Development of an Upper Extremity Fracture Model

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Table of Contents

Abstract

A team of four biomedical engineers focused on creating an upper extremity fracture model to enable medical school residents to train and learn how to apply and remove casts from a forearm fracture. After researching available sensors and applied force systems, the group found devices that could be modified for function and serve as a solution to the problem. Through brainstorming and design matrices, the team decided on final product incorporating two PVC pipes to represent both the ulna and the radius, a pneumatic force system and a custom pressure mapping system. The final design allows a practice tool that will determine the pressure applied, temperature and allow for a modular resistance in the fracture. In the future, materials will be purchased and testing on the fracture displacement and pressure sensors will be performed before producing a final prototype.

Client

Dr. Matt Halanski of orthopedics and rehabilitation at the UW School of Medicine and Public Health submitted this project to the University of Wisconsin-Madison Biomedical Engineering Department. He requested that a design team continue to engineer an upper extremity fracture model that records and displays pressure and temperature, creates modular resistance in the fracture and represents a true pediatric forearm.

Problem Statement

To develop a pediatric forearm fracture model that provides temperature, skin surface pressure, and bone alignment feedback for use by medical school residents in order to practice and learn safe, effective casting techniques.

Introduction and Project Motivation

Fractures are common in pediatrics, representing a major public health problem. Between 0 and 16 years of age, 42% of boys and 27% of girls experience at least one fracture and 84% of those fractures are upper limb fractures. Even though genetic or systemic illnesses can cause fractures, the majority of children with fractures are healthy. Bone mass, bone mineral density, low calcium intake, high body mass index (BMI), inactivity, behavioral difficulties and consumption of carbonated beverages have been associated with fractures in children [1].

The most serious complication of casting is compartment syndrome which is a condition of increased pressure within a closed space that disables blood flow and tissue perfusion. Thermal injuries to the skin can also occur after casting. The most common related problem is

skin breakdown which may be caused by pressure from a wrinkled, unpadded or under-padded area of the arm [2]. Currently there are not any commercially available models to teach medical school residents how to properly apply and remove a cast from a fracture.

As seen in Figure 1, the current model that Dr. Halanski uses is made primarily of PVC pipes connected to a wood board. The PVC pipes make an L-shape with the tail end representing the forearm. A thin layer of copper foil represents the skin of the forearm. The residents practice applying and removing casts on the copper-coated PVC pipe. If the copper is damaged during removal of the cast, the user will know they cut too deep. The cast saw has temperature loggers on the blade that track the temperature of the blade. The client's current model is only useful for recording the cast saw blade temperature and showing the user whether they have cut too deep. Ideally, the model should have the ability to display fracture alignment, applied pressure, and skin surface temperature.

Figure 1: Photo of client's current forearm model

Background Research

Pediatric bone is less brittle, has a higher ultimate strain than adult bone and is stronger in tension than compression. Growth plates are unique in pediatrics since it is weaker than bone in torsion, shear and bending which allows for injury at or through the growth plate area. The plates are cartilaginous and vary in thickness and location. Ligaments are generally stronger than bone in children which explains the greater fracture rate in pediatric patients [3].

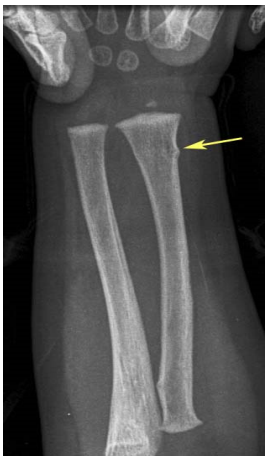

Figure 2: Buckle fracture at metaphyseal-diaphyseal joint

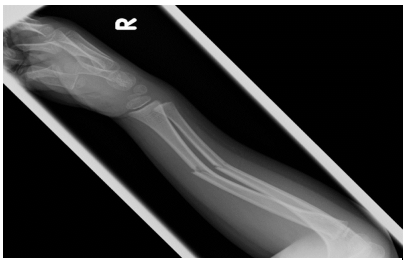

Figure 3: Radial and ulnar greenstick fracture in a child

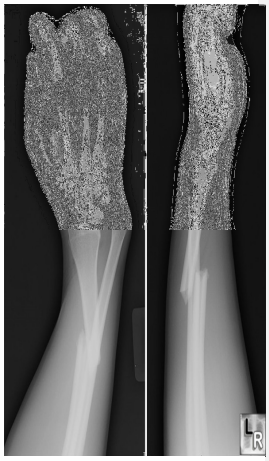

Figure 4: Monteggia fracture in ulna and radius in a child

Pediatric fractures are a result of compression, torsion or bending moments because they occur at a lower energy than adult fractures. "Buckle" fractures are compression fractures that occur at the metaphyseal-diaphyseal intersection and can cause angular deformity. As seen in Figure 2, the top layer of bone on one side of the bone is compressed causing the other side to bend away. This is a stable fracture and broken pieces have not been displaced. Bending moments can cause a greenstick fracture seen in Figure 3, which results in a deformity on the concave side of the fracture since the bone is incompletely fractured. Bending moments can also cause microscopic fractures in which there is deformation of the bone but no visible fracture lines. The Galeazzi fracture is a middle or distal radius fracture with an unaffected ulna. This is rare in children since it disrupts the distal radio-ulnar joint [3]. The Monteggia fracture affects both the radius and the ulna. As depicted above in Figure 4, there is a fracture in the ulna and the top of the radius is dislocated. This injury requires immediate care. Growth plate fractures are unique to pediatrics in that the fracture occurs at or across a growth plate of the radius near the wrist as displayed below in Figure 5. This is also called a physeal fracture [4].

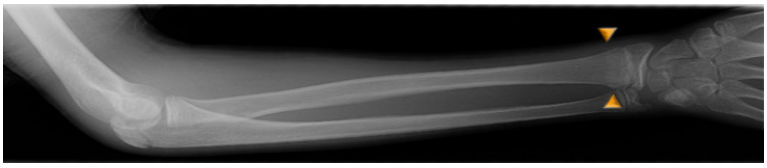

Figure 5: Growth plate fracture across radial growth plate

Forearm injuries are very common, counting for 40% of all pediatric fractures. The peak occurrence is when the child is greater than 5 years of age when the bone is weakest due to velocity of growth. The radius is a curved bone in the proximal third that is flat distally. The

ulna has a triangular shape throughout with an apex in the proximal third. The two bones are stabilized distally and proximally by the triangular fibrocartilage complex and the annular ligament [3]. Most forearm fractures occur in the radius but sometimes can be both a radial and ulnar fracture. Distal radius fractures account for 75% of all forearm fractures in children. Often distal radius fractures, seen in Figure 6, are accompanied by a wrist fracture because of contact [5]. Forearm fractures can be caused by indirect or direct contact. Indirect contact involves a fall in which a flexion injury causes dorsal angulation and an extension injury causes volar angulation. Direct contact involves trauma to the radial or ulnar shaft [3]. In distal fractures, the proximal part will be in neutral or slight supination. The weight of the hand and the pronator quadratus pronates the distal fragment [6].

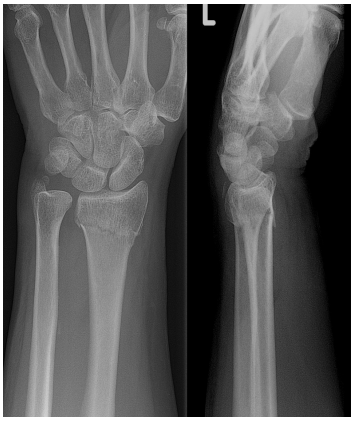

Figure 6: Distal radial fracture in pediatric patient

Incomplete fractures are treated by completing the fracture and correcting the bones into a natural position. Most fractures can be reduced by rotating the palm toward the deformity. After reduction, the arm should be immobilized into the position that corrected the fracture. Distal radius fractures are reduced with traction, angulation and rotation of the palm in the direction of the angulation. As long as angulation and rotation are reduced, it is okay to leave some fragments overlapping. All fractures are eventually casted with the elbow at 90 degrees. Both anterior and posterior pressure is applied over the interosseous membrane to mold casts. This separates bones and increases the cast stability. After reduction and immobilization, patients return for a follow up x-ray 1 or 2 weeks after the injury. If there is re-angulation, the cast is removed and reduction is performed once again. If there is no angulation, the cast is removed after 6 to 8 weeks of healing [6].

From this research, the design team has decided to benefit the largest population of pediatric fractures. The goal is to create a radius-only distal fracture that can have varying resistance. Also, it would be beneficial to mimic a greenstick fracture since it is a very common fracture found in children. It is important to allow traction, angulation and rotation in order to create an acceptable learning tool for residents to assist them in various types of fractures that they will experience.

Previous Team Prototype

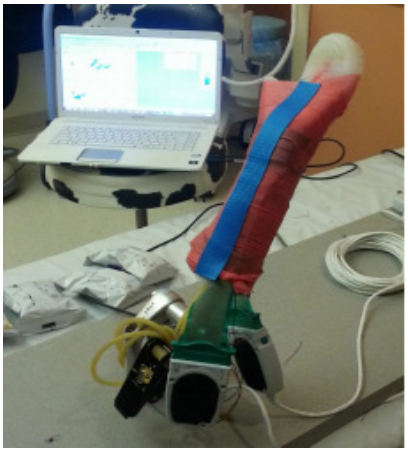

Figure 7: Photo of past BME design team's model

This project is a continuation of a previous BME design team. The past team delivered a model capable of detecting pressure, temperature, and alignment along a forearm model. However, the past team's model had several flaws. The primary issue with the model is the lack of usability. The client was not capable of setting up the model and software independently. Other issues with the past team's model included the pressure mapping system, poor accuracy with the alignment sensors, fracture location, lack of modular resistance, and no protection for hardware. Due to cost issues and time constraints, the past team went with a foot pressure mapping system. This is not ideal due to compromised accuracy and the fact that the packaged software displays an outline of a foot in the program. The system for detecting the alignment of the fracture reduction only operates in one place; therefore, it does not account for bone twisting. The model has the simulated fracture in the middle of the forearm. In order to accurately portray the most common pediatric forearm fractures, the fracture must be moved distally. The past team used latex surgical tubing to create resistance for the fracture, which did not allow the user to vary the pressure needed for reducing the fracture. Lastly, the group did not have time to develop a system for protecting the hardware from the cast saw and heat during the casting procedure.

The major concerns are listed above; however, there are several other aspects of the design that have not been discussed. The past team modeled the bones of the forearm as ¼-PVC pipe. Platsil Gel-10 was used as the soft tissue representation. Thermosistors were used for detecting temperature along the model. Figure 7 displays a photo of the past team's completed model.

Design Specifications

In this section, the key design upgrades to the previous team's model will be summarized. The client has specified that the initial upgrades should be for the usability, pressure mapping system, alignment detection, location of the fracture, and modular resistance. The client is unable to set up the current model on his own; therefore, the future model should have a fully integrated software package that would allow the client and residents to simply insert a USB cable into a computer, which would launch the program automatically. Ideally, the pressure mapping system

will be upgraded from the foot system to a custom pressure mapping system designed specifically for the forearm fracture model. A new system for detecting the alignment of the fracture reduction must be developed. The system should account for not only the angle of separation of the fracture, but also whether or not the bone has twisted. Finally, the fracture must be moved distally, and modular resistance needs to be added to the model. Moving the fracture distally will include revamping the mechanism for causing the fracture and allow for a newly developed system for varying resistances to be added.

There are several secondary upgrades that should be made to the system once the aforementioned upgrades have been made. The following systems should be upgraded or added to the system: temperature detection, protection for hardware, and realistic representation of the skin tissue in a pediatric forearm. The client has noted that the temperature detection system is not a priority at the moment, and its development can wait until the primary issues have been resolved. Before the model experiences wide use, a system for protecting the hardware will need to be developed in order to lengthen the life expectancy of the model. Lastly, the model should be as anatomically correct as possible to provide the users with the best representation possible of a fractured pediatric forearm.

Design Considerations and Decision Matrix

Pressure Mapping System

An important component of the design considerations is the pressure mapping system which is used to record the pressure applied to the fractured bone during the casting process. The pressure mapping system should be able to accurately calculate the amount of pressure that is applied to the bone and cover the entire casting area. Another important consideration when deciding between mapping system is cost, since the different mapping systems range from $5,000 to $50,000. This deserves attention when evaluating the budget of the prototype. The designs considered were evaluated based on accuracy, data output, usability, cost, and safety.

Table 1: The design matrix for the pressure mapping system.

Design Criteria	Weight	TekScan (Foot)		TactArray		Custom Forearm Sensors	
Accuracy	30	2	12	3	18		
Data Output	25	3	15	3	15		
Usability	20	2	8	4	16		
Cost	15	3	9	1	3		
Safety	10	4	8	4	8		
Total	**100**	**52**		**62**			

The TekScan pressure mapping system is actually a foot pressure mapping system, seen in Figure 8, which can superimpose onto the forearm. This system was used in the previous prototype and is not ideal, however, the price was acceptable and it can record pressure readings. This device received a low score in accuracy and data output as displayed in Table 1. The mapping system is in the shape of a foot, therefore, when placed on the forearm model, some gaps were present between the sensors and forearm and pressure data was missing. The software for the mapping system is not user friendly since the programs do not launch and display automatically, which explains the low scores in usability. Ideally, a customized software system should be implemented for the system in order to better display the pressure and temperature readings that the user requires [7].

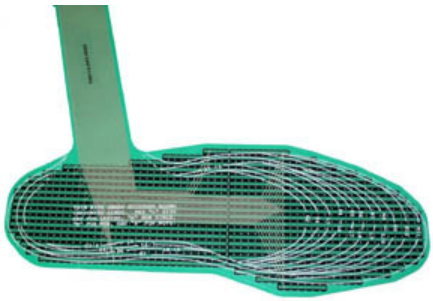

Figure 8: TekScan foot pressure mapping system currently being used

The TactArray pressure mapping system is a cutting edge technology developed by Pressure Profile Systems Inc. The company has a pressure mapping system, seen to the right in Figure 9, which is stretchable and ideal for a pediatric forearm, since the sizes are customizable. The device is constructed with a padded material that allows the system to stretch for a close fit on the most complex shapes, including

Figure 9: Tact Array sensor

the human body. The previous team also looked into using this design. However, the cost of the system inhibited the purchase and implementation of the TactArray into the design. If the product cost did not have any effect, this design would be ideal. Understanding this, the final pressure system chosen should have similar properties to this advanced system [8].

The custom design is still under much investigation. Due to the current system using a foot pressure mapping system and the TactArray sensor exceeding the budget, the client has proposed a custom pressure mapping system made by Dr. Carla Pugh at the University of Wisconsin-Madison Hospital. According to the client, the custom system can be made to fit any area of the body and should not exceed the price limit for the prototype. This provides a promising option that will be explored during a meeting with Dr. Pugh this week.

Modular Fracture System

Another component of the design that requires re-evaluation is the fracturing system used to displace the bone. The fracture modular system must be comparative to an actual radial fracture, with the ability for variable resistance. The range of variability can demonstrate the different types of breaks, regarding amount of pressure needed to realign the bone. The structure of the bone will consist of the radius and ulna. Considering the ulna will be fixed in the upright position and the radius will be the bone that displaces, the fracture system will be mounted onto the ulna and extend part of the radius bone. There are three different designs that could potentially be used for this process: elastic bands, a mechanical system or a pneumatic system. They were evaluated on resistance variability, usability, manufacturability, cost, and safety.

Table 2: The design matrix for the modular fracture system.

Design Criteria	Weight	Bands		Pneumatic System		Mechanical System	
Resistance Variability	30	2	12	5	30	4	25
Usability	25	2	10	4	20	3	15
Manufacturability	25	4	20	3	15	3	15
Cost	10	5	10	3	6	4	8
Safety	10	4	8	4	8	4	8
Total	**100**	**60**		**77**		**71**	

Commented [CAE1]:

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The previous team working on the project used elastic surgical bands to induce the forearm fracture. These type of bands are easily accessible, therefore low in cost as displayed in Table 2. The bands were hooked through the PVC pipe that represents the bone. The bands were tied to a mechanical system at the base of the forearm and a crank could be used to tighten or loosen the bands, therefore inducing a fracture. This system was able to create a displacement, however, it was hard to tell exactly how much the bone had displaced. This explains the low score in the resistance variability and usability category. The prototype must have a more sophisticated mechanism in order to induce a more realistic fracture, create various fracture types and to produce more accurate displacement data.

One plausible option for creating variable bone displacement is a mechanical system displayed in Figure 10. The design would consist of a spring connected to the fixed ulna bone that pushes against the radius. The force that the spring creates on the radius is determined by the change in length of the spring. Therefore, to increase the force on the radius, a crank system would move the spring, causing a decrease in spring length and increase in force. This provides the user with a range of forces that may be applied to the bone, which would demonstrate various types of forearm fractures. The problem with creating a mechanical system inside the cast is identifying how much pressure is being applied to the system. Therefore, the mechanical system scored lower in manufacturability and usability.

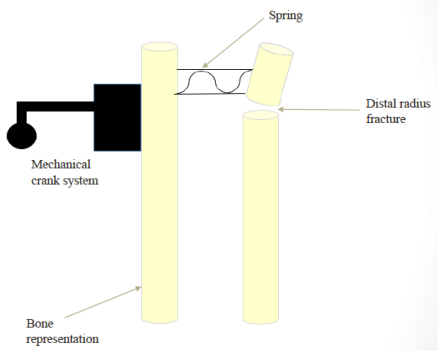

Figure 10: A possible mechanical system to cause radial bone displacement

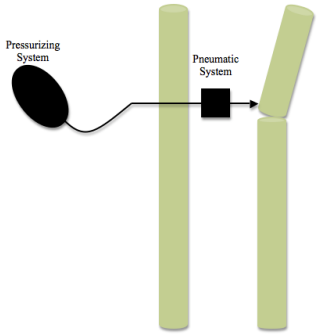

Figure 11: A possible pneumatic system to cause radial bone displacement

Another system that provides a viable option for the radial bone displacement is a pneumatic system. The pneumatic design seen in Figure 11, uses pressure to increase or decrease the amount of bone displacement in the radius. The pump located outside of the cast would be connected by a tube that delivers air pressure to the system inside. Ideally, the system inside the cast would work like a tire pressure gage. As the pressure increases, a fixed rod would increase in length and displace the radial bone. This type of system would allow the user to read exactly how much pressure is being

applied to the bone and the displacement could be measured. This would increase ease of use and resistance variability.

Final Design

The final design for the forearm fracture model incorporates multiple components with complex physical and technical interactions in order to be an effective teaching tool. These elements include a bone representation with a fracture creating device, tissue representation, and multiple electronic units interfacing with a software package. Each part has a specific goal that it accomplishes while working within parameters presented by the project as well as other parts.

The first design element is the bone and fracture modeling. Two fixed half-inch PVC pipes will represent the two bones of the forearm, the radius and the ulna, with the radius cut in the distal portion to simulate a fracture. A variable pneumatic system will create separation and resistance to reduction in the fracture. This system will consist of an air bladder or piston forcing one portion of the radius out of alignment with the other fixed portion at a pressure and displacement based on the amount of air forced into the system by a pump.

The second element is the forearm tissue representation. Platsil Gel-10 will be molded around the simulated fracture into the shape and size of an average pediatric forearm. This material is continued from the last project because it is a quality, cost effective simulation of tissue that has the thermal resistance and mechanical properties necessary for an effective model. A second layer of tissue representing skin will be added over the Plastil to cover electronic elements from heat or force damage due to the casting procedure.

A third element in the model will be electronic sensors to provide quantitative measurements of skin surface pressure and bone alignment during the casting process. A custom pressure mapping system will show skin surface pressure of the cast through the use of a sheet containing piezoelectric elements to measure force based on changing resistances in the material due to material displacement. This will cover the entire arm to provide data for the entire model. Bone alignment data will be collected by strain gage potentiometers placed across the fracture to measure fracture displacement and orientation.

The final element of this design will be a software package that collects and records data from electrical elements to display live numerical and visual feedback. This portion will consolidate all data into one efficient, easy to use program. Due to the lack of programming expertise of the team, this portion will be accomplished by an outside source based on system requirements set forth by the design team. At outline of the system requirements is found in Appendix (Software Requirements).

Experimental Testing

The testing procedure for the fracture model can be broken down into qualitative and quantitative sections. Each component must be tested separately to ensure accuracy and precision. Once this is accomplished, the assembled forearm model must be tested again for accuracy while interacting with other parts. A qualitative test of the model will be completed by residents as well as physicians to obtain feedback on usability and accuracy in physical feel.

Component testing will be relatively simple. For the pressure mapping system, a set of incremental known pressures will be applied systematically across mapped locations on the system to determine the precision and accuracy of the output. The alignment sensor's accuracy will be tested by setting the fracture known displacements and orientations and comparing to system output.

Once assembled, a similar protocol will be applied to the device as a whole. Control values for pressure and alignment will be applied to ensure the accuracy of the components in the assembled fracture-simulating device.

Qualitative data will be gathered in the form of a questionnaire completed by experienced physicians and residents to determine the quality of the device as a teaching tool. Usability of the software, data representation, and accuracy of the physical characteristics of the device will be specific areas of interest.

Future Work

Multiple aspects of the project must be addressed in the future to continue making progress in completing this design. All physical dimensions of the design must be finalized to allow for the PVC and Platsil to be ordered. The pneumatic system must be thoroughly researched in order to determine the most effective design for the fracture-creating device so it can be fabricated in a timely fashion. A meeting with Dr. Halanski's associate has been arranged and will be completed to finalize the custom skin surface pressure mapping system. The exact components of the alignment system must be determined and purchased. The team must also find a programmer to write the software code based on given detailed specifications. Once all of the parts have been received, the team will begin component testing and assembly of the final fracture model leading to final testing. The timeline for the end of the semester is outlined in Table 3.

Table 3: Future work timeline for this semester

Tasks	September				October				November					Dec
	6	13	20	27	4	11	18	25	1	8	15	22	29	6
Background Info	X	X	X	X	X									
Design Alternatives				X	X									
Final Design						X								
Materials						X	X	X						
Construction							X	X	X	X	X			
Testing											X	X	X	X
Mid-Semester					X									
Final														X
Mid-Semester Report					X									
Final Report														X

Conclusion

The most common pediatric forearm fracture is a distal radius greenstick fracture accounting for 75% of all forearm fractures. Of all pediatric fractures, upper limb fractures account for 84% of the injuries. Currently there are no commercially available forearm fracture models for residents to learn and train with. The previous design team created a sufficient prototype, however, there are many issues including location of fracture, little modular resistance for fracture, inaccurate pressure mapping system, no protective sleeve for hardware and the alignment sensors do not detect potential twisting of the bone during fracture. The design team has envisioned a pneumatic modular force system to create the fracture displacement, a customized pressure mapping system for a pediatric forearm and representation of both the ulna and radius in the model. In the future it will also be important to look into an integrated software program that includes color coded systems, easy to read display as well as an automatic program launch feature.

Acknowledgements

The design team would like to give special thanks to Professor Mitch Tyler and the UW Madison Biomedical Engineering Department for guidance and input throughout the entire design process thus far. Additionally, special thanks to the client Dr. Matt Halanski for providing

the team with the existing prototype and insight on future work. The team would like to thank Professor John Kao for helping with biomaterials research. Lastly, it is important to recognize Gabe Bautista and Professor Tom Yen of the design team last year for meeting with the team to discuss past progress.

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Appendix

Product Design Specifications

Product Design Specifications for Upper Extremity Fracture Model
Team: Colin Dunn, Lucas Haug, Max Schultz, and Taylor Moehling

Function: To develop a pediatric forearm fracture model that provides temperature, skin surface pressure, and bone alignment feedback for use by medical school residents in order to practice and learn safe, effective casting techniques.

Client Requirements:

- Create distal fracture in model
- Computer interface that is easy to use
- Provide modular resistance for the fracture
- Record pressure and temperature during casting and removal
- Protect hardware from heat and force
- Create a realistic model of the pediatric forearm

Design Requirements:

1. Physical and Operational Characteristics

a. *Performance requirements*: As a teaching aid, the device must be reusable. It must withstand repeated temperature and pressure changes, with pressure and temperature sensors remaining accurate for an extended period of time.
b. *Safety*: The device must withstand changes in temperature up to 70^{o} C and mechanical force (pressure of approximately 150 mmHg) without catastrophic failure that could result in injury.
c. *Accuracy and Reliability*: The device should be accurate within 5% of true pressure and temperature values and should also be precise to create an optimal teaching tool.
d. *Life in Service*: The device will allow for multiple sequential casting procedures in order to give many residents the necessary experience before real time scenarios.
e. *Shelf Life*: The device should last at least 5 years assuming no damage to device during casting.
f. *Operating Environment*: The Platsil, PVC and other materials must withstand pressure and temperature changes associated with the casting process. It should exhibit no reaction to any material used in this process. It must be able to maintain its physical characteristics with repeated use.
g. *Ergonomics*: Must resemble the average size of a child's forearm and allow for modular resistance to create different distal fractures of the radius. The ulna must remain in a fixed position to represent a greenstick fracture.
h. *Size*: The model arm should be the size of a pediatric forearm and the base should be large enough to support the arm during casting but also keeping in mind ease of transport.

i. *Weight*: Less than 50 pounds to be easily transported but not crucial to project.
j. *Materials*: The materials must be inert with respect to all materials used in the casting process and show no degradation from these materials or in the range of temperatures and mechanical forces utilized during use. The bones in the forearm will be represented with PVC piping and Platsil will be used to symbolize skin.
k. *Aesthetics*, *Appearance, and Finish*: This device must be representative of a human forearm including a representative ulna and radius and skin tissue. The software should display pressure and temperature readings on an easy-to-read screen with color distinctions.

2. Production Characteristics

a. *Quantity*: 1 initially
b. *Target Product Cost*: $10,000

3. Miscellaneous

a. *Standards and Specifications*: N/A
b. *Customer*: Medical Schools and ultimately residents.
c. *Competition*: Past design group's prototype. Simplistic models of extremities exist, but nothing of technical complexity that displays data.

Software Requirements

1. Program will open upon model connection to computer
2. Data from pressure, thermal, and alignment sensors will be displayed in single user interface.
3. User interface will display an image of a forearm (model)
4. Pressure Mapping System
    a. Pressure mapping data will be displayed live on the user interface
    b. Pressure data points will be displayed along the image of the forearm (model)
    c. Pressure data points will be color coded
        i. Pressure too high will be red
        ii. Pressure correct will be green
        iii. Not enough pressure will be grey
    d. An alarm will be activated if pressure is too high
5. Thermal Data
    a. The temperature of inside of cast will be displayed
    b. The temperature of outside of cast will be displayed
    c. There will be an alert system is temperatures are too high
6. Alignment Sensor Data
    a. The degree of fracture will be displayed
    b. There will be an alert system if alignment is incorrect
7. Data logging
    a. All data for each trial will be stored
        i. Pressure data will be stored
        ii. Thermal data will be stored
        iii. Alignment data will be stored

b. Data at specific points in time can be reviewed in the user interface