressures on the actual shape to which the sensors are bonded [12].

5.1.2. Design Matrix

Table 1: Design Matrix for Force Sensors.

	Weight	TechScan (Individual Sensors)	Zebra Sensor (SensorTech)	Tactile Sensor (Pressure Profile)
Cost	20%	5	3	1
Compatibility	15%	1	4	4
Precision	30%	3	3	5
Resolution	25%	1	2	5
Ease of Use	10%	1	4	4
TOTAL:	100%	2.4	3	3.95

The three proposed sensors were assessed on five categories (cost, compatibility, precision, resolution, and ease of use) to determine the best option for this project (Table 1). Each of the sensors was assigned a score of one to five, with five being the highest, for each category. Since each category has a unique weight based on their relative importance, the scores from each category were multiplied by their respective factors. The final scores for each design were reached by adding the scores of each individual category.

Precision and resolution were considered the most important categories in the design matrix due to the client's requirement of being able to create and reproduce normalized data for resident training from Pediatrics experts. In these categories the TactArray sensor scored the highest possible score due to its very high resolution of 2mm and high precision. In the compatibility and ease of use categories the Zebra™ sensor and TactArray sensor scored very high due to the hardware and software that comes with them as well as for the fact that they can be wrapped or molded into various shapes. Finally, in the cost category, the single Flexiforce® sensors scored the highest due to their relatively cheap value.

After summing the scores for each of the designs, TactArray Sensor had the highest score, followed by the Zebra™ Sensor with the second highest score, and then the Flexiforce® sensor with the lowest score of the three alternatives. The TactArray Sensor was chosen as our final design.

5.2. Temperature Sensors

5.2.1. Design Options

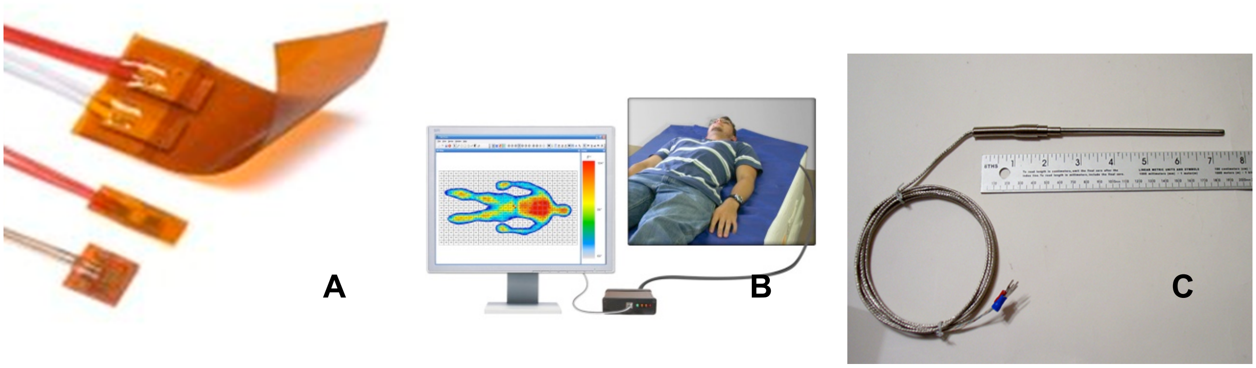


Figure 8: Possible temperature sensors. A) Thermal Ribbon Thermistors [13]. B) Tactilus Temperature mapping [14]. C) Thermocouple [15].

The team analyzed three different sensors in order to measure and display artificial skin temperature during cast application and removal, shown in Figure 8. The first design alternative is the thermal ribbon thermistors, which would be placed at various locations underneath the skin and protective sleeve of the fracture model simulator. These thermistors use semi-conductor materials to measure temperature by using electrical impulses and internal electrodes to sense surrounding heat. A decrease in thermistor resistance indicates an increase in temperature of the surroundings.

The second temperature sensor alternative is the Tactilus® temperature sensor system by Sensortech, which includes software that displays temperature mapping on a Windows computer. The mapping system is composed of sensing cells which cover the surface of the skin-like material which allow for temperature analysis at any point over the region of contact. These data are then captured from the sensor points and assimilated into a colorized temperature map display. Thermistor technology is used in the sensing cells and the mapping system is accurate up to +/-10% and has a customizable resolution of 9mm.

The final design alternative that the team considered is the thermocouple, which measures the difference in temperature between two points using two distinct materials. The difference in temperature from end to end creates a voltage between the two ends. A greater difference in temperature yields a higher current, and the temperature differential is calculated based on that.

5.2.2. Design Matrix

Table 2: Design Matrix for Temperature Sensors

	Weight	Thermal Ribbon Thermistors	Temperature Mapping	Thermocouple
Cost	35%	3	1	5
Compatibility	10%	2	4	2
Precision	10%	4	4	3
Resolution	25%	3	5	3
Ease of Use	20%	2	4	2
TOTAL:	100%	2.8	3.2	3.4

The three proposed sensors were assessed on five categories (cost, compatibility, precision, resolution, and ease of use) to determine the best option for this project (Table 2). Each of the sensors was assigned a score of one to five, with five being the highest, for each category. Since each category has a unique weight based on their relative importance, the scores from each category were multiplied by their respective factors. The final scores for each design were reached by adding the scores of each individual category.

Cost and resolution were considered the most important categories in the design matrix due to the wide range of differences in cost and the client's requirement of being able to measure and display temperature at any point on the artificial skin surface. Ease of use is also important, as the sensor data must be easy to interpret and display quickly. In these categories the Thermocouple sensor scored the highest possible score due to its high resolution and low cost. In the compatibility and ease of use categories the Tactilus® temperature mapping system and Thermocouple sensor had high scores. This was due to the software that comes with the sensor and the ease of reading and displaying temperature differential based on information provided by the thermocouple.

After summing the scores for each of the designs, the Thermocouple sensor had the highest score, followed by the Temperature mapping system with the second highest score, and then the

Thermal Ribbon Thermistors with the lowest score of the three alternatives. The Thermocouple was chosen as the temperature sensor for the final design.

5.3. Alignment Sensors

5.3.1. Design Options

The client desires to have a real time indicator to determine correct reduction (i.e. proper positioning) of the bone. The initial though was a mechanical option were the bone snapped into place once enough force was applied. The client expressed that this would less ideal as he wants the person applying the cast to maintain proper pressure throughout the casting process. In addition, it was determined that it would be advantageous to run wires down the long axis of the bone model. Therefore, three other sensors were identified: an optical sensor, a complete circuit/button pressed, and a capacitive sensor.

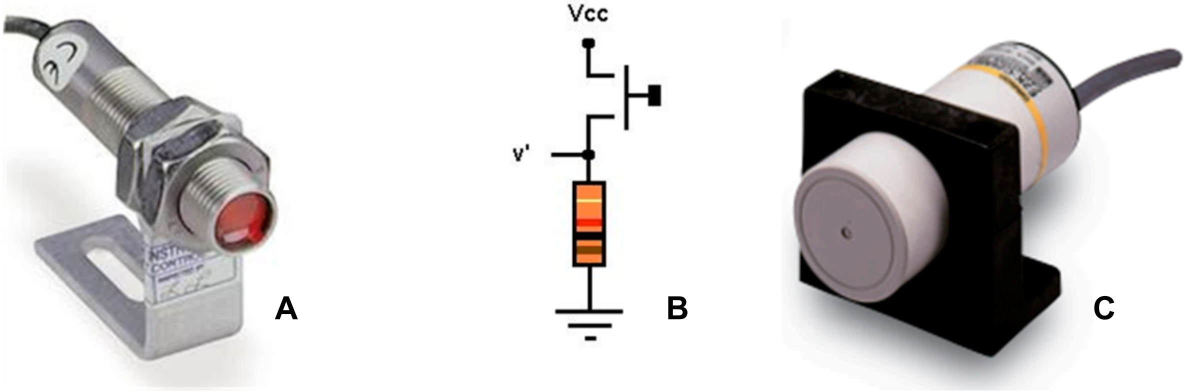


Figure 9: A. Optical sensor [16]. B. Complete circuit [17]. C. Capacitive sensor [18].

An example of an optical sensor is shown in Figure 9 A. This type of sensor functions by measuring an intensity change in one or more light beams and converting it to an electrical signal. Benefits of optical sensors include greater sensitivity, wide dynamic range, electrical passiveness, and no electromagnetic interference [19]. In the forearm model, one side of the “bone” would contain a light source at the plane of the fracture. The opposing face of the fracture would contain the optical sensor. Alignment of the bone pieces would be determined based upon the amount of light that reaches the sensor. Perfect alignment would produce the largest signal.

Another design is the capacitive sensor, as seen in Figure 9 C. This type of sensor functions based upon the electrical property of capacitance. When supplied with alternating current, the opposing sides of the sensor act as two flat conductive surfaces with an electric field between them. The amount of capacitance is directly proportional to the surface area of the sensor and the dielectric constant of the material between them and inversely proportional to the distance between the plates. The area of the sensors and the material between them are assumed to be constant. Therefore, the changes in capacitance result from a change in distance of the sensors. This can be measured as changes in voltage. Advantages of capacitive sensors include high resolutions, little sensitivity to material changes, inexpensive and small. Capacitive sensors do not function well in dirty or wet environments or when there is a large gap between the sensor and target [20]. For the forearm model, the capacitive sensors would be placed on the mating surfaces at the plane of the fracture. When perfectly aligned, the capacitive sensors would touch and there would be no voltage change (i.e. a complete circuit is created).

The final and most simple design option is the complete circuit as seen in Figure 9 B. This functions like the capacitive sensors but does not give information about the positioning of the bone pieces when not in contact. The circuit would also contain a light or signal on the user interface to alert the user when the bones are aligned.

5.3.2. Design Matrix

Table 3: Design Matrix for Alignment Sensors

	Weight	Optical Sensor	Complete Circuit	Capacitive Sensor
Cost	35%	1	5	2
Compatibility	20%	3	5	3
Precision	30%	2	2	4
Ease of Use	15%	3	5	3
TOTAL:	100%	2.00	4.10	2.95

A design matrix was created to compare the alignment sensors as seen in Table 3. The sensors were evaluated based upon cost, compatibility, precision and ease of use.

The optical sensor ranked the lowest. This option had the high cost (relative to other options) and a low precision due to possible inaccuracy resulting from light scattering inside the forearm model.

The capacitive sensor also ranked relatively low. Despite the high level of precision, this option had a high cost. It remains unclear how the gel tissue-mimicking components would affect the dielectric constant.

The complete circuit ranked the highest due to its simplicity. By nature, the circuit is composed of inexpensive parts resulting in a low total cost. The complete circuit option is also easy to assemble and highly compatible with materials and easy to incorporate into a user interface. This option was also supported by the client.

5.4. Protective Sleeve

In order to protect the many expensive sensors that our design will include, a metal mesh protective sleeve will be added directly below the skin-mimicking layer. The sleeve will be a stainless steel material that will prevent the cast saw blade from cutting through and damaging the force and temperature sensors. Since the material will be very thin and also made of metal, it should not drastically affect the output of the pressure and temperature sensors. However further testing of the compatibility of our materials in conjunction with one another will be performed in the future to determine any necessary adjustments.

5.5. Inductive Sensors

In order to detect the saw as it comes close to the skin during the cast removal simulation, inductive sensors will be used. Inductive sensors detect whether or not a metal object is near the sensor without touching the object. The inductive sensor as seen in Figure 10 consists of an induction loop, where a magnetic field is generated by electric current. As the metal object nears, power is consumed by the currents because of the induced resistance in the loop, which causes a change in energy. The inductance loop is paired with sensing circuitry, which communicates the change in energy as it is detected to another device [21].

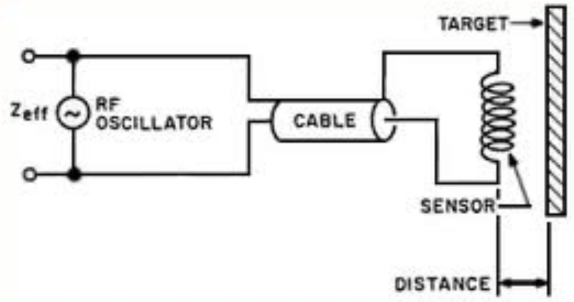


Figure 10: Circuit diagram of an inductive sensor [22].

5.6. Tissue-Mimicking Materials

In order to create a realistic fracture simulation device, the materials used for the skin, soft tissue and bone of the forearm must have realistic physical and mechanical properties and be compatible with the sensors used in the device.

5.6.1. Skin Material

Thin layers of low density Polydimethylsiloxane (PDMS) gel or PlatSil Gel-10 will be used to mimic the skin of the forearm. This material was recommended and has been shown to effectively mimic skin. PlatSil Gel10-10 is a translucent Platinum Silicone skin material that is easy to mold and shape [23].

5.6.2. Soft Tissue Material

Either high density PDMS gel will be used to mimic the soft tissue surrounding the bone. PDMS gel was recommended as an effective soft tissue material [23].

5.6.3. Bone Material

Either acrylic or PVC will be used to mimic the bone for the fracture model simulator. Since the bone is the most internal element of the forearm model, it doesn't have to correspond to the exact shape of the radius and ulna bones as long as the correct amount of resistance can be applied in order to practice the three point molding technique for reducing the fracture.

6. Final Design

Based upon the design matrices, the final design is a combination of pressure mapping system, thermistors and complete circuit for alignment. The design also will include a metal mesh protective sleeve and tissue mimicking materials as seen in Figures 11 and 12.

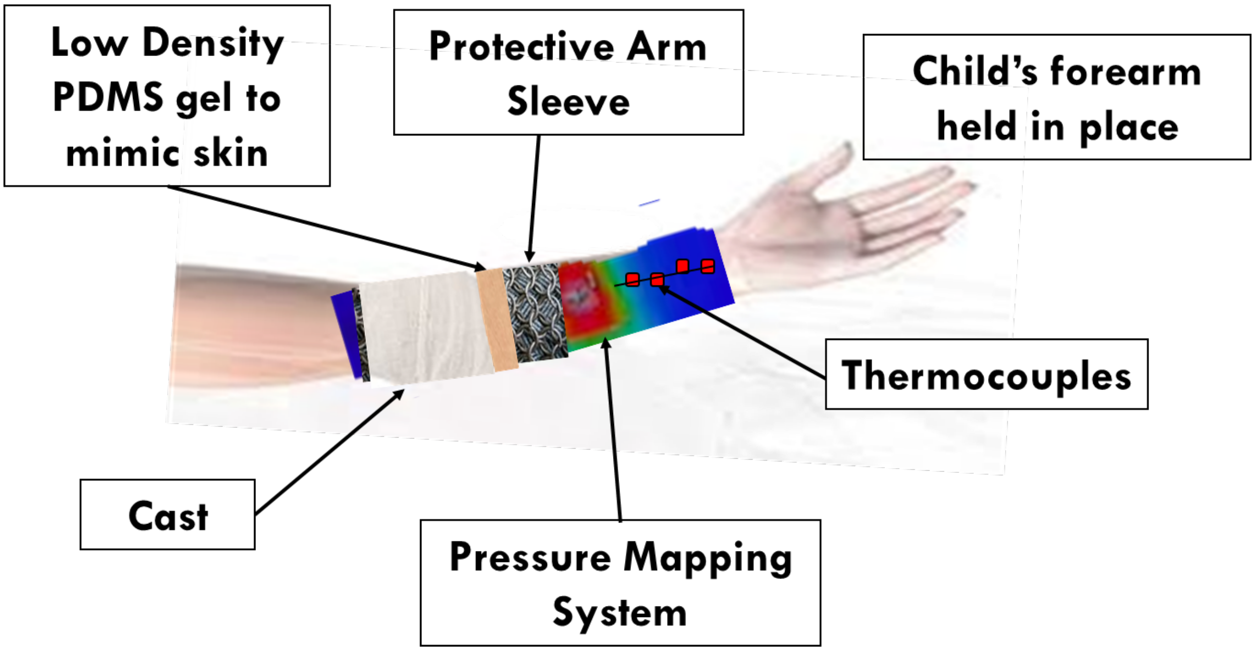


Figure 11: Diagram of forearm model with all design components.

The forearm model will be mounted on a vertical PVC post on a piece of plywood for stability as seen in Figure 12. The spring serves as resistance to create more realistic conditions for the fracture reduction. All electronic design components will be connected to a laptop based user interface to display alignment, pressure and temperature in real time.

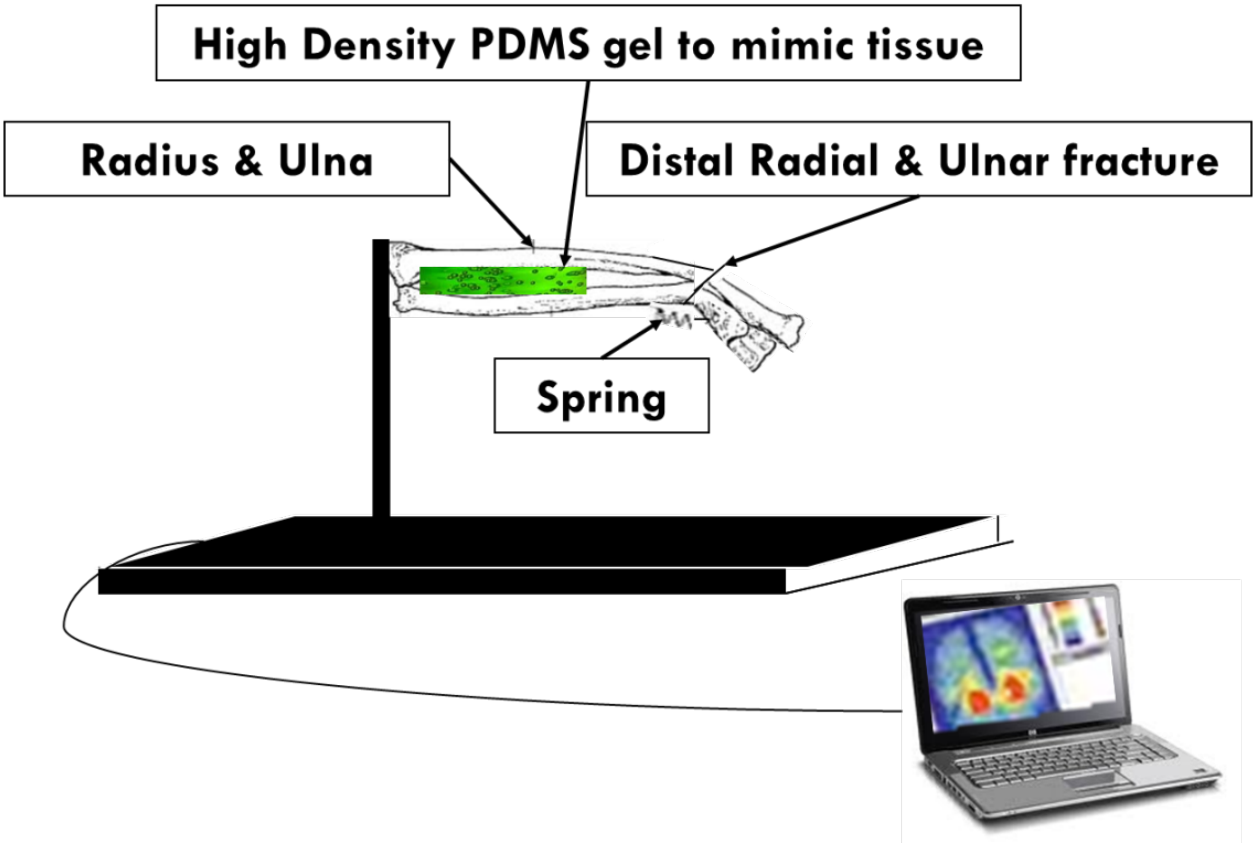


Figure 12: Diagram of entire casting model.

7. Future Work

7.1. Forearm Model Construction

In order to begin constructing the final design, the sensors and materials must be purchased. All components will be configured individually. A pediatric forearm will need to be casted to provide mold for skin and soft tissue components.

Compatibility between pairs of components will then be studied. This will allow the team to optimize the function of the fracture simulator. A component of key importance is determining the optimal location of the temperature sensors and their effect upon the pressure mapping output. In addition, the effect of the metal mesh sleeve protective element on the temperature and pressure sensors must be determined and accounted for. Finally, a user interface will be created to integrate all components.

7.2. Verification

The fracture model will be used by professionals with extensive casting procedure to create teaching modules. Pressure and temperature readings from these experiments will be averaged to create a baseline for students. The resistance to reduction via a spring will be studied to enhance the realism of the model.

7.3. Budget

The client allotted no more than $20,000 for the completion of this project. Current preliminary cost estimates are seen in the table below. The team is still inquiring about cost for the pressure mapping device from Pressure Profile Systems.

Table 4: Cost Analysis

Material	**Quantity**	**Cost Estimate**
Plywood Base [24]	1	$10
PVC Pipes [24]	1	$20
Radius & Ulna Models [25]	1	$50
Thermocouples [26]	5	$50
Thermocouple Amplifier [27]	1	$20
Microcontroller [27]	1	$50
Protective Sleeve [28]	2	$20
Casting Materials [29]	1	$100
Low Density PDMS [30]	1	$100
High Density PDMS [31]	1	$200
3D Printed Bone Material	1	$0
Springs [24]	3	$10
	TOTAL:	$630