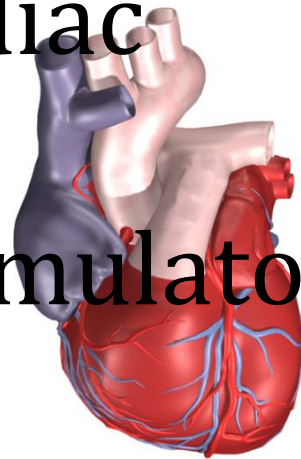


Emergency Cardiac Anterolateral Thoracotomy Simulator



ME 450 Fall 2009

[3]

TEAM THORACIC PARK [#7]

Josh Rollins
Ofra Rybak
Carly Schiffer
Wajiha Shahid

Section Instructor

Professor Kathleen Sienko

Sponsor

Clinical Simulation Center
University of Michigan Hospital

Mentor

Dr. Pamela Andreatta

Student Mentor

Joey Perosky
Specialization in Global Health student

Table of Contents

Executive Summary	4
Appendix A	15
Problem Description	15
Need for Emergency Department Thoracotomy Training	15
Ethics in Surgery	15
Anatomy	16
Procedure for an Emergency Anterolateral Cardiac Thoracotomy	17
Information Sources	19
Types of Simulators and Simulator Selection	19
Simulation: Past and Present	21
Overview of Current Simulation Facilities at the Clinical Simulation Center, University of Michigan (69)	23
The Effects of Simulation on Performance	25
Figure 19: Improvements in Student Performance from 48.5 ±4.9 minutes to 34.8 ±5 minutes between Study Week 2 and 3. (22)	26
User Requirements and Engineering Specifications	26
Table 1: Comprehensive List of User Requirements and Rankings	33
Table 1: Comprehensive List of User Requirements and Rankings	33
Breakdown of Representative Parts	36
The Thoracic Cavity	36
Figure 24: The Thoracic Cavity (36)	36
Table 9: Dimensions of the thoracic cavity and the Pleura. (35)	36
The Sternum	37
Figure 25: The Sternum (67)	37
Table 10: Dimensions of the Sternum (59)	37
The Heart	38
Figure 26: The Heart (75)	38
Table 11: Characteristics of the Heart and the Pericardium	38
The Lungs	39
Figure 27: The Lungs (45)	39
Table 12: Dimensions of a Lung (34)	39
The Aorta	40
Figure 28: The Aorta (10), (16)	40
Table 13: Dimensions of the Aorta	40

The Pulmonary Artery	41
Figure 29: The Pulmonary Artery (4)	41
Table 14: Dimensions of the Main Pulmonary Artery	41
The Phrenic Nerve	42
Concept Generation/Selection.....	43
Functional Decomposition	43
<i>Pugh charts</i>	47
The Alpha Design	55
Final Design Description	67
Prototype (Beta) Design.....	67
Parameter Analysis	82
Initial Fabrication Plans - Manufacturing	102
Initial Fabrication Plans - Assembly	113
Validation Results	117
Summary and Conclusion	135
Appendix E	136
What specific problem or challenges do you think this simulator would help you address?	147
How does this simulator compare to other methods of training this particular skill set?	147
What are the main advantages this simulator would provide to your specialty/department?	148

Executive Summary

A thoracotomy procedure consists of making an incision into the pleural space of the chest to access the organs in the thoracic cavity. This procedure is often initiated for a wide variety of life saving procedures concerning trauma to the thoracic region. The prime motivation for developing an exclusive thoracotomy simulator is that a thoracotomy is a rare emergency procedure, and often front line emergency personnel lack the skill of making split second critical decisions involved in accessing the thoracic cavity to locate and mend the trauma affected structures. Since simulation techniques have proven successful in the teaching of several resuscitative medical procedures and since no thoracotomy simulator exists in the market currently, our team has taken the initiative of developing one dedicated exclusively to practicing thoracotomies.

Several discussions with the team sponsor Dr. Pamela Andreatta resulted in the compilation of the desired user requirements and their corresponding engineering specifications for the simulator. Some of the prime user requirements included the simulator comprising key thoracic cavity organs (heart, lungs, and ribs) and their ability to respond correctly to induced trauma. Another chief requirement was the ability of the organs to allow the surgeon to replicate the motions involved in a real surgery. Our team observed cadaver dissections at the University of Michigan Medical School to ensure that the thoracotomy model would be anatomically correct. We also engaged in discussions with Dr. Andreatta, Randy Richter (Clinical Coordinator at the University of Michigan Clinical Simulation Center) and Joey Perosky (student mentor) to discuss raw material selection for a preliminary model of the thoracic cavity.

Brainstorming sessions for each simulator component revealed several challenges with executing certain ideas and we were able to realize tradeoffs of including/excluding certain user requirements in our simulator. The team also came to a consensus that achieving certain engineering specifications such as modeling blood flow would be too complex, given the time line for presenting project deliverables, and could therefore be forgone in this initial prototype of the simulator. Constructing a CAD also helped in envisioning the placement of the organs in the thoracic enclosure. Our final raw material selection was based on our document work with pugh charts, functional decomposition charts, go no-go screening and our most recent interview with Dr. Andreatta and Mr. Richter. For deriving feedback from the heart, we chose to embed sensors strategically around the heart and determined that a cam/motor configuration will work best in simulating the heart beat. A summary of the remaining results to date can be viewed in Table 15 on page 44.

The final prototype has been derived from the concept selection discussed earlier, as well as engineering design parameter analysis, experimentation and user feedback. All of these methods allowed us to narrow down our materials and designs into a final prototype that fulfills all of the user requirements we aimed to incorporate. The working prototype was then assembled and evaluated.

Put paper number here

DEVELOPING AN EMERGENCY CARDIAC ANTEROLATERAL THORACOTOMY SIMULATOR

Wajiha Shahid
University of Michigan
Ann Arbor, MI, USA

Ofra Rybak
University of Michigan
Ann Arbor, MI, USA

Josh Rollins
University of Michigan
Ann Arbor, MI, USA

Carly Schiffer
University of Michigan
Ann Arbor, MI, USA

Kathleen Sienko, PhD
University of Michigan
Ann Arbor, MI, USA

Pamela Andreatta, PhD
University of Michigan
Ann Arbor, MI, USA

ABSTRACT

Trauma is the leading cause of death in persons younger than 44 years old and fifty percent of the deaths occur within the first hour after incident. Penetrating cardiac injuries are an increasing cause of death in urban areas. Such trauma patients represent a population for whom survival is occasionally possible if an aggressive approach using Emergency Department Thoracotomy (EDT) is taken. A cardiac emergency thoracotomy entails the surgeon performing large and rapid incisions into the pleural space of the thoracic cavity to resuscitate patients who have suffered penetrating chest trauma. This procedure is highly invasive, rare and is conducted outside the operating theater in the absence of a trained cardiothoracic surgeon. Therefore, most emergency clinicians are not trained to perform EDT and there is often hesitation to perform it, until a poor outcome is inevitable. Traditional training methods for EDT evoke a strong ethical argument because they involve using animals or learning while treating trauma patients in

critical condition. The use of clinical simulators offers the potential to eliminate these concerns; however, current medical simulators are not dedicated to the training of EDT. Therefore, the goal of this work was to design and build a simulator to mimic the functionality of the rib cage and the components within the thoracic cavity to serve as a learning and assessment tool for conducting EDT. This design paper presents the user requirements and engineering specifications for the simulator, explains the material selection approach employed for the thoracic components, and describes the iterative approach for designing, fabricating and validating the EDT simulator.

1 INTRODUCTION

Trauma is the leading cause of death in persons younger than 44 years old and penetrating cardiac injuries are an increasing cause of death in urban areas

[1]. Fifty percent of the deaths typically occur within the first hour after a major trauma incident. For selected patients among the group of survivors, receiving an Emergency Department Thoracotomy (EDT) in the hands of trained emergency specialists can make the difference between life or death [2]. However, EDT is a difficult procedure under the best of circumstances. Thus it is necessary that emergency physicians are aware of the general indications and the techniques of emergency thoracotomy and those specific instances in which thoracotomy presents some reasonable chance of a favorable outcome [2]. Presently, physicians learn to perform EDT by training on live anesthetized animals or while actually treating a patient in need. There are ethical and educational disadvantages to both of these methods and an alternative instructional approach is desirable for trauma training.

The need for use of simulators to train clinicians for EDT is particularly powerful because the training agenda can be determined by the needs of the learner and the learner can progress at his/her own rate without the distractions and patient safety concerns of treating a real trauma patient [3]. Additionally, learning in a simulated environment allows students to make mistakes so that they can explore the limits of each technique without concerns for patient safety [3, 4]. Apart from their worth as training instruments, simulators can also be valuable for formative and summative assessment because they enable standardized training and repeated practice of procedures under standardized conditions [4]. Clinical simulation provides an excellent option for training low frequency, high acuity procedures like EDT, and is invaluable to emergency clinicians faced with the task of performing this uncommon, intricate procedure.

EDTs start with an incision through the skin, fatty layer, and layers of muscles surrounding the thorax. Under circumstances of acute deterioration or cardiac arrest, a left anterolateral thoracotomy is performed because it allows for treatment of a large percentage of cardiac injuries. For a cardiac anterolateral thoracotomy, a left anterolateral incision is made between the 3rd and 4th intercostal space, just below the nipple of the patient. Next, the left lung is often collapsed away from the chest wall in order to provide greater working room for the surgeon. This is followed by performing an incision into the pleura. The ribs are then separated using a chest wall retractor (rib spreader) to provide the surgeon access to components within the chest cavity. Once the surgeon has successfully entered the rib cavity, he/she must identify the location affected by the trauma. An analysis of pre hospital time in penetrating chest trauma patients receiving EDT demonstrated that patient survival rate was zero when time exceeded 30 minutes [1]. Therefore, it is critical for the surgeon to work swiftly to stabilize the patient. After obtaining access to the heart by cutting through the pericardium, the surgeon must control any hemorrhaging cardiac wounds by using staples or sutures. After sealing any cardiac wounds, the surgeon closes the chest by

Characteristic	Dimension Value
Average Width	9 cm
Average Height	13 cm
Stroke Volume	0.28 liters
Heart Rate	70 beats/min
Flow Rate	5 liters/min
Pericardium Thickness	0.7-1.2 mm
Beat Time Ratio	0.3

suturing the pericardium, re-inflating the lung, inserting a chest tube, and suturing the skin.

**2
M
ETHO**

D OF APPROACH

2.1 User Requirements and Engineering Specifications. Design guidelines were developed so that the simulator could reproduce the response of the chest cavity during a trauma situation. The user requirements were obtained from interviews with anatomists, emergency medicine physicians, cardiothoracic surgeons, medical educators and reference literature. These requirements were translated into engineering sample

specifications that were ranked for priority of need (Table 1). The primary design driver was that EDT simulator replicates each step of the procedure accurately. The sternum, skin, ribs, heart, lungs, pericardium, pleura, aorta, pulmonary artery and the phrenic nerve were chosen as the primary components of the simulator. The numerical specifications for the individual components were obtained from multiple medical literature sources and anthropomorphic journals. Table 2 lists the sample characteristics of the heart and the pericardium dimensions and the dimensions for each of the remaining thoracic components were quantified in a similar fashion (not shown).

Table 1: List of primary user requirements, specifications and rankings

Rank	User Requirements	Engineering Specifications
1	Include Key Thoracic Components (Heart, Pericardium, Phrenic Nerve, Ribcage, Pleura, Lungs, Aorta, Pulmonary Artery, Skin)	Yes; e.g. skin covers 100% area of thoracic cavity
2	Be Anatomically Correct	Yes; e.g. refer to Table 2
3	Have Skin That Allows Thoracic Cavity Access	Yes
4	Have Spreadable Ribs	Separation of 8 cm [5]
5	Have Penetrable Pleura	Thickness of 0.14 mm [6]
6	Responds Correctly	Eg. rib spread force of 100 N
7	Have Reconfigurable Skin	Access points ≥ 3
8	Have Penetrable Pericardium	Thickness of 0.7-1.2 mm [7]
9	Provide Evaluative Feedback	E.g. variable heart beat rate

Table 2: Characteristics of the heart and the pericardium

most basic level depended on the fidelity of these systems in their response to human pressure, it was critical to analyze the amount of force they could tolerate without causing damage to the simulator. However, a simpler analysis was conducted on the remaining components (pleura, pericardium, etc.) to determine their behavior in relation to the minimal loading they were expected to support during a simulated procedure.

2.2 Concept Generation/Selection.

A functional decomposition was performed based on the inputs (energy or material) provided by the emergency clinician and the expected outputs. The spatial orientation of the components within the thoracic cavity in relation to the rib cage was determined based on observations made during multiple cadaver dissection labs at the University of Michigan Medical School¹. Possible material candidates were identified for each simulator component and based on how well they could replicate the functionality of their respective real organ counterparts. To quantify the extent to which the user specifications (Table 1) were fulfilled, go-no-go screenings were used. Following the go-no-go screening process, pugh charts were used to select the top material candidates. For instance, one rejected concept for obtaining feedback from the heart during tactile examination involved placing bubble wrap at various locations of interest. The surgeon would be instructed to examine the surface of the heart for the bubble wrap and pop them. Though this idea for obtaining performance feedback fulfilled the design requirements of being easily transportable, affordable and having the minimum number of replaceable parts, this suggestion was eliminated because it promoted the use of substantial force to pop the bubbles which could potentially harm the patient.

¹ Medical Gross Anatomy – Dissection 4 and 5, University of Michigan Medical School, 10/6 and 10/8. Conducted by Dr. Ameer Raouf.

The second highest ranking requirement was that each representative component within the thoracic cavity needed to replicate the functionality of its real counterpart to provide accurate response feedback to the trainee. For instance, the model heart was required to respond mechanically to simulate the nominal heart beat rate of an average adult while mimicking the tactility of the heart. The latter quality was vital because in an emergency procedure the surgeon relies strongly on tactile senses to detect the presence of ruptures in the heart muscle. Another requirement for the simulator was that its representative components be replaceable or reusable to enable continuous and cost effective use of the simulator for routine training.

Additional lower ranking design requirements consisted of the simulator being affordable, transportable, and capable of simulating multiple trauma scenarios and blood flow. These lower ranking requirements were identified for subsequent design iteration.

The heart, the ribs and the lungs were analyzed because these components represented the mechanical structures that were required to withstand the forces exerted by the surgeon at each step of the thoracotomy procedure. Since the functionality of the simulator at the

2.3 Engineering Analysis. SolidWorks Finite Element Analysis (FEA) feature (2009 SP3.0) was used to characterize the stress and strain profiles of a single rib in response to a 100 N [5] transverse force. The stress analysis was conducted for a rib oriented at an angle of 20° with respect to the breastbone (Figure1). Figures 2 and 3 shows the resulting stress and strain concentrations attained when the FEA was conducted with a safety factor of 3.75.

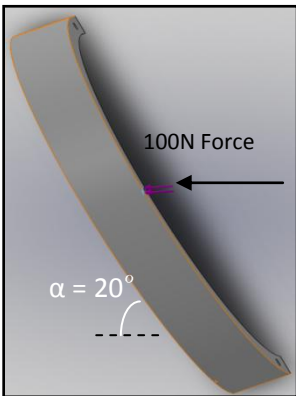


Figure 1: Locations on the ribs that experience the maximum stress and the 100N force.

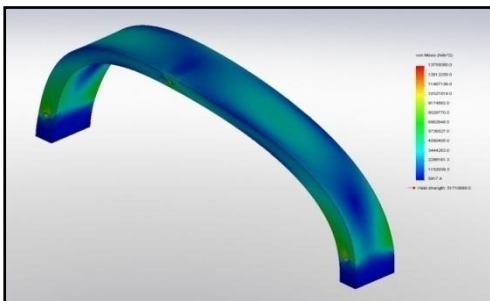


Figure 2: The resultant stress distribution on the rib

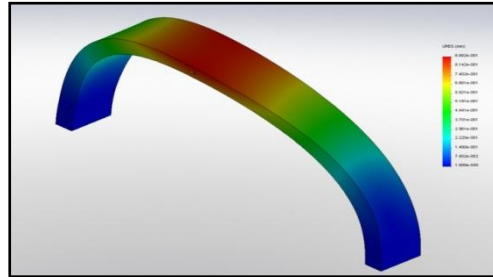


Figure 3: The resultant strain distribution on the rib

The FEA analysis confirmed that each individual rib would be able to withstand a force of 375N and that the maximum stress occurred at the ends of the ribs which were fixed (modeled as points of attachment).

3 DESIGN DETAILS

3.1 Passive Systems. Passive systems in the simulator are defined as the components that are mechanically static. These comprise the pericardium, pleura, skin, aorta, pulmonary artery and phrenic nerve.

3.1.1 Pericardium: The pericardium is a thin two walled sac that surrounds the heart and its chief function in the simulator is to allow access to the heart after exposing the thoracic cavity. A thick balloon was used to model the pericardium, so that it could simultaneously replicate the elasticity and the thickness of a real pericardium surrounding the heart. Balloons were also useful because they were inexpensive and could be replaced conveniently after each procedure.

3.1.2 Phrenic Nerve. The phrenic nerve controls involuntary respiration and runs anterior to the internal thoracic cavity as it crosses alongside the heart. The phrenic nerve was modeled as a taut elastic band such that if it was touched by a sharp surgical tool, it would snap to indicate an error.

3.1.3 Aorta and the Pulmonary Artery. The two main greater vessels of the heart, the aorta and the pulmonary

artery, were modeled using clear one inch surgical PVC tubing since the tubing is conveniently pliant. The main purpose of including the greater vessels in the prototype was to ensure an anatomically correct model while serving as a conduit for wires associated with the active systems (Section 3.2).

3.1.4 Pleura. The pleura is a thin membrane that surrounds the inside of the rib cages. Its inclusion was significant in the simulator because it is necessary to cut through the pleura before spreading the ribs. Shrink wrap was selected to model the pleura because it mimicked the cadaver pleura in terms of its elasticity. Using the shrink wrap was advantageous because it was also relatively cheap. The pleura is required to be replaced following each simulation. Hence using the shrink wrap had the additional benefit of being inexpensive.

3.1.5 Skin. Neoprene was selected to model the simulator skin because it can be repeatedly sutured without substantial degradation. A disadvantage of using neoprene was that it did not replicate the texture of human skin. Estimating a suitable thickness for the neoprene to closely mimic the fat content under the skin was also challenging, since the amount of fat beneath the skin varies across people. Maneuvering between the fat layers swiftly and efficiently to place the correct incision is critical for this emergency procedure especially if the patient is overweight or obese.

3.2 Active Systems. The active systems in this prototype include a beating heart, breathing lungs and spreadable ribs.

3.2.1 Rib Cage. The function of the ribcage was to provide spreadable ribs that exerted realistic resistive force to the surgeon's input mechanical energy. The rib cage comprised the sternum and the back plate, each manufactured from quarter inch masonite. Masonite was used because it could be laser cut precisely to mimic

the identical shape of a real rib cage, thereby preserving the aesthetic similarity of the simulator to its real, human counterpart. A six inch diameter PVC pipe was used to model sixteen ribs for the rib cage. The sternum and back plate provided the rotation capability to open the rib cage for easy access to the components inside the thoracic cavity. Cabinet hinges enabled one half of the rib cage to conveniently swing open. Each rib was required to withstand a tension force of approximately 100N without fracturing to achieve a minimum separation of approximately 8 centimeters between the ribs.

3.2.2 Lungs. The primary function of the lungs was to simulate respiration. An air pump was also used to inflate the lungs at 0.42 cubic feet per minute. The lungs comprised a plastic bag surrounded by half inch open cell backer board foam. The bag and the foam inflated and deflated as the pump displaced air in and out of the bag. The foam was used to reproduce a texture similar to that of actual human lungs, and to function as a landmark for informing the trainee about the location of the lungs. A valve was attached from the hose to the left lung. When closed, it blocked the air supply to the left lung, simulating surgical deflation.

3.2.3 Heart. The heart was created out of PVC plastisol and poured into molds made from a plaster based powder material. To assess the most realistic texture of the heart, the plastisol was mixed and heated to approximately 350 degrees Fahrenheit with different combinations of plastic softeners. A servo motor and a cam design were embedded within the heart to simulate a realistic rhythmic heart beat. A motor was connected to a cam design by a shaft that rotated the cam at a speed of approximately 70 revolutions per minute. Twelve vibration sensors were embedded within the surface of the heart in order to characterize the extent to which the trainee explored the heart. LEDs corresponding to each sensor were illuminated on a stand-alone display board to provide post examination feedback regarding the extent of the heart evaluation. A

microprocessor circuit was constructed to assemble and power the sensors leading to twelve light emitting diodes (LEDs). A microprocessor was programmed to recognize that if the sensor voltage rose above a certain threshold voltage, the digital output would transmit an electrical signal of 5 V to the LED, causing the LED to switch on. It was also possible to cover the board so that the trainee could evaluate and review his/her performance after performing the procedure rather than during it.

4 RESULTS

The Computer Aided Design (CAD) LED Board the final prototype is illustrated in Figure 4.

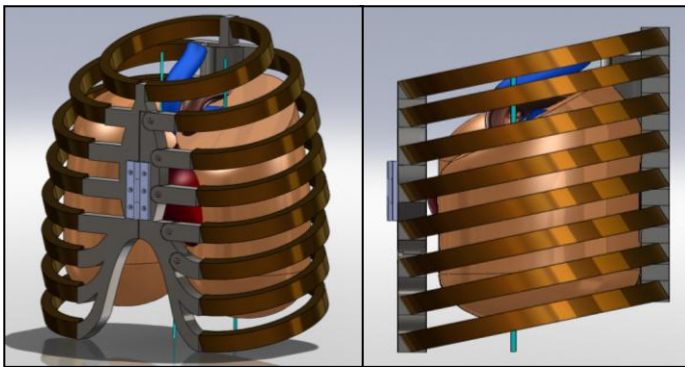


Figure 4: Isometric view (Left) and side view (Right) of the final design.

Figure 5 indicates the complete setup for the proof-of-concept design of the simulator. The heart is not visible in the graphic below because it is obscured by the sternum.

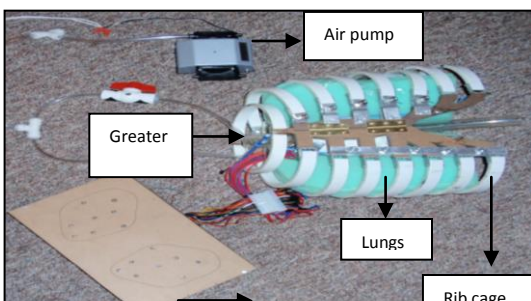


Figure 5: The simulator prototype

4.1 Includes Key Thoracic Components. Figure 5 shows the simulator decomposed into each of its various parts. The pleura is not visible in the figure since it was modeled using a transparent shrink wrap.

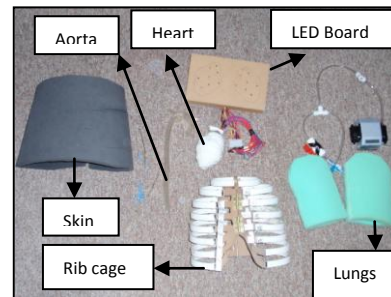


Figure 6: The individual components of the simulator.

4.2 Is Anatomically Correct. Dimensional characteristics of each thoracic cavity components were measured using a set of vernier calipers the results were comparable to physiological specifications.

4.3 Have Skin That Allows Thoracic Cavity Access. Figure 6 below indicates the opening in the neoprene to reveal the pleura and lungs.



inches would have better mimicked the tactile response of skin.

Figure 7: Separating the skin to reveal the lungs, pleura and the ribs (Left). Separating the ribs to ensure that they were spreadable (Right).

4.4 Have Spreadable Ribs, Penetrable Pleura and

Pericardium. Vernier calipers were used to verify the thickness of the pleura and the pericardium, and the measured thicknesses were comparable to physiological dimensions. Rib separations (Figure 6) of at least 8 cm were achieved when 100 N was applied.

4.5 Responds Correctly. An experiment (Figure 7) was conducted to test whether the ribs could withstand a separation force of 100 N and to verify whether the analytical results obtained from FEA analysis were valid for the rib cage. A rib was securely fastened to a wooden platform using brackets and a force was applied at a 20 degree angle to replicate the rib spreader force. The rib was loaded in increments of 10 lbs.

Samples for the heart prepared from a variety of plastisol and hardener ratios were compared to a sheep heart in a blinded touch test. The combination with 75% plastisol and 25% hardener was consistently voted the best model in simulating the feel of the heart.

5 Discussion

The paper presents a novel low-cost, low-tech EDT simulator for training and evaluating the EDT procedure. The simulator comprises the essential components in the thoracic cavity and ensures that the active components in the simulator provide evaluative feedback to the emergency clinician.

The neoprene withstood repeated suturing; however, its texture functioned better to replicate the feel of the tough muscle rather than to model the soft skin tissue. Using a neoprene sheet thickness of 0.5 versus 0.75

Future design iterations should model the fibrous muscle between the ribs, in order to simulate the depth of incisions. However, the PVC proved to be a robust choice for the fabrication of the ribs because experimental loading tests indicated that the ribs could withstand a load approximately 7.5 lbs greater than the load they were expected to support based on the FEA results.

Subsequent testing is required to thoroughly validate the active systems. Additional validation is also required to address the effectiveness of the simulator as a whole. Institutional Review Board approval will be sought prior to conducting human subject tests. Future validation will comprise testing the simulator with clinicians of varying degrees of expertise to gain insight into the ability of the simulator to discriminate among the different skill levels.

REFERENCES

- [1] Roberts, J. R., & Hedges, J. R. *Clinical procedures in emergency medicine*, 4th edition. Elsevier Health Sciences, 2004.
- [2] *Emergency Department Thoracotomy*, Retrieved on 12/08/2009 from <http://www.sciencedirect.com>
- [3] TOBIN, J. Reality check: Medical training goes virtual. *Medicine at Michigan*, Summer 2007. Retrieved 9/24/2009, from: <http://www.medicineatmichigan.org/magazine/2007/summer/clinsim/default.asp>
- [4] Andreatta PB, Woodrum DT, Birkmeyer JD, Yellamanchilli RK, Doherty GM, Gauger PG, Minter RM. Laparoscopic skills are improved with LapMentor training: Results of a randomized, double-blinded study. *Ann Surg.* 2006 Jun;243(6):854-60; discussion 860-3

[5] Bolotin, G., Buckner, G. D., Jardine, K.J (2006). A novel instrumented retractor to monitor tissue-disruptive forces during lateral thoracotomy. *The Annals of Thoracic Surgery*.

[5] Andreatta PB, Gruppen LD. Conceptualising and classifying validity evidence for simulation. *Med Educ*. 2009 Nov;43(11):1028-35.

[6] *Imaging of pleural effusions in adults* Retrieved 9/24/2009, <http://www.uptodate.com/patients/content/topic.do?topicKey=~9gaOHSBXGIPdLQ>

[7] Bull, R., Edwards, P., & Dixon, A. (1998). CT dimensions

of the normal pericardium. *The British Institute of Radiology*, 923.

Appendix A

Problem Description

A thoracotomy is an incision into the pleural space of the chest, necessary for a wide variety of procedures concerning trauma to the thoracic region. These procedures include removal of cancerous pulmonary tissue, stoppage of internal bleeding caused by a car accident, and emergency heart-by-pass surgery. Most elective thoracotomies can be done with minor incisions for minimal scarring and quick recovery. However, emergency thoracotomies are performed on patients who are in a fatal state and, to save precious time, the surgeon must make relatively large and rapid incisions to save the patient's life.

Need for Emergency Department Thoracotomy Training

Trauma is the leading cause of death in persons younger than 44 years old and 50 percent of the deaths occur within the first hour after incident. Research also suggests that penetrating cardiac injuries are an increasing cause of death in urban areas. Such trauma patients represent a population for whom survival is occasionally possible if an aggressive approach using emergency department thoracotomy (EDT) is taken. (57)

EDT is a procedure that is used rarely and in the absence of trained cardiothoracic surgeons. Most emergency clinicians are not trained to perform this highly invasive procedure and therefore delay its performance until the patient is terminal. With EDT training, however, emergency clinicians would be less reluctant to execute the procedure when necessary and without hesitation. Though the survival rates for EDT are dismal, dramatic patient resuscitation is sometimes still possible if the decision to perform the procedure is made swiftly. Furthermore, few of the 6900 registered hospitals in the United States are Level I trauma centers where EDTs are more commonly attempted, whereas nearly all hospitals provide 24-hour emergency clinician coverage. Consequently, the need for EDT training is prevalent. (57)

Ethics in Surgery

The debate over painful experimentation on animals enjoins us to consider the decisions of inflicting pain and the duty to respect the lives of all creatures, while also considering our obligations to promote human welfare and prevent animal and human suffering alike (8). Though animal testing has yielded invaluable contributions in the medical research arena, the argument in favor of adopting simulation techniques is powerful because it offers the potential to do away with practicing on animals or even humans altogether.

Simulation offers useful prospects for training for EDT because currently, the two best training methods for surgeons have large disadvantages. The first method includes practicing procedures on animals and the second method entails practicing on patients during a "real-time" emergency.

Animal testing practices are being questioned because, firstly, animal rights activists have staged several protests to urge a ban on the practices. For instance, the Physicians Committee for Responsible Medicine filed a complaint with the United States Department of Agriculture, which administers the Animal Welfare Act against the University of Michigan (U-M) Health Centers. The group outcried that U-M was one of only a handful of medical schools across the country that used anesthetized dogs rather than human cadavers or life-like human models. (37) U-M has

since then halted and discontinued the use of dogs as test subjects. Secondly, anti animal testing groups also point out the incidence of animal tests failing to reveal damage to which humans are highly susceptible due to the inherent differences in the anatomy of animals and humans. For example despite the massive animal testing carried out in many countries, the harmful effects of asbestos could not be reproduced in the animals. Governments therefore did nothing to clean up the asbestos mines until the 1960's. These test failed because asbestos related diseases have latency periods from 20 to 40 years, far longer than the lifespan of animals used in the trials, thereby proving that results based on animal experimentation may not necessarily prove promising for humans. (8)

The second training method of learning in a “real-time” emergency is unfeasible, particularly for an EDT procedure because it is more likely to subject the patient, who is already in critical condition, to care based on trial and error. A study estimated that a surgeon needed to perform a procedure up to 100 times before having the ability to complete the procedure with minimal complications (22). Therefore for a rare yet critical procedure such as EDT, it is would be would be virtually impossible for a novice surgeon to become relatively competent at a high risk surgery after a bare minimum of 100 surgeries.

Anatomy

The thoracic cavity, or chest cavity, is the space within the human body enclosed by the rib cage and which spans from the diaphragm to the neck. It is comprised of the lungs (1), the heart (2), and the primary blood vessels, such as the aorta (3) and the pulmonary artery (4), as can be seen in Figure 1 below. Surrounding the thoracic cavity and lying just under the rib cage is the pleura, a lining which helps cushion and protect the lungs. Another important lining is that which surrounds the heart called the pericardium. The phrenic nerve runs vertically on either side of the heart and gives the diaphragm the ability to contract. More detailed descriptions of these parts can be found in the Breakdown of Representative Parts section on pages 25-31.

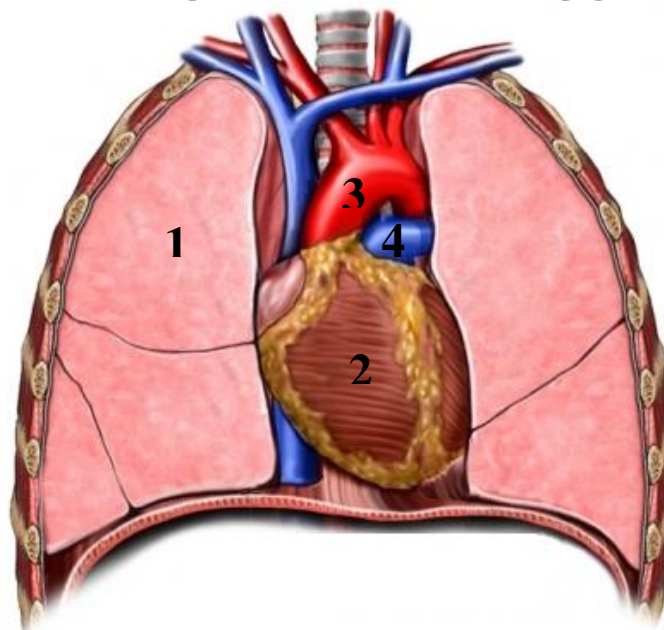


Figure 1: The thoracic cavity (46)

Procedure for an Emergency Anterolateral Cardiac Thoracotomy

Emergency thoracotomies start with an incision through the skin, fatty layer, and layers of muscles surrounding the thorax. Various incision locations, which are shown in Figure 23, page 21, are available for thoracic trauma and depend on the suspected injury. Under circumstances of acute deterioration or cardiac arrest, a left anterolateral thoracotomy is used because it allows for treatment of a large percentage of cardiac injuries. (57) For this specific procedure, a left anterolateral incision should be made in the 3rd or 4th intercostal space, just below the nipple of the patient, as indicated by the dotted line in Figure 2, page 7.

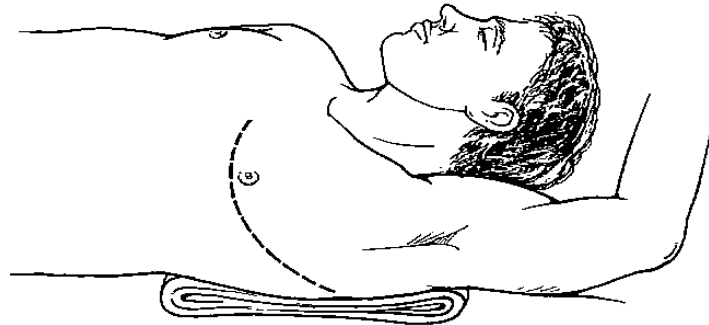


Figure 2: Location of incision for a left anterolateral emergency thoracotomy. (57)

At this point, the left lung is often collapsed away from the chest wall in order to provide more working room for the surgeon as shown in Figure 3 below.

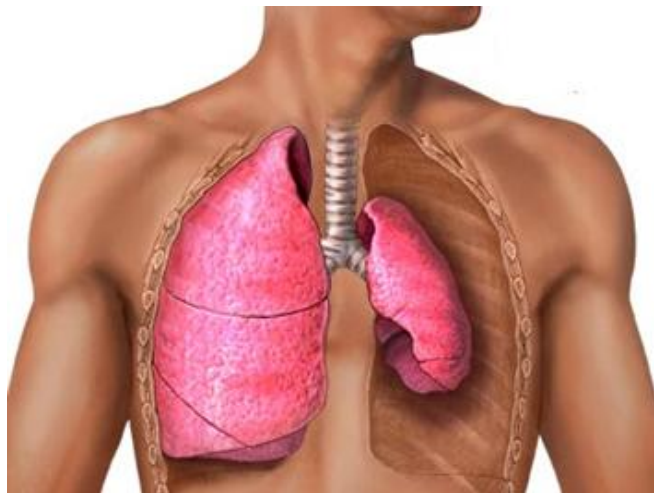


Figure 3: Collapsed left lung. (3)

Next, an incision is made in the pleura as shown in Figure 4 below.

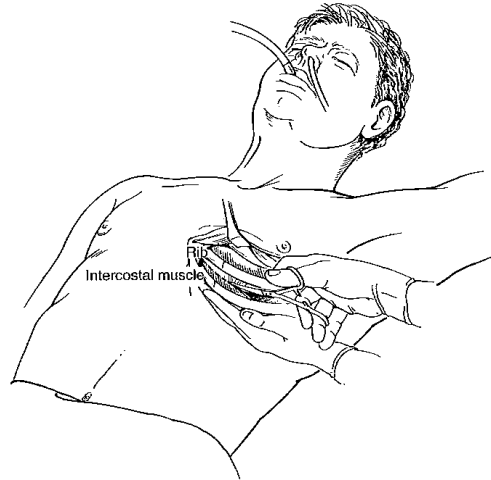


Figure 4: Incision into the Pleural Space (57)

Then, in order to obtain good exposure, the ribs are separated using a chest wall retractor (rib spreader) as shown below in Figure 5. At this point, the surgeon must determine the problem and fix it as quickly as possible. For instance, the patient may have experienced a blunt force trauma to the chest and his/her heart could potentially be secreting blood into the pericardium. This excess blood can build up in the pericardium and create pressure on the heart, making it difficult for the heart to function properly. Here the surgeon would need to make an incision in the pericardium to relieve the pressure and examine the heart as is also shown below in Figure 5.

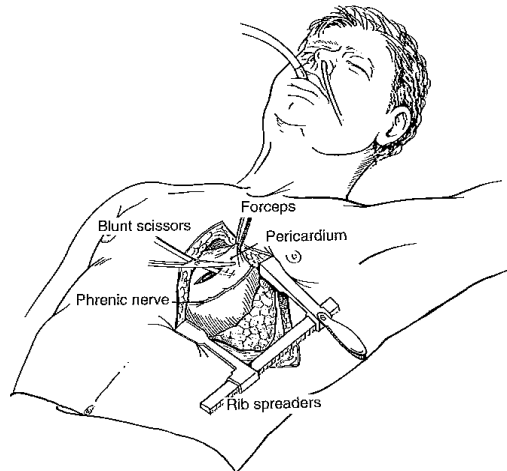


Figure 5: Rib spreaders are used to gain access to the pleural space. (57)

After obtaining access to the heart by cutting through the pericardium, the surgeon must then gain control over any hemorrhaging cardiac wounds, which can be done using materials such as staples or sutures. The technique of cardiac stapling and suturing are shown below in Figure 6.

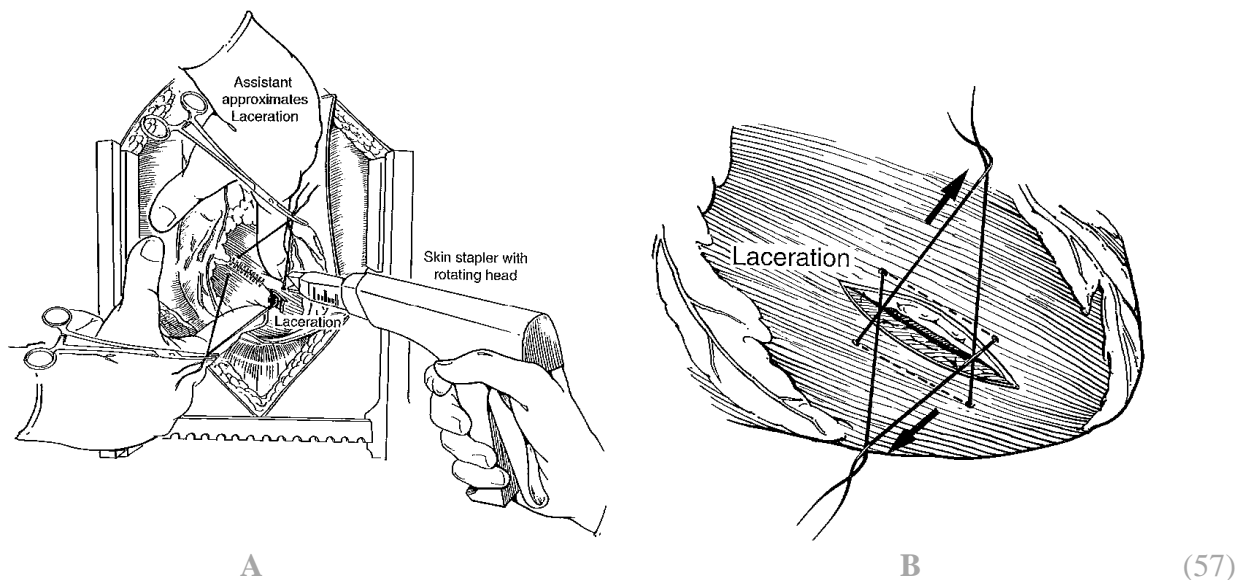


Figure 6: A, Hemorrhage control via cardiac stapling. B, Hemorrhage control via suturing.

After closing any cardiac wounds, the surgeon must exit the patient by closing up the pericardium, re-inflating the lung, inserting a chest tube, and suturing the skin. A chest tube is used to remove any access air or blood in the chest cavity that, if not removed, could cause the lung to re-collapse. A chest tube is shown below in Figure 7.

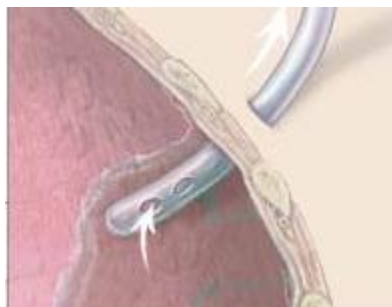


Figure 7: Chest Tube (5)

Information Sources

Types of Simulators and Simulator Selection

The following describes three main classifications of simulators based on their medium of simulating. (62)

Model based simulators: These simulators are also called part task trainers. Part task trainers are devices designed to replicate a particular part of the anatomy. These are used to practice specific, focused procedures or interventions. Examples include urinary catheter trainers, plastic arms for intravenous line placement, airway management heads, central line placement torsos, and spinal

columns (for spinal taps and epidural placement). Figure 8 and 9 below show two of these types of simulators.



Figure 8: Practicing blood withdrawal using the Model FemoraLineMan System (32)



Figure 9: An anatomically correct spine model (44)

Computer based simulators: Computers and virtual reality currently allow users to interact with an environment whose output is in 2-D through a computer screen. An example of this type of simulation is an endovascular catheterization or stenting procedure where doctors use their hands to manipulate catheters which they watch on the screen, or a bronchoscopy, in which the operator guides a scope looking into the airways of the lung, which is projected on the screen as shown in Figure 10 on page 12.

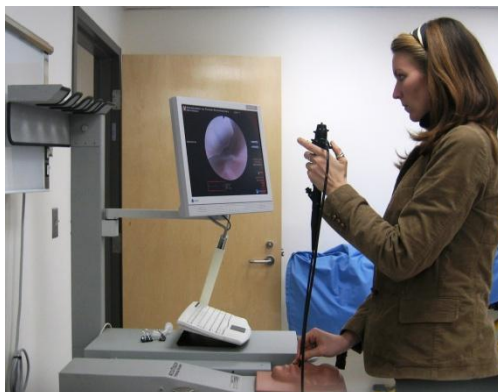


Figure 10: The AccuTouch bronchoscope simulation system (19)

Hybrid Simulators: Hybrid simulation combines characteristics of both model based as well as computer based simulators. For instance, a surgeon may be asked to place a urinary catheter into a model which appears to be part of an actual person (mannequin patient). Similarly, suture skills can be practiced on a plastic suture model which is affixed to the arm of a standard model of a patient. A hybrid simulator can be seen in Figure 11 below.



Figure 11: Working with SimMan, a hybrid simulator (47)

It is significant to note that we will be specifically making use of a model based simulator because, as per the requirement of the project, a model based simulator will enable us to adequately mimic the ‘feel’ of the heart and lungs and other internal entities in its vicinity. A computer based simulation will not be effective because its output will be in 2-D.

Simulation: Past and Present

While simulation and simulators have a long history in training programs in various domains, such as the military and aviation, their appearance on the scene of surgical training is more recent (69). The following traces the history and highlights the prominent features of the some of the earliest examples of model based simulators.

Resusci-Anne (Figure 12, page 13): While not computer driven and having relatively limited functionality, Resusci-Anne marked the beginning of the origin of the human patient simulators. Created in the early 1960s, this mannequin was used for cardiopulmonary resuscitation training. The airway could be obstructed, and it was necessary to use hyperextension of the neck and

forward thrust of the chin to open the airway before initiating insufflations of air into the mannequin by the mouth to mouth technique. Later, based on evidence of the efficacy of closed chest massage an internal spring was attached to the mannequin's chest wall, which permitted simulation of cardiac compression. (56)



Figure 12: Resuci-Anne (21)

Sim One (Figure 13 below): In the mid 1960's Sim One became the first true computer controlled mannequin simulator, particularly for simulation of the entire patient. Sim One had many high fidelity features: the chest was anatomically shaped and moved with breathing, the eyes blinked, the pupils dilated and constricted and the jaw opened and closed; unfortunately the price of computer technology was too high for commercialization and Sim One did not achieve acceptance.



Figure 13: Sim One in the late 1960's (25)

Harvey (Figure 14, page 14): In 1968, Harvey, a full sized mannequin that could simulate 27 cardiac conditions, was developed. Harvey was unique because it could display blood pressure findings by auscultation, bilateral jugular venous pulse wave forms and arterial pulses, precordial impulses, and auscultatory events in the four classic areas; these are synchronized with the pulse and vary with respiration. Harvey could even simulate a spectrum of cardiac disease by varying blood pressure, breathing, pulses, normal heart sounds, and murmurs. Harvey also inspired the development of smaller, more portable cardiology patient simulators, for example, Simulator K.



Figure 14: Harvey in the early 1970s (25)

CASE 1.2 (Figure 15 below): At the Stanford Medical School- affiliated Veteran's Affair Palo Alto Health Care System, researchers fabricated the first prototype of a human mannequin simulator for investigating human performance under anesthesia. In early 1987, the original version used for experimentation and testing was numbered CASE 1.2 (Comprehensive Anesthesia Simulation Environment). It combined commercially available waveform generators and virtual instruments. Placed in a real operating room, this was the beginning of the high realism, physical simulation environment. (33)



Figure 15: A pre-prototype of CASE 1.2 (25)

Overview of Current Simulation Facilities at the Clinical Simulation Center, University of Michigan (69)

The clinical simulation center allows faculty and trainees to use state-of-the-art simulators to learn the practice of medicine. This facility is accredited by the American College of Surgeons as a Level 1 training center. The following are examples of model based simulators that are being utilized at the facility to model medical procedures:

Trauma Man (Figure 16 below): Trauma Man is a mannequin that can simulate a variety of trauma procedures including chest tube insertion and pericardiocentesis. The Trauma Man is unique because it was the first simulator to be approved for Advanced Trauma Life Support training and certification by the College of Surgeons Committee on Trauma. This simulator includes a layer of simulated skin, a layer of simulated tissue to mimic the intercostal muscles and parietal pleura, ribs, airflow inside the pleura for a realistic response during a procedure and inflatable lungs to simulate breathing.



Figure 16: Trauma Man (61)

SimMAN (Figure 17 below): SimMAN is a life-size intubatable mannequin with a computerized graphical user interface. SimMAN can be very effectively used to teach clinical and decision making skills during realistic patient care scenarios. SimMan can also simulate airway complications, perform CPR functions, administer drugs and reproduce realistic heart and breath sounds.



Figure 17: Simulator ‘SimMan’ (69)

Human Patient Simulator [HPS] (Figure 18, page 16): The HPS is METI's top-of-the-line, fully automatic, high-fidelity patient simulator specifically designed for training in anesthesia, respiratory and critical care. What differentiates the HPS from any other simulator available on the market today, is its high level of automatic and enhanced features. The HPS is the only patient simulator with the ability to provide respiratory gas exchange, anesthesia delivery, and patient monitoring with real physiological clinical monitors.



Figure 18: Human Patient Simulator [HPS] (39)

The Effects of Simulation on Performance

Simulation techniques have been shown to prevent harm and discomfort to patients and to shorten learning curves, the latter implying that they also offer cost benefits. They can be tailored to individual learners, enabling them to progress at their own rate (73). Additionally, learning in a simulated environment allows learners to make mistakes. This is important considering that learning from one's errors is a key component of skills development (73). Apart from their worth as training instruments, simulators can also be valuable for formative and summative assessment because they enable standardized training and repeated practice of procedures under standardized conditions (73). According to Dr. Andreatta, Assistant Professor and Director of the Clinical Simulation Center at the University of Michigan, simulation is ideal for "low frequency, high acuity procedures". This describes how simulation might be invaluable to a surgeon/emergency personnel faced with the task of performing an uncommon, intricate procedure (54).

The Journal of American Medical Association article by Gallagher and Cates details the recent Food and Drug Administration decision to require simulation training prior to certification to perform carotid stenting. It contains a summary of references documenting the efficacy of simulation as a training tool in procedural medicine (particularly for laparoscopic surgery) (63). Also a 2003 study results indicated that the simulated cases could assess cognitive and procedural skills in performing interventional cardiology procedures, and could discriminate between novice and advanced skill levels of physicians performing interventional cardiology procedures (24).

In another study in 2009 conducted at Georgetown University Medical Center, replicas of a human torso with a posterolateral thoracotomy incision were constructed to house a bovine lung and student volunteers were asked to perform a lobectomy after reviewing computer simulated material. Figure 19 on page 17 indicates that the average time to complete the simulated lobectomy significantly decreased during the third week of the study to 34.8 ± 5 minutes. This improvement in operative times was sustained into the fourth week. (22)

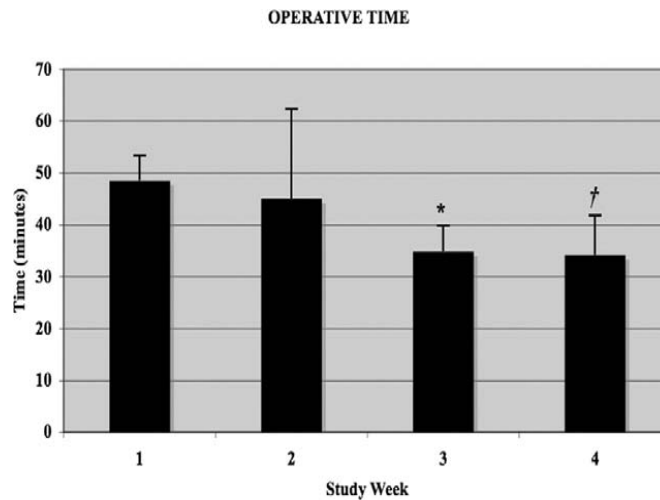


Figure 19: Improvements in Student Performance from 48.5 ±4.9 minutes to 34.8 ±5 minutes between Study Week 2 and 3. (22)

User Requirements and Engineering Specifications

The twelve customer needs were determined and weighted after discussing the problem description and the simulator requirements with our mentor at the UM Clinical Center for Simulation, Dr. Pamela Andreatta, and other clinicians at the UM Hospital. The customer requirements were based on the need that the simulator must be able to train surgeons to perform an emergency thoracotomy procedure, with robust features that enable the simulator to reproduce and fine tune the response of the organs in the chest cavity in a trauma situation.

After weighing our customer needs, we have determined the most important aspects of our prototype. The ranking of all of the user requirements and engineering specifications can be seen in Table 1 on page 24. The engineering specifications are listed as “Technical Requirements” in the table. We have divided our table into two main requirement sections: “Must Have Requirements” and “Luxury Requirements”. The “Must Have Requirements” contain the user requirements and specifications that are required for the simulator to work effectively. The “Luxury Requirements” are things that would add realism or convenience to our product but are not vital to its design. Due to the nature of our prototype, it contains many subsystems including organs, ribs, arteries and nerves that all require their own specifications pertaining to their function. This means that along with our main table, we also included sub-tables that go into more detail concerning specific components within the ranked user requirements.

We defined our user requirements by finishing the sentence: “Our simulator needs to...” By defining our requirements in this way, it made it easier to visualize how each requirement is directly related to our simulator.

Include Key Thoracic Components: The most important user requirement was determined to be the inclusion of key thoracic components. These components are listed in Table 1, page 24,

which were identified by our mentor, and their individual specifications are included in Tables 2-7, pages 24-25. Having components such as the heart, lungs, ribs and skin are absolutely necessary in the simulator because without them, there is no physical simulator on which to practice. We acquired all of the specifications for the individual components through multiple literature sources that are referenced in the tables on pages 22-23.

Be Anatomically Correct: The next most important user requirement is for the simulator to be anatomically correct. This is very important because most of the procedure is done using feel alone, and the trainees need to be able to feel around the thoracic cavity and locate landmarks within that space. We found various pictures of the relative locations of the components we are using such as Figure 21-22, page 19 or Figures 20 below, and we also attended a thoracic cadaver dissection. This allowed us to feel and see where the body parts are relative to each other within the thoracic cavity.

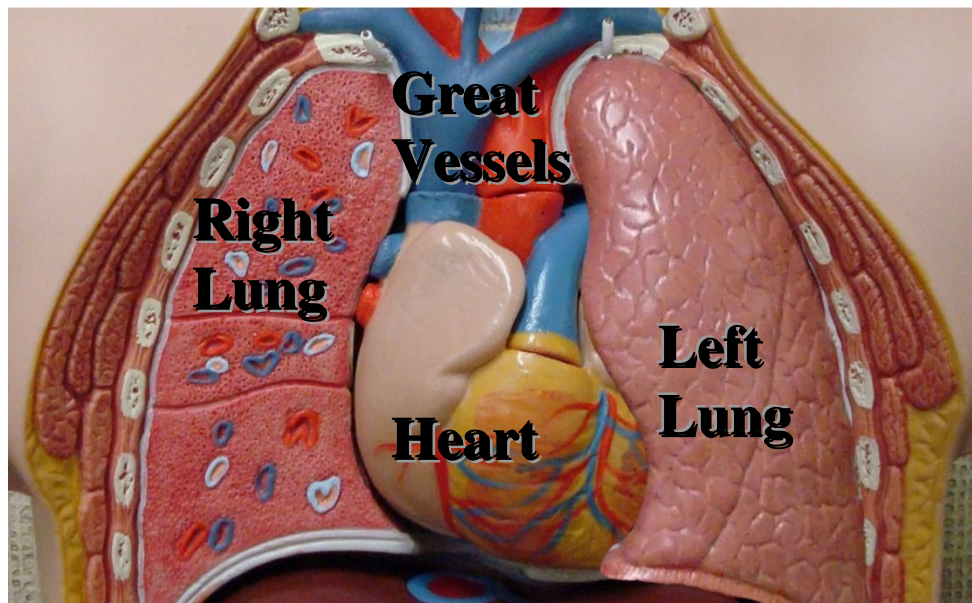


Figure 20: Relative locations of key thoracic components. (17)

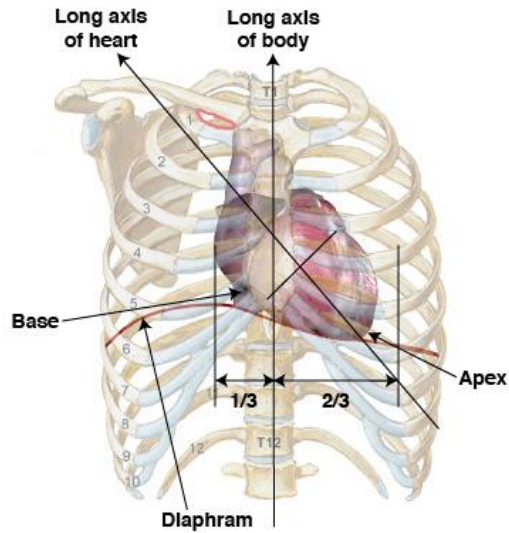


Figure 21: Position of the heart in relation to the ribs and diaphragm. (11)

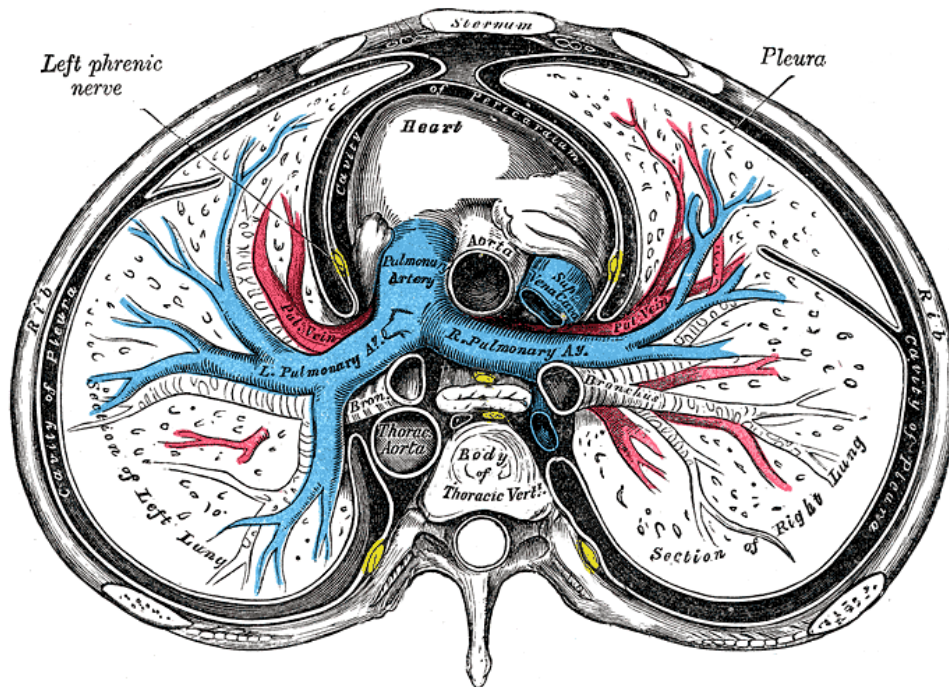


Figure 22: Transverse view of thoracic cavity. (41)

Have Skin That Allows Thoracic Cavity Access, Have Spreadable Ribs, and Have Penetrable Pleura: Skin that allows access to the thoracic cavity as well as spreadable ribs and a penetrable pleura are all ranked just below anatomically correct, and are strongly correlated. The skin and the pleura must open to allow access to everything beneath them, which is quantified by their thicknesses found from literature sources. Having ribs that can be spread to allow access to the thoracic cavity is vital in the training of surgeons, because they need to be able to correctly open the ribs and gain access without causing any more damage to the body. We consulted with our

mentor and other physicians to determine how much the ribs need to be spread in order to allow access to the thoracic cavity, which was found to be approximately 8 cm.

Respond Correctly: To enable the surgeon to learn each step in the procedure and to have a sound understanding of the repercussions of each intricate move in performing the surgery, it is critical that the organs representing the thoracic cavity respond precisely in the way that they are required to. The ribs must be able to respond in terms of caving relating to the force the surgeon applies. In a heart specific thoracotomy, the heart must not only *respond* to trauma, it must also *'feel'* real because in an emergency procedure the surgeon will rely strongly on his tactile sense to detect presence of ruptures in the heart muscle. This requirement will be evaluated after the creation of our first prototype with Likert based surveys and a Likert scale value of greater than or equal to three will be acceptable, which was decided upon by our mentor.

Throughout this report, we will make references to our components both 'responding correctly' and 'feeling real'. There is a subtle but important difference between the two concepts. In the scope of this report, 'responding correctly' is an all-encompassing term in which 'feeling real' is included, along with other characteristics. We want to make this distinction because 'feeling real' is an important aspect for components such as the heart and the lungs, because we decided in our concept generation that it is necessary to provide an accurate simulation. On the other hand, an analogous characteristic for the ribs and pleura would be modulus of elasticity because it is a main factor that defines the response we are looking for with those components. Both properties are important for their respective components and both properties can be included in the broader requirement of having a correct response.

Have Reconfigurable Skin: Reconfigurable skin is lower on the list but we feel it is important to include in our design. Reconfigurable implies that there will be three or more access points on the skin, of which the trainee must pick the correct one. This is important because in an emergency it can be easy to make simple mistakes and it is necessary to train surgeons to know exactly where to enter the skin every time. The correct incision location and direction which we will incorporate into our simulator was shown in Figure 23, page 21. We will also place some other possible entry points in commonly used but incorrect locations on the torso, which are also shown on page 21 in Figure 23.

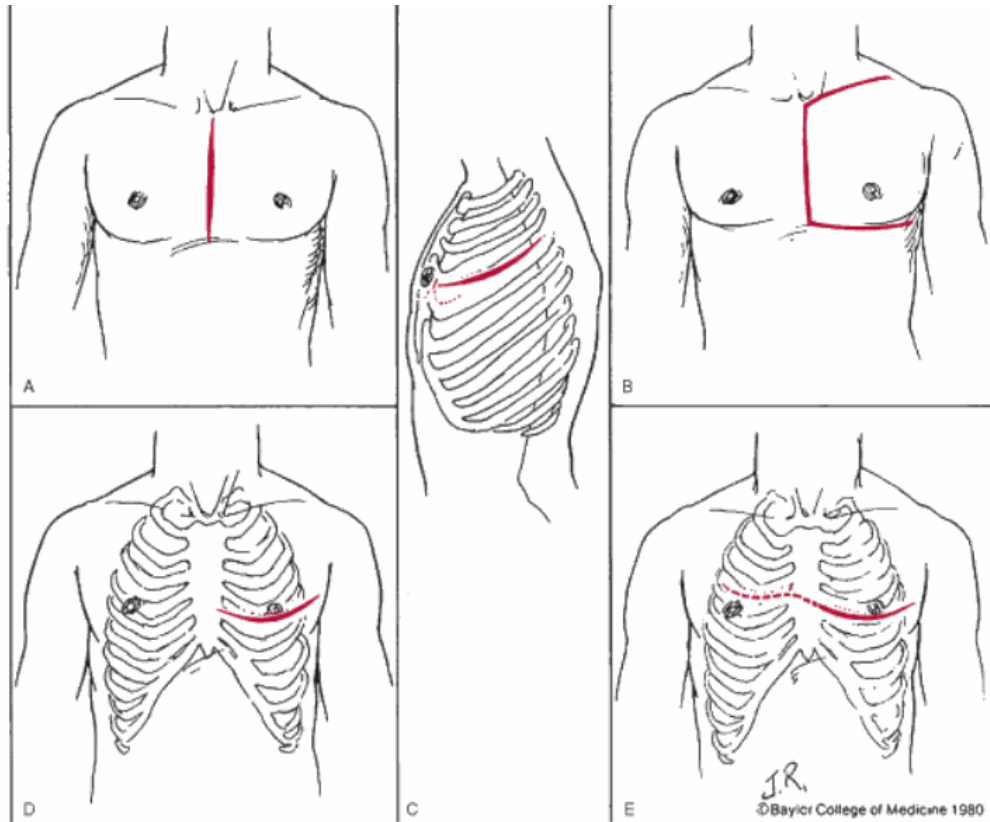


Figure 23: Various Thoracic Incisions for Trauma (31)

Have Penetrable Pericardium: Once the trainee has gotten through the skin, ribs and pleura, they must feel around and locate the heart which is surrounded by the pericardium. Having a penetrable pericardium is necessary because it is something the surgeon must be able to navigate through in order to get to the heart and fix whatever the problem may be. This is quantified by pericardium thickness, which was found from a literature source.

It is at this point that we feel it is necessary to clarify a unique aspect of our requirements table. Although requirements such as evaluative feedback are listed at lower rankings than the above requirements, it is not meant to imply significantly less importance than those ranked higher on the chart. The top eight requirements are all involved with making the actual simulator. However, having a physical simulator is only half of the project. We also need to incorporate a way to train and rate the users that practice on the simulator and that is where evaluative feedback comes into play. We ranked all of our must-have requirements against each other because we need a way to evaluate the relative important of each requirement. In order for our simulator to work as requested, all of the top ten requirements are necessary, regardless of rank. We want to make this distinction because relatively speaking, we put a lot of thought and time into the feedback system of the heart and lungs as described later in this report. This is because as previously mentioned, the first eight requirements and the last two requirements in the must-have portion combine to make two halves of a whole, working simulator.

Provide Evaluative Feedback: Evaluative feedback is an important feature of the simulator as well because it provides a tangible way to measure a surgeon's performance. It is critical in

allowing the surgeon to learn from his/her mistakes and make steps to correct them. Feedback types include 100% tactile examination of all the surfaces/structures of the heart, correct location and direction of the incision and correct location and translocation of the rib spread (summarized in Table 8 on page 26). These feedback types were decided on and quantified by our mentor as well as literature sources ((31), (57)).

Have Collapsible Lung: Having a deflatable lung is last on the “Must Have” requirements because while it is not a completely necessary step in performing emergency thoracotomies, it is a widely used asset to gain more working space during this critical procedure. (57)The trainee needs to be able to judge for themselves if they need more space, and they need the ability to train with and without a collapsed lung available. The lung must go from being 100% filled with air to being less than or equal to 10% filled with air, which was decided upon by our mentor.

(The following user requirements are solely for luxury purposes and are not vital in the design of the simulator, though they still will be taken into consideration.)

Be Affordable: For any prototype to culminate in a successful design, it is imperative to make sure that the deliverable is affordable. In terms of designing the thoracotomy simulator, our costs will be directly defined by the number of materials we use to manufacture our representative organs, the cost of each of those materials and how many times we are able to use that material before we can discard it. The simulator must cost, in total, less than \$400.

Use Standard Power Source: A usable power source only depends on the source voltage available; in the US this would mean 120V.

Have Minimum Replaceable Parts: This quality has a strong correlation with the reusability of the representative organs in the simulator because the fewer times the parts need to be replaced, the more advantage we gain in terms of cost effectiveness. In particular, if the heart muscle does not need to be replaced as often, this means that the heart material has the quality of being more replaceable. Our simulator must have less than four replaceable parts, which was decided after researching other simulators.

Be Reusable: The components of the simulator must be reusable because this is a vital quality that will distinguish it from the expensive varieties currently available. For example, the Trauma Man’s skin can be reused 5-8 times but each of its skin sections cost almost \$8000, which makes Trauma Man inefficient in terms of cost. If the components in our model can be used to simulate a procedure multiple times, it would have a direct impact in terms of possible cost reduction. Based on the reusability of other simulators, it was decided that our simulator components must be able to be reused greater than five times.

Be Transportable: This criterion certainly correlates strongly with the physical considerations of the simulator such that the overall dimensions should not be bulky in terms of the weight nor the volume. The simulator should weigh no more than 8 kg, which was decided after researching other simulators, and should have dimensions as outlined in Table 3 on page 25 in order to be anatomically correct.

Have Injury Options: The greater the number of thoracotomy procedures the simulator is able to recreate, the more specialized and detailed the model of the representative heart would be. For instance, while the heart bleeding into the pericardium such that cardiac tamponade is present is an option, the heart may instead be leaking into to the thoracic cavity due to a previously ruptured pericardium. Our simulator should provide greater than one trauma scenario, which was decided by our mentor.

Be Easy to Manufacture: This is an important quality because ease of manufacturing means that housing /mounting the representative organs will not be tedious. The ease in manufacturing will make it easier to monitor responses such as beating rate/breathing rate and for performing procedures such as deflating one of the lungs to reach near the heart. We have quantified this as number of materials used, which should be less than ten.

Have Blood Flow: Being able to monitor this characteristic is important because we are interested in performing a heart thoracotomy. Therefore we must be able to adequately quantify vital heart monitoring characteristics such as the heart beat rate and the blood loss to get a precise indication of the health of the heart muscles. Our simulator should pump blood at a rate of 50-150 mL/s, which was determined through literature sources.

Table 1: Comprehensive List of User Requirements and Rankings

	User Requirements	Rank	Technical Requirements
Must Have Requirements	Include key thoracic cavity components: Heart } Pericardium } Phrenic Nerve } Ribcage } Pleura } Lungs Aorta Pulmonary Artery Skin	1	See Table 2 See Table 3 See Table 4 See Table 5 See Table 6 Must Cover Thoracic Cavity
	Be Anatomically Correct	2	See Tables 2-7
	Have Skin That Allows Thoracic Cavity Access	3	Yes
	Have Spreadable Ribs	4	Separate 8 cm
	Have Penetrable Pleura	5	See Pleura Thickness in Table 3
	Respond Correctly	6	Likert Scale Value ≥ 3 & See Table 7 Rib Spread Force ≈ 100 N
	Have Reconfigurable Skin	7	≥ 3 access points
	Have Penetrable Pericardium	8	See Pericardium Thickness in Table 2
	Provide Evaluative Feedback	9	See Table 8
	Have Collapsible Lung	10	From 100% to $\leq 10\%$ filled with air
Luxury Requirements	Be Affordable	11	Less than \$400
	Use Standard Power Source	12	Can use 120V outlet
	Have Minimum Replaceable Parts	13	Less than 4
	Be Reusable	14	Greater than 5
	Be Transportable	15	See Table 3 & Less than 8 kg
	Have Injury Options	16	Provide > 1 trauma scenario
	Be Easy to Manufacture	17	Less than 10 materials used
	Have Blood Flow	18	50 – 150 mL/ s

Table 2: Characteristics of the Heart, the Pericardium, and the Phrenic Nerve

Characteristic	Dimension
Average Width	9 cm
Average Height	13 cm
Stroke Volume	0.28 liters (26)
Heart Rate	70 beats/min (38)
Flow Rate	5 liters/min (23)
Beat Time Ratio	$(t_{21} / t_{tot}) = 0.3$ (12)
Pericardium Thickness	0.7-1.2 mm (20)
Phrenic Nerve Length	20-24 cm (68)
Phrenic Nerve Diameter	0.76 mm (68)

Table 3: Dimensions of the Thoracic Cavity and the Pleura

Characteristic	Dimension
Height	32 cm
Width	32 cm
Depth	24 cm
Average Circumference	95 cm
Cavity Volume	25 liters
Pleura Thickness	0.14 mm (42)

Table 4: Dimensions of a Lung (34)

Characteristic	Dimension
Inspiratory Volume	3.5 liters
Expiratory Volume	3 liters
Inspiratory Height	23 cm
Expiratory Height	25 cm
Breathing Rate	12 breaths/min (60)
Breath Length	2.5 s

Table 5: Dimensions of the Aorta

Characteristic	Dimension
Diameter	2.5-3 cm (27)
Length of Ascending Aorta	5 cm (65)
Length of Descending Aorta	20 cm (65)

Table 6: Dimensions of the Main Pulmonary Artery

Characteristic	Dimension
Diameter	2.72 cm (18)
Length	5 cm (66)

Table 7: Material Properties of Components

Characteristic	Modulus of Elasticity (MPa)	Poisson's Ratio	Ultimate Tensile Strength (MPa)
Cartilages	$E_{\text{tensile}} = 24$ $E_{\text{compressive}} = 483$ $E_{\text{equivalent}} = 64$	0.1	4.7
Ribs	12,000	0.2	124
Sternum	12,000	0.2	124
Heart	0.021	0.3	-
Lung	0.0066	0.45	-
Pericardium	100	-	-
Aorta (14)	0.4 – 1.0	0.3 - 0.7	-
Pulmonary Artery (13)	0.1-0.5	-	-

Table 8: Types of Feedback

Component	Feedback Type	Specification
Heart	Tactile examination of major surfaces/structures	100% of surface examined
Incision	Location	3 rd or 4 th intercostal space
	Direction	See Figure 23, page 21
Ribs	Location of spread	3 rd or 4 th intercostal space
	Translocation of spread	Perpendicular to rib direction

Breakdown of Representative Parts

The Thoracic Cavity

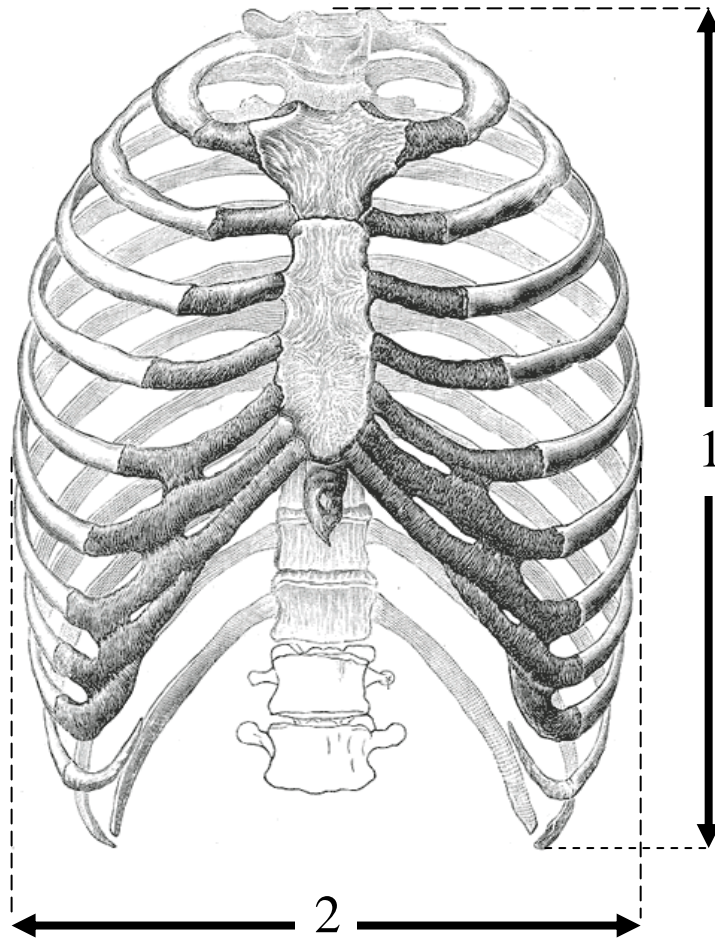


Figure 24: The Thoracic Cavity (36)

The thoracic cavity contains everything in the thorax region, which includes vital organs such as the heart and lungs, as well as the aorta, rib cage, and various other nerves and arteries. The pleura is a thin covering that lies just underneath the rib cage, which protects and cushions the lungs. The dimensions of the thorax can be estimated by the overall dimensions of the rib cage, which are given in Table 2 below. The thickness of the pleura is given here as well.

Table 9: Dimensions of the thoracic cavity and the Pleura. (35)

Height (1)	32 cm
Length (2)	32 cm
Depth	24 cm
Top Circumference	100 cm
Bottom Circumference	90 cm
Cavity Volume	25 liters
Pleura Thickness	0.14 mm (42)

The Sternum

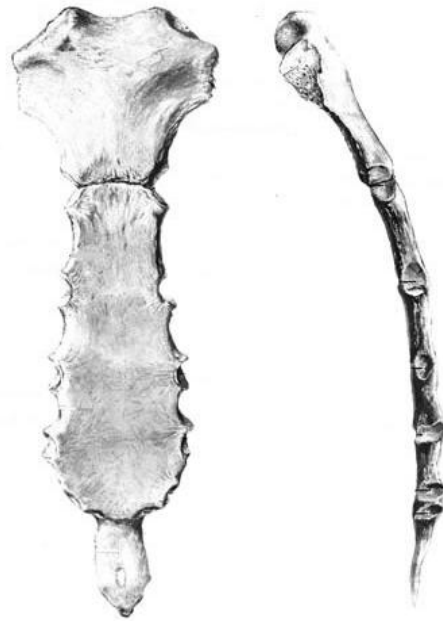


Figure 25: The Sternum (67)

The sternum is a long flat bone located in the middle of the thorax. It connects to the ribs via cartilage, forming a protective cage around the vital organs and arteries in this region. The approximate dimensions of the sternum are given below in Table 3.

Table 10: Dimensions of the Sternum (59)

Total Height	20 cm
Area	64 cm ²
Volume	73 cm ³

The Heart



Figure 26: The Heart (75)

The heart is one of the most important organs in the human body, as it pumps blood throughout the circulatory system. The heart is surrounded by a thin two-walled sac called the pericardium. Table 4 below includes some of the characteristics of the heart and its surrounding sac.

Table 11: Characteristics of the Heart and the Pericardium

Average Width	9 cm
Average Height	13 cm
Stroke Volume	0.28 liters (26)
Heart Rate	70 beats/min (38)
Flow Rate	5 liters/min (23)
Beat Time Ratio	$(t_{21}/t_{tot}) = 0.3$ (12)
Pericardium Thickness	0.7-1.2 mm (20)

The Lungs



Figure 27: The Lungs (45)

The lungs are two spongy organs whose main function is to transport oxygen into the bloodstream from the air and to transport carbon dioxide into the air from the bloodstream. They are the essential organs in a human's respiration system. The dimensions of a lung are given in Table 5 below.

Table 12: Dimensions of a Lung (34)

Inspiratory Volume	7 liters
Expiratory Volume	6 liters
Inspiratory Height	23 cm
Expiratory Height	25 cm
Breathing Rate	12 breaths/min (60)
Breath Length	2.5 s

The Aorta

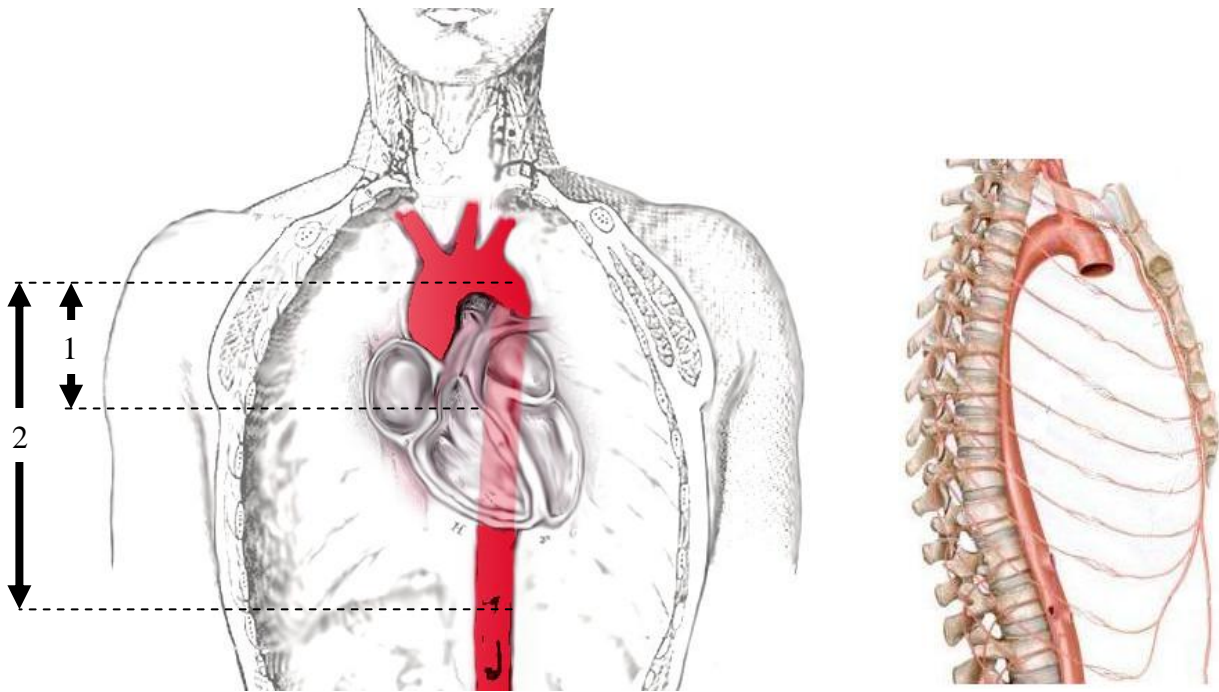


Figure 28: The Aorta (10), (16)

The aorta is the largest blood vessel in the human body; it originates from the left ventricle of the heart, ascends for a bit (ascending aorta), bends over, and then continues down through the thoracic cavity (descending aorta). The approximate dimensions of the aorta are given in Table 6 below.

Table 13: Dimensions of the Aorta

Diameter	2.5-3 cm (27)
Length of Ascending Aorta (1)	5 cm (65)
Length of Descending Aorta (2)	20 cm (65)

The Pulmonary Artery

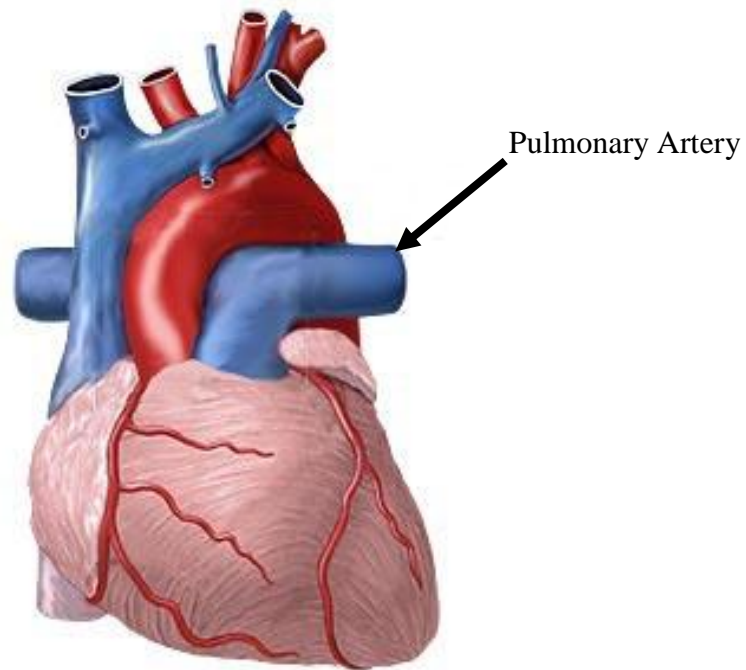


Figure 29: The Pulmonary Artery (4)

The pulmonary artery carries blood from the heart to the lungs. The main pulmonary artery, which is shown in blue above, originates from the base of the right ventricle and its dimensions are given below in Table 7.

Table 14: Dimensions of the Main Pulmonary Artery

Diameter	2.72 cm (18)
Length	5 cm (66)

The Phrenic Nerve

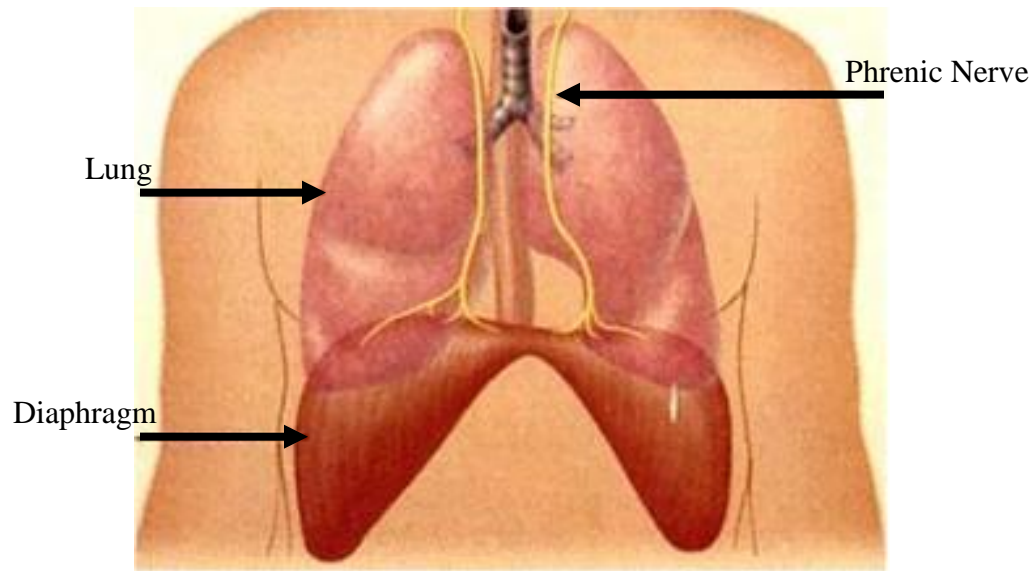


Figure 30: The Phrenic Nerve (51)

The phrenic nerve is a nerve which runs from the neck to the diaphragm and gives the diaphragm the ability to contract. The human body has left and right phrenic nerves which run vertically on either side of the heart. This nerve also supplies some sensation to the chest and upper abdomen. Each of these nerves should be 20-24 cm long (68).

Concept Generation/Selection

In order to facilitate our generation and selection of design ideas for our thoracotomy simulator, we broke down our process into several steps, which are outlined below:

1. Create functional decomposition
2. Attend anatomy lab
3. Brainstorm
4. Systematic elimination/selection:
 - a. Go/no-go screening
 - b. Pugh Charts

The following sections describe the thought process for brainstorming ideas and the methods we used to arrive at decisions pertaining to material and mechanism selection for each component in our simulator.

Functional Decomposition

In order to begin creating different concepts for the individual components of our simulator, we decided to create our own version of a functional decomposition as seen on page 36. Since the process of performing a thoracotomy procedure is based on humans operating on specific component organs within the thoracic cavity, we divided the functional decomposition into each of the six components representative of structures found in the thoracic cavity. These structures included the skin, ribs, pleura, lungs, pericardium and the heart. They are listed sequentially on a time scale, in the order that a surgeon would interact with them while he/she is performing a thoracotomy. Next, we determined the general inputs and outputs of each component, along with the basic function each component must perform.

The 'Function' section of the functional decomposition described the action expected from each component once an input was supplied to it. For instance the skin, pericardium and pleura were expected to 'open' to allow access to the next component in the thoracic cavity. Similarly, the heart was expected to simulate a rhythmic 'beat' to mimic a realistic feel of performing the procedure.

Inputs to our simulator were classified as 'materials' or 'energy'. 'Materials' included the instruments we will use to access the thoracic cavity. For instance, materials such as rib spreaders could be used to spread the ribs or a blade could be used to create an incision on the skin. 'Energy' inputs include human, electrical, mechanical, or chemical. For example, energy expended from a human is needed to perform procedures such as creating the incision on the skin or spreading the ribs. Also, electrical energy was an input to the heart, since the motor will require an electrical source.

Outputs typically comprised visual or tactile information in order to communicate feedback of each procedural step back to the surgeon. An example of a visual output was the ability to view the pleural cavity after spreading the ribs. An example of a tactile output was the ability of the surgeon to feel the structures on the heart so that sensing an anomalous feature would be an indication of the need for a more thorough examination of that region.

We further divided the entire process of concept decomposition into two stages: “Entry” and “Fixing the Problem”. This distinction was necessary in order to distinguish between components and procedures that were needed to gain access to the thoracic cavity and those that were necessary in locating and mending the regions affected by trauma.

After deconstructing the entire process into our functional decomposition, we were then able to concentrate on the brainstorming and design of each individual component more effectively.

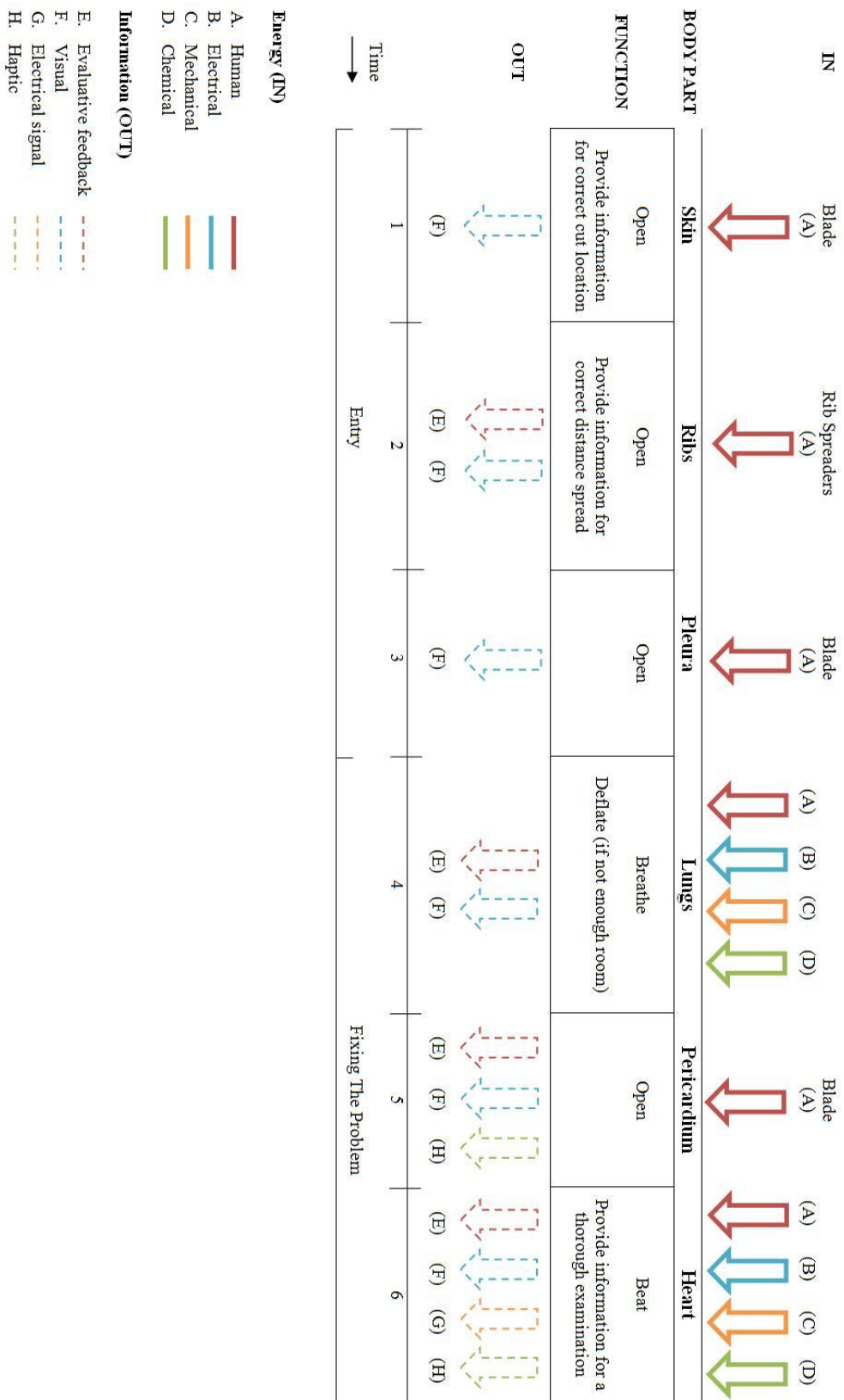


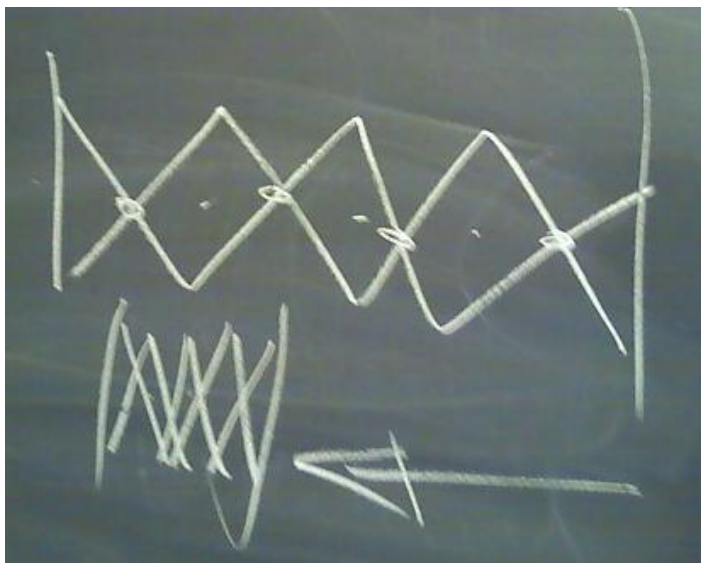
Figure 31: Functional Decomposition

Anatomy Lab

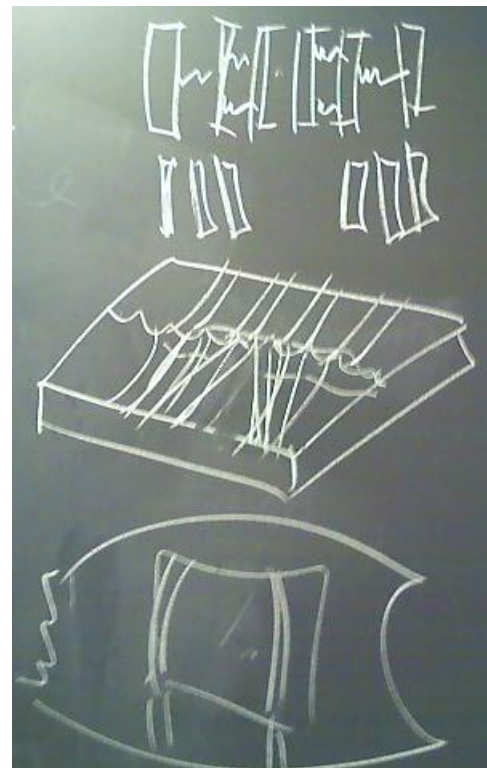
We also had the opportunity to visit an anatomy lab² and view a cadaver dissection. This allowed us to get a better grasp of the spatial location of each component within the thoracic cavity in relation to other components. We were also able to learn how each of the components were connected and intertwined with each other and how they felt. This allowed us to have a better idea of what exactly we were going to model, hence aiding us in our brainstorming process.

Brainstorm

The next step was to use our functional decomposition chart to facilitate the brainstorming process for material selection. For this process, the team decided to forgo all barriers to thought and criteria and first compiled a vast list of possible raw materials/mechanical parts for each function of each thoracic component. For example, the rib cage was brainstormed in two main sections: creation of rib joints to allow for spreading and selection of materials to mimic the correct rib response. Suggestions for rib joints included using torsional springs, linear springs, tracks, rubber, pneumatics, or scissor hinges. The ideas of utilizing scissor hinges (A) and linear springs (B) for joints are shown below in Figure 32. Suggestions for raw materials for modeling the rib cage ranged from using wood, plastic, or metal to bacon, noodles, or paper mache. Similar analysis was done for the rest of the thoracic components and a list of all ideas for raw materials/mechanical parts can be viewed in the [appendix on pages 112-115](#).



A



B

Figure 32: Sample Rib Concepts: A, Scissor Hinge. B, Linear Springs.

² Medical Gross Anatomy – Dissection 4 and 5, University of Michigan Medical School, 10/6 and 10/8

Systematic Elimination/Selection

Go/No-Go Screening

After accumulating as many ideas as possible, we began a discussion phase leading to systematic elimination. The elimination began by applying Go/No-Go screening tests to evaluate each concept based on how well they fit in with the user requirements. Performing this step was helpful in identifying and hence eliminating ideas that were impractical from either a manufacturing or from an end user's requirement point of view. For instance, bacon was suggested as a possible raw material for modeling the rib because it would fulfill the criteria of being cheap. However, we eliminated this option (by assigning it a 'No' in the screening) instantly due to the inconvenience in manipulating it for manufacturing. Bacon would also not fulfill the important requirement of being reusable since it might rot over time, and it would not fulfill the requirement of being anatomically correct. On the other hand PVC was retained as a viable raw material option for the ribs by assigning it a 'Yes' in the go/no-go screening process. This was because PVC fulfilled the requirement of being cheap and being capable of providing the quality of a realistic feel for the ribs. A second example would include the initial idea of using dead fish as lung material. During screening, we concluded that, even though a dead fish would fulfill the criteria of being cheap and imitate the feeling of 'real' fibrous lung muscle, it was eliminated instantly due to the inconvenience in manipulating it for manufacturing (by assigning it a 'No'). The dead fish would also create an unpleasant odor and would not fulfill the important requirement of being reusable since it might rot over time. A material such as foam, however, was a feasible option and therefore was assigned a 'Yes'. A similar trade off analysis was conducted to draw out the best contenders for all the remaining components.

Pugh charts

Next, we used pugh charts to create a selection matrix, in order to rate the remaining feasible concepts versus applicable user requirements. The pugh chart represents the ideas which were narrowed down from the brainstorming session for their feasibility in representing the thoracic cavity organs in accordance with the user requirements.

Ribs: Figure 32 below shows the pugh chart created for the ribs. First, the ideas which fell into the two main sections, rib joints and rib material, were listed and ranked individually. All of the specifications related to the specific component were listed under the selection criteria and weighted in the same order as they are listed in the user specifications table (Table 1 on page 24).

Ribs		Joints				Material		
		Accordion	Torsion Springs	Slide on Track	Rubber	Plastic/Laser	PVC	Metal
Selection Criteria	Weight							
Is Anatomically Correct	9	1	9	1	9	9	9	9
Has Spreadable Ribs	8	9	9	9	9	9	9	9
Responds Correctly/ Feels Real	7	1	9	1	9	3	9	1
Provides Evaluative Feedback	6	9	9	9	9	9	9	9
Affordable	5	3	3	3	9	3	3	3
Minimum Replaceable Parts	4	9	9	9	9	9	9	9
Reusable	3	9	9	9	9	9	9	9
Transportable	2	3	9	3	9	9	9	3
Ease of Manufacturing	1	1	3	1	1	9	1	3
Total Score		227	369	227	397	333	367	301
Rank					Winner		Winner	

Figure 33: Rib Pugh Chart

As shown in the pugh chart (Figure 33, page 38), options for rib joints included using ‘accordion’ style hinges, torsional springs, sliding tracks, or rubber. We evaluated that an ‘accordion’ style of ribs, or scissor hinges, could compress or expand with great ease. The scissor hinges could be sandwiched between two sheet metal plates and therefore had potential to even model the slightly slanted, downward facing curvature of the ribs. However, the pugh chart analysis revealed the shortcomings of this design because this configuration neither covered the important user requirements of feeling similar to real ribs in touch, nor did it entail the requirement of ease in manufacturing. We also realized that this configuration would be anatomically incorrect, therefore we eliminated this idea.

Incorporating torsional springs in our design for rib joints was the next option. Torsional springs could imitate the responsive forces of the ribs well, making the spreading of them feel very real. Placing the torsional springs at the actual location of rib rotation could also allow the ribs to be anatomically correct. They would also be extremely reusable, as they would hold up well and be very stable. However, torsional springs can be complicated to use in manufacturing/assembly and are not very cheap compared to other materials. Therefore, this design idea was discarded in the pugh chart comparison.

Another possible option for modeling the rib joints was to use tracks to slide the ribs on. Though this design could be reusable, could allow for the ribs to spread and even could have minimum replaceable parts, we concluded that the tracks would be complicated to manufacture. This drawback would not allow for the correct rib response, and therefore make the rib structure anatomically incorrect. Hence, this idea was eliminated.

The last idea in the pugh chart comparison for rib joints was rubber. Rubber could allow for the ribs to be spread in an anatomically correct way, would be cheap to use, and would allow the ribs to respond correctly. We determined that the only downfall of this idea was that it may be difficult to use in manufacturing due to considerations of the tough texture of rubber and its interaction with other component materials. Rubber won in the pugh chart comparison because it excelled in other areas of fulfilling the user requirements ranging from providing effective feedback, being affordable, reusable and having the minimum number of replaceable parts.

Options for rib material, as shown in the pugh chart (Figure 33, pg. 38), included thin plastic, PVC and metal. Thin plastic could allow the ribs to be anatomically correct, it would be easy to manufacture, and would be very reusable. However, it would not fulfill the very important user requirement of “feeling real”. PVC could have a response very similar to that of real ribs, it would be cheap and easy to make and it will last through many procedures; however PVC is not very easy to use in manufacturing. Metal would also allow the ribs to be anatomically correct and spreadable, but this material is not very affordable and not easy to use in manufacturing, nor would allow for the ribs to have the correct response. Subsequently, PVC won in this pugh chart comparison for rib material.

Similar pugh chart analysis was conducted for the remaining concepts, relating raw materials/mechanical parts of other components in the model thoracic cavity. This analysis is outlined in the discussion below.

Skin: For the skin component, comparisons fell into three categories: general incision ideas, specific materials, and openings for the materials as can be seen in the skin pugh chart in Figure 34 below.

Skin

Selection Criteria	Weight	General Ideas		Specific Material				
		Malleable	Material w Openings	Leather	Ballistics Gel	Rubber	Wet Suit Material	Towels/cloth
		Is Anatomically Correct	10	9	9	9	9	9
Has Skin That Allows Thoracic Cavity Access	9	9	9	9	9	9	9	9
Responds Correctly/ Feels Real	8	3	3	3	9	9	9	1
Has Reconfigurable Skin	7	3	9	9	9	9	9	9
Provides Evaluative Feedback	6	9	9	9	9	9	9	9
Affordable	5	3	9	1	3	3	1	9
Minimum Replaceable Parts	4	0	9	0	0	0	0	0
Reusable	3	0	9	0	0	0	0	0
Transportable	2	1	9	9	9	9	9	9
Ease of Manufacturing	1	9	1	9	3	9	9	9
Total Score		296	439	344	396	402	392	368
Rank		Lose	Win			Winner		

Openings for Material						
Zipper	Velcro	Magnets	Buttons	Flap/door (hinged)	Ziplock	Laces/Sutures
9	1	1	1	3	9	9
9	9	9	9	9	9	9
9	1	1	1	3	3	9
9	9	9	9	3	9	9
9	9	9	9	9	9	9
9	9	3	9	3	9	9
9	9	9	9	9	9	9
9	9	9	9	9	9	9
9	9	9	9	9	9	9
3	9	9	9	3	3	9
489	351	321	351	309	441	495
						Winner

Figure 34: Skin Pugh Chart

The general options of using a malleable skin material that would allow the surgeon to cut through the material during each simulated procedure and using a material with pre-made openings/closings that would be resealable after each procedure was first compared. This comparison can be seen in the first section of the skin pugh chart above (Figure 34). We favored the pre-cut design over the malleable skin material because it would truly test a surgeon's assessment and evaluative skills in selecting the correct location for the incision amongst a varied group of incorrect options.

Next, we pooled ideas for types of raw materials we could use to create pre-made openings and for types of mechanisms that would allow for such a configuration, which can also be seen in the skin pugh chart above (Figure 34). The ideas for the materials for the pre-made openings included leather, ballistics gel, rubber, wet suit material (neoprene) and towels. The leather and cloth received the lowest scores on the pugh chart evaluation because they failed to satisfy the

essential requirement of feeling or responding similar to real skin. The ballistics gel and the neoprene ranked higher on the pugh charts; however, the main specifications where these materials differed were in terms of their affordability and in their ease of manufacturing. Overall, the rubber won because it was able to score high in terms of providing ease of manufacturing, easy access to the thoracic cavity, being reconfigurable and, most importantly, being anatomically correct within the chest.

As a final step in developing methods for simulating skin, we brainstormed for ways that the raw materials could open to allow for access to the components in the thoracic cavity. These mechanisms included using zippers, Ziploc bags, Velcro material, magnets, buttons, laces/sutures and hinged doors. An essential criterion for the selection of the opening mechanism was to ensure that it mimicked the hand movement of a surgeon creating a skin incision. Using this requirement in conjunction with the remaining specifications, we determined that the hinged door configuration ranked the lowest on the pugh chart because it failed to fulfill the indispensable requirements of being anatomically correct and of mimicking a surgeon’s hand movement. The magnets, ranked second lowest, were deemed unusable because of high price and lack of ease in manufacturing, along with their inability to simulate the action for creating an incision. The Velcro and the buttons tied for the third lowest rank because they both ranked low in providing a correct response and in replicating the feel or response of sutures and incisions for a real skin. The configuration involving the laces ranked the highest because they demonstrated the most potential for fulfilling the entire spectrum of our user specifications for the simulator.

Lungs:

The pugh chart for the lungs (shown below in Figure 35) is comprised a comparison of possible lung materials which included Nerf balls, ballistics gel, balloons, wet suit material, and foam. User specifications were then applied to each option to single out a successful raw material. The Nerf ball possessed qualities of being reusable and easily replaceable, with minimum replaceable parts but was not selected because we determined that the Nerf ball would not be easy to use in manufacturing; because of its set shape, it would not be able to be manipulated into the correct lung shap. Furthermore, it would not be able to characterize the correct response expected from a model lung in the simulator. Ultimately, foam was selected for representing the lungs because it ranked the highest in fulfilling the entire range of user specifications.

Lungs		Nerf Ball	Ballistics Gel	Balloon	Wet Suit	Foam
Selection Criteria	Weight					
Is Anatomically Correct	9	9	9	3	9	9
Responds Correctly/ Feels Real	8	3	9	3	9	9
Provides Evaluative Feedback	7	9	9	9	9	9
Has Collapsible Lung	6	0	9	9	9	9
Affordable	5	9	9	9	1	9
Minimum Replaceable Parts	4	9	9	9	9	9
Reusable	3	9	9	3	9	9
Transportable	2	9	3	9	9	9
Ease of Manufacturing	1	1	3	9	1	9
Total Score		295	387	285	357	405
Rank						First Place

Figure 35: Lung Pugh Chart

Design ideas to allow the lungs to breathe were coupled with the ideas to make the heart pump; therefore, only one pugh chart for this function was created. The variety of options we explored

are discussed later in the heart section. We chose to select an electric fluid pump relative to a hand pump to provide the ‘breathing’ functionality to the lungs. An electric pump would be practically feasible because the surgeon will not be distracted by the task of pumping the hand pump while performing the thoracotomy procedure simultaneously.

Thin Linings (Pleura and Pericardium): The primary challenge in modeling these linings was the material selection to account for the texture of the material in surrounding and supporting the organs in their vicinity. The pugh charts for both thin linings are shown below in Figure 36.

Thin Linings

Pleura

		Plastic Bag	Cellophane	Silly Putty	Touchable Bubbles
Selection Criteria	Weight				
Is Anatomically Correct	9	9	9	9	9
Has Penetrable Pleura	8	9	9	9	9
Responds Correctly/ Feels Real	7	9	3	1	9
Provides Evaluative Feedback	6	9	9	9	9
Affordable	5	9	9	3	3
Minimum Replaceable Parts	4	1	1	9	1
Reusable	3	0	0	9	0
Transportable	2	9	9	9	3
Ease of Manufacturing	1	9	9	1	1
Total Score		346	304	311	296
Rank		Numba 1			

Pericardium

		Plastic Bag	Cellophane	Zip-Lock Bag	Silly Putty	Thick Balloon
Selection Criteria	Weight					
Is Anatomically Correct	9	9	9	9	9	9
Responds Correctly/ Feels Real	8	9	3	3	1	9
Has Penetrable Pericardium	7	9	9	9	9	9
Provides Evaluative Feedback	6	9	9	9	9	9
Affordable	5	9	9	9	3	9
Minimum Replaceable Parts	4	1	1	1	9	9
Reusable	3	0	0	0	9	0
Transportable	2	9	9	9	9	9
Ease of Manufacturing	1	9	9	9	1	9
Total Score		346	298	298	303	378
Rank		Da Bomb				

Figure 36: Pugh Charts for the Thin Linings

Concepts of using touchable bubbles or silly putty were attractive for the pleura because they could ultimately be made to model thin sacs and therefore come very close to replicating the role of these linings in the real human body. However, both the silly putty and the touchable bubbles were eliminated because they lacked the essential quality of being easy to manufacture. The options of using the plastic bag and the cellophane were in close contest with each other; however, the plastic bag was selected. This was because firstly it fulfilled virtually the entire spectrum of specifications. Secondly, discussion with Dr. Andreatta confirmed that choosing the plastic bag was a more realistic model for the pleura because if an equal force was applied perpendicularly to both a taught plastic bag and a taught piece of cellophane, the cellophane would stretch more before ‘popping’ relative to the plastic bag (which would ‘pop’ instantly) . This property of mimicking the ‘popping’ of the pleura was necessary to replicate the correct response of this component.

For modeling the pericardium, we initially thought that using Ziploc bags would be useful due to its material properties and thickness. However, we realized that the bags would need to be melted in order to account for correctness in shape to fulfill the essential criteria of being anatomically correct. Next, we considered using a plastic bag; however, we eliminated this option because the plastic bag would involve the tediousness of replacement after each puncture/accidental tear. Hence our remaining contenders were thick balloons and cellophane. Cellophane ultimately lost to the thick balloons in the criteria of having minimum replaceable parts for the mechanism. We also consulted Dr. Andreatta for further input on analyzing the two materials and she advised on selecting the thick balloons based on the fact that they would be more successful in replicating the tensile and thickness properties of the pericardium

Phrenic Nerve: Just like the thin linings and the lungs, ideas compared for the phrenic nerve were also based solely on material selection. They included considerations for materials such as a tourniquet, a shoe lace, dental floss, or surgical tubing. The ideas of using a tourniquet and a shoe lace tied in the pugh chart comparison for this material (this can be seen in the phrenic nerve pugh chart in Figure 37 below). These ideas received high scores due to their anatomical correctness, for their ability to provide evaluative feedback and for their quality of being easily reusable and replaceable. However, we decided to select the shoe lace instead of the tourniquet because we found the tourniquet to be significantly more elastic than a real phrenic nerve. This deduction for the right feel was based on the memory of the feel of the phrenic nerve from the dissections in the anatomy lab, along with input in this matter from Dr. Andreatta.

Phrenic Nerve

		Yarn	Dental Floss	Rubber Band	Shoe Lace	Surgical Tube	Turquoise Material
Selection Criteria	Weight						
Is Anatomically Correct	8	9	9	9	9	9	9
Responds Correctly/ Feels Real	7	3	9	1	9	3	3
Provides Evaluative Feedback	6	9	9	9	9	9	9
Affordable	5	9	9	9	9	9	9
Minimum Replaceable Parts	4	9	9	9	9	9	9
Reusable	3	9	9	9	9	9	9
Transportable	2	9	9	9	9	9	9
Ease of Manufacturing	1	9	1	3	9	9	9
Total Score		282	316	262	324	282	282
Rank					Winner		

Figure 37: Phrenic Nerve Pugh Chart

Heart: Ideas for the heart component were broken into three main sections; exterior material selection, pump capability, and feedback system as shown in its pugh chart (Figure 38).



Figure 38: Heart Pugh Chart

For modeling the skin of the heart we initially believed that using a regular cloth fabric would be sufficient for the exterior of the heart. However, deliberation with Dr. Andreatta confirmed that this would not be the best choice in terms of providing the feel of holding a real human heart. Also, the fabric would not be able to simulate any blood flow if we decided to account for that option in our design. The pugh charts for the exterior materials for the heart indicate how we considered other material options ranging from rubber, latex, balloon and gauze. However, these primarily failed because of low rankings on the criteria for ease of manufacturing and for feeling real and responding correctly. Even though the rubber and gauze illustrate a difference in the overall ratings over a very small margin, we selected rubber as the heart skin due to its ease in manufacturing relative to handling gauze.

The options for the pumping capacity of the heart ranged from using electric fluid pumps, hand pumps, pneumatics, pocket pumps and motor cam configurations. The hand pump and the motor cam configurations came close to each other on the pugh chart analysis because these mechanisms fulfilled the primary requirements of replicating a heart beat that responded correctly. However, the motor cam configuration won the highest points because of its feature of

utilizing a continuous non human source for power. For initial prototyping purposes, even though the hand pump might be good enough to replicate a heartbeat; in a more realistic scenario, the surgeon performing a thoracotomy cannot physically use a hand pump at the same time.

For the feedback systems, one of the ideas for obtaining feedback from the heart in terms of examining it for trauma injury was placing bubble wraps at each location to simulate each location that needed to be examined. As the surgeon would have to feel around the surface of the heart he/she would need to search for the bubble wrap and pop it. Though this idea for assessing the surgeons' performance ranked well on the pugh chart in terms of being easily transportable, affordable and having minimum replaceable parts, we ultimately eliminated this design. This elimination was based on its inability in terms of providing the surgeon with the correct 'feel' of the organ and in terms of its inability to be reusable after being popped. It would also require a substantial amount of force to pop these bubbles, which could potentially cause damage to the heart. Other suggestions for the feedback capabilities ranged from using teeter totter switches, piezo sensors and liquid packets; the winning idea for feedback involved using a keyboard button that the surgeon could press for each location he/she examined on the heart.

Additional Comments

In general, ideas for material selection of our components stemmed from our visit to the anatomy lab and discussions with our mentor. For inspiration, we obtained samples of various materials from different stores such as Lowes or even Toys R Us. We also looked to sources which have already used certain materials to simulate human body parts. For example, the idea of using ballistics gel stemmed from the use of this material in the popular science television program MythBusters. In this program, they use the ballistics gel to imitate human skin, so the inclusion of this material was rather important. The Clinical Simulation center also supplied us with samples of various materials, such as neoprene and old Trauma Man skin. Through these sources, we were able to decide that we comprehensively explored the material space.

The Alpha Design

The concept selection phase enabled us to compile a preliminary list of the raw materials/mechanisms we believed would best fulfill the user requirements for the thoracotomy simulator. However, based on regular discussions with Dr. Andreatta and Mr. Randy Richter, we modified our analysis to include/eliminate some of the raw materials to simulate the model organs in the thoracic cavity with higher fidelity. Below is a description of the revised material selection for each simulator component and the model layout for our alpha design.

This section also introduces new auxiliary components of the simulator to account for structural integrity of the simulator. The material selection for these components was based on intuition and basic knowledge from referencing to materials handbooks. To support the ribs we decided to include a back plate for the entire rib cage and a plate to replicate the sternum. The great arteries or the main arteries (pulmonary artery and the aorta) will also be represented using surgical tubing material. The pulmonary artery is necessary because it directly supplies blood to the lungs and the aorta is the largest blood vessel in the body. These arteries in the simulator will warn the surgeons to be mindful of their presence.

Figures 39-41 below show the Computer Aided Design (CAD) model, as well as a picture of the mockup we created of our Alpha Design. These pictures are described in detail in the following sections and a summary of the design decisions is shown in Table 15 on page 44.

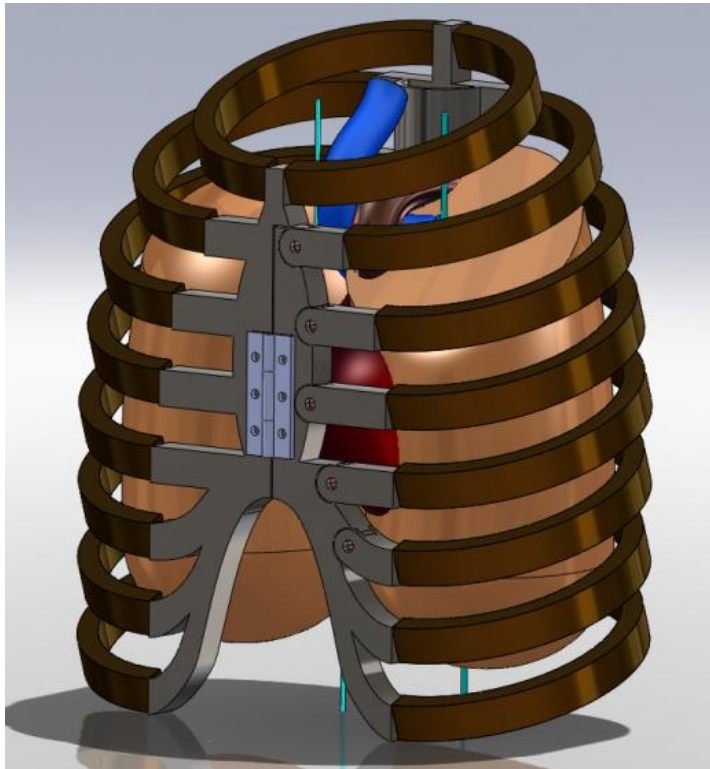


Figure 39: Isometric view of Alpha Design



Figure 40: Side view of Alpha Design.

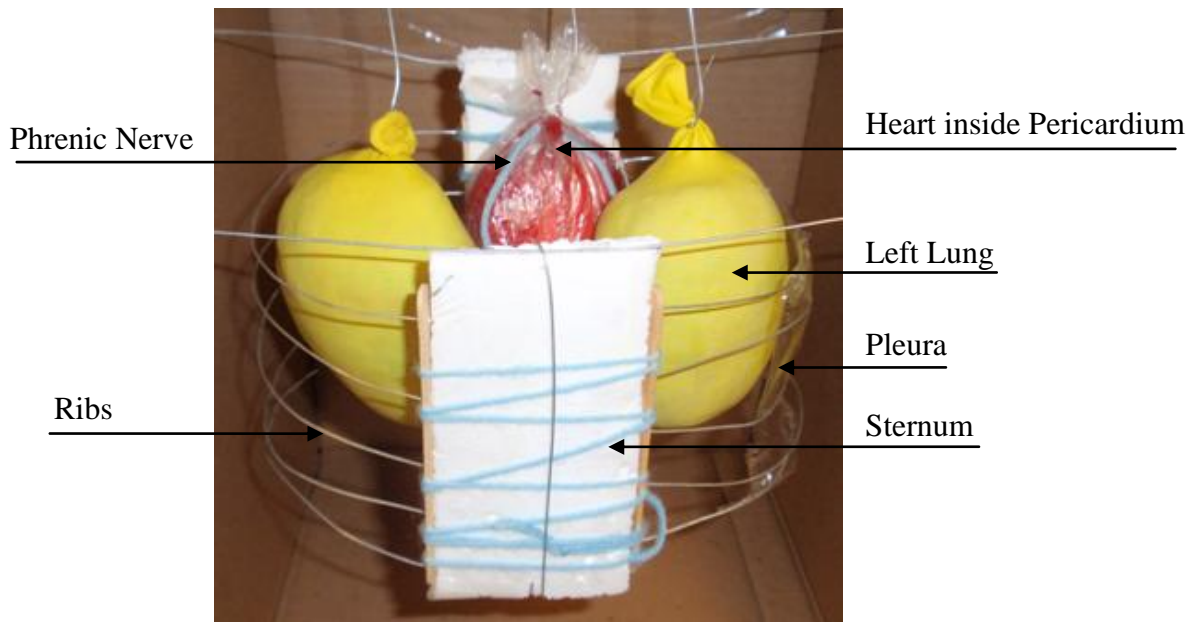


Figure 41: Mockup of Alpha Design.

Alpha Design: Skin

For the skin component of our simulator, we have chosen to use neoprene, which is shown below in Figure 42. The main function of the skin is to provide access to the ribs and the thoracic cavity, as well as to provide information for the correct cut location. Even though our pugh chart analysis indicated that using rubber to model the skin would perform well in fulfilling the critical user specifications of feeling real, being anatomically correct and responding correctly to trauma; based on discussion with Dr. Andreatta, we confirmed that neoprene was capable of fulfilling the same functions even better. This is because neoprene's chief advantage is to withstand repeated openings and closings without much wear and tear; hence we conclude that by using this material instead of rubber, the user will be able to not only sew up the opening after completing the surgery, but will also be able to cut through the previous sutures. The ability of the simulator to provide this capability will enable the surgeon to become proficient in locating and performing the incision. Even though neoprene is relatively expensive compared to some of the other options we considered, we are confident that its reusability will make up for the initial high cost.

The mechanism for providing an opening for entrance to the chest cavity using the laces/sutures was retained from the initial pugh chart considerations discussed in the previous section.

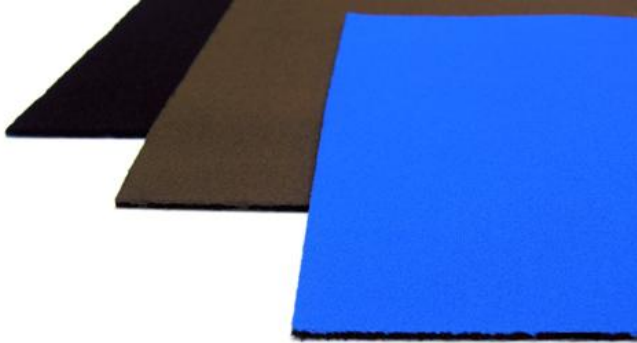


Figure 42: Neoprene (50)

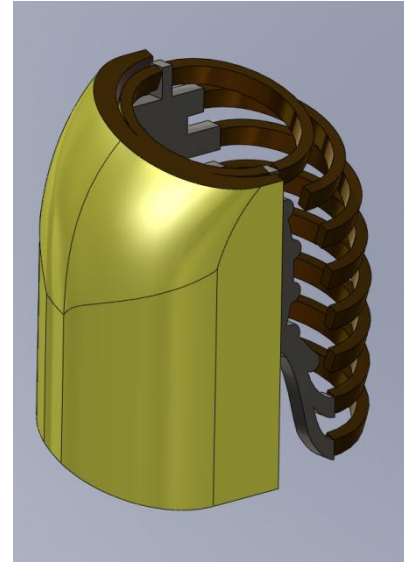


Figure 43: Skin on Rib Cage.

Alpha Design: Ribcage

The ribcage, which is shown in Figure 44, will be replicated by PVC and sheet metal and will be allowed to be spread with the use of pin joints and torsional springs. As indicated by our user requirements, the ribs must be spreadable and must have a similar reactive force as actual ribs would when being spread in order to respond correctly. They also must be strong enough to support the rib spreader during the entirety of the simulation, as well as withstand numerous uses. After consulting with our mentor, we confirmed that PVC would be a suitable choice (indicated by the pugh charts) for this application because it was strong and easy to manipulate. Based on our memory of the feel of a rib during the anatomy lab, we also believed it would respond with similar ‘feel’ characteristics as real ribs.

We decided to use torsion springs instead of rubber as the joints, even though the rubber had the highest ranking in the pugh chart table for the ribs. This was because we reasoned that the springs will be easier to incorporate into the design, will last longer and cost about the same as rubber. Torsional springs will also be more useful to mimic the reactive force of the ribs while being spread. We also decided to use sheet metal for the sternum and the back support of the entire structure and to use a PVC pipe, cut in half down its axis, for the spine. Though we have not decided on the type of sheet metal we intend to use, the decision will be based on the ease of manufacturing of the material. As an added feature, we will include a hinge on the sternum and a latch on the back plate to allow for replacement of components within the ribcage such as the pleura and the pericardium, which will be discussed in the next section.

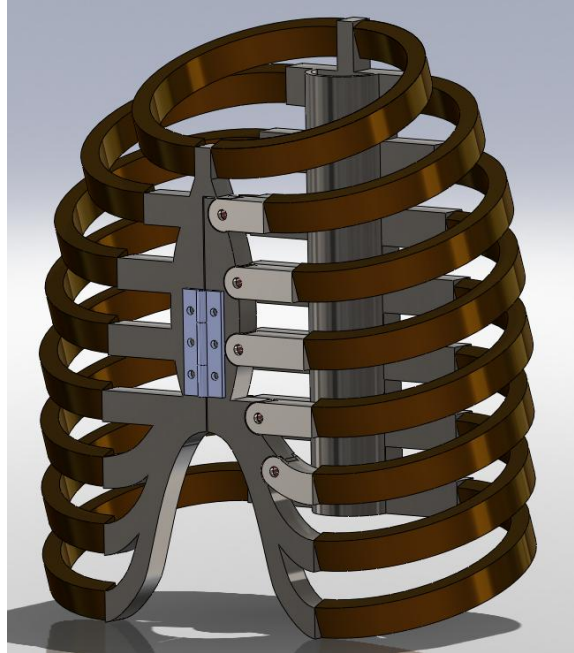


Figure 44: The Ribcage

Alpha Design: Thin Linings

As determined by analysis using the pugh charts, we will be using a plastic bag to replicate the pleura and a thick, large balloon to replicate the pericardium in our simulator, which are shown below in Figures 45 and 46. A unique feature of both these linings is that they must each be penetrable, as per our user requirements. For the pleura replica, we recognize that a difficulty will be not only having to replace the bag after every use, but also making sure that the pleura is stretched and tight against the rib cage. Placement of the pleura will be made with double-stick tape. The pericardium replica will have to be replaced after each use as well. As discussed in the previous section, we plan on allowing the rib cage to pivot open to allow easy access to the thoracic cavity, and thus ensure easy replacement of both the pleura and the pericardium.



Figure 45: Plastic bag used for Pleura. (52)



Figure 46: Balloon used for Pericardium. (2)

Alpha Design: Lungs

In order to replicate the lungs on our simulator, we will be using packing bags surrounded by foam, as shown in Figure 47 below. The lungs must also be able to inflate and deflate repeatedly at a normal breathing rate. This will be accomplished using an electric air pump. Furthermore, the option must exist for the left lung to deflate for creating extra room for examination, if needed. This will be accomplished with the use of a valve to enable the air to escape. The foam surrounding the lungs will not provide any structural support; it is only there to meet the user requirement of providing a realistic response and feel for the user. The main advantages to this idea is it would provide a very easy and effective way to inflate and deflate the lung, as well as provide the most realistic feel compared to the other options. A disadvantage of the foam may be that may be that the foam will have to be replaced numerous times.

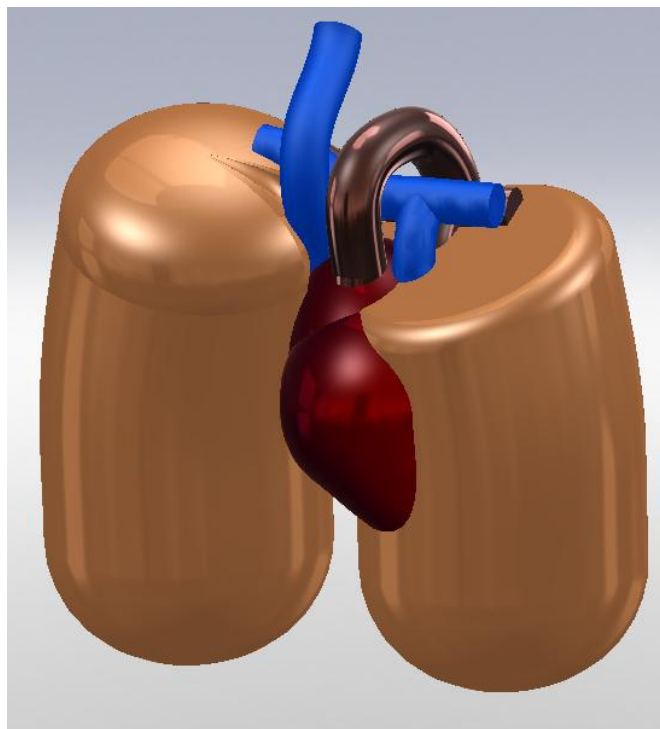


Figure 47: The Lungs

Alpha Design: The Phrenic Nerve

For the phrenic nerve component, we have chosen to use an elastic band or tourniquet, as shown in Figure 48 below. This decision is a deviation from the original analysis from the pugh charts where we predicted that a shoes lace would be adequate in complying with the user specifications for representing the phrenic nerve. This change was necessitated after discussion with Dr. Andreatta, who suggested that the tourniquet material will be more suitable because under tension, it will be the most obvious to the user if cut by accident. It is also cheap and easy to install, so if it is cut, replacement is not a major issue.

The phrenic nerve is necessary to place in our simulator because if damaged, the patient would no longer be able to breathe involuntarily. Hence, the main function of the phrenic nerve is to make its presence known to the user, so it is not overlooked in an actual surgery.



Figure 48: Tourniquet used for phrenic nerve. (72)

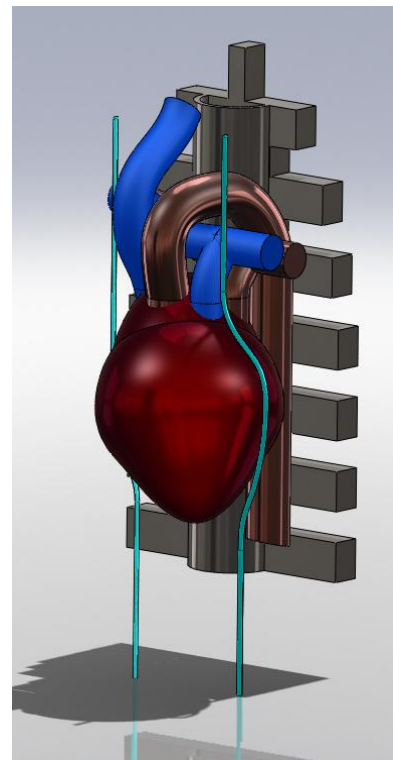


Figure 49: Phrenic Nerves.

Alpha Design: The Heart and the Great Vessels

In order to replicate the heart, a motor and cam system surrounded by rubber will be used, as shown in Figures 50-51, along with a feedback system using keyboard buttons and an LED board.

The rubber will provide the correct heart elasticity, making it respond and feel like a real heart. The motor and cam system will allow us to provide a realistic heart beat; however, it will be a challenge to construct the inside track that the cam can rotate on, as well as to stabilize the motor inside of the heart, while still allowing the cam to rotate freely. For the feedback, we decided to incorporate numerous tactile-button sensors, which will be embedded into the surface of the heart and connected to corresponding lights on a board that the user can see. The lights will provide the user with real-time feedback concerning which areas he/she has examined and which

areas still need to be felt over. This will allow the simulator to be used both for training and for testing, because the feedback LED board can be covered up and evaluated after the user has completed the entire procedure as a means to assess the success of the training.

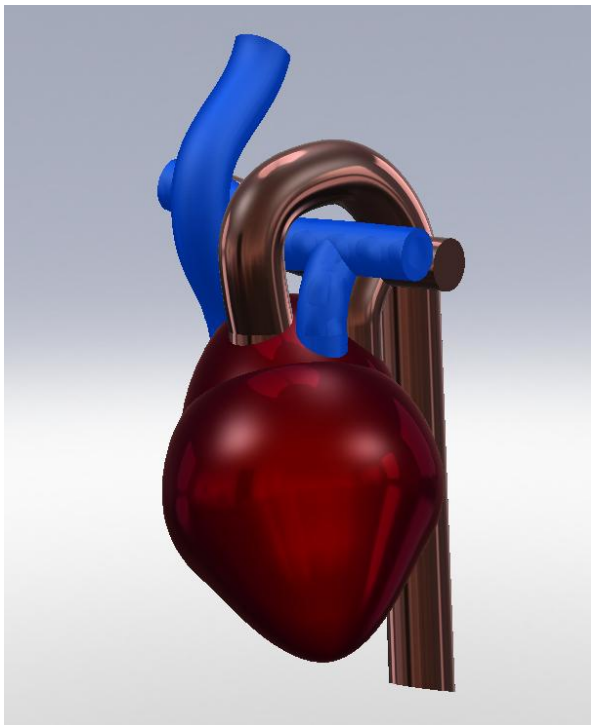


Figure 50: The Heart

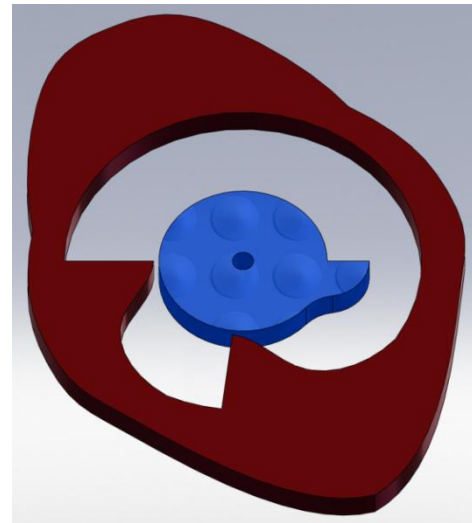


Figure 51: Motor and Cam System

Alpha Design: The Great Vessels

The great vessels, such as the aorta and the pulmonary artery, will be made using surgical tubing, shown below in Figure 46. The specific tubing will need to be picked to be the same diameter and to mimic the same elastic properties as the real vessels.



Figure 52: Surgical Tubing used for the great vessels. (29)

Table 15: Summary of Alpha Design Decisions

Part	Design
Skin	Neoprene
Re-seal	Sutures
Ribcage	Large PVC Tube
Sternum	Sheet Metal
Back Plate	Sheet Metal with hinge supports
Set-up	Hinge on Sternum & Latch on Back Plate
Spine	PVC tube cut in half down its axis
<i>Moveable Ribs</i>	
Joints	Pin Joints
Reaction Force	Torsional Springs
Pleura	Plastic Bag
Placement	Double-stick Tape
Pericardium	Thick & Large Balloon
Lungs	Foam
Breathing	Packing Bags with Electric Air Pump
Phrenic Nerve	Elastic Band/ Tourniquet
Heart	Rubber
Beating	Cam & Electric Motor
Feed Back	Keyboard Buttons & Piezo Sensors
	LED board
Great Vessels	Surgical Tubing

Concept Description: Using the Simulator to Imitate an Emergency Thoracotomy Procedure

As described in the Problem Description section on pages **XX-XX**, a thoracotomy is a multiple step procedure, requiring high precision and accuracy at a rapid pace. The following will help demonstrate how the simulator is utilized in imitating said procedure.

Figures 53 and 54 show the complete setup of the simulator as well as an exploded view of all of its components.

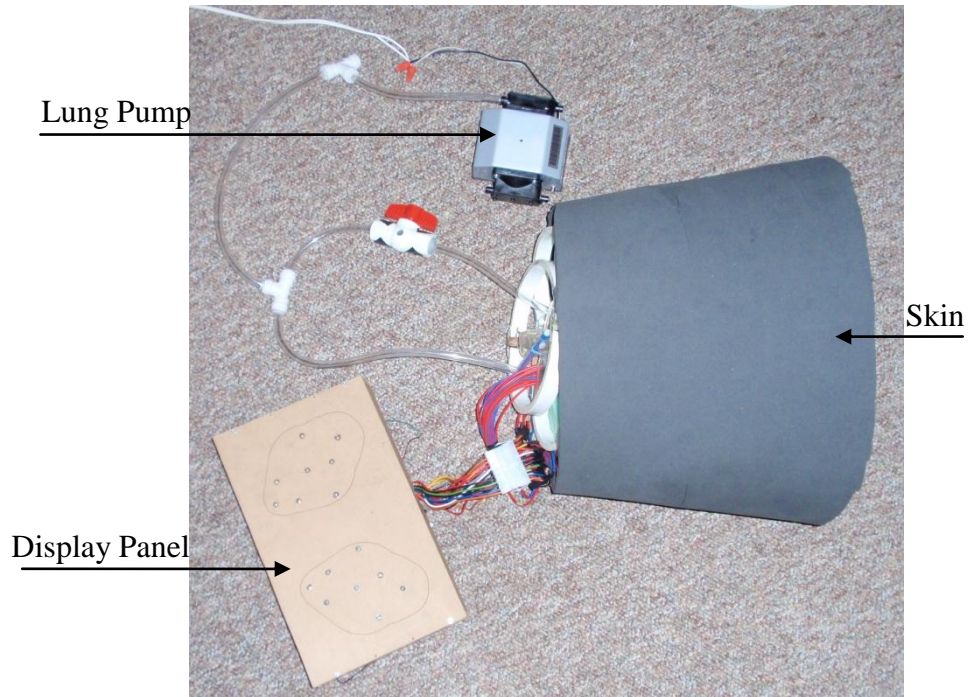


Figure 53: Full Setup of the Simulator

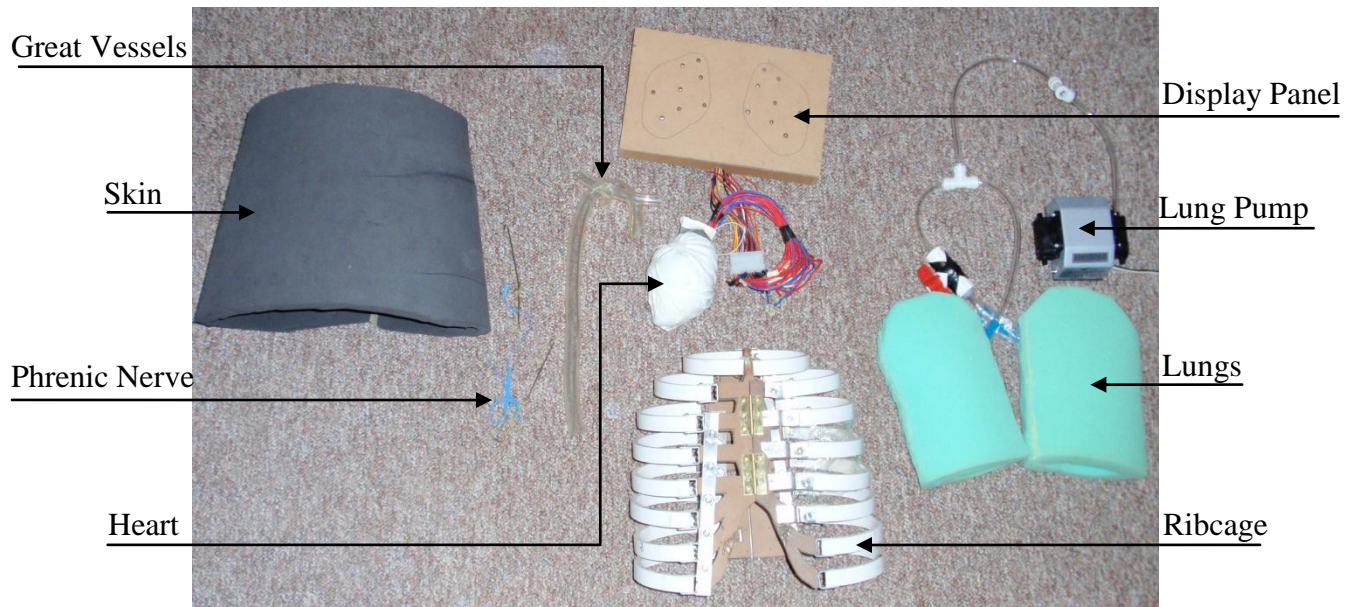


Figure 54: Exploded View of the Simulator

In an emergency anterolateral cardiac thoracotomy, the surgeon first makes a left anterolateral incision in the 3rd or 4th intercostal space as shown in Figure 55 below.

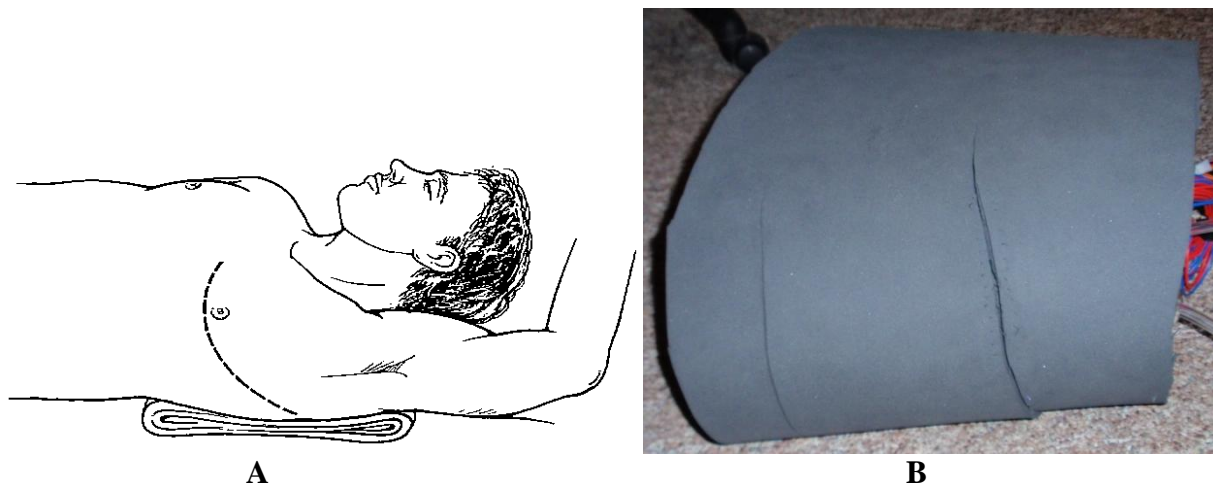


Figure 55: A, Incision Location on Patient. B, Equivalent Location of Incision on Simulator.

Next the left lung is often collapsed to allow for more working room for the surgeon. This can be accomplished with our simulator by turning the pressure valve connected via the tubing to the left lung, which redirects the air into the atmosphere. The air flow through the tubing to the lungs with the valve open (A) and closed (B) are shown in Figure 56.

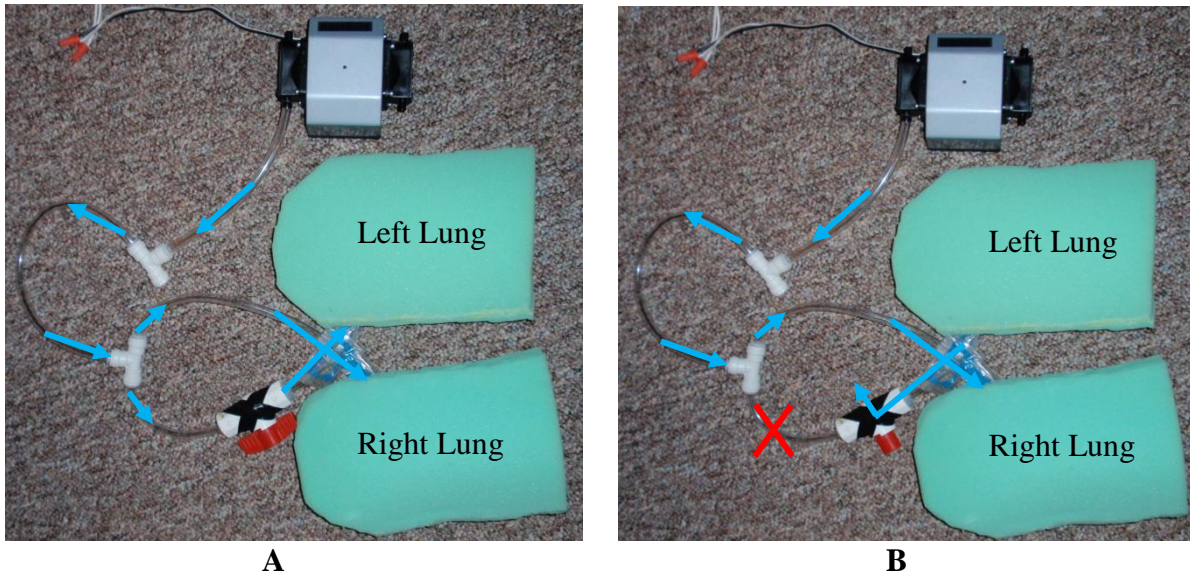


Figure 56: Collapsing of Left Lung. A, Normal Air Flow. B, Air Flow after Turning Valve

Next, an incision is made into the pleura and the ribs are spread. This is shown in Figure 57 below, where the pleura can be seen as the plastic shrink wrap under the ribs.

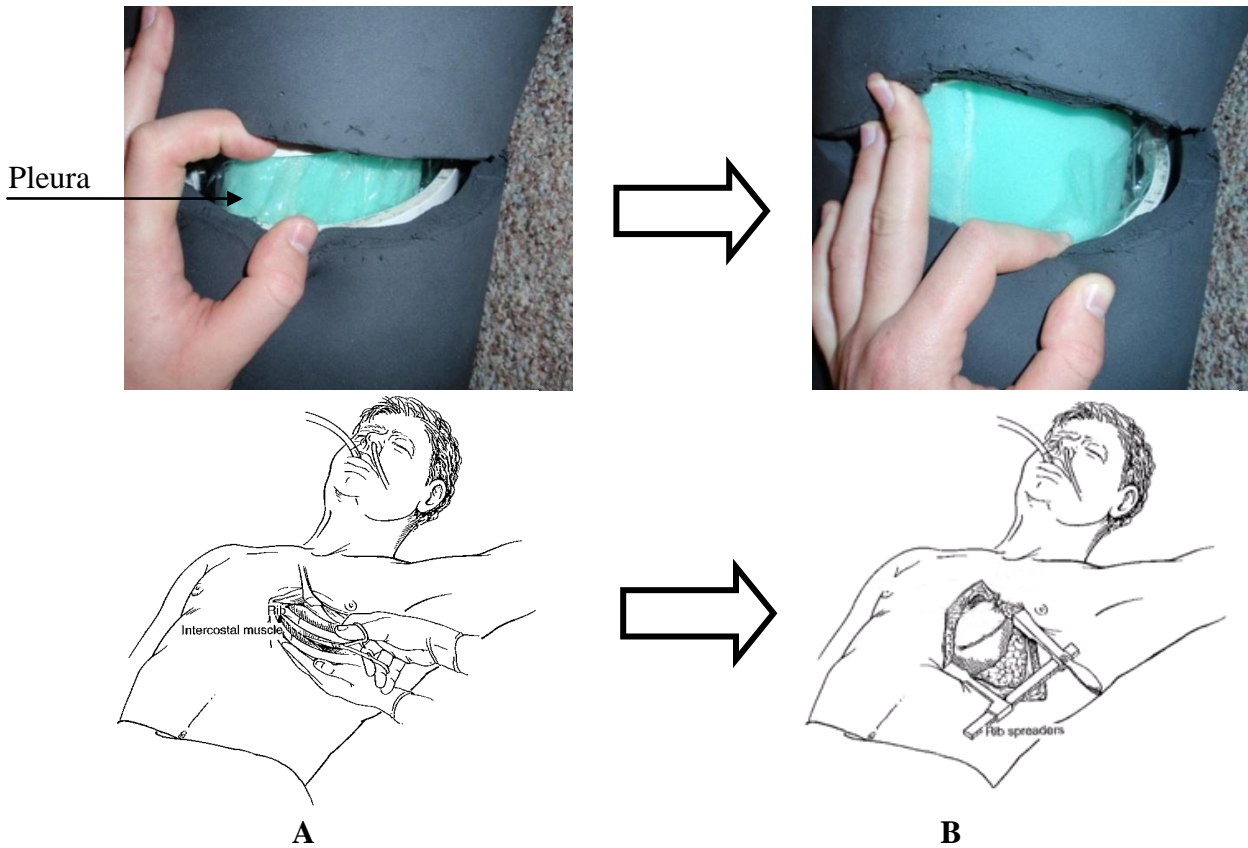


Figure 57: A, The Pleura is Penetrated. B, The Ribs are Spread.

Now, the surgeon will cut through the pericardium. While cutting through the pericardium, care must be taken to avoid cutting the phrenic nerve, seen as a blue elastic tourniquet in Figure 58 below.



Figure 58: Simulator State before the Pericardium is Penetrated

Finally, in a real setting, the surgeon would now fix any hemorrhaging cardiac wounds. In our simulator, instead of performing this step, the surgeon will now thoroughly examine the heart. This would translate into the surgeon adequately assessing the state of the heart and finding any wounds that need to be repaired. The heart is embedded with twelve sensors, which will light up corresponding light emitting diodes (LED) when pressed on a display panel, as shown in Figure 59 below. Lighting up all twelve of these LEDs corresponds to examining 100% of the heart's surfaces and structures, thereby indicating a thorough examination.

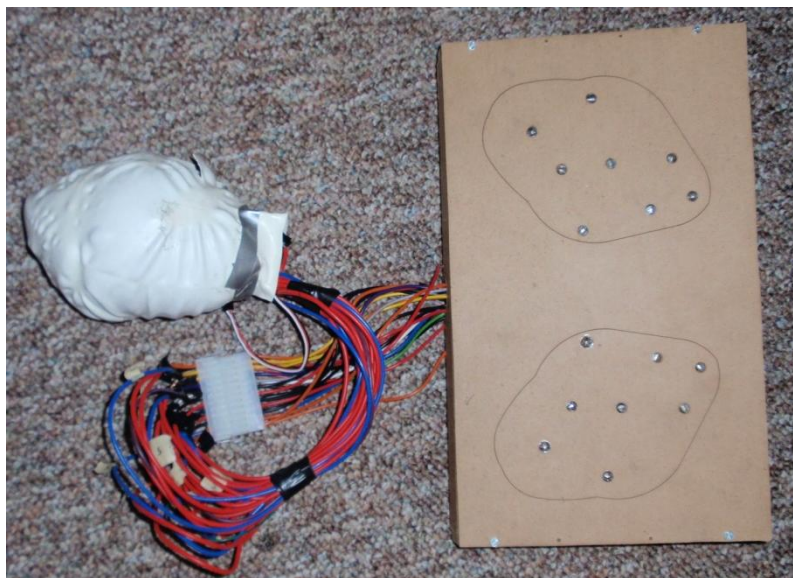


Figure 59: The Heart and the Display Panel

Final Design Description

From the beginning, we understood that there were many aspects of our user requirements that would not be accounted for in the prototype. This is why we divided our user requirements into ‘must have’ requirements and ‘luxury’ requirements. For our prototype, we concentrated on accomplishing the ‘must have’ requirements, and left the ‘luxury’ requirements to be dealt with at a later time. Our final design description is analogous with the idea that if we had all the time and money we wanted, we would incorporate all eighteen of the user requirements, not just the top ten. We did not design for our final design concept while prototyping, but we did keep in mind what we would improve or add if we had the chance. In the prototype description section below, the design for the prototype is compared to the theoretical design that we were unable to incorporate into our final design given the set constraints. The 3D CAD model of our final design can be seen in Figure 60 below.

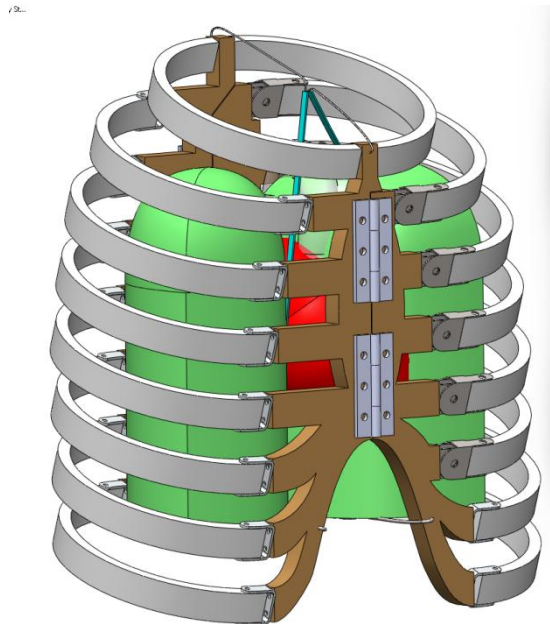


Figure 60: Final Design

Prototype (Beta) Design

In the beginning, the main focus of this prototype was to provide a simulator that would have a beating heart and breathing lungs, a luxury that is difficult to find in current simulators. As we learned more and developed a better understanding of what was expected of our simulator, we created a list of user requirements that would inevitably change numerous times. This list, as seen in its most comprehensive and up to date form in Tables 1-8, is what we have used as a foundation for ensuring our prototype accomplishes the most important aspects of our project.

Of these many user requirements that were created for our ideal prototype, it was essential to determine which requirements were necessities and which were luxuries; hence, the list was divided into two parts: must haves and luxuries. These two sections also represent the main differences between what our prototype will be and what it could be. It will also become clear

that in the prototype, emphasis was put on the procedural aspect of the design as opposed to the structural aspect. This means that we decided it was more important to include features that allow the procedure to be accomplished and not concentrate as much on the aesthetics or exact correct response of a component. The easiest way to discuss these differences is to analyze each component individually and explain not only how each one fulfills the ‘must have’ requirements, but also how it could be perfected within the ‘luxury’ requirements if much more time and money were available.

Beta Design: Skin

The skin, shown in Figure 61 below, must fulfill the requirement of allowing access to and covering the thoracic cavity as well as provide the ability to be reconfigurable. For our prototype, we will be using neoprene to mimic the skin. The neoprene is a good option for several reasons. It allows us to include multiple access points on different locations of the chest and thus provides access to the thoracic cavity. All of the openings in the neoprene will be pre-cut in order to allow for as much reusability as possible, in the locations and direction as specified in Table 8. There is only one correct opening, between the 3rd or 4th intercostal space, which the user must find. This is necessary because it is important for the user to be able to identify the correct location to enter the chest cavity. Another benefit of the neoprene which was not originally considered is the ability to suture it like real skin. This allows the user to practice an important skill every time he/she finishes the thoracotomy. The sutures also allow the user, when first entering the thoracic cavity, to practice the act of ‘cutting through skin’. With all of the components, it is essential that they allow the user to imitate the actions involved in a real thoracotomy, even if they do not mimic the response perfectly.

A downside of neoprene is it does not mimic the feel of real skin as well as other materials. In the final prototype, more time and money would be invested in finding a material that not only does what the neoprene can do, but also could respond and feel more like real skin. Another factor we do not have time to consider as closely as we would like has to do with the thickness of human skin. The thickness of skin, as well as the fat below can vary from person to person and sometimes, the fat and/or skin thickness of a patient can be a huge factor in surgical outcomes. Surgeon’s maneuverability within the body and ability to locate anatomical landmarks during a procedure are hindered when fat and skin thicknesses are large. The final design would include not just skin that is closer to the actual thickness, but also another material between it and the ribs to serve as fat. The neoprene must be thicker in the prototype than normal skin to allow for suturing, but that could be resolved if a second layer was incorporated. In terms of reusability, we may incorporate patches of skin to allow for cheaper, easier to replace skin.

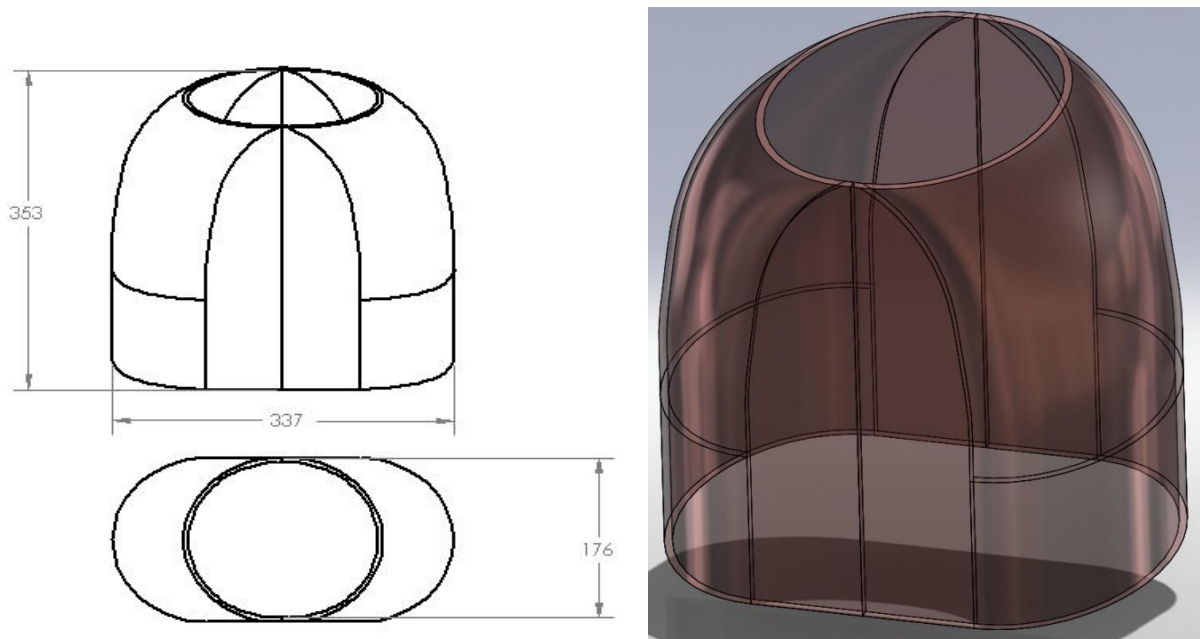


Figure 61: Neoprene Skin (Dimensions in mm)

Beta Design: Pleura

The pleura is a thin membrane that surrounds the inside of the rib cages. It was incorporated into the prototype because poking through the pleura before spreading the ribs is an important step in performing a thoracotomy. We are using shrink wrap because it mimics the elasticity of the pleura well and it is very cheap. In this case, being inexpensive is relatively important because we intend for the pleura to be replaced after every use. We intend to attach the pleura to three ribs – the three surrounding the 3rd and 4th intercostal spaces – by attaching double sided tape to each rib and then sticking the shrink wrap on that. After the shrink wrap is secure, we will use a hair dryer to make it taught across the intercostal spaces.

As far as material is concerned, the shrink wrap is a very good substitute for the pleura. Ideally, the pleura would be spread across all of the ribs, not just the three we are accessing, to provide a more realistic model. The main difficulty with attaching the pleura arises with respect to the fact that each rib is a different distance away from the center of the thoracic cavity, and applying a single piece of shrink wrap so that it leaves no gaps between the ribs is not very easy.

Beta Design: Ribcage

The rib cage, shown in Figure 62 below, was a deceptively complex component to replicate accurately, which may not be so obvious in the prototype. There are in fact four separate components that comprise the rib cage: the sternum, back plate, connector and individual ribs. The main function of the ribcage is to provide spreadable ribs as well as a realistic resistive force while being spread.

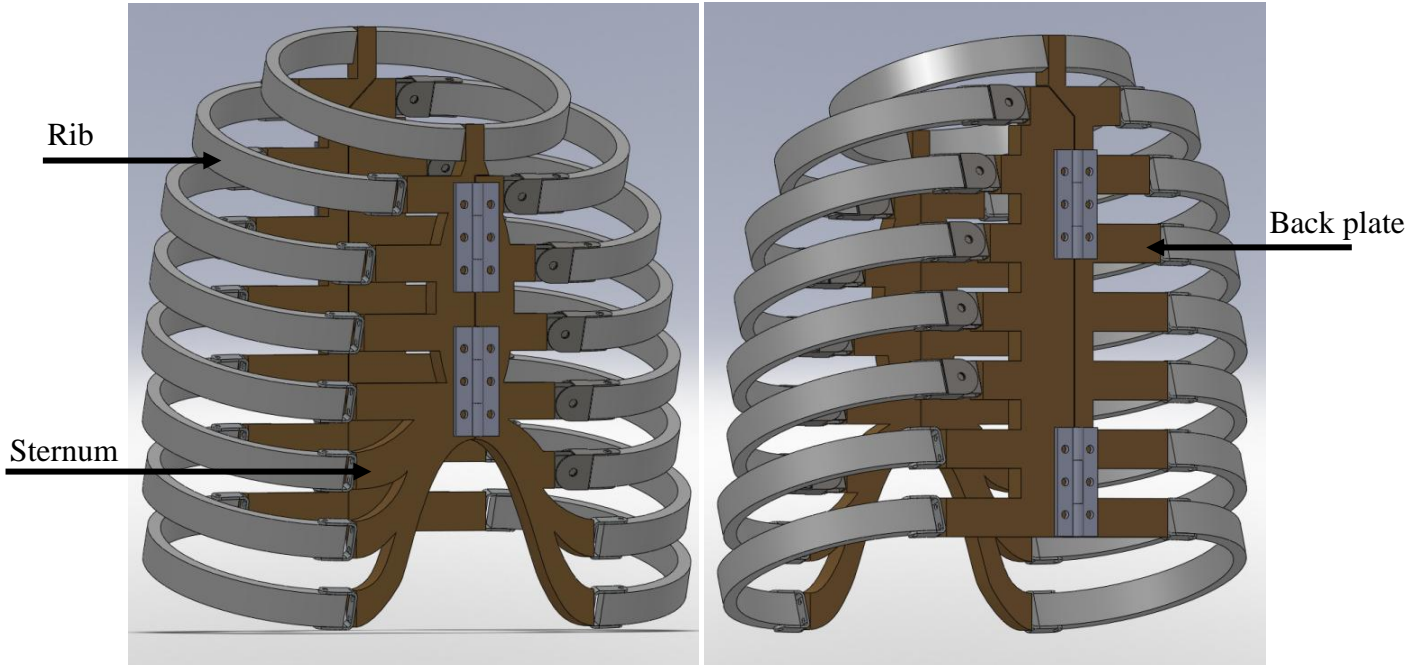


Figure 62: The Ribcage

Sternum and Back Plate:

The sternum and back plate are both made from laser cut masonite and are shown in Figures 63 - 68 below.



Figure 63: The Back Plate



Figure 64: The Sternum

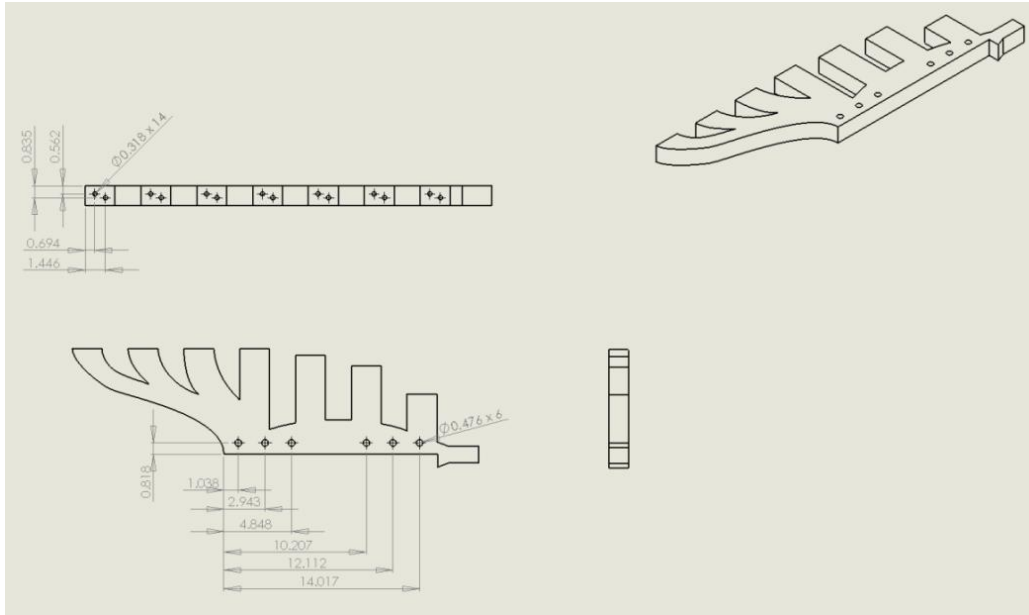


Figure 65: Right Sternum Plate Engineering Drawing [cm]

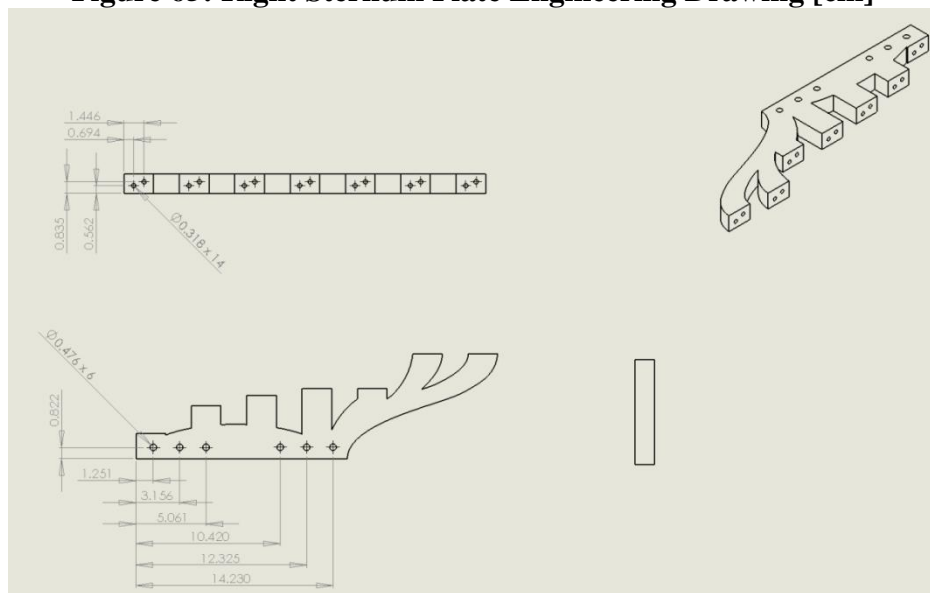


Figure 66: Left Sternum Plate Engineering Drawing [cm]

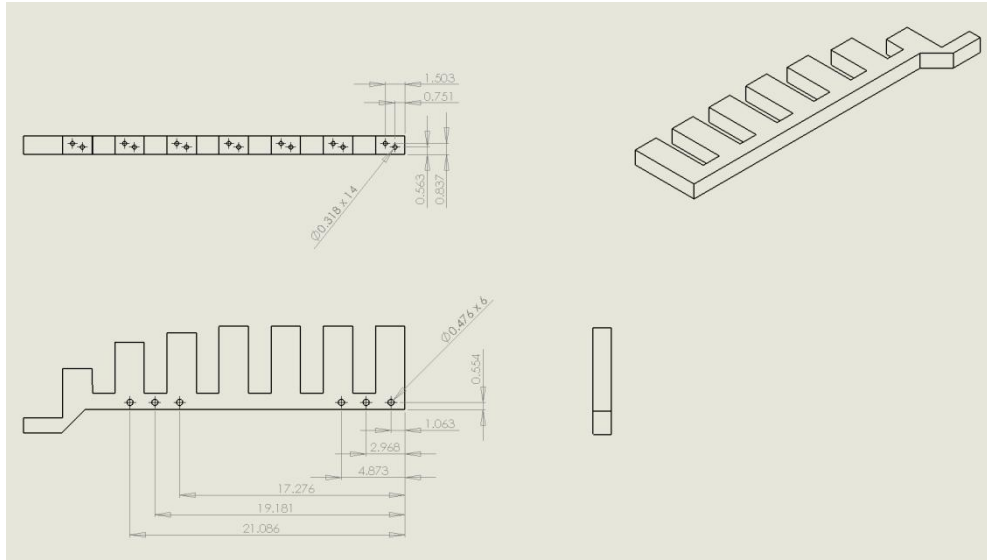


Figure 67: Right Back Plate Engineering Drawing [cm]

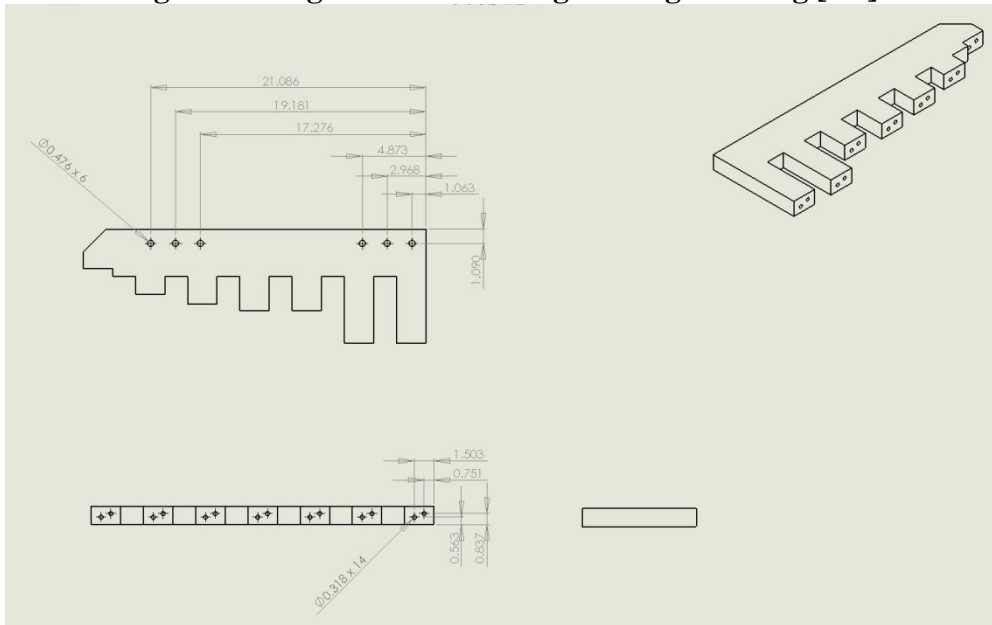


Figure 68: Left Back Plate Engineering Drawing [cm]

The sternum and the back plate must be strong enough to hold the ribcage together, along with providing support to the ribs while they are spread. Another function we felt was necessary to incorporate was the ability to hinge open in order to allow easy access to the cavity when the need to replace or fix components arises. This was achieved by using a common cabinet door hinge, as seen in Figure 69 below, on the sternum along with a hook on the back plate to secure the ribcage together while in use.



Figure 69: Door Hinge (1)

Connectors

The connectors are necessary to not only attach the ribs to the sternum and back plate, but to also give the necessary ribs an axis about which they can rotate when being spread. They are manufactured out of 1018 sheet metal and can be seen in Figure 70. There are also torsional springs attached to the connectors that rotate, in order to provide the correct reactive force response when the user is spreading the ribs. Torsional spring selection can be seen in the parameter analysis section.

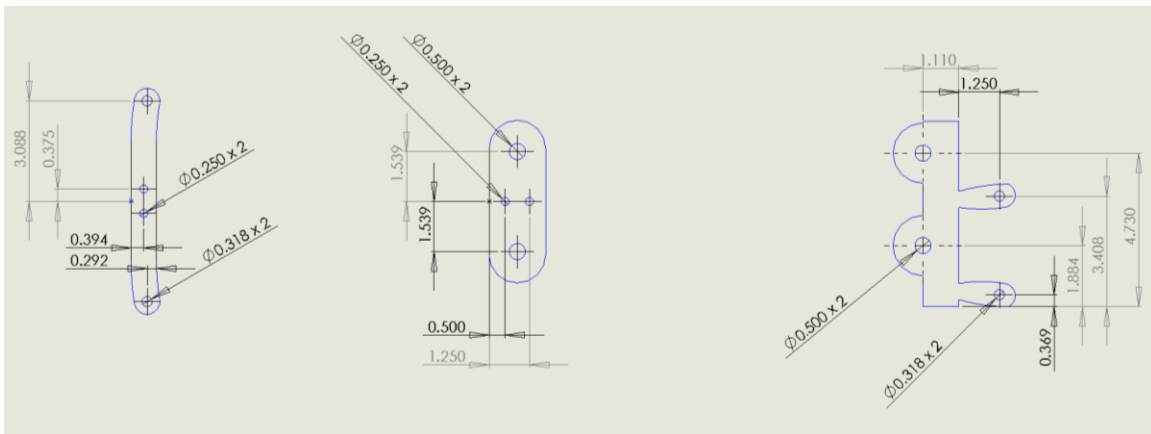
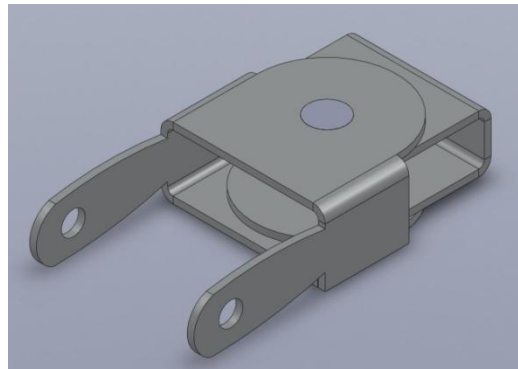


Figure 70: Rib Connector and Rib Connector Engineering Drawing [cm]

Individual Ribs

The ribs are made from 6" PVC pipe cut to a realistic thickness. The ribs, as shown in Figure 71 and 72, are attached to the connectors and provide a good approximation of response to that of real ribs. The main concern was that they will not be strong enough to withstand the 100 N of force applied to them, but FEA analysis and testing shows that the ribs will be strong enough as shown in the parameter analysis section.

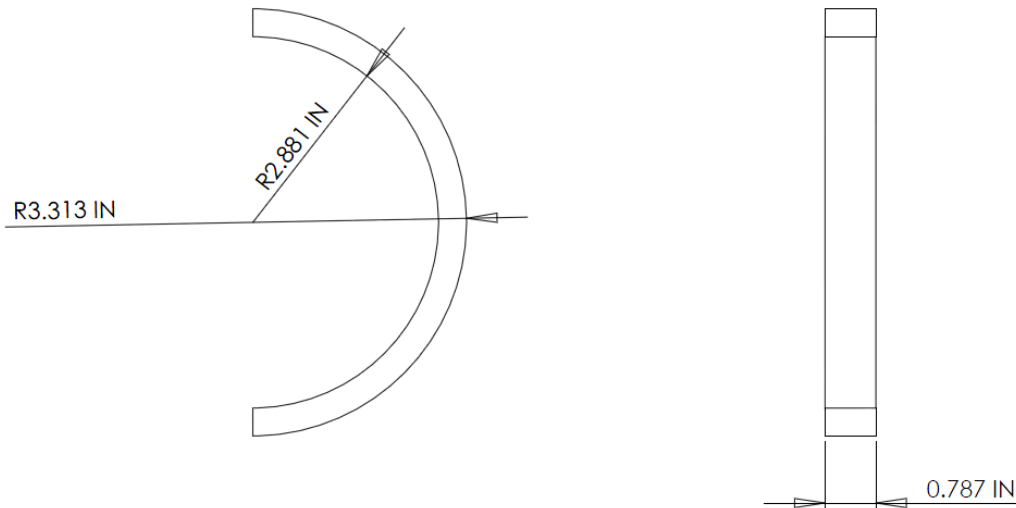


Figure 71: Rib Engineering Drawing

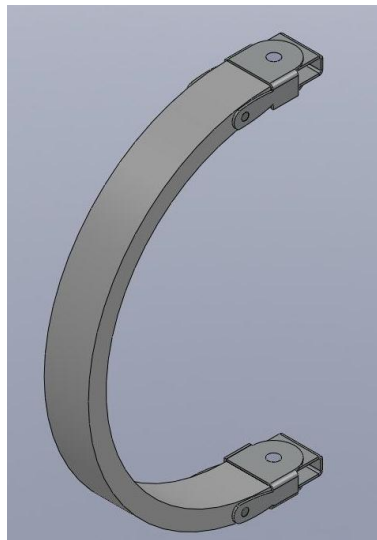


Figure 72: Rib with Connectors

The biggest difference between the beta design and the final design ribcage is the ribcage itself. In the final design, a pre-made replica of a true ribcage would be incorporated, which would eliminate the need to fabricate the sternum and back plate, connectors and individual ribs. It will still be necessary to use torsional springs on the ribs in order to provide the correct reactive force. The springs will also be placed on the majority of the ribs instead of just three, to create yet more

realism within the simulator. Also, while the prototype only has a total of sixteen ribs, the final design would have all twenty-four of them. The replica ribs would not only look and feel much more real than the components we are using, they would also provide a more realistic surrounding in which to put the other components. They would have more detailed features such as the backbone which was left out of the prototype because, while it is helpful in providing landmarks for the user to identify, it wasn't necessary to complete the procedure correctly.

Beta Design: Lungs

The main function of the lungs is to breathe, and the left lung should be deflated on command if required. The lungs can be seen below in Figure 73. We are using an air pump to inflate the lungs at 0.42 CFM as calculated in the parameter analysis section. The lungs are comprised of a plastic bag surround by foam. The bag inflates and deflates in accordance with the pump, and the foam that is glued around the bag also inflates to simulate with breathing process. The main purpose for using the foam is it provides a feel similar to that of real lungs, and will give the user feedback concerning the location and activity of the lungs. A valve is attached to the air hose connected to the left lung, and if requested, the valve can be closed thereby collapsing the lung.

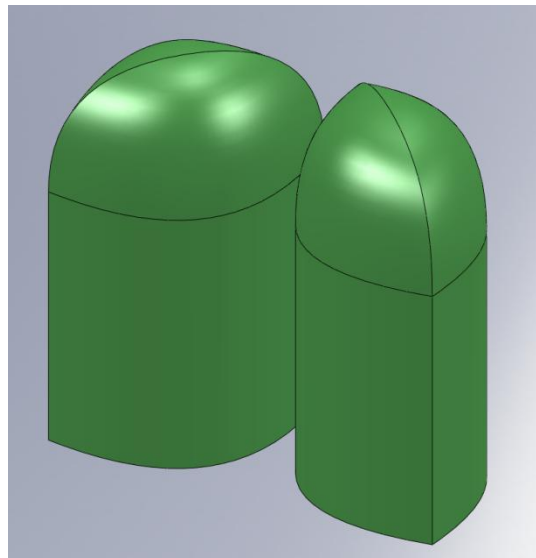


Figure 73: The Lungs

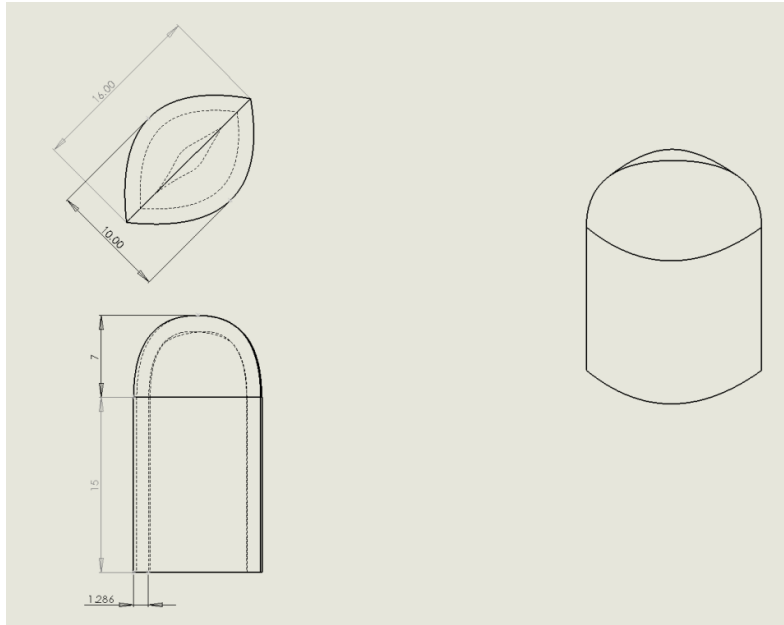


Figure 74: Lung Engineering Drawing [cm]

The lungs in the final design will be much improved over the prototype. A better pump will be incorporated; one that will allow the breathing rate to speed up or slow down depending on the situation. This will play a role in providing a better, more realistic feedback to the user. Also, the lungs will be most likely made from a PVC plastisol polymer, one that is mixed such that the material is very soft and sponge-like, more closely imitating the feel of a real lung. A more effective and easy to use valve will be placed in the system, allowing more control over the response of the simulator. We would also incorporate an open loop timing system, which would help further simulate the response of a human in surgery, and even have an option for the simulator to ‘expire’ if the user takes too long to operate.

Beta Design: Phrenic Nerve

The phrenic nerve, as shown in Figure 75, was not included originally, but was deemed important because it lies in close proximity to the pericardium and the heart and it controls involuntary breathing. For the prototype, the phrenic nerve is modeled using a small elastic band. It is stretched and attached to the top and bottom of the chest cavity using wire, and will run on either side of the heart just outside of the pericardium. If accidentally cut, it will snap and it should be very obvious to the user that he/she made a mistake.

In the final design, the phrenic nerve would have higher fidelity and respond more like the real nerve. We would take more time to research the properties of the phrenic nerve, and find more realistic material to simulate it. The real phrenic nerve runs just within the wall of the pericardium, while the one in the prototype will be completely outside of it. In the final design, it would either be embedded in the pericardium like it is in real life, or applied directly to the surface of it. We would also include a dye or electrical signal in the nerve that would alert the user immediately if he/she has damaged it in order to provide better evaluative feedback.

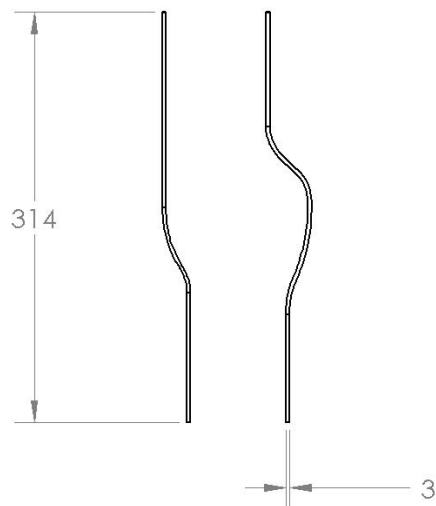


Figure 75: The Phrenic Nerve (Dimensions in mm)

Beta Design: Pericardium

We used a thick balloon for the pericardium, so that we could stretch it around the heart easily and it would also mimic the thickness and response of the real component. The pericardium's main function is to allow access to the heart after opening. The balloons are good to use because they are relatively inexpensive and will be replaced after every procedure along with the pleura.

The final design pericardium will be of the same material as the prototype. A less opaque balloon would be used to replicate the color of the pericardium more accurately. In the future, we would like to include a way to be able to open and reseal the pericardium, in order to simulate more trauma options. This would also increase the reusability and lifetime use of the pericardium.

Beta Design: Heart

The heart is by far the most complicated component of the simulator. It needs to be able to beat as well as provide feedback concerning how well the user examines 100% of the surface of the heart. The heart is made from PVC plastisol with a ratio of approximately 75% plastic and 25% hardener. This was determined by making numerous mixtures of different ratios and then having clinicians and other professions give feedback as to which ratio had the most realistic response. This ratio gives a very realistic feel to that of a real heart, and the plastic allows us to mold it into any shape. In order to achieve a realistic beat, we will be using a servo motor and cam design within the heart as described in the parameter analysis section. To provide user feedback, we will be embedding pressure sensors within the surface of the heart, and they will be connected to LEDs that will be displayed on a board. The LEDs will light up when the corresponding sensor is activated, and it will also inform the user where on the heart he/she has just touched. The board can also be covered up and used to evaluate performance after the user has trained on it enough to become proficient.

If there was more time and resources, the heart would be much more complex. We would do much more experimenting with the PVC plastisol to find the optimal ratio of plastic to softener.

We would also spend a lot more time making a mold that is better representative of a real heart. The shape of a heart is very complex, and it is not feasible to be able to mimic it exactly for the prototype. In the final design, the cam used to make the heart beat would be tweaked and/or redesigned so that it would mimic the beating with higher fidelity. Possibly, it could have even included a completely different design to mimic heart beating, such as utilizing two pocket pumps, as shown below in Figure 76, that would expand and contract with each beat.



Figure 76: Pocket Pump (53)

Beta Design: Aorta and Pulmonary Artery

The two main greater vessels of the heart, the aorta and the pulmonary artery shown in Figure 77, are represented by surgical tubing because it is flexible and easy to use. The main purpose of the greater vessels is to provide a more anatomically correct model, and they also act as a conduit for our sensor and servo motor wires. They will be held in place by shaping them around coat hanger wire.

In the final design, the greater vessels would be more functional than just providing aesthetics. They would be connected to the heart and fluid pump, and act as real arteries and veins. They would most likely be made out of the same surgical tubing, but they would also be responsible for some of the trauma options as well. The user may have to find a problem with not only the heart, but one of the great vessels as well. The other large veins and arteries attached to the heart would also be included, as well as some other major nerves. They would run throughout the cavity just as one would see in a real thoracic surgery, to provide more realism and feedback to the user.

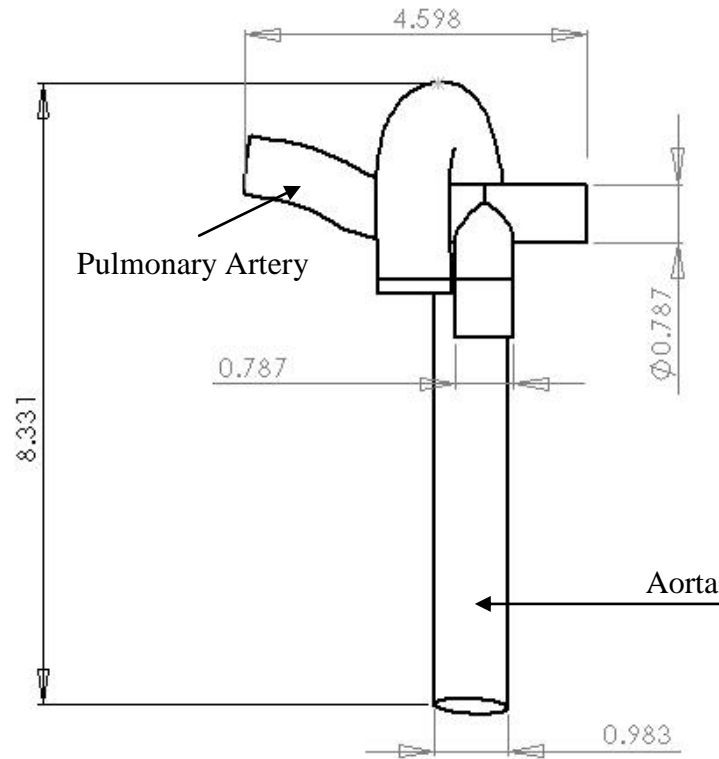


Figure 77: The Aorta and the Pulmonary Artery (Dimensions in mm)

Overall Design – Luxury Requirements

The preceding information has mainly discussed the ‘must have’ requirements with a little touch on some of the ‘luxury’ requirements such as having injury options and blood flow. It is also important to note that the first eight ‘must have’ requirements in Table 1 are specific to having a general working simulator, while the last two incorporate what makes the simulator we are making unique.

Being affordable is something all teams strive for, no matter what the project. While it is true that incorporating all of the features discussed earlier will add significant cost to the overall price of the simulator, it will still be relatively inexpensive compared to the most similar models, and none of the other simulators will be able to do what ours does as well.

Using a standard power source is not a big issue with the prototype since not much power will be required. With the final design however, much more power will be needed to run the appropriate pumps, sensors and equipment associated with the improved design. Ideally, we would want to use as little power as possible, so that a battery option could be applicable. This would allow the prototype to be transportable as well, and it could be used in resource-limited settings where similar technologies are unavailable.

While the prototype has also taken into account reusability and minimum replaceable parts, the final design would attempt to take these requirements one step further. The ultimate goal is to have to replace the most expensive components, such as the heart, ribs, lungs and skin as

infrequently as possible. The cheaper components such as the phrenic nerve, pleura and pericardium will be replaced more often than the other components, especially since the pleura and pericardium are cut every time. As mentioned before, the final design would have a pericardium that can be resealable, increasing the lifetime of the component.

Overall, both the prototype and the final design should be easy to manufacture. The most difficult aspects are making the molds and the sheet metal parts. Once the molds are made, they can be used many times without need for a new one, and the sheet metal parts should last the longest out of all of the materials. The other materials, such as those for the skin, pleura and pericardium are both easy to obtain and easy to install on the prototype.

Validation

As mentioned before, the prototype we made very different from the final design we envisioned. This is because we did not plan on making our final design, due to budget and time constraints. It is possible to say that because the validation of the ribs and lungs were a success, the same ideas could be applied to the final design. However, we cannot use the validation of our prototype to validate the final design, because the final design will be so different.

Performance

The prototype have many components, and because of the complexities involved with many so many components work individually and together, we expect our prototype to perform in a way such that it fulfills the intended user requirements, but is not necessarily as good as it could be given more time. We ended up designing the components in a way that they all had around the same fidelity, as opposed to some that were much better than others. Because of this decision, it is understood that the prototype will have good performance, but not great.

In order to validate if our final design is on target, we included it in the Validation Results section.

Bill of Materials

Table 16 below indicates the Bill of Materials.

Table 16: Parts List of Major Components

Component	Item	Quantity	Source	Catalog Number	Cost
Plates	Masonite	1	Fingerly Lumber	1	\$12.35
	Elmers Wood Glue	1	Fingerly Lumber		\$4.89
	Small Hinge	4	Lowes	36140	\$1.03
Ribs	6" x 10' SCH40 PVC Pipe	1	Lowes	86806	\$26.33
Connectors	Water Jet	1	Manufacturing Lab		\$80.00

	1/8" x 1/2" Wood screws	64	Carpenter Brothers		\$5.60
Heart	Hear Mold	1	3D Lab		\$280.00
	Plastic Softener	1 Pint	MF Manufacturing	4116S	\$9.90
	Regular Liquid Plastic	1 Quart	MF Manufacturing	2132LP	\$18.10
Feedback	Piezo Vibration Sensor - Large w/ Mass	20	Sparkfun	SEN-09197	\$14.75
	Circuit Board	1	Radio Shack		\$14.99
	Microprocessor	1	Sparkfun		\$65.00
Lungs	Air Pump	1	Gast	GP40-101	\$200
	1/2" PVC Ball Valve	1	Stadium Hardware		\$2.95
	1/4" tubing	1	Lowes		\$10.27
	Open Cell Backer Board Foam	1	Nomaco	N/A	\$29
	Bags for Lungs	2	Simulation Center		
Nerve	Coat Hangers	2	Ofra's Closet		
	Elastic Band	8	Simulation Center		
Pleura	Shrink wrap with double sided tape	1	Lowes		\$21.75
Skin	Neoprene	1	FoamOrder.com	N/A	\$51.43
	3/4" Stick Velcro Roll	1	Michaels		\$4.35
Vessels	Rubber Hoses	3	TSC	309357	\$12

Parameter Analysis

Since one of the primary requirements of the simulator is that the model organs within the thoracic cavity must respond correctly at each stage of performing the thoracotomy procedure, we conducted a rigorous engineering analysis to determine the specific parameters for the ribs and the heart in the simulator. The heart, the ribs and the lungs are the only three components that demand a rigorous quantitative engineering analysis at the preliminary design and prototype phase of the simulator. This is because firstly, these components represent the mechanical structures that will be required to withstand the forces exerted by the surgeon at each step of the thoracotomy procedure. Since the functionality of the simulator at the most basic level depends on the fidelity of these systems in their response to human pressure, it is critical to analyze the amount of force they can tolerate before causing damage to the simulator. However, a simple analysis can be done on the remaining components (pleura, pericardium, etc.) to determine their behavior in relation to the minimal loading they bear during a simulated procedure.

As a first step in approaching the parameter analysis, we conducted an extensive literature and journal search to determine the dimensions for an average human heart, lungs and ribs. We also confirmed these dimensions after discussions with Dr. Andreatta.

Lungs

To satisfy the key user requirement of the components of the simulator being anatomically correct, as well as to satisfy the requirement of the components feeling real and responding correctly, the lungs must replicate the process of breathing. Hence the first step in moving towards analyzing the lungs from a mathematical perspective would be to identify its characteristics for an average person and to quantify them by ascribing a dimension to each characteristic. The following table indicates the lung characteristics and their corresponding dimensions as previously mentioned in [Table X](#).

Table 17: Lung characteristics and dimensions to define an average lung

Characteristic	Dimension
Inspiratory Volume	3.5 liters
Expiratory Volume	3 liters
Breathing Rate	12 breaths/minute
Breath Length	2.5 s

These dimensions were useful in calculating the average volume flow rate through our model of lungs. Calculating the volume flow rate in turn enabled us to select the appropriate ventilator that would provide us with the required air capacity.

Fluid mechanics analysis: The fundamental assumption in applying an engineering analysis to calculating the fluid flow rate was that the mass of air was conserved at all times such that the air that entered the lungs was exactly equivalent to the air exiting it. The following equations were used to calculate the required flow rate in CFM (cubic feet per minute):

Table 18: The air pump was required to pump 0.42 CFM of air

<i>Breathing Rate (x)</i>	5 seconds/breathe
<i>Air Displacement of Lungs(y)</i>	0.5 Liters
<i>Breathing Rate for Inhalation and Exhalation(z)</i>	2.5 seconds/breathe
<i>Volume Flow Rate(c)</i>	0.42 CFM

$$Volume\ Flow\ Rate = \frac{y}{x/2} \tag{Eq 1}$$

$$x = \frac{60seconds}{BreathsPerMinute} \tag{Eq 2}$$

$$y = Inspiratory\ Volume - Expiratory\ Volume \tag{Eq 3}$$

$$z = x/2 \tag{Eq 4}$$

$$c = y/z$$

Using the volume flow rate, we used the following Bernoulli equation to solve for the approximate pressure in the lungs:

$$\left(\frac{1}{2} pV^2 + P + pgz\right)_{pump} = \left(\frac{1}{2} pV^2 + P + pgz\right)_{Lungs} \tag{Eq 5}$$

where V is the air velocity, p is the density of air (1.205 kg/m^3 at 20°C (6)), P is the pressure, g is the gravitational acceleration and z is the distance. While applying this equation we assumed that the changes in z between the lungs and pump were small enough to be neglected and that the V_{lung} could be approximated to zero if the lungs were considered to be a very large cylinder. We also assumed that the air was incompressible, inviscid and followed a no-slip condition. (49)

These calculations resulted in the following equation reduction:

$$\left(\frac{1}{2} pV^2 + P\right)_{pump} = P_{Lungs} \tag{Eq 6}$$

The first step was to use the specification chart relating the flow rate (CFM) and the compressor pressure (psig) to read off the compressor pressure (psig) corresponding to the theoretical volume flow rate of 0.42 CFM. This pressure was approximately 5 psig and this was converted to Pascals (Pa) by dividing by a conversion factor of 0.000145. Next, to find the maximum air velocity of the compressor, we divided the volume flow rate of 0.42 CFM ($0.00019\text{ m}^3/\text{s}$) by the cross sectional area (0.000031 m^2) of a 0.25 inch tube leading from the compressor. Using the simplified equation above, we calculated that the approximate pressure in the lungs was approximately 33127.13 Pa (4.8 psi).

Failure mechanics analysis: Once we obtained the pressure in the lungs, we proceeded to conduct an analysis to test whether the foam material would succumb to yielding or not. For the purposes of simplification, we modeled the lungs as a pressurized hollow vessel with a radius 6.4 cm and thickness of 2 cm. Next we assumed that the radius of the vessel was significantly less

than its thickness. We also made the following assumptions about the principle stresses in the three dimensions:

$$\sigma_{rr} = -\frac{p}{2} \approx 0; \sigma_{\theta\theta} = \frac{pR}{t}; \sigma_{zz} = \frac{pR}{2t}, \quad \text{Eq 8, 9 \& 10}$$

where σ_{rr} , $\sigma_{\theta\theta}$ and σ_{zz} are the principle stresses in the each of the polar coordinates, as indicated in Figure 62 below, p is the pressure, R is the radius and t is the thickness.

Next, we calculated the Von Mises effective stress for the loading parameter for yield. This was calculated by the following Von Mises equation approximation:

$$\sigma_H \approx \left(\frac{1}{2} \left[\left(\frac{pR}{t} \right)^2 + \left(\frac{pR}{2t} \right)^2 + \left(\frac{pR}{2t} \right)^2 \right] \right)^{0.5} \approx \frac{\sqrt{3}}{2} \frac{pR}{t}, \text{ where } \sigma_H \text{ is the loading parameter for yield.}$$

We determined that the yield stress (σ_Y) for the foam for the lungs was 17 psi (48) (1.17×10^7 Pa). The yield criterion was $\sigma_H \geq \sigma_Y$, therefore to avoid yielding, we deduced that the foam would need to fulfill the following criterion:

$$\frac{pR}{t} \leq \frac{2\sigma_Y}{\sqrt{3}}. \quad \text{Eq. 11}$$

For our foam specification where the radius was 6.4 cm and the thickness was 2 cm, the foam fulfilled the yield criterion because R/t was equal to 3.2 and $\frac{2\sigma_Y}{\sqrt{3}}$ was equal to 4.08. Hence we conclude that the foam will not yield under the pressure exerted by the compressor.

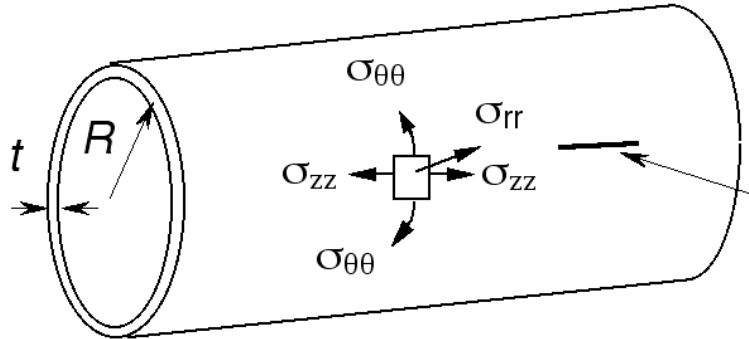


Figure 78: A schematic indicating the principle stresses on a pressure vessel (30)

Analysis: As evident from the analysis above, we chose to conduct an engineering analysis from a fluid dynamics perspective using the Bernoulli equation to predict the approximate pressure exerted within the lung due to the air from the compressor. To verify that the foam surrounding the lungs could withstand this pressure, we ensured that the lungs fulfilled the criterion against yielding. We believe that this level of analysis was adequate on a preliminary level to for a pump with the current chosen specifications. However, if we had an infinite amount of time to create a perfect model for the lungs, we would certainly want to conduct a more rigorous, but similar fluid and failure mechanics analysis. This analysis could be conducted with several varieties of raw materials and each of these can be subjected to further scrutiny by conducting a mesh

analysis using fluid dynamics software (Fluent, Gambit) and Finite Element Analysis software (FEA).

To make sure we have analytically verified our model from several engineering principles, we also recommend modeling the lungs from different mechanical or electromechanical perspective. For instance, since the lungs expand and contract with a constant rhythm, they could even be modeled using a spring dashpot assembly to model their visco-elastic behavior, where E_1 and E_2 are springs, R_1 is a single airway and R_2 is a dashpot. (55)

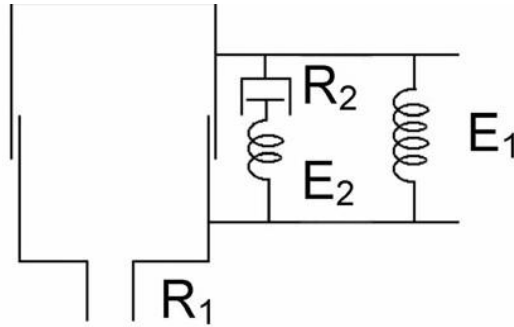


Figure 79: Modeling of the lungs using an alternative spring damper approach Heart (55)

Ribs

The ribs were chosen to be made out of PVC pipe for a number of reasons. First, it was possible to get the PVC in a shape that was already very close to that of real ribs, which meant less manufacturing. The pipe also had a similar thickness to that of ribs. As seen in Table 9, the depth of the ribs is 24 cm or about 9.5 in. This makes the effective radius of the ribs about 5 in. We chose the 6 in pipe diameter because after tilting it at a 20 degree angle to the horizontal, the effective radius became about 5.6 in. We decided this was well within a reasonable range, considering the size of the rib cage can vary drastically from person to person.

Once we determined the material we would use to replicate the ribs, we had to conduct analysis to ensure the ribs would be able to withstand the forces that a rib spreader would exert during a procedure. After a lot of research, we discovered the force applied on each rib to spread them effectively on a sheep was on average 100 N. Knowing this force, the first thing we did was attempt to solve for the area of maximum stress analytically. Our engineering intuition told us the maximum stress would most likely be created around the holes used to attach the ribs to the connectors as seen in Figure 80. It can also be seen in Figure 80 the force applied is at a 20 degree angle to the rib, due to the fact the ribs are rotated within the ribcage.

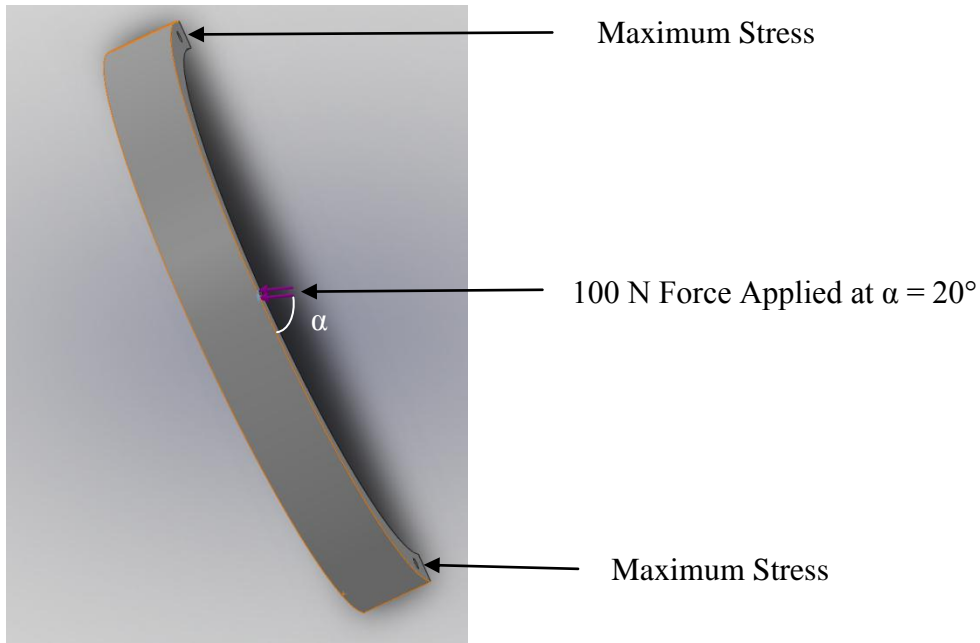


Figure 80: Location of Force Applied and Theoretical Maximum Stress

After talking with Professor Daly and Professor Wineman, we determined that trying to calculate the stresses rigorously would be extremely difficult to attempt within the scope of this class. Professor Wineman mentioned that if we were to assume the radius is much larger than the thickness of the rib, we can approximate it as a beam. The error, however, would be substantial, ranging from 40-50%. Therefore, we concluded that Finite Element Analysis (FEA) would be a better approximation for this application.

Using FEA, the first step was to perform a stress analysis on the rib. It turned out that Solid works has an FEA built in, and also have the material properties of PVC pipe built in as well. This made using FEA much easier than solving analytically. After applying constraints at the holes near the ends of the rib, and applying a 100 N force in the location and direction as shown in Figure 80 above, we ran the FEA analysis. Figures 81 and 82 show the results with a safety factor of 3.75 incorporated into the design. Figure 81 shows the stress distribution and Figure 82 shows the total displacement of the rib.

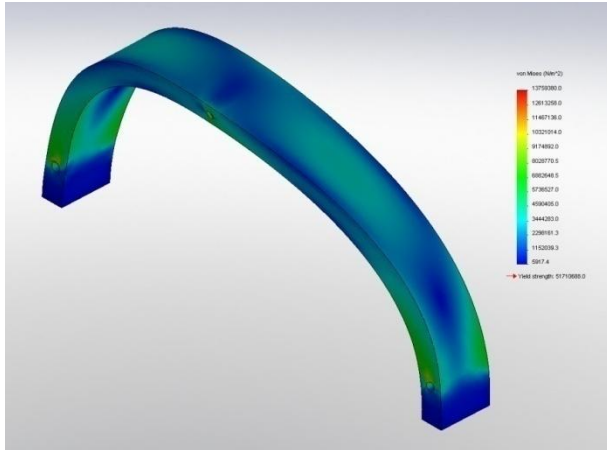


Figure 81: Stress Distribution

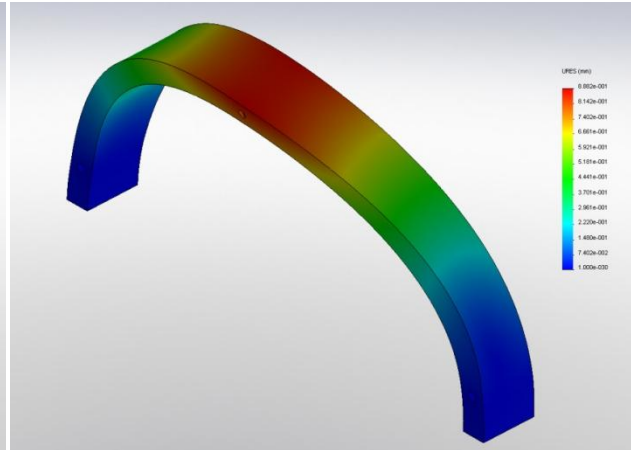


Figure 82: Strain Distribution

After analyzing the results, it is clear that the most stress does in fact occur at the hole like we first hypothesized. The results also show that the rib will not break under the forces that will be applied during the procedure. In fact, according to the FEA, the rib will be able to withstand up to 375 N of force which is well beyond anything we will see in any aspect of the prototype. While these findings are very encouraging, we do not want to take the results of FEA for granted. The next step in validating the ribs is with actual testing.

Testing will not be performed before this report has been completed, but it is planned to be done as soon as possible, within the next few days. A mounting bracket for the rib will be fabricated and bolted to a piece of wood that will serve as a support plate as shown in Figure 83 below. Once the rib is securely attached to the brackets in the same fashion it would be secured to the connectors, a force (F) will be applied at a 20 degree angle to replicate the rib spreader force. Weight will be added in 5 lb increments until failure occurs or the force exceeds 200 N [44 lbs].

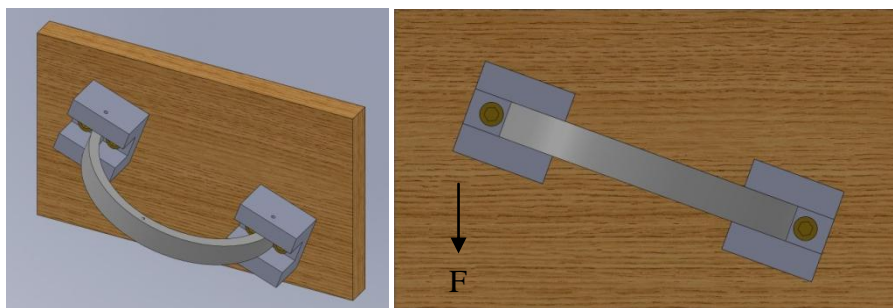


Figure 83: Rib Testing Setup

After testing is completed, if the results confirm FEA analysis, we will be able to continue manufacturing and assembly the rib cage with full confidence the ribs will not fail. If it turns out that the ribs cannot withstand a sufficient amount of force, a redesign of the connectors to add more support to the ribs will be evaluated.

After using FEA to analyze the strength of the rib, we wanted to conduct a real test. We constructed a setup, as seen in Figure 84 and added increasing amounts on weight onto the rib in

order to determine if the rib could withstand the 100 N (approximately 20 pounds) that would be applied during routine procedure. We attached the weights to the rib using a simple shoelace.

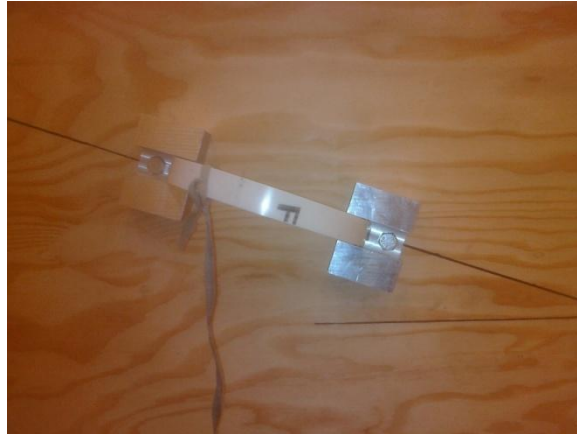


Figure 84: Experimental Setup

We also made sure to place the rib at a 20 degree angle from the weight in order to simulate the correct direction of force. Weight was added in 2.5 pound increments until we reached 27.5 pounds, a force well above what is required.

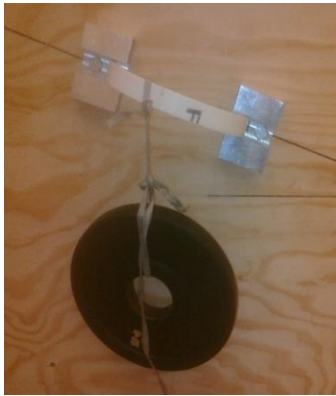


Figure 85: 10 lb Force



Figure 86: 17.5 lb Force



Figure 87: 27.5 lb Force

As Figures 85-87 above show, the validation test for the rib was very successful, and we were able to continue manufacturing our prototype with the knowledge that the ribs would not fail.

Springs

Not only will the ribs have to withstand at least 100 N, they will have to be able to provide that force to the rib spreaders. This will be accomplished by the use of torsional springs on each of the connectors of the rotating ribs. In order to determine which springs to use, the spring constant, k , must be determined. The spring constant can be determined using a moment balance equation around the axis of rotation as shown by Equation 12 below, where F is the applied force perpendicular to the lever arm, M_s is the moment created by the spring force and L is the distance between the force and the axis of rotation.

$$M_s = FL \quad \text{Eq. 12}$$

Substituting in $M_s = k \cdot \phi$, and then $\phi = \tan^{-1}\left(\frac{d}{L}\right)$, where d is the total displacement of the rib, and ϕ is the corresponding angle of displacement, we can solve for k using Equation 13 below. All of the variables can be seen in Figures 68 and 69 below.

$$k = \frac{FL}{\tan^{-1}\left(\frac{d}{L}\right)} \quad \text{Eq. 13}$$

Using $F = 100 \cdot \cos(20^\circ) = 93.969$ N, $L = 0.0833$ m, and $d = 0.03$ m, we have determined:

$$k = 0.417 \frac{Nm}{deg}$$

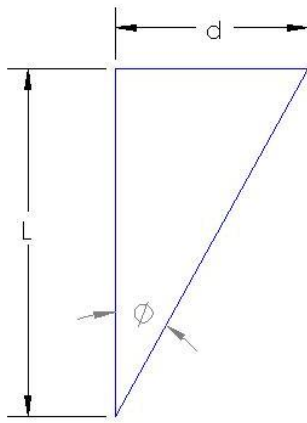


Figure 88: Dimension Variables

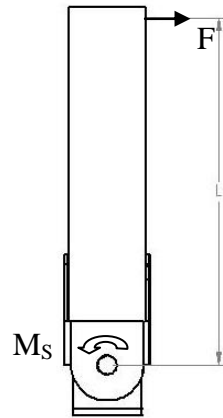


Figure 89: Force Variables

It should be noted however that it is intended to use two springs on each rib; one on each connector. To account for this, simply divide the spring constant in half and the real spring constant becomes:

$$k = 0.2085 \frac{Nm}{deg}$$

All of the preceding analysis pertaining to the ribs was done to ensure both proper response and a sound design.

The Heart - Cam Development

In order to create a realistic heart beat, a cam design was developed to be installed within the modeled heart. This cam, paired with the correct motor selection, would allow us to make the heart beat in the correct location and at the correct time.

The Cardiac Cycle: The human heart has four chambers; a right atrium and ventricle and a left atrium and ventricle as shown in Figure 90 below. During the cardiac cycle, four sounds are generated by the heart, two of which can be heard through a stethoscope. The first and loudest sound is generated at the onset of ventricular systole, when the muscles surrounding the left and right ventricles contract. The sound is created due to the closing of the atrioventricular valves, or the valves located between the right atrium and ventricle (1) and between the left atrium and ventricle (2). This is shown in Figure 91 as the second cluster of waves (labeled as “1”) and the shape of the heart during this contraction can be seen in Figure 92. The second loudest sound is generated by the closure of the valves located between the right ventricle and the aorta (3) and the valve located between the left ventricle and the pulmonary artery (4). This occurs at the onset of atrial systole, when the right and left atrium contract. This is shown in Figure 91 as the third cluster of waves (labeled as “2”) and the shape of the heart during this state is shown in Figure 93. The sounds labeled “4” and “3” are created due to other factors not affecting the overall movement of the heart and, therefore, were not taken into consideration when designing the cam.

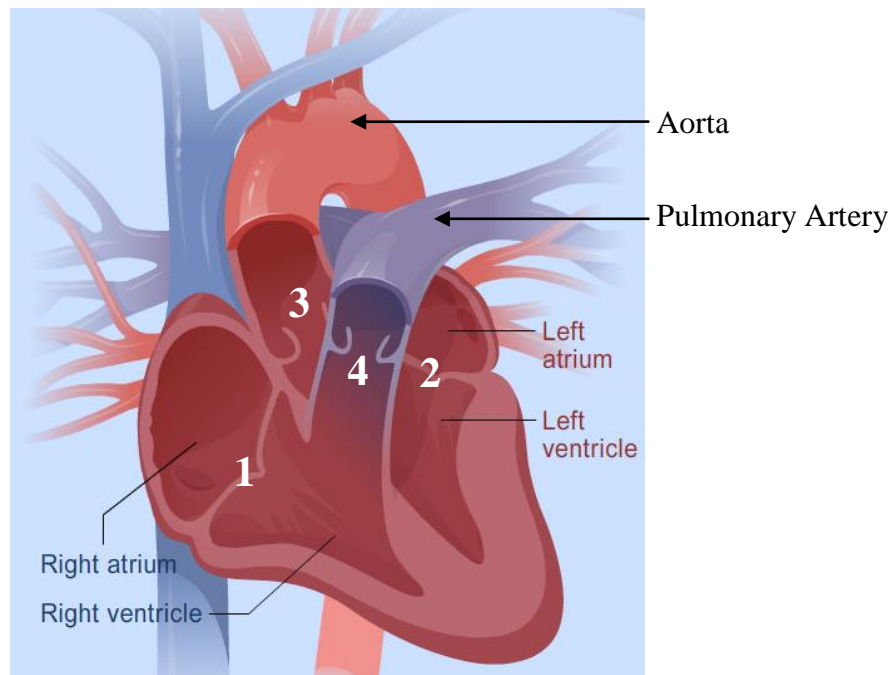


Figure 90: The Chambers of the Heart (9)

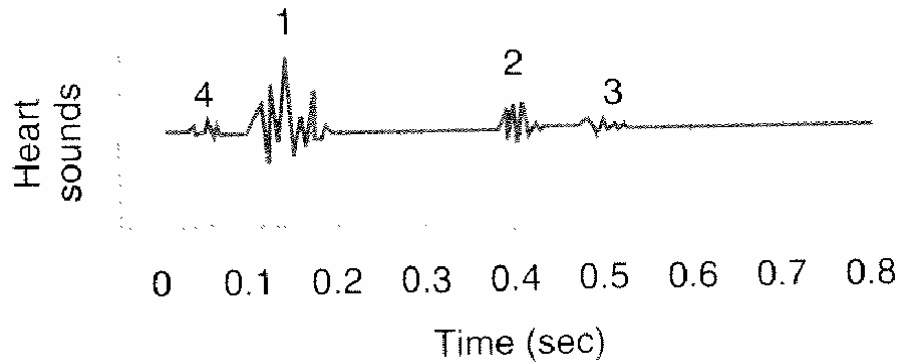


Figure 91: Heart Beat Timing (12)



Figure 92: Ventricular Systole (76)



Figure 93: Atrial Systole (76)

Transformation of Cardiac Function into Cam Rotation: The cam design is shown in Figure 94 and the form of the inside of the heart in order to make the cam produce the correct heart movements is shown in Figures 94 & 95. It is important to mention here that, although a real heart contracts, our simulator heart will not. Instead, it will expand and subsequently “collapse” to imitate the contracting motion.

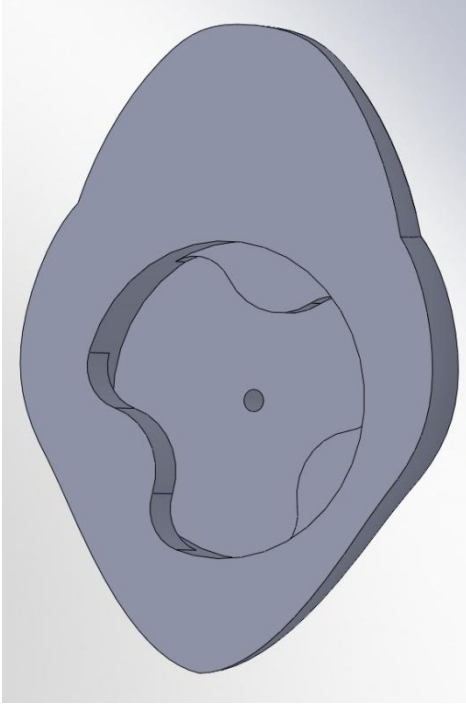


Figure 94: Cross-sectional View of the Heart

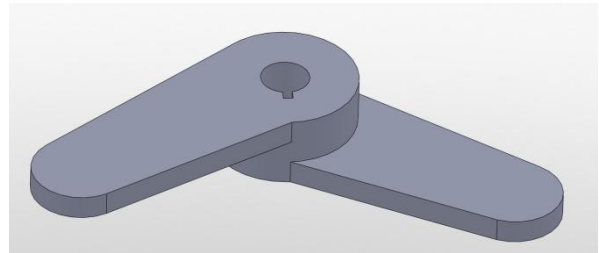


Figure 95: The Cam

Incorporating Heart Beat Timing

In order to produce this design, the beat time ratio of the two loudest beats of the heart was initially determined. This ratio allowed us to determine how far apart the bumps inside the heart would have to be in order to make the heart move in the correct fashion. As shown in Figure 76 below, the time between the first and second beats, t_{21} , is approximately $0.4 - 0.15 = 0.25$ seconds and the time to complete one cardiac cycle, t_{tot} , is 0.8 seconds.

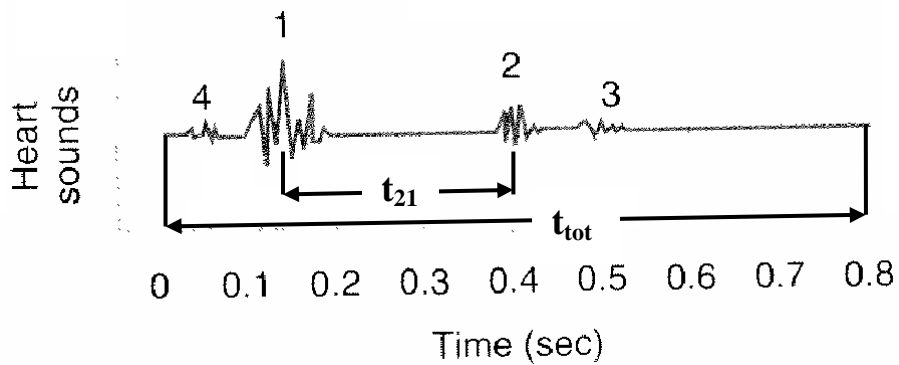


Figure 96: Heart Beat Timing – Beat Time Ratio (12)

Using this information, we can obtain the time beat ratio of the first two beats of the heart:

$$\frac{t_{21}}{t_{tot}} = .3125$$

This means that the time from when the two ventricles contract to when the two atria contract is about 31.25% of the overall time it takes to complete a full cardiac cycle. In one cycle, the cam will rotate 360°, so the angle between the lower bump on the bottom of the heart and the bump on the top of the heart shown in Figure 77 below can be determined by:

$$0.3125 \times 360^\circ = 112.50^\circ$$

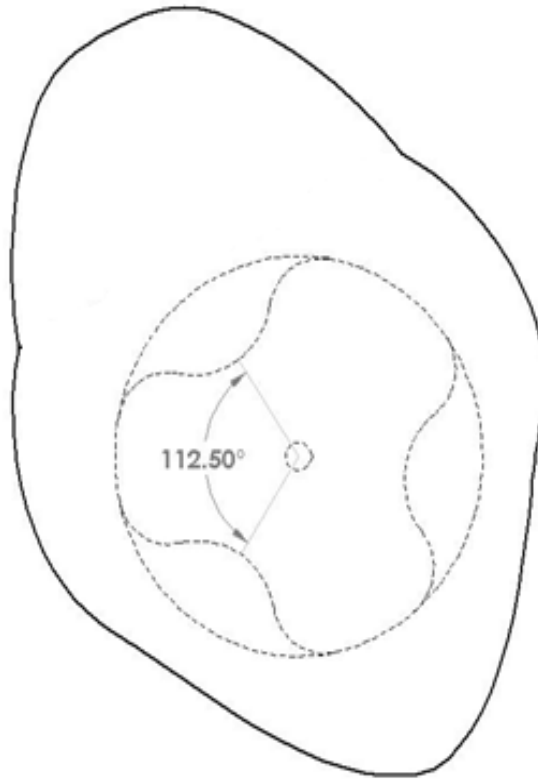


Figure 97: Front-view of the Heart

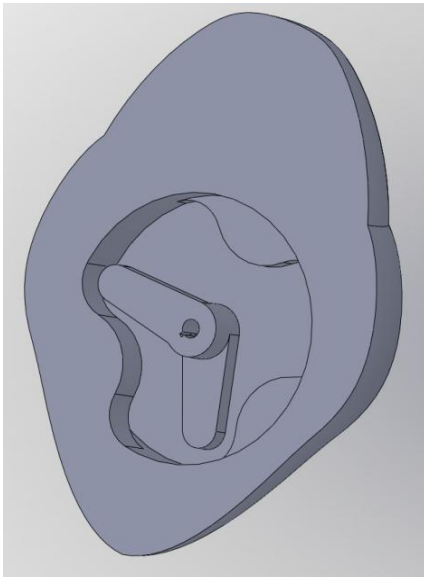
Operation of the Heart

During operation, a motor connected to the cam by a shaft will rotate the cam at a constant speed of 70 revolutions/minute corresponding to the user specification of 70 heart beats/minute, as can be seen in the user specifications in Table 1. This motor was selected so that, for the given size constraints, it would produce as much torque as possible for the given speed of 70 rpm. The selected motor is shown in Figure 98 and, at a supply voltage of 6 volts, it will run at a speed of 70 rpm and produce a torque of 4.8 kg/cm. (64) We believe this will be a sufficient amount of torque to rotate the cam within the heart, expanding the pliable PVC plastisol as it passes over bumps.

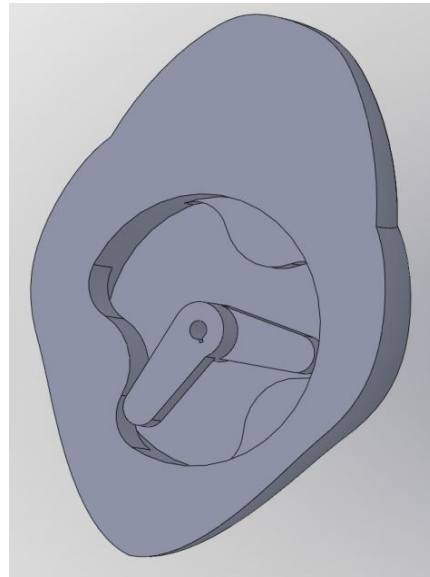


Figure 98: Motor Selected for Cam (64)

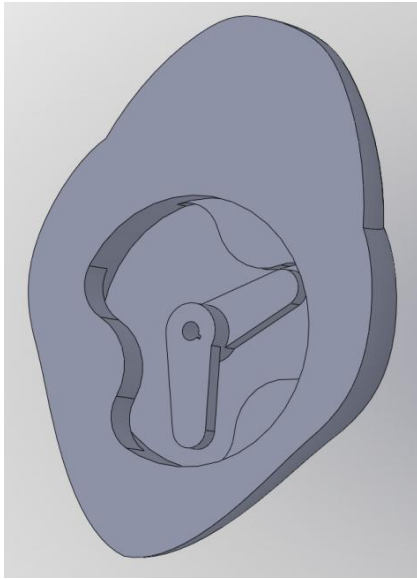
States of operation of the cam within the heart are shown in Figure 99. When the cam moves from state 1 to 2, both arms of the cam press against the two bottom bumps, causing the bottom of the heart to expand. Directly after this, between states 2 and 3, the bottom of the heart relaxes, corresponding to the “contraction” of the ventricles (ventricular systole). Next, between states 3 and 4, the lower arm of the cam will press on the upper bump, causing the top of the heart to expand. Due to the geometry of the cam, its upper arm will not be in contact with the heart at all at this point because it will be passing over the lower right bump instead of pressing against it. Directly after this, between states 4 and 1, the top of the heart relaxes, corresponding to the “contraction” of the atria (atrial systole). The cycle repeats continuously until the motor is turned off.



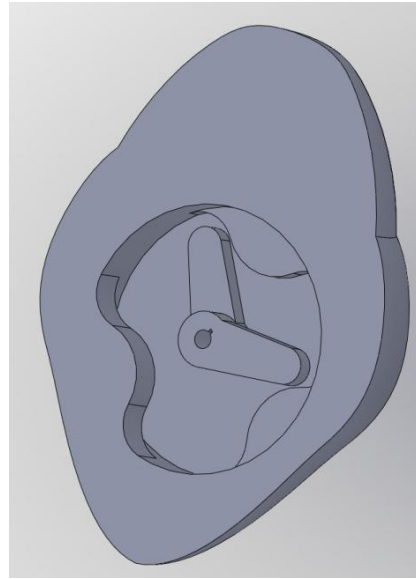
1) Pre-expansion of ventricles



2) Post-expansion/“compression” of ventricles



3) *Pre-expansion of atria*



4) *Post-expansion/ “compression” of atria*

Figure 99: Operation of the Heart

Additional Remarks: A few assumptions were made in accordance with the development of this cam design. The transient response of the motor is assumed to be inconsequential and the motor is assumed to behave linearly so that it will maintain a constant speed once its operating point has been reached. It is also assumed that the torque produced by the motor is sufficient enough to press the cam against the bumps, without significant deceleration. Furthermore, it is assumed that the heart material will not be put under any stress above its yield strength, so it will continue to behave elastically throughout multiple simulations and not be deformed in the process. Additionally, it is assumed that when the cam hits each bump, the force applied on the inside of the heart will translate to movement on the surface of the heart. If the plastic material used to create the heart absorbs most of the energy rather than transmitting it to its body, then we will not see much movement. Due to the fact that we are creating our own plastic mixture, there is no way for us to know what its material properties are. Therefore, calculations as to whether or not the material would deform under the applied stresses as well as whether or not it will act as a shock absorber cannot be done unless the properties are obtained experimentally. With more time, the material properties would be found experimentally and a Finite Element Analysis would be done to see if the heart would fail under the appropriate loadings. Since we cannot do this, we will use a trial-and-error approach in which we will build our model, see if it moves in the correct fashion, and make revisions accordingly.

The Heart – Feedback System

The following is a discussion of the mathematical analysis of the heart involving the theory of electrical circuitry and programming language. Since a thorough examination of the heart is one of the primary aims of the thoracotomy simulator, we had to provide a mechanism whereby the surgeon can obtain evaluative feedback to assess his/her performance during the procedure. In order to provide the surgeon with visual feedback, a panel board was created with light emitting diodes (LEDs) that correspond to each examination site on the heart. Each LED was linked to an Arduino Mega microcontroller, which, in turn, was linked via programming to respective piezo

sensors placed on the heart. When touched, each piezo sensor translated the force from the user into an oscillation in voltage, thereby triggering the LED on the panel board to light up. The sensor is shown below in Figure 100 and the Arduino Mega microcontroller (Mega) is shown below in Figure 101 .

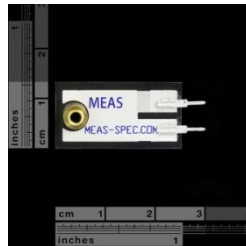


Figure 100: Piezo Sensor (77)



Figure 101: Arduino Mega Microcontroller (78)

The complete circuit diagram for an individual sensor/LED system for surgeon feedback is shown below in Figure 102.

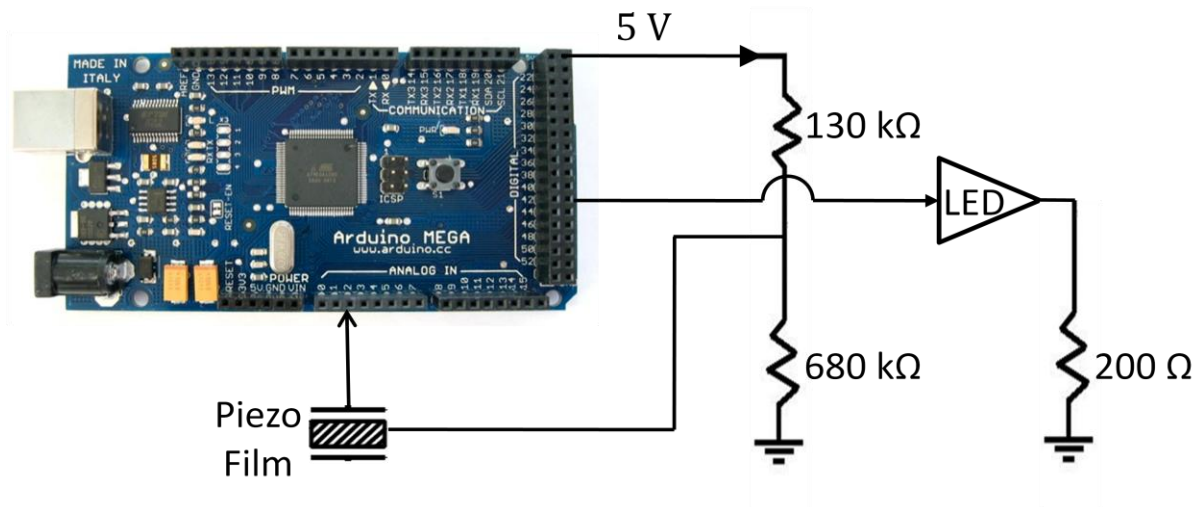


Figure 102: Schematic of the Sensor/LED Circuit

Sensors: We will be using piezo vibration sensors to act as force sensors in detecting the surgeons' tactile input and translating that into a voltage change that can be directed to the LED. The figure below indicates the alignment of the axes. These sensors are anisotropic, meaning that their electrical and mechanical responses differ depending on the axis of the applied electric field or stress or strain.

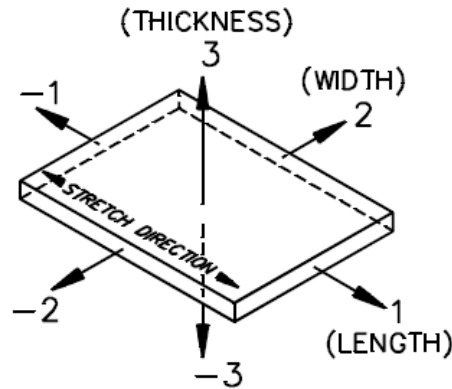


Figure 103: Numerical classification of axes (43)

Typically, the sensor is used in the mechanical 1 direction for low frequency sensing and actuation (frequency < 100KHz) and in mechanical 3 direction for high frequency sensing and actuation. When these piezo sensors are squeezed, they generate an electrical charge so that a voltage appears between the electrodes. The amplitude and frequency of the signal produced is directly proportional to the mechanical deformation of the sensor material.

Circuitry

One lead of each sensor was connected to an *analog in* pin on the Mega. These pins map input voltages between 0 and 5 volts to integer values between 0 and 1023, due to the 10-bit analog to digital converter that the Mega contains. The other lead was connected to the 5V pin on the Mega through a voltage divider, which supplied a constant voltage to the sensor. A voltage divider, as shown in Figure 104 below, works to decrease the voltage supplied to the divider, V_{in} , to the voltage exiting the divider, V_{out} . This divider was also connected to the *ground* pin on the Mega in order to complete the circuit. Such a divider was needed because, through initial tests, the sensor output was shown to oscillate occasionally to values that were higher than 5 volts, which was the maximum voltage the Mega could read. Using this divider, the oscillatory output of the sensor was lowered to be within the 0-5 volt range.

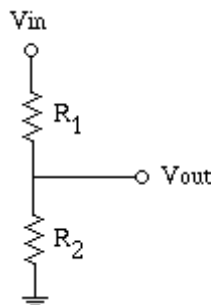


Figure 104: Voltage Divider (79)

Since a constant 5 volts are being supplied from the Mega out of its 5V pin, $V_{in} = 5$ volts. Experimenting with different resistors, we determined resistances $R_1 = 130 \text{ k}\Omega$ and $R_2 = 680 \text{ k}\Omega$, so that all sensor outputs would fall in the 0-5 volt input range of the Mega. Using equation 14 below, V_{out} was determined using the following.

$$V_{out} = \frac{R_2}{R_1 + R_2} V_{in} \quad \text{Eq. 14}$$

$$V_{out} = \frac{680 \text{ k}\Omega}{130 \text{ k}\Omega + 680 \text{ k}\Omega} * 5 \text{ V} = 4.2 \text{ V}$$

Therefore, the voltage supplied to each sensor is 4.2 volts.

LEDs: It is significant to note that the LED only conducts current in one direction (the direction in which it is pointing forward). We will use the forward conducting, reverse blocking type of LEDs so this configuration acts as a restricted switch. Figure 105 below indicates the I-V characteristics of a typical diode. (71) The forward biased region in the plot is depicted by the voltage across the diode (in the first quadrant) of the plot. As the diode conducts, the current across it starts off as being initially small (usually between 0.5 V to 0.7 V) and then increases. The plot depicts a simplified linear behavior of the current versus voltage after the threshold voltage, A , is crossed. In a real diode, the increment in current versus voltage trend is non linear. This portion is of particular importance to us because is the voltage across the diode exceeds its defined threshold voltage, the diode conducts. The negative values of the voltage across the diode indicate a reverse bias condition where the LED will not conduct any current at all due to the direction of the current direction being reversed.

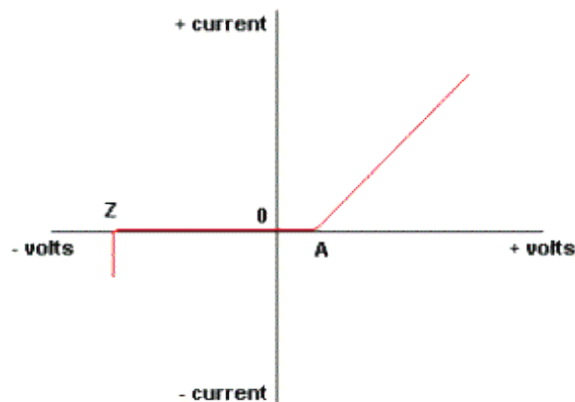


Figure 105: The current and voltage characteristics of an Ideal Light Emitting Diode (28)

Circuitry

The positive lead of each LED was connected to a *digital* pin on the Mega; these pins can read/supply either 0 or 5 volts. In our system, these pins will be acting as *digital out* pins, supplying 5 volts to the LED when requested. The negative lead of the LED was connected to the *ground* pin of the Mega, through a 200 k Ω resistor. The equivalent circuit diagram is shown below in Figure X.

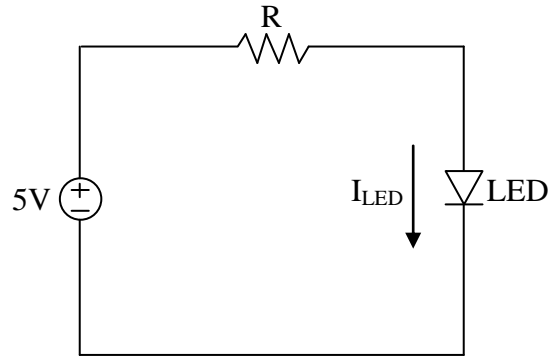


Figure 106: Equivalent LED Circuit Diagram

According to the technical specifications, the absolute maximum forward voltage supplied to the LED is 2.0-2.4 volts, at a forward current of 20 mA [80]. Since the supply voltage of 5 volts is obviously too high, a resistor was needed to lower the voltage drop across the LED to this maximum voltage rating. Using $I_{LED} = 20$ mA and using the voltage across the LED as 2.4 volts, the required voltage drop across the resistor, V_R , can be found using Kirchoff's voltage law, shown in Eq. 15 below, where N is the number of dissipaters of energy in the circuit and V is the voltage drop across them. In our circuit, $N=3$, corresponding to the supply voltage from the Mega, the voltage across the resistor, and the voltage across the LED.

$$\sum_{i=1}^N V_i = 0 \quad \text{Eq. 15}$$

$$-5 \text{ V} + V_R + 2.4 \text{ V} = 0$$

So, $V_R = 2.6$ V. Now, the resistance R can be found using Ohm's law:

$$R = \frac{V}{I} = \frac{2.6 \text{ V}}{20 \text{ mA}} = 130 \Omega$$

This means the absolute lowest resistance, R , that can be used is 130Ω . However, according to the technical specifications, the suggested amperage for the LED is between 16-18 mA. Therefore, a higher resistance of 200Ω was used, with a safety factor of approximately 1.5. In addition, through trial and error, this resistance was shown to be the highest possible resistance that could be used for the LED to glow brightly.

Programming the Arduino Mega Microcontroller: In order to control the LEDs through oscillating sensor input, an Arduino Mega microcontroller was programmed in the Arduino language, based on C/C++, using the Arduino v.0017 software. In our system, when a certain sensor was pressed, we needed the Mega to read its analog input, determine if it was above/below a certain value, and then send out 5 volts to its respective LED, thereby turning that LED on. These threshold values were different for each sensor and can be seen in the final program in Appendix E.

At first, the program was based solely on threshold voltages; if the voltage exceeded or fell below a certain limit, the LED was to turn on. After experimenting with the setup, however, it was found that the sensors were extremely sensitive and would turn on the LEDs after only being slightly grazed. Because of this, a time-based control was setup. This meant that if the sensor

output voltage exceeded a certain limit, for a certain amount of time, the LED should light up. These time thresholds were determined via a trial and error approach.

Even with this configuration, however, there were still some problems. When one sensor was pressed, its respective LED would turn on but other LEDs corresponding to different sensors would turn on as well. With the help of the graduate student instructor, Dan Johnson, it was determined that the output of one sensor was affecting the outputs of the other sensors, thereby turning the other LEDs on. By tracking the outputs of all sensors and examining the voltage oscillations of the other sensors as one was pressed, voltage limits were tweaked until the optimal threshold values were found. Now, each LED turned on with the pressing of its respective piezo sensor.

Though all problems seemed to be solved at this point, another was encountered when an attempt was made to connect a sensor to one of the second set of analog inputs (analog in pins 8-15). Looking at the values that were being read from these pins, the Mega was oddly reading a constant voltage input from the sensor, instead of an oscillating voltage. After a great deal of searching, it was found from an Arduino forum that this was a bug in the Arduino v.0017 software[<http://www.arduino.cc/cgi-bin/yabb2/YaBB.pl?num=1250970792>]. After fixing this, the system worked to have each LED light up when its corresponding sensor was pressed.

Other Components

For the less complicated components such as the pleura, pericardium and phrenic nerve, a simple stress/elongation test would be used to determine the Young's modulus. These moduli could then be compared to data found concerning the real components and help to prove or disprove correct response characteristics. It would be assumed that the strain varies linearly with stress and no energy is dissipated through heat or friction. We would use the equation $\sigma = E \cdot \epsilon$, where σ is the stress applied to the material, ϵ is the corresponding displacement or strain, and E is Young's modulus. Using a rectangular strip of each material, we would pull on each end with a constant force and measure the displacement of the material from its original state. We could calculate the stress using the equation $\sigma = \frac{F}{A}$, where F is the force applied and A is the cross-sectional area. This experimental and analytical process could not be accomplished within the scope of this class, but it is something to consider for later iterations of the prototype design.

Summary of Design Analysis

Material and Manufacturing Process Selection

In order to determine which material was to be used in our design, we incorporated the help of clinicians as well as CES software. Unfortunately for our design, the CES software was not extremely helpful, because many of the materials, such as PVC plastisol and foam were not listed in the software. The software helped us to see what other potential materials were available, but it ultimately did not have the materials we ended up selecting. The primary method of selecting material was done by having clinicians and our group members touch and compare materials, since material properties of components like the heart and lungs are not readily available for use in the CES software.

Design for Environmental Sustainability

The SimaPro software we used to determine the environmental impact of the foam and PVC plastisol turned out to be very useful. It was determined that the overall environmental impact of the foam was much greater than that of the PVC plastisol. This help us decided to use PVC plastisol for both the heart and lungs if our simulator was mass produced. It also made us realize how much of a factor both material play in the detriment of human health. The PVC plastisol is worse than the foam in the respect that it takes up more room in landfills, has a higher ecotoxicity and affects climate change more. We think that because the PVC plastisol will last longer and can be reused many times will make up for much of those issues.

Design for Safety

The prototype we built did not have many significant safety issues associated with it. The majority of the parts we made were done in the machine shop, where proper training and safety protocols were more than enough to avoid any issues. The biggest safety issue we had was making the PVC plastisol. When it is heated, the PVC plastisol gives off toxic fumes, which we dealt with by using a ventilation hood to suck the gasses away from the work area. With the supervision of our student instructor, Dan Johnson, making the PVC plastisol was very successful, and very safe.

Initial Fabrication Plans - Manufacturing

Table 20 below is a compilation of the machining processes that must be done in order to make all of the components in the simulator.

Table 20: Summary of Machining Processes

Part	Material	Action	Tools	Notes
Ribs	6"D schedule 40 PVC tubing	Cut tube to 2cm thick rings	Drop Saw	
	6"D schedule 40 PVC tubing	Cut rings in half	Band Saw	
	6"D schedule 40 PVC tubing	Drill holes for connectors	Drill press	1/8" Twist drill bit at 1500 RPM
Connectors	6061 Aluminum 0.063" thick	Cut exterior shape	Water Jet	
	6061 Aluminum 0.063" thick	Drill holes to plates	Drill press	1/8" Twist drill bit at 1300 RPM
	6061 Aluminum 0.063" thick	Drill holes to Ribs	Drill press	#34 Twist drill bit at 1300 RPM
	6061 Aluminum 0.063" thick	Drill holes for rotating joint	Drill press	1/4" Twist drill bit at 1300 RPM
Sternum Plates	1/4" Masonite	Etch exterior shape on surface	Laser cutter	2 layers
	1/4" Masonite	cut exterior shape	Band Saw	
	1/8" Masonite	cut exterior shape	Laser cutter	1 layer
	1/4" Masonite	Drill holes for connectors	Drill press	#38 Twist drill bit at 1,000 RPM
	1/4" Masonite	Drill holes for Hinge	Drill press	3/16" Twist drill bit at 1,000 RPM
Back plates	1/4" Masonite	cut exterior shape	Laser cutter	3 layers
	1/4" Masonite	Drill holes for connectors	Drill press	1/8" Twist drill bit at 1,000 RPM
	1/4" Masonite	Drill holes for phrenic nerves	Drill press	# 47 Twist drill bit at 1,000 RPM
	1/4" Masonite	Drill holes for Latch	Drill press	3/16" Twist drill bit at 1,000 RPM
Long Supports	6061 Aluminum 0.063" thick	Cut exterior shape	Band Saw	
	6061 Aluminum 0.063" thick	Drill holes for through bolts	Drill press	1/4" Twist drill bit at 1300 RPM
Cap Supports	6061 Aluminum 0.063" thick	Cut exterior shape	Band Saw	
	6061 Aluminum 0.063" thick	Drill holes for connectors	Drill press	#38 Twist drill bit at 1,000 RPM
Skin	3/4" thick Black Neoprene	Cut exterior shape	Scissors	
	3/4" width Velcro Strip	Cut to length	Scissors	30 cm long
	3/4" thick Black Neoprene	Cut slits	Utility Knife	24 cm long
Lungs	1/2" Open cell backer board Foam	Cut foam	Scissors	
	3/8" Tubing	Cut to length	Scissors	

Phrenic Nerve	Elastic Band	Cut to length	Scissors	
	Metal Coat hanger	Cut to length	Wire cutters	
	Metal Coat hanger	Bend to shape	Pliers	
Pleura Pulmonary Artery	Shrink Wrap	Cut exterior shape	Scissors	
	3/4" Clear PVC tubing	Cut to length	Utility Knife	
	3/4" Clear PVC tubing	Cut Fish mouth	Utility Knife	
Aorta	3/4" Clear PVC tubing	Cut hole	Utility Knife	
	1" Clear PVC tubing	Cut wedges	Utility Knife	
	Metal Coat hanger	Cut to length	Wire cutters	
Heart	Metal Coat hanger	Bend to shape	Hands	
	Plaster-based Powder	Rapid Prototype	Spectrum Z510	3:1 Worm Plastic to Softener
	Worm Plastic	Mix	Pot	350 Degrees Fahrenheit
Motor	Worm Plastic	Heat	Hot Plate	
	ROB-09347 Servo Motor	Cut tabs off	Hacksaw	
	Mild Steel Bolt 1/4"D	Extend Shaft	Hacksaw & Table Clamp	400 RPM
Cam	1/4" Plexiglas	Cut exterior shape	Laser cutter	
Display Panel	1/4" Masonite	Cut exterior shape	Laser cutter	6 different pieces
	1/4" Masonite	Drill holes for assembly	Drill Press	1/8" Twist drill bit at 1,000 RPM

Ribs

We began manufacturing in the GGB lab by making what would represent our ribs. They were cut out of a tube of Schedule 40, PVC tube of outer diameter 16.82cm (nominal 6 in) and wall thickness of 0.76cm. Using a drop saw, we will first cut the tube into 8 rings of 2cm thickness. Then we cut each ring in half using a band saw. Using a drill press and a 1/8" twist bit we then made a hole parallel to the axes of the original tube in each end of every rib. These holes were used to bolt the ribs to the connectors and can be seen in Figure 107.

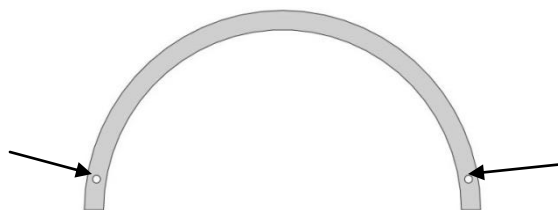


Figure 107: Rib with Connector Holes

Rib Connectors

To connect the ribs to the sternum and back plate we made three different types of connectors. These connectors were made out of 0.063" thick 6061 Aluminum. The first type (Figure 108) connects all of the stationary ribs to either the sternum or the back plate and is therefore referred to as the stationary connectors. The other two create the joint that the rotating ribs rotate around. One of the connectors goes from rib to joint (Figure 109) and the other from joint to sternum or back plate (Figure 110). We cut the exterior of all three shapes (shown in Appendix A) using the water jet, which is why no dimensions are needed for these parts. Do to the relatively smaller size of our pieces we had to have the water jet cut groups of connectors that were all linked together. This made it so that they would not get pushed around and lost or damaged in the water jet.

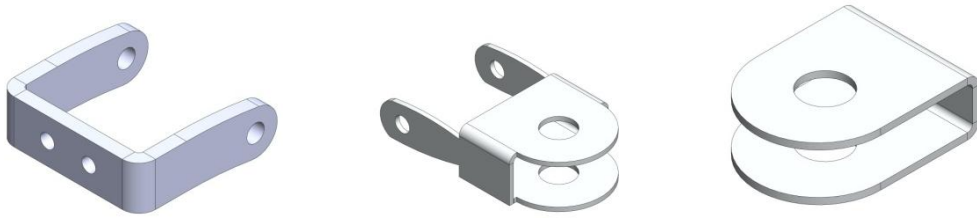


Figure 108: Fixed Connector Figure 109: Rib Connector Figure 110: Sternum Connector

We made 22 stationary connectors, and 10 of each of the joint connectors. With their exterior shape cut out we then drilled holes in them. To anchor the ribs to the connectors that needed to be we drilled two holes with a #34 twist drill bit. This is just smaller than the 1/8" diameter threaded bolts so that we could simply screw them in and have them stay without needing a nut. To anchor the connectors to the plates we drilled two holes toward the center to connect to the plates using a 1/8" drill bit. To create the holes on the center of the joints we drilled 1/4" diameter holes. With all the holes drilled we then bent all the connectors 90 degrees (all in the same direction) on the dashed lines shown in Figure 111. Lastly we did all the bending using a sheet metal bender, a table clamp, some scrap metal, and a rubber mallet.

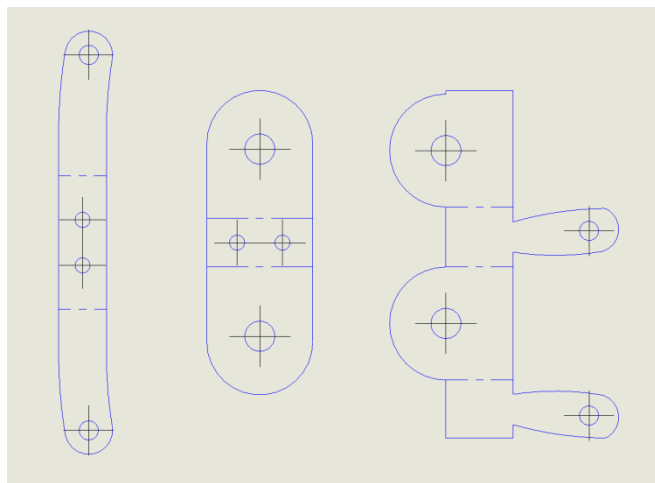


Figure 111: Bend the Connectors on Dashed Lines

Sternum and Back Plates

To make our sternum and back plate there are four different parts, two pieces for the back plate and two pieces for the sternum plate. We made these parts out of three layers of masonite. To create our designed shape we wanted to use the laser cutter. We were informed that the laser cutter would cut up to 1/4" thick masonite. So we planned to cut two layers of 1/4" thick masonite and one layer of 1/8" masonite for each of the four parts. We approximated our 2 dimensional sketch of each part using arcs and lines (no splines), saved it as a .dxf file and put it into BobCAD. However, after multiple passes of the laser cutter at many different speed and power settings. It was clear it could not cut the 1/4" thick masonite. Therefore we took the 1/4" masonite with the correct shape etched in it, to the band saw and jig saw, where we were able to cut out the shapes we needed. The laser cutter was capable of cutting through the 1/8" thick masonite, and we did use it for that. We then glued and clamped the four sets of three identical pieces together. To spread the glue we used our fingers and worked over a table covered in paper. We placed a scrap strip of wood found at the shop on each side of the parts between the masonite and the clamp. Resting them carefully on the paper covered table we let them sit overnight to dry.

The following day we removed the clamps and began drilling. We started with the holes for the connectors. Using the drill press and a #38 twist drill bit, we drilled 56, holes around the edges for the connectors. These holes are represented in the figure 112 below by the blue circles. To get the correct placement of these holes we will held the connectors in their correct places with our hands and marked the center of one hole with a marker. We drilled all 32 holes and screwed on the connectors and the ribs. This created two halves of our ribcage, but it was still able to rotate so that we could measure our 20 degree angle on a much bigger scale. We set our two halves on the table with the PVC ribs as the high point. We measured our 20 degree angle on both halves from above and traced each connector's position on to the sternum and back plates. We then un-bolted the ribs, and marked the location of the second hole of each connector on the sternum. To mark these we lined the connectors up to the lines we had just made. This made sure we got the correct angle over all the ribs while accounting for variations in both the ribs and the connectors. The final set of holes drilled where for the two hinges on the front and back plate. These holes are 3/16" diameter and are represented by green circles in Figure 112 below.

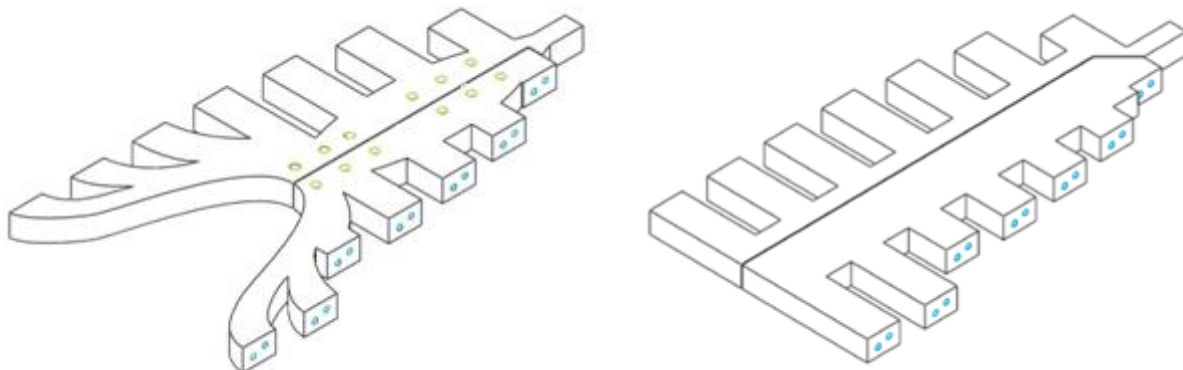


Figure 112: Hole Locations for Sternum and Back Plate

Supports

While drilling the holes in to the sternum and back plate for the connectors, the masonite split along the planes in which we had glued them. To reinforce them we created supports for them. We created two different kinds of supports.

The cap supports are for the locations where the sternum attaches to the rotating ribs as seen in Figure 113. Therefore there are five of them and they were created by cutting 0.063" thick aluminum into 2.14cm by 4.65cm pieces. We then measured out 5/16 from the center in both directions and bent them up 90 degrees. This made the support fit over the end of the masonite like a cap. We then drilled through both the support and the masonite with a 1/4" drill in the same direction as the holes for the hinges. Placing a 5/16" diameter 1 1/4" long bolt through this hole we were able to screw a nut on and get the masonite back to the correct position.



Figure 113: Cap Supports

The second sets of supports are referred to as long supports. They were made by cutting six strips of 0.063" thick 6061 Aluminum into 2cm by 24cm. We then drilled six, 1/4" diameter holes down the center of each piece. These holes were evenly placed with 4cm between centers. This way when we placed one strip on each side of the masonite back plates we could bolt them together using a 5/16" diameter bolt in between the "ribs" of the plate itself. We made three of the long supports and placed them on both back plates as well as the right sternum.

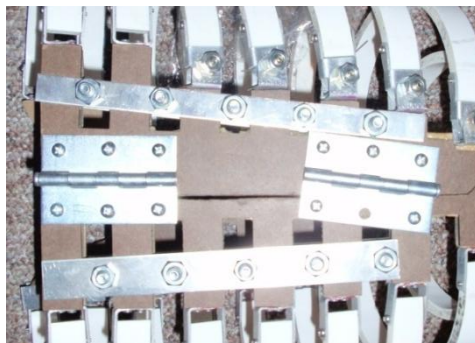


Figure 114: Long Supports

Pleura

Shrink wrap was cut into 24cm by 10cm parallelograms with an acute angle of 70 degrees. These sections are used as the Pleura. A sketch of this shape is show in Figure 115.

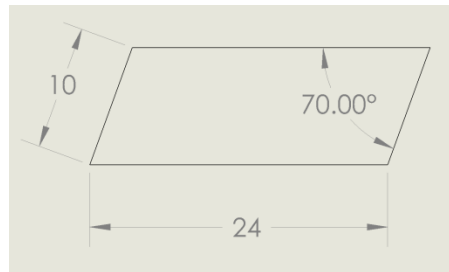


Figure 115: Pleura Dimensions

We then cut the double sided tape that came with the shrink wrap into two 24cm long pieces. Removing the covering from one side we stuck the tape to the inter side of the 3rd and 5th rib from the top.

Skin

The rib cage of our simulator was completely covered with 3/4inch neoprene by wrapping a large sheet around it. It was wrapped so that the neoprene overlapped on the back plate as seen in Figure 116. We then marked a line running along the spine of the back plate on both pieces of overlapping neoprene and cut along them. This got rid of the overlapping material and created a strait seam down the center of the back plate. We then cut a strip of 3/4inch thick sticky-back Velcro to a length of 30cm. Pulling off the coverings to the sticky sides, we placed the Velcro strip in the seam we had made down the center of the back plate. With the Velcro connected to the neoprene we connected it all together to get a tube of neoprene around our rib cage. We then cut the top and bottom of the neoprene tube to make it flush with the top and bottom of the rib cage. This lined the two openings up quite accurately. Using a utility knife, we cut three slits of approximately 24 cm on the outside of the neoprene. These slits did not go the whole way through. One slit was cut down the center of the sternum. The other two slits were cut one on each side of the rib cage, running parallel to the ribs, in between the 3rd and forth rib from the top as seen in Figure 117. We then removed the neoprene from the rib cage by opening the Velcro seam and laid it flat on the table. We cut the slit on the left side of the rib cage the whole way through and used surgical sutures to sew the hole shut.



Figure 116: Skin



Figure 117: Skin with Cuts in Side

Lungs

Plastic bags provided to us from the Clinical Simulation Center had hoses attached to their opening and sealed with epoxy. The lungs are made of sheets of open cell backer board foam held together using epoxy. We created the exterior shape of a deflated lung to the best of our ability using many different anatomy pictures, as well as making them fit inside of our assembled rib cage. Both the foam and the hose were cut using scissors. Upon completion of the lung shape, we inserted the plastic bags into the lungs up through the bottom, and cut a hole on the side to put the tubes through. We then placed a three way valve along the tube leading to the left lung. The three way valve was created out of a PVC ball valve. Making it into a three way valve required the use of a 1/4" drill bit. We turned the valve to the closed position and drilled through one side of the ball by placing the bit in an inlet/outlet opening. Leaving the valve in the closed position we then drilled a hole in the center of the outer casing of the ball, so that when the bit was through the outer casing it went into the empty space of the ball valve. Because the smallest size PVC ball valve we could get was a 1/2" inlet/outlet diameter we had to wrap the tubing with duct tape until it created a tight fit. We also used epoxy to secure the tubing to the valve. The MSDS information concerning the foam used can be found in Appendix C.



Figure 118: Lung Setup

Heart

The heart was molded out of worm plastic in two pieces. The mold was created in the 3D Lab of the Duderstadt center. It was done using the Spectrum Z510 from Z Corporation and created out of a plaster based powder material. We made four separate parts in the 3D Lab, two for each side of the heart as is shown in Figure 119. We then lightly sanded the mold to obtain a smoother finish on our final product as well as to get it to fit inside of each other correctly. The next step was to create the worm plastic. We then covered the entire mold in Vaseline using our fingers and cue tips. We had decided to use a 4:1 ratio of worm plastic and plastic softener. Both liquids were poured into a pan and mixed well. Then it was heated to approximately 350 degrees Fahrenheit, measured with a candy thermometer. This was done on a hot plate in the manufacturing lab with a vacuum hood right next to it. Once we poured the liquid in the mold we placed them outside in a cardboard box to cool. The fit between the two sides of the mold was so snug that we didn't need anything to hold them together other than their own pressure and friction. The worm plastic left in the hole we poured through, was then cut out using an exact-o blade. We opened and removed the worm plastic from the molds as carefully as possible.

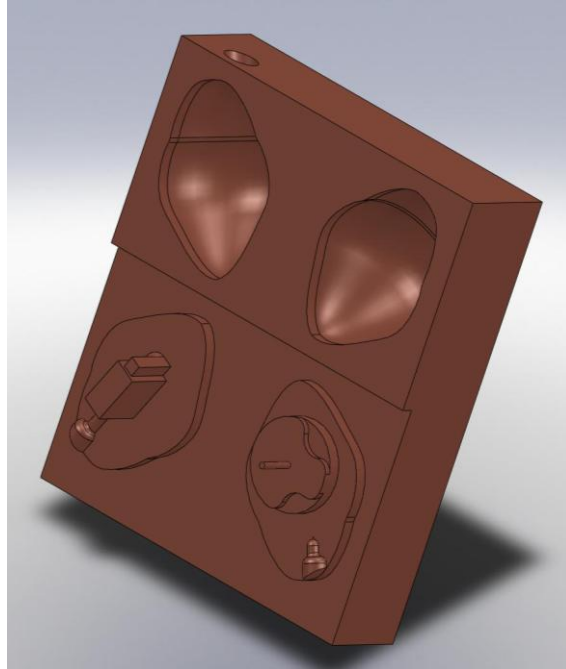


Figure 119: Heart Mold

Making the Plastic: As determined in the material selection process, we chose to use PVC plastisol as the material with which to make the heart. A benefit of this material, besides its molding capabilities, is that we can control how the material response by varying the ratio of plastic, hardener and softener. In order to determine the best ratio to use, we made six samples, each with a different ratio of ingredients. All six samples can be seen in Figure 120 below. Table 21 below lists the ratio of softener/hardener to plastic used in each sample. The MSDS for PVC Plastisol can be found in Appendix C.



Figure 120: Sample Plastics Used to Compare with Heart

Table 21: Ratio of Softener/Hardener to Plastic

Sample	Plastic	Softener	Hardener
1	25%	75%	0%
2	50%	50%	0%
3	75%	25%	0%
4	100%	0%	0%
5	75%	0%	25%
6	50%	0%	50%

Procedure: Making the plastic was very straight forward, as directions were provided by the manufacturer. First, the predetermined ratio of softener/hardener to plastic was measured out using a measuring cup. Each sample had a total of 2 fluid ounces of liquid, independent of the ratio used. The mixture was then poured into a pouring pan and heated slowly over a hot plate until a temperature of about 350°F was reached. A candy thermometer was used to ensure accurate temperature monitoring, as can be seen in the setup in Figure 121 below. At that point, the mixture changed from a milky white to clear, indicating it was ready to be formed. After the mixture turned clear, it was poured into the baking tray as indicated in Figure 120, and allowed to cool. This procedure was then repeated for each of the six samples.



Figure 121: Plastic Making Setup

Motor and Cam

The servo motor had two tabs on the sides cut off using a table clamp and a hacksaw and sanded smooth. We cut two pieces of 1/4" Plexiglas on the laser cutter shown in Figure 122. We then attached the two pieces to one of the provided cams using epoxy to side away from the motor. To line these up all we had to do was place the creases on the outer shape of them right on top of each other. Finally we cut a 1/8" bolt off to a length of 2.5cm and used epoxy to secure it inside of the two Plexiglas pieces. Then we placed the cam on the motor.

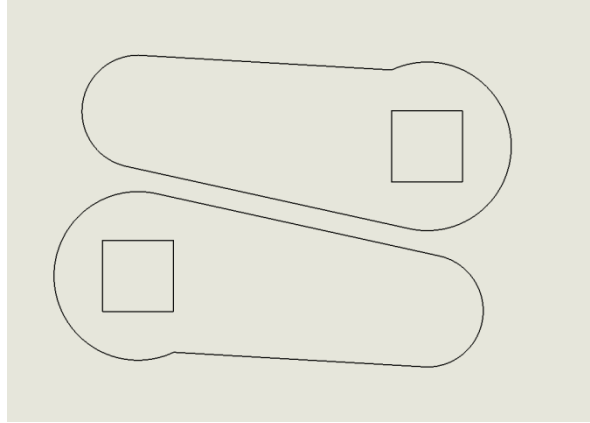


Figure 122: Laser Cut Cam Pieces

Vessels

The aorta was cut out of a 1”D clear PVC tube, to a length of 30cm. All cuts on clear PCV tubing was done using a utility knife. A straitened metal coat hanger was also cut to 30cm using wire cutters. The wire was placed inside the tube. We bent the metal coat hanger inside the clear PVC tubing, to hold the tube in our desired shape. Because the tubing was too stiff to maintain a circular cross section and create the smaller radii, we had to cut wedges out of the inter side of the bend. We bent the tube over the wedges so that they look like slits in the final position as shown in Figure 123 below.



Figure 123: Wedge cuts to help bend Aorta

The pulmonary artery was constructed out of two pieces of 3/8”D clear PVC. One is 10cm long and the other is 5cm. One hole was cut on the side of the longer tube. One end of the short tube will be cut into a fish mouth opening as shown in Figure 124 below. The purpose of the fish mouth opening is to allow the shorter piece to be flush up against the side of another tube.

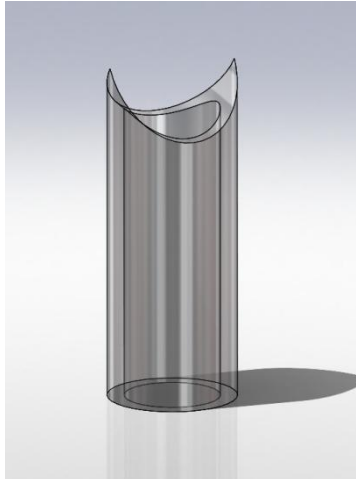


Figure 124: Shorter tube with fish mouth opening

Display Panel

The display panel is made of 5 pieces of 1/4" masonite shown below. We used the laser cutter to get the outline of what we needed to cut out as well as the outline of the heart and the location of the sensors. We then cut the pieces out on the band saw and predrilled holes for wood screws using a 1/8" drill bit, and drilled holes for the LEDs using a 1/4" drill bit.

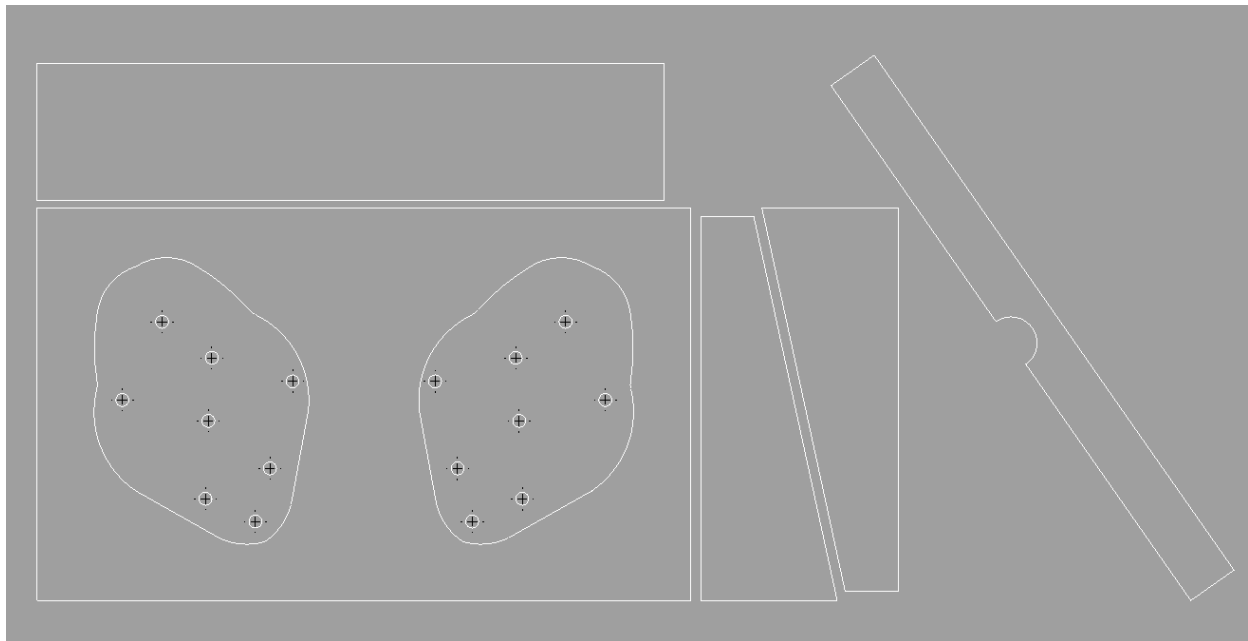


Figure 125: Display Panel Cut Out

To create the circuit of sensors on the heart and LEDs on the display panel we started by wiring 12 separate voltage dividers on a circuit board. Each voltage divider has three wires connected to it. An input from the 5 volt power supply of the Arduino Mega Microprocessor, an output to the 24-pin connector, and the last is an output to ground. Both sides of the Piezo sensors where

wired to the other side of the 24-pin connector. The remaining 24-pin connector wires were hooked up to the analog inputs of the Microprocessor and the Digital outputs of the microprocessor were connected to one side of the LED's. The remaining ends of the LED's were wired to a 200 ohm resistor leading to ground. All of these wires were held together using solder and then covered in electrical tape.

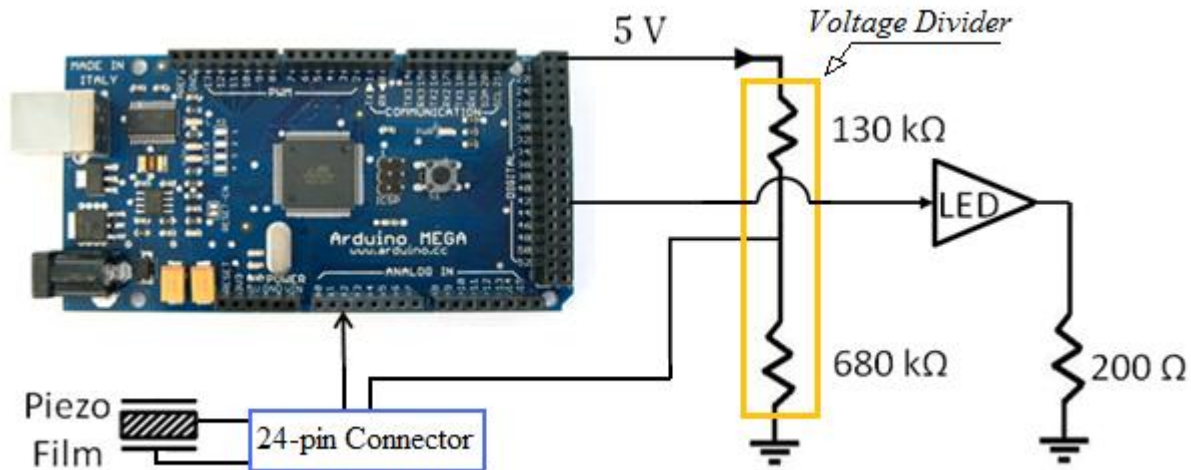


Figure 126: Schematic of the Sensor/LED Circuit

<http://reprap.org/pub/Main/PCPowerSupply/atx-power-connector.jpg>

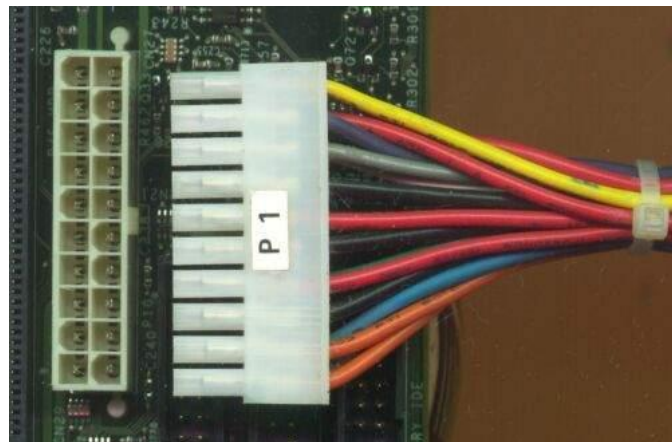


Figure 127: 24-pin connector

Initial Fabrication Plans - Assembly Heart

We placed the servo motor with the cam attached, into the mold. We then placed the sensors in their correct location and used medical sutures to hold them in place. We ran all the wires from the sensors to one line and then out the top of the heart. We used electrical tape to hold the mass wire column together, made of all the individual wires together. Then we stretched a cut balloon around the heart, sensors and wires included, and duct taped the balloon back together.

Vessels

The two pieces of the pulmonary artery were glued together using epoxy. The vessels were then placed in their appropriate locations.

Rib cage

To assemble the rib cage we used a Philips head screw driver and a set of wrenches. First we bolted all the supports on to the plates. Second we screwed all the connectors that go on the sternum and back plate into place. Then we screwed all the 1/8" diameter bolts in to join the ribs to their appropriate connector. Then we assembled the joints of the rotating ribs. This involved placing the torsion springs inside of the connectors and running a bolt through all three pieces. Then we connected the two halves together by screwing on the hinges to the sternum and the back plate. The last pieces to put on the rib cage were the wires to hold the phrenic nerves. They were bent, cut to fit and epoxyed in place.

Display Panel

All five pieces of the display panel were screwed together using screws. We inserted LED bulbs in every hole on the top of display panel and glue them in place with epoxy.

With the rib cage completed, we uncover the outward facing side of the two sided tape on the inside of the 3rd and 5th rib. This allowed us to stick the pleura on to the ribs and heat it up using a hair dryer. We then removed the excess plastic with scissors. Next we placed the lungs inside of the rib cage and ran the hoses out through the neck hole. Once the lungs were inside the cavity we connected both hoses to one tube, that went to a three way connector. One of the other sides of the three way connector went to our air pump while the third side remained open. Then we placed the heart with the vessels inside, running the electrical wires out the neck hole. Next the phrenic nerves were tied in place by tying surgical elastic to the notches in the wires. Finally we encase our entire thoracic cavity inside the neoprene skin and Velcro it shut so that the Velcro is on the back.

Mass Production and Assembly Plan

We would assemble the entire ribcage, Heart with feedback system, and the Lung system. However, we would not assemble the rest of the simulator. This includes the Pleura, Pericardium, Skin, and Phrenic Nerve. These items will be left for the user to assemble. We feel this is acceptable because they are already replacing parts with each use of our simulator. It will also help with the overall speed of the manufacturing process.

Rib Cage

There are two major components of the whole ribcage that are stationary and then there are five rotating ribs. We would have these parts made by injection molding PVC, into appropriate molds. This would allow us to make the simulator much more anatomically correct. The entire right side of the ribcage is stationary, and would therefore, be one part. The left side of the ribcage would be a mirrored image of the right, only without the second through sixth ribs. The rotating ribs (second through sixth) would each have their own molds. Though the molds would

be different for each rib, they would all have the same structure on the ends so the joints do not have to be unique to each rib. The two main parts of the ribcage would be molded to snap together on the back side. They would also have indents for the wires that hold the phrenic nerve in place to lock into place. The location of joins and hinges would also be made apparent on the molds by having their exact indent placed on the surface.

Hardware

With the injection molded back plate that snaps together, we no longer need a separate latch on the back of our simulator. We would still by the hinges for the front of the sternum as well as torsion springs for the joints. The wires used to hold the phrenic nerves and Aorta in place will be bent and cut using a punch. The Joints would still be made of two pieces of aluminum, however they would be injection molded into their correct shapes. These shapes will include divots for the torsion springs to be held in place. All of the joints will be exactly the same, making only two different molds, one for each side of the joint. There will be a total of ten assembled joints, and three wires to hold the phrenic nerve on each simulator.

The joints would all be connected to the ribs and stationary plates by hand, using a low geared electric drill. Next, springs would be placed in their designated locations and the two parts of the joints would be joined to create the assembled ribcage. Instead of using bolts to join the joints we would use rivets to make the structure as a whole smother. The rivets would also be put in by hand. This allows for human inspection throughout the assembly and guaranties the structure is all correctly locked together.

Skin and Vessels

We would cut the neoprene to our desired shape, on a press cutting machine for fabric. A strip of stick on Velcro would also be cut to the correct length using a sheet cutter and placed on the neoprene by hand. The vessels would be cut out of a softer form of PVC tubing, using a tube cutting machine. The Pulmonary Artery would have two dimensional dove tailed slots for each piece to fit into the other. The Aorta would be cut to length with wedges on the side, just as in our prototype, only this would be done on a tube cutting machine. The aorta tube will be pulled over its corresponding punched wire.

Worm Plastic

The Heart and Lungs would both be poured out of the worm plastic we used for the heart. We would make the mold for the heart better by having the exact shape of the sensors indented on the surface of it, channels for the sensors wires to run along, as well as making it more anatomically correct in general. The mold for the lungs would be made to fill the entire thoracic cavity with all other components in it. They lungs, like the heart, will have to be made in two halves. This will allow us to easily place air tight bags inside of them. Both of these molds would be made using a 3D modeling lab and then coated with a sealer so as to be used many times over. We would also make a sheet of approximately 1/8" thickness out of worm plastic. With this we would cut out pieces to fit over top of the sensors on the heart, using a press cutting machine.

Lung System

The breathing system would be made out of three sections. Each of the lungs are to be made of worm plastic and air tight bags will be placed between the halves. The halves would then be sealed together by reheating the plastic around the bag with an iron, and letting them set in the assembled position. The second section is the tubing, which is shown in Figure 128. All tubes are 1/4" diameter. Due to the thinness of the tubes and the lack of precision required, we would cut all tubes to length using a sheet cutter. All valves would be pre-purchased, as would the motors which are the final part to the system.

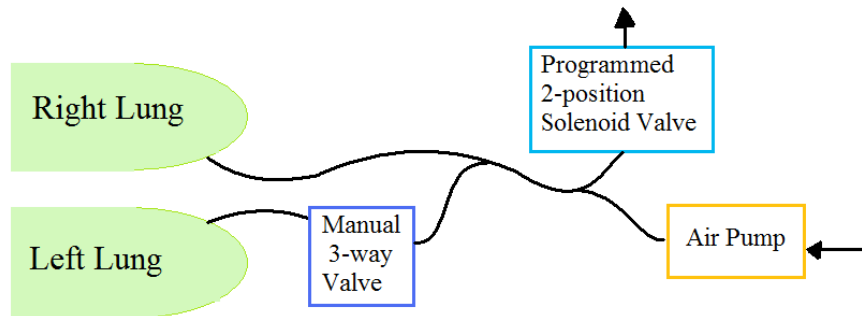


Figure 128: Breathing System

Display Panel

Manufacturing of the Display Panel would not change much from our prototypes manufacturing. It would still be cut on a laser cutter out of a particle board. The only difference is that we would use the laser cutter to cut all the holes that we then had to drill in it. It would then still need holes pre-drilled for structural screws.

Feed Back System

The LED's on the display panel would be wired to a circuit board in the correct places to match their sensors location on the heart. This circuit board would also include the microprocessor and the voltage divider, and would be secured to the back side of the display panel, with screws. The display panel would then only have wires going out to the heart and a power cord coming out the back.

Heart System

We would per purchase the motor for the heart beat and injection mold the cam and shaft as one part out of the same PVC as the ribs. The motor and cam would be assembled by hand, placed in the heart mold, and sealed shut the same as the Lungs. With the heart made of worm plastic and the feedback circuit completed we would then have the sensors placed around the heart in their correct locations by hand. The sensors would be secured in place by putting a piece of worm plastic over each one, and melting the worm plastic into place. Then all the wires would be placed in their designated divots and run up and out the top of the heart.

Unassembled

The phrenic nerve and pleura would be supplied to the users in raw form. We would include in our package, a roll of elastic band material and a box of shrink wrap with double stick tape. This would come with directions of how long to cut the phrenic nerve and double stick tape. As well as a paper cut out of the correct size and shape needed to cut the pleura.

Validation Results

Validating the Simulator

In order to validate our simulator and demonstrate that the engineering specifications have been met, various techniques will be employed. For most of the specifications, a simple measurement would verify its validity. For others, subjective testing involving clinicians was necessary. The initial validation was broken down into two sections: individual component validation and overall simulator validation.

Individual Component Validation: As each component was manufactured, it was tested to make sure it fit user specifications as defined in Table 1. In Table 22-28 below, a summary of validation steps taken to fulfill the “must have” user requirements can be seen.

Table 22: Validation of Must Have User Requirements

Method of Validation	User Requirements	Target Value	Actual Value
Inspection	Include key thoracic cavity components: Heart Pericardium Phrenic Nerve Ribcage Pleura Lungs Aorta Pulmonary Artery Skin	Yes	Yes
-	Be Anatomically Correct	See Tables 23-27	-
Inspection	Have Skin That Allows Thoracic Cavity Access	Yes	Yes
Ruler	Have Spreadable Ribs	Separate 8 cm	Separates 8.5 cm
Inspection	Have Penetrable Pleura	Yes	Yes
Subjective Testing Strain Gauge	Respond Correctly	Likert Scale Value ≥ 3 Rib Spread Force ≈ 100 N	- Rib Spread Force ≈ 95 N
Inspection	Have Reconfigurable Skin	≥ 3 access points	3 access points
Inspection	Have Penetrable	Yes	Yes

	Pericardium		
-	Provide Evaluative Feedback	See Table 28	-
Inspection	Have Collapsible Lung	From 100% to $\leq 10\%$ filled with air	From 100% to 0% filled with air

Table 23: Validation of Heart, Pericardium, and Phrenic Nerve Characteristics

Method of Validation	Characteristic	Target Value	Actual Value
Ruler	Average Width	9 cm	10 cm
	Average Height	13 cm	14 cm
Stopwatch	Heart Rate	70 beats/min (38)	60 beats/min
	Beat Time Ratio	$(t_{21}/t_{tot}) = 0.3$ (12)	0.25
Calipers	Pericardium Thickness	0.7-1.2 mm (20)	1 mm
Ruler	Phrenic Nerve Length	20-24 cm (68)	28 cm
Calipers	Phrenic Nerve Diameter	0.76 mm (68)	1 mm

Table 24: Validation of Thoracic Cavity and Pleura Dimensions

Method of Validation	Characteristic	Target Value	Actual Value
Ruler	Height	32 cm	28 cm
	Width	32 cm	33 cm
	Depth	24 cm	18 cm
	Average Circumference	95 cm	84 cm
Calipers	Pleura Thickness	0.14 mm (42)	0.1 mm

Table 25: Validation of Lung Dimensions (34)

Method of Validation	Characteristic	Target Value	Actual Value
Ruler	Inspiratory Volume	3.5 liters	3.9 liters
	Expiratory Volume	3 liters	4.16 liters
	Inspiratory Height	23 cm	26 cm
	Expiratory Height	25 cm	26 cm
Stopwatch	Breathing Rate	12 breaths/min (60)	12 breaths/min
	Breath Length	2.5 s	2.5 s

Table 26: Validation of Aorta Dimensions

Method of Validation	Characteristic	Target Value	Actual Value
Ruler	Diameter	2.5-3 cm (27)	2.5 cm
	Length of Ascending Aorta	5 cm (65)	6 cm
	Length of Descending Aorta	20 cm (65)	19 cm

Table 27: Validation of Main Pulmonary Artery Dimensions

Method of	Characteristic	Target Value	Actual Value
-----------	----------------	--------------	--------------

Validation			
Ruler	Diameter	2.72 cm (18)	2 cm
	Length	5 cm (66)	5 cm

Table 28: Validation of Feedback Types

Method of Validation	Component	Feedback Type	Specification	Actual Value
Inspection	Heart	Tactile examination of major surfaces/structures	100% of surface examined	100% of surface examined
	Incision	Location	3 rd or 4 th intercostal space	3 rd intercostal space
		Direction	See Figure 23,	See Figure 23
	Ribs	Location of spread	3 rd or 4 th intercostal space	3 rd intercostal space
		Translocation of spread	Perpendicular to rib direction	Perpendicular to rib direction

As can be seen in Table 28 above, the dimensions of all of the thoracic cavity components were measured using a set of calipers, a ruler (size of all the components), or a stopwatch (heart and lung rates). The rib spread force was measured with a strain gauge to ensure 100 N of reactive force. A fairly large margin of error of 25% from the target values for these measurements was considered satisfactory. This is due to the fact that these values are already averages gathered from various literature sources (as referenced in Table 1), since the dimensions of human body components can vary significantly from one body to the next. Other specifications were verified by inspection, such as the inclusion of all the thoracic cavity components and the ability of the skin to allow access to the thoracic cavity.

For the specifications dealing with the model responding correctly, an experiment was developed for verification. Due to the nature of this specification, quantifying the material properties of various components would not be a complete validation. Therefore, an experiment determined if the individual components and the overall thoracic structure “felt” real. In order to test the correct feel of the heart, a control model was set, against which the feel of the modeled organ could be compared. A lamb heart was purchased from Knight’s market to act as an ideal control model for feel. The next step in the experiment was to get participants to hold and thoroughly feel the control organ and samples of the modeled organ material. The participants were then requested to pick which sample of the modeled organ material mimicked the feel of the real organ. This enabled us to pick and also verify that the material we used for the heart felt like an actual one. Verifying the material properties of the modeled organs can be conducted as an additional method to justify the material selection, however, this step was not considered due to time constraints

For the rest of the components, the correct feel was verified after the model was completely assembled. For this validation step, an associate professor of surgery, Dr. Melissa E. Brunsvold, was consulted. Dr. Brunsvold has experience in performing an emergency thoracotomy procedure and, therefore, was an excellent source. In this validation step, we were also able to somewhat

verify anatomical correctness. Her comments and suggestions are listed in Table 29 and will be very valuable to us in future endeavors for simulator improvement.

Table 29: The Comments and Suggestions of Dr. Brunsvold

Thoracic Cavity Component	Comments/Suggestions
Skin	<ul style="list-style-type: none"> • Neoprene imitated muscle well • Cover neoprene in rubbery material to simulate skin • Neoprene should have extended in between intercostal spaces to simulate intercostal muscle
Pericardium	<ul style="list-style-type: none"> • Balloon should be less opaque
Lungs	<ul style="list-style-type: none"> • The lungs should fill up the entire space to cover the heart • They should be “expanding in your face” • The size of our lungs in their inflated state is actually the size of the lungs in their deflated state.
Phrenic Nerve	<ul style="list-style-type: none"> • Does not need to snap because only extraordinarily inexperienced surgeons would cut it • Very beneficial inclusion for the simulator
Heart	<ul style="list-style-type: none"> • In correct position in the thoracic cavity • Correct size, proportional to rib cage size • Should be encompassed by lungs • Feels a little too firm

Due to the state of our simulator at the time of testing for validity, we were not able to put a Likert based scale in place. Future work would be to further quantify such specifications as “real feel” and anatomical correctness. In addition, tests for the accuracy of the overall simulation created by the model should be measured using a medical simulator evaluation form. This form was developed by our mentor and it is included in the Appendix E. This survey will allow for the evaluation of the simulator with regards to its ability to mimic the surgery it is intended to represent. Authenticity, value, and evaluative feedback capabilities will be addressed here and a Likert scale will be used again to quantify the assessments made.

Validating the Simulator’s Ability to Evaluate Surgical Performance

After completing these initial tests, various steps must be taken to validate the final assembled model concerning its ability to fulfill its functions as being an effective tool for learning and assessment. All of these tests will help in the validation of the engineering specification concerning evaluative feedback and were established based on mentor input. However, due to time constraints and the necessity for human research and, therefore, Institutional Review Board (IRB) approval, these tests will not be able to be completed within the scope of this class.

Applied Testing

In this validation step, the simulator will be used in an applied setting. A novice user will be given a pre-test, be trained on the simulator, and then be given a post-test. This will show how well the simulator is able to improve the performance of a surgeon; a feature that is crucial in simulator use.

Construct Validity

In this step, the simulator will be used by surgeons having a wide range of expertise (i.e. a novice, a first resident, a third year resident, emergency room faculty, trauma surgeons, etc.) and will be evaluated in its ability to discriminate between skill levels.

Transfer Validity

This validation step will test whether or not the simulator actually improves a surgeon's performance in the field. Specifically, it will determine if improved performance on the simulator indicates an equivalent improved performance on a real human being.

Discussion and Recommendations

There were many aspects of the prototype that, in hindsight, would have been done differently. As in the other sections, the best way to analyze them is to go through the design component by component. This section will be formatted such that the changes that would be made can be considered to be recommendations for anyone looking to improve our prototype.

Skin

The main issue we had with the skin was that it was too thick. The neoprene that was ordered was $\frac{3}{4}$ " thick, while a thickness of around half of that would have been desired. This made it very difficult to work with, in terms of being able to tailor it easily to the ribcage. However, the neoprene held up very well to the stresses applied, and had a realistic response. It also was very good to suture with so, besides the thickness, it worked out very well.

Ribcage

Ribs: The PVC pipe used for the ribs ended up being a very good material. It was strong enough and the correct size for our application. The main issue with the ribs was drilling the holes which were responsible for connecting the ribs to the connectors. Because of the small thickness and relatively unusual shape of each rib, it was very difficult to manually drill the necessary holes in the correct locations. If we were to do it again, the best way to ensure accuracy and precision would be to make a guide that would slide onto each rib and force the drill bit to go into the right location. This would have ensured that all of the ribs are drilled consistently.

Connectors: The main issue with the connectors was similar to that of the ribs. Since the connectors were so small and had an odd shape, it was nearly impossible to drill holes in the correct locations by hand. Even after center punching and pre-drilling, it seemed luck had the biggest influence as to where the holes ended up. Once again, a good way to alleviate this issue would be to make a guide, which would ensure consistent and accurate holes on every piece. Another issue was the fact the connectors had to be bent by hand. While making the correct bends became easier and more consistent with practice, the small tolerances we had for the holes left almost no room for error. A guide would be useful, but it would still be hard to ensure consistent results for every piece. The best way to manufacture these connectors would be to program a robot or machine to make all of the holes and bends, but that is clearly not within the scope of this project.

Another change would be to the bolts which fasten the connectors to each other, allowing the ribs to rotate. Originally, we planned on using shoulder screws, as seen in Figure 129, which would provide a smooth surface on which the connectors could rotate. Unfortunately, the shoulder screws could not be used due to poor tolerances, so regular bolts had to be used instead as seen in Figure 130. If the accuracy and consistency of the holes in the connectors were improved, it would be possible to use the shoulder screws, thereby allowing for a much smoother rotation of the ribs.

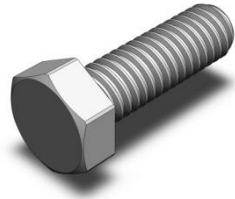


Figure 129: Bolt



Figure 130: Shoulder Screw

Backplate/Sternum: Using Masonite was a good choice because it allowed us to use wood screws to attach the connectors to it. A large drawback was that we could only laser cut sheets that were about one third of the thickness we needed, so we had to glue 3 pieces together in order to achieve the desired total thickness. This made the components very susceptible to cracking and even after pre-drilling, the material still began splitting and could not support the ribs and connectors. We solved this problem by attaching reinforcement plates to each side of the sternum and backplate, but that was only a temporary solution. It would have been best to use sheet metal, like the aluminum we used to make the connectors. With such material, it would have been more difficult to manufacture the parts, but they would have been much stronger and would have not needed any extra reinforcement. Furthermore, the sides on which the connectors attached would have been much straighter than the Masonite, which would have made measuring and attaching easier. It was also very difficult to measure and drill the holes for the connectors because there was no efficient way to measure or mark them. The holes had to ensure that the ribs were at an angle of 20 degrees from the vertical, as well as line up with the holes on the connectors. Once again, it seems the best way to remedy this issue is to make a guide for each side to ensure the holes are accurate and consistent.

Phrenic Nerve, Pleura and Pericardium

All of these components performed very well and the design of them would not be changed drastically.

The phrenic nerve, which was made from an elastic tourniquet, imitated an actual phrenic nerve very well. It snapped when nicked by a scalpel and was easy to manipulate into place. The only change would be to use one in a different color in order to provide more realism.

The shrink wrap that was used for the pleura ended up worked very well for our application. The double sided tape provided a strong but removable way to attach the plastic, and once heated the plastic simulated real pleura very well.

The balloon used for the pericardium was good, but would be changed slightly. The first issue was it was too small to fit over the heart, so we would have to find a larger balloon. The second issue was that it was too opaque; a real pericardium is much more transparent. This could also easily be fixed by find a larger balloon that is less opaque.

Lungs

The foam used for the lungs was a good option, but it wasn't optimal. The first problem was we had to use epoxy to glue them together, which made the sides of the lungs very hard and rigid. The other problem was that because of the rigid sides, the lungs only expanded in two dimensions, not three. The plastic bag inside of the foam also only expanded in two dimensions, which added to the problem. While the foam felt realistic, it did not work as well as we would have liked. Another problem was that the lungs were supposed to fill the entire side of the ribcage, while ours only filled the bottom half. The first change that would be made is to make the lungs out of the PVC plastisol that was used for the heart instead of the foam. We would make a mold for the lungs, which would be a relatively simple shape, and then cut out a slit in the middle to slide in a balloon. We would use a cylindrical balloon, or multiple ones to ensure the lungs expanded in all three directions. Using the PVC plastisol would eliminate edges and hard areas, as well as better replicate the feel of real lungs.

The pump we purchased provided enough air to fill the lungs, but we would want to by a pump with a slightly higher air capacity next time. This would give us more room to vary the air flow and change the breathing rate to simulate more conditions. Also, in order to allow the lungs to breathe out, we had a release port in the pipe that we controlled with our thumbs. A better solution would be to purchase a solenoid valve, so that the lungs could breathe completely autonomously.

Heart

PVC Plastisol: PVC plastisol was used in a ratio of 80% plastic and 20% softener in order to achieve a response as close to a real heart as possible. A mold of each half of the heart was made in which to pour the mixture and allow it to set. This set up worked very well, and would not be changed. We learned that the plastic shrinks a lot as it cools, and so there ended up being a fairly larger hole at the top of the heart where the plastic receded. This could be fixed by making sure to continually add plastic until the mold dries in order to provide a fully formed piece. We included indentations on the surface of the heart where the sensors would go, but they ended up making it hard to actually attach the sensors. One solution was to sew the sensors onto the surface, but that was just a temporary fix. It would have been better to, instead of making indentations on the heart surface, cut slits into the surface to slide the sensors into. This would provide a secure way to hold the sensors, since they would then be completely surrounded by the plastic. Another change that could be applied is adding red food coloring or dye to the plastic while cooking to provide a more realistic looking heart.

Sensors: The sensors ended up creating a lot of issues for us. We found out after the fact that we ordered vibration sensors, when we wanted to order force sensors. That explained why it was so difficult to calibrate the sensors to detect the force of the user's hand on the heart. The next time around, we would use the correct sensors, as well as smaller wire to connect them to the LED display. The wire we ended up using was extremely thick in diameter, and was hard to

route them along the side of the heart. We would also have used more heat shrink connectors on the wires, to ensure a better connection. The last issue was connecting the wires to the processor. We did not have the correct male connector for the microprocessor, so we ended up just sticking the wires into the correct terminals. This connection was not very secure, and the wires kept coming out of the microprocessor. In order to improve this, we would search more and get the correct connectors, to ensure a proper connection to the board.

Entire Simulator

The simulator is a sum of its individual components, and so improvement of the components would obviously lead to an improvement of the simulator as a whole. The simulator itself is not very heavy, about 10 pounds, but the use of lighter components for the sternum and backplate, as well as the ribs could help to reduce the weight even more. It would also be helpful to redesign the simulator so it can replicate more trauma options. For instance, adding blood flow to the heart and major vessels would add more realism to the surgery. Also, common procedures like cross-clamping the aorta could be incorporated. These features would improve the simulator by allowing the user to practice all of the possible procedures they may come across, instead of just one. In the future, it might even be feasible to be able to open the rib cage from the top, simulating an open heart surgery, in order to better replicate the options that could be available for a surgeon in a real surgery.

Appendix B: Bill of Materials

Component	Item	Quantity	Source	Catalog Number	Cost
Plates	Masonite	1	Fingerly Lumber	1	\$12.35
	Elmers Wood Glue	1	Fingerly Lumber		\$4.89
	Small Hinge	4	Lowes	36140	\$1.03
Ribs	6" x 10' SCH40 PVC Pipe	1	Lowes	86806	\$26.33
Connectors	Water Jet	1	Manufacturing Lab		\$80.00
	1/8" x 1/2" Wood screws	64	Carpenter Brothers		\$5.60
Heart	Hear Mold	1	3D Lab		\$280.00
	Plastic Softener	1 Pint	MF Manufacturing	4116S	\$9.90
	Regular Liquid Plastic	1 Quart	MF Manufacturing	2132LP	\$18.10
Feedback	Piezo Vibration Sensor - Large w/ Mass	20	Sparkfun	SEN-09197	\$14.75
	Circuit Board	1	Radio Shack		\$14.99

	Microprocessor	1	Sparkfun		\$65.00
Lungs	Air Pump	1	Gast	GP40-101	\$200
	1/2" PVC Ball Valve	1	Stadium Hardware		\$2.95
	1/4" tubing	1	Lowes		\$10.27
	Open Cell Backer Board Foam	1	Nomaco	N/A	\$29
	Bags for Lungs	2	Simulation Center		
Nerve	Coat Hangers	2	Ofra's Closet		
	Elastic Band	8	Simulation Center		
Pleura	Shrink wrap with double sided tape	1	Lowes		\$21.75
Skin	Neoprene	1	FoamOrder.com	N/A	\$51.43
	3/4" Stick Velcro Roll	1	Michaels		\$4.35
Vessels	Rubber Hoses	3	TSC	309357	\$12

Appendix C: Description of Engineering Changes since Design Review #3

There were not many changes between the design from DR #3 and our actual prototype, but there are a few minor ones worth mentioning.

One change that occurred in manufacturing was the use of machine bolts instead of shoulder bolts for the connectors. We were going to use 1/4" shoulder bolts as the axis on which the connectors would rotate in order to reduce friction. When the connectors were made, however, it was determined that the holes on the connectors were not within a close enough tolerance of each other to use the shoulder bolts. We then opted for 5/16" machine bolts which fit into the holes better. This change was documented in Figure 131 below.

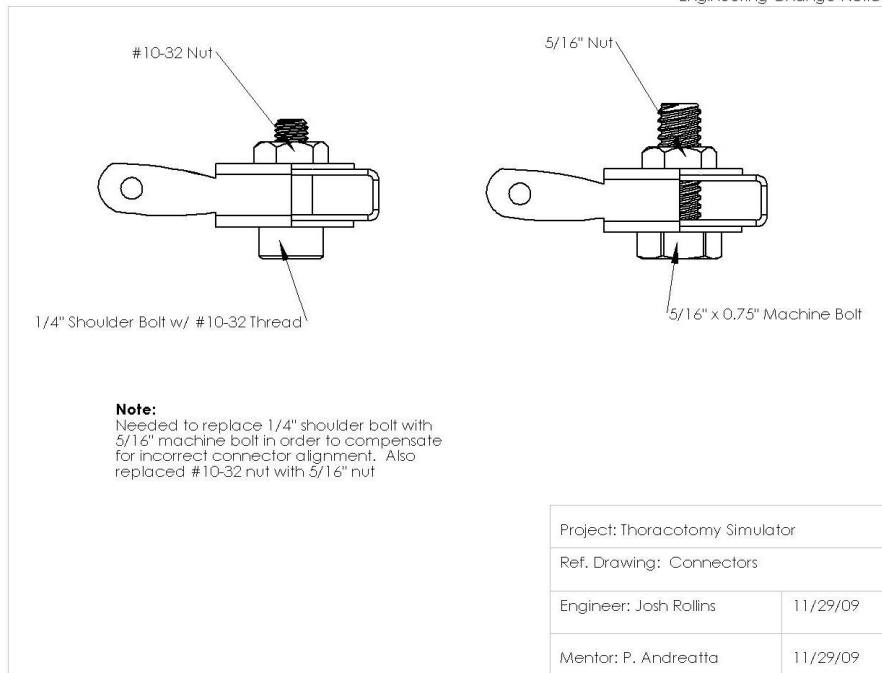


Figure 131: Design Change for Connector Bolts

As far as the pleura is concerned, we were planning on using a plastic bag which would have been connected to the ribs using coat hangers placed in a slot in the ribs. This idea was scrapped just before the design expo, when it was discovered that shrink wrap would work just as well, and could easily be stuck on the ribs using double sided tape. The different ideas can be seen in Figures 132 and 133.

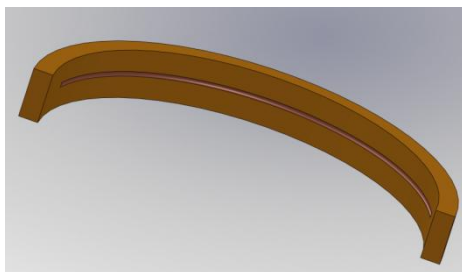


Figure 132: Rib with Groove



Figure 133: Ribs with Shrink Wrap

The last change that was made concerns how the rib cage was held shut. Originally, we were planning on using an eye and hook fastener to keep the ribcage together as seen in Figure 134. We ended up using two hinges in the back, with removable pins instead as seen in Figure 135.

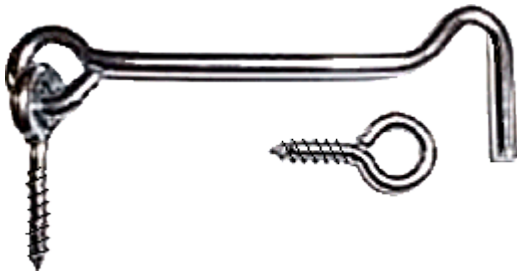


Figure 134: Eye and Hook Fastener



Figure 135: Hinges on Backplate

Appendix D: Analysis Assignment from Lecture

Material Selection – Functional Performance

Ribs: The primary function of the ribs is to provide access to the thoracic cavity by allowing the user to spread them apart, mimicking ribs in a true thoracic surgery. The ribs must not only imitate the action of real ribs, but also be anatomically correct. The most relevant material indices of ribs were the modulus of elasticity of 12 GPa and an ultimate tensile strength of 124 MPa. Using these parameters proved to be difficult however, because there is no material in the CES software with such a high tensile strength. We decided that since the main forces on the ribs would be involved with pulling the ribs apart from the center, and not in the tensile direction, it was reasonable to choose a material with a lower tensile strength. As mentioned before, there were no materials with the tensile strength we desired, so we opted for materials with an equal or greater modulus of elasticity. The highest strength materials we considered using were tungsten and titanium alloys. Both metals have very high tensile strengths and Young's modulus, but they were way above our budget, difficult to manufacture and would not mimic the feel or response of real ribs very well. We also looked at GRFP epoxy matrix, wood and PVC as options. The GRFP epoxy seemed to be the best choice as far as response was concerned but it was deemed to also be too expensive and much too difficult to manufacture. Wood, typical along the grain, has a very similar modulus of elasticity, and a higher tensile strength than PVC. The main reason we chose PVC over wood is because we can get PVC already formed with a circular cross section. Also wood can be bent to a certain degree, we decided PVC would last longer and be more resistant to decay and damage.

Heart: The primary function of the heart, besides beating and providing examination feedback, is to feel real to the user. The mechanical property that is most closely related to the feel is Young's modulus. Using CES software, Young's modulus was graphed versus price in order to determine the best material options. The results can be seen in Figure 150 on page 135. The materials with the lowest modulus of elasticity were flexible polymer foam (VLD), neoprene, butyl rubber, flexible polymer foam (LD), and polyisoprene rubber (IIR). We also considered PVC plastisol as an option. We decided against the neoprene and butyl rubber because they were the most expensive and not as easy to manipulate. We narrowed it down to the flexible polymer foam (VLD) and the PVC plastisol because they could give us a lower modulus of elasticity and thus a more realistic response than the other options of equal price. We eventually decided to use the PVC plastisol as the material for the heart, because we had the most control over how soft/hard it is and we can mold it, which is a huge bonus given the electronics and servo motor we intend to place inside of the heart. We also decided that although the plastisol is more expensive than the foam, it mimics the response of the heart much better. We determined this via comparison of the materials with our experience in the dissection lab.

Lungs: The lungs' primary function is to breathe and be collapsible. We also want them to have a realistic response. Material selection for the lungs was nearly identical to that of the heart, and the same CES selection was used as seen in Figure 150 on page 135. The lungs have a slightly high Young's modulus, but still well below any of the materials CES provided. We decided that because the need for molding and realistic response was not as much of a necessity as that of the heart, the flexible polymer foam (VLD) was the best option, as it was cheaper than the PVC polymer as well.

Material Selection – Environmental Performance

After using SimaPro to analysis the environmental impact of the heart's top two material selections, it seems very clear that the rubber foam, which, as mentioned before, will be used on the lungs has a much larger environmental impact that the PVC plastisol. Raw material usage for both materials is substantially higher than air, waste and water combined as seen in Figure 136. The raw material usage for the foam is over twice that of the PVC plastisol. Also, after looking at Figure 138 on page 133, it is clear that human health is most severely affected, with the foam being slightly higher than the PVC plastisol.

After speaking with the manufacturers of both products, we were told that the lifetime of both products were comparable. From a cost stand point, it is more effective to use the foam for both the heart and the lungs, but from an environmental stand point, it is more effective to use the PVC plastisol for both components. Since we do not intend to produce a large amount of simulators in immediate future, we will use the PVC plastisol for the heart and foam for the lungs to save on cost. In the future however, we would probably use the PVC plastisol for both components if we planned on mass producing our simulator, because while it would be more expensive, the environmental impact would be greatly reduced. If we had more time, we would research other potential materials because even though the PVC plastisol is an improvement over the foam, there is still a lot of room for improvement as far as cost and environmental impact are concerned.

Manufacturing Process Selection

Real World Production Volume: After validation and testing, the simulator has the opportunity to help many people. The largest customer of would most likely be hospitals in need of a simulator to train their students and surgeons. The total production volume would be around a few hundred, depending on how many clinicians wanted the device and how many they wanted. It is also possible the simulator would be made for use in other countries, especially those who don't have modern medical resources available.

After building the prototype using both materials for their respective components, it was determined that a few things would change for mass production. It is hard to use CES Manufacturing to justify the choices, mainly because material selection is based primarily on feel. While material properties like Young's Modulus do play a role in the feel and response of the materials we use, the main mode of material selection is through volunteer sample testing. CES Manufacturing was used to narrow down the choices for the lungs and heart by finding the materials with a very low Young's Modulus. From a mass production, environmental and cost stand point, it would be most effective to use the PVC plastisol for not only both the heart and lungs, but also for other components such as the Aorta and Pulmonary artery.

PVC plastisol is the material of choice for many reasons. The first is its versatility concerning both feel and adaptability. By changing the amount of hardener and softener in the mixture, the ideal ratio for each individual component can be determined. The feel of a component is very important in simulators, and once the correct ratio is determined, engineering analysis can be

perform on samples to determine the exact material properties that correspond with the desired feel. The plastic lasts almost indefinitely and it would never need to be thrown out. If it is ripped or damaged, it can be melted down and reformed many times. The foam on the other hand, can only be used until it is damaged or wears out, and then must be completely replaced. It is also much more difficult to find a wide range of foam with varying degrees of softness/hardness.

The environmental issues of the foam are also much more prevalent than those of the PVC plastisol. Not only would the foam be thrown away after it can no longer be used, but the making of the foam is more costly for the environment as well. Also, an epoxy would be needed to glue the foam together, which would add to the environmental issues even more.

The manufacturing of the parts would also be much more efficient. With the PVC plastisol, all that is needed is a mold to pour it into once melted. Once the material has solidified in the mold, it would be ready to use. A less significant feature of the PVC plastisol is that it can be colored very easily using food coloring or dye to any desired color, which would provide more realism to each component. A few molds of each component would be enough to produce hundreds of the components, and while the cost of the molds would be expensive in the short term, they would pay for themselves both in repeated usability and in reduction of manufacturing time. The foam is more difficult to shape and requires more manpower to produce.

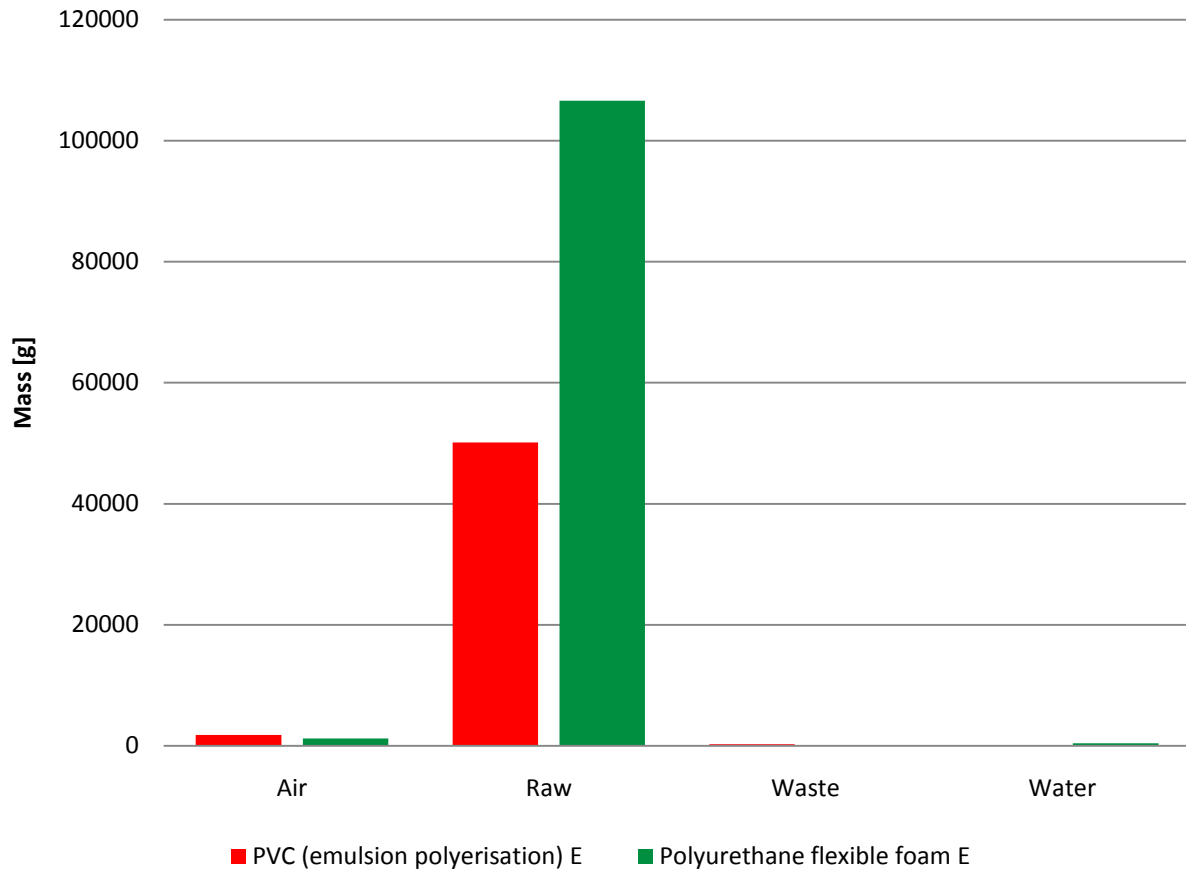


Figure 136

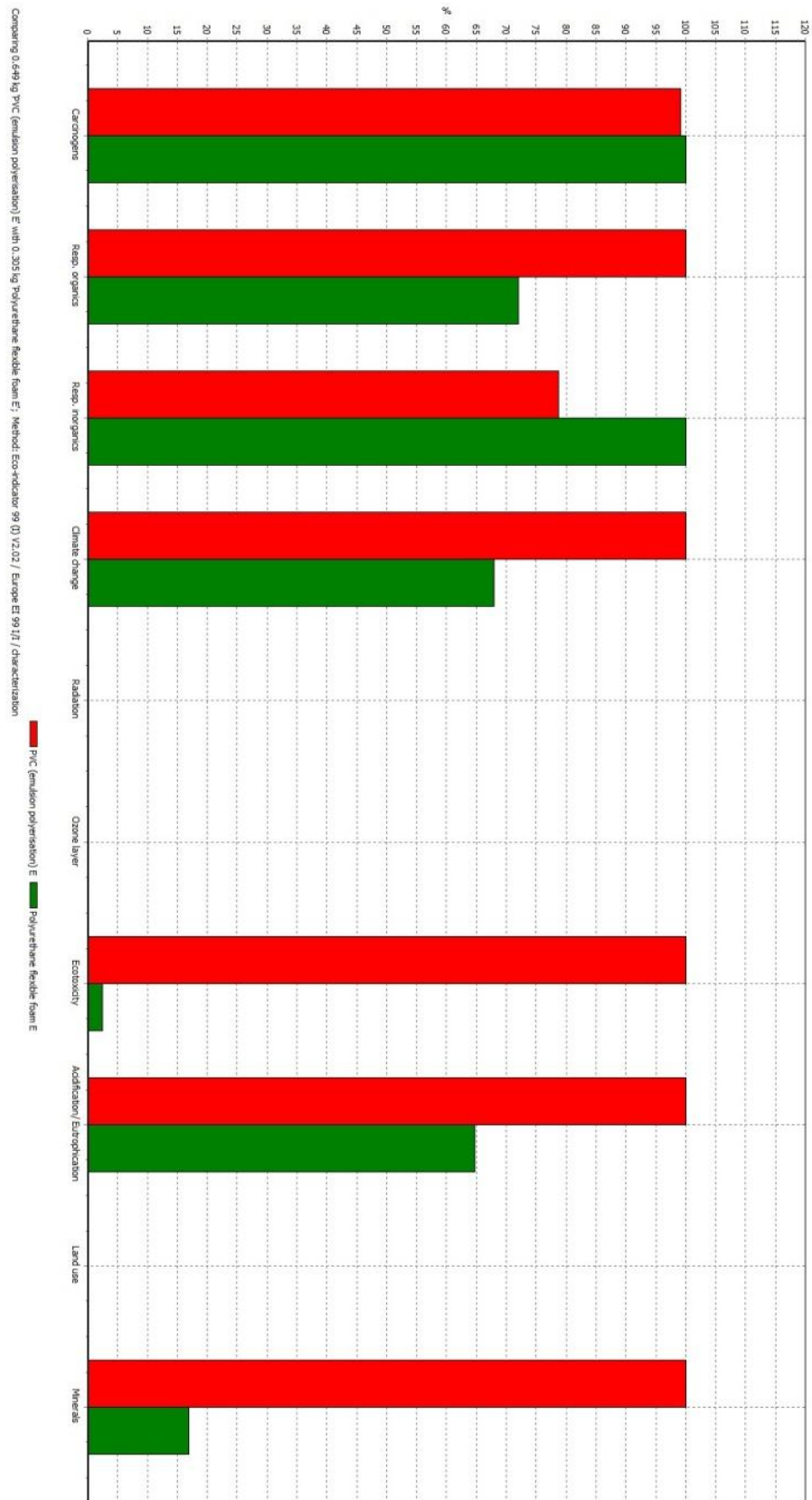


Figure 137

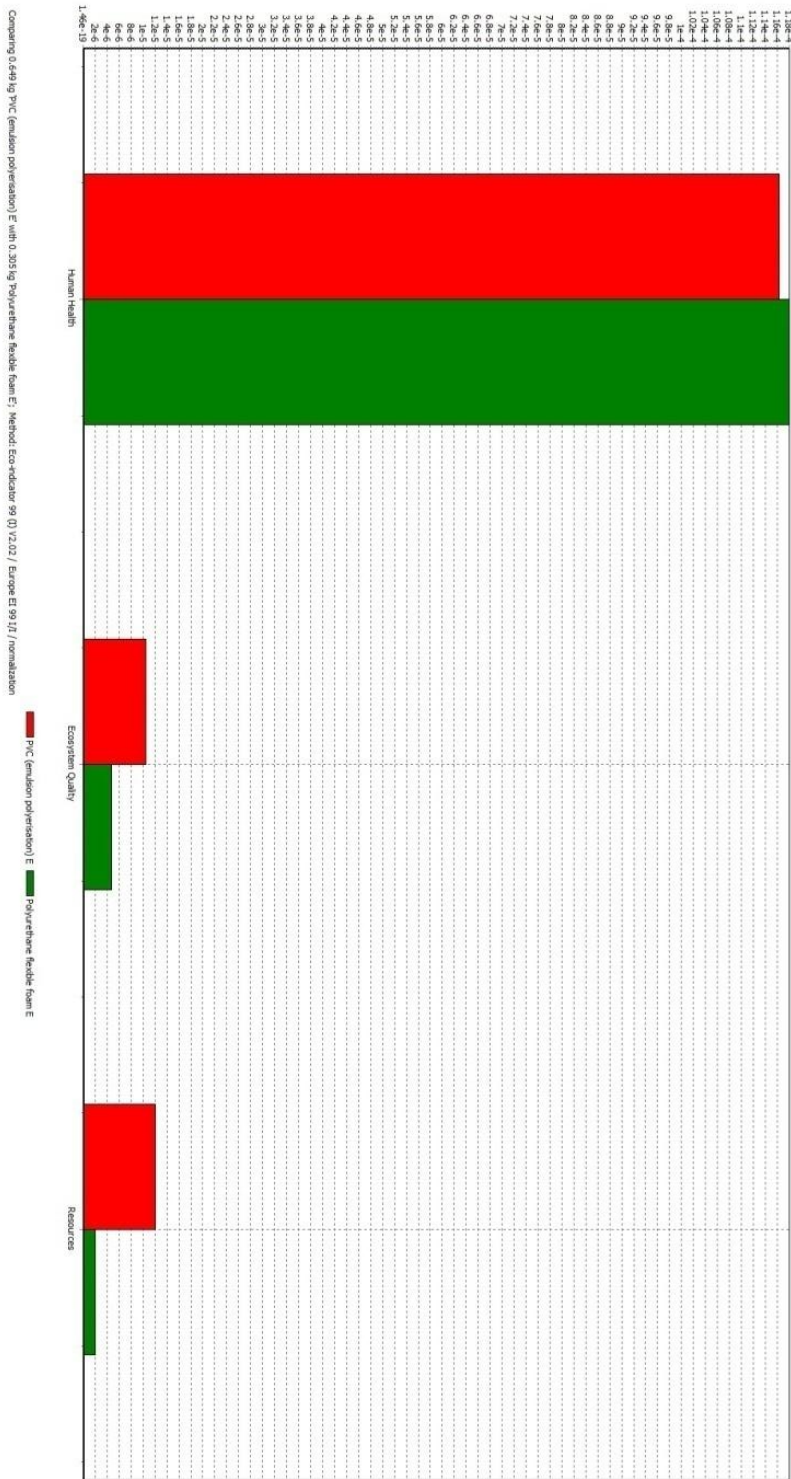


Figure 138

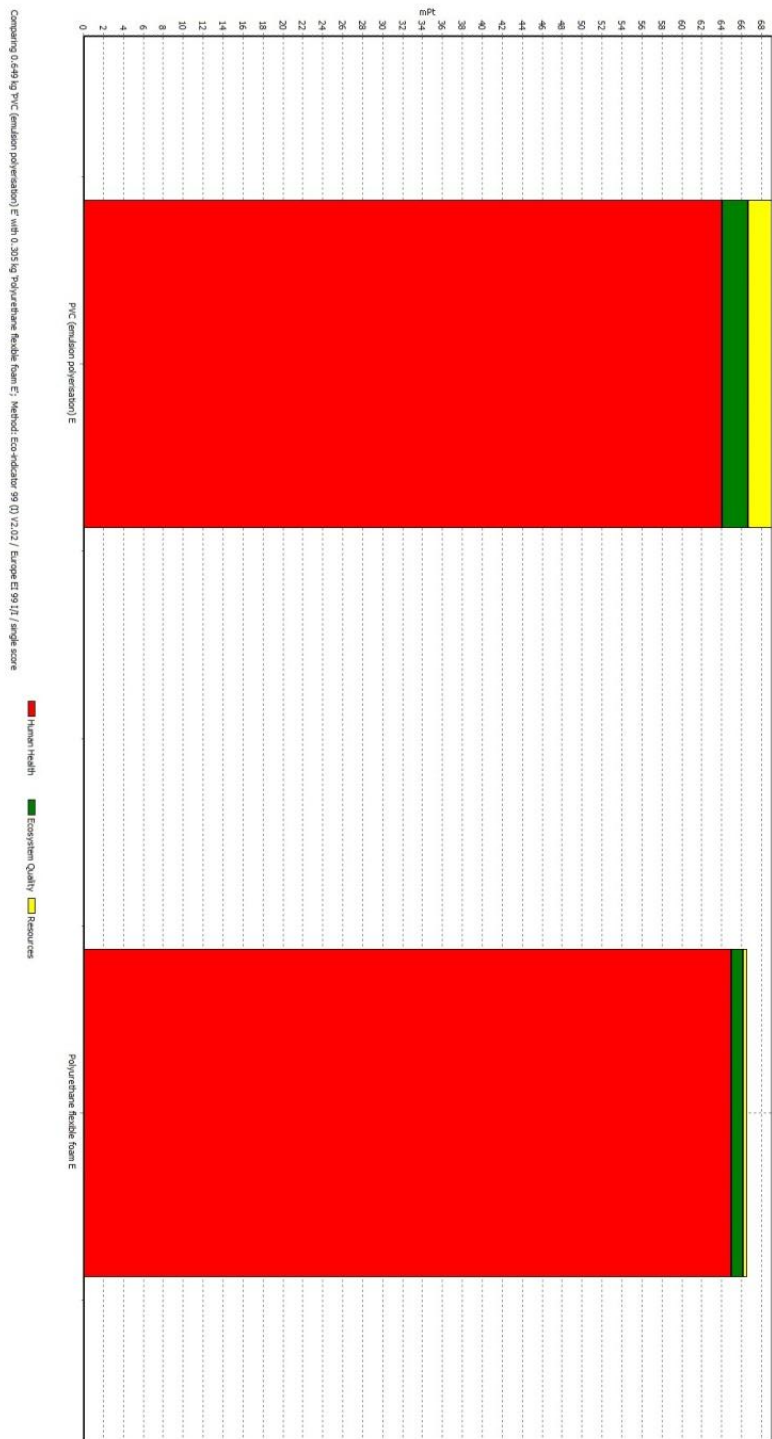


Figure 139

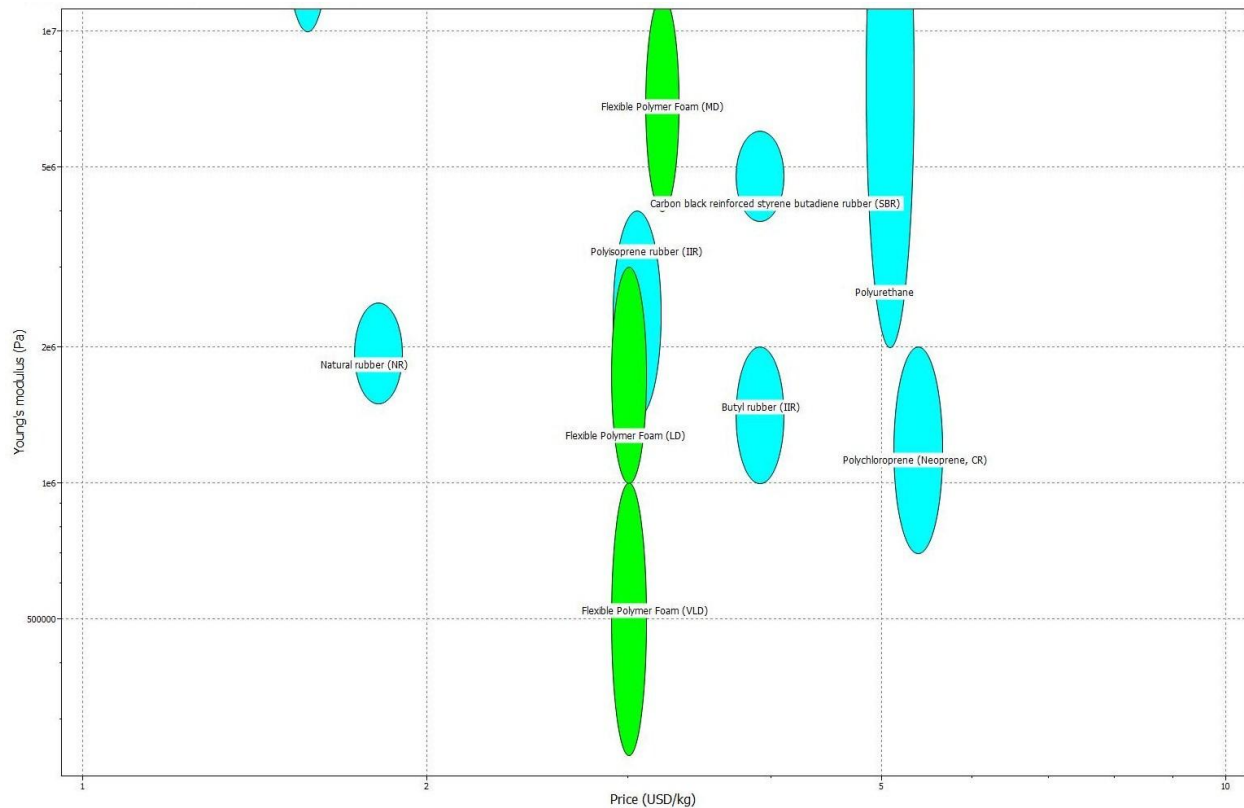


Figure 150: Young's Modulus vs Price

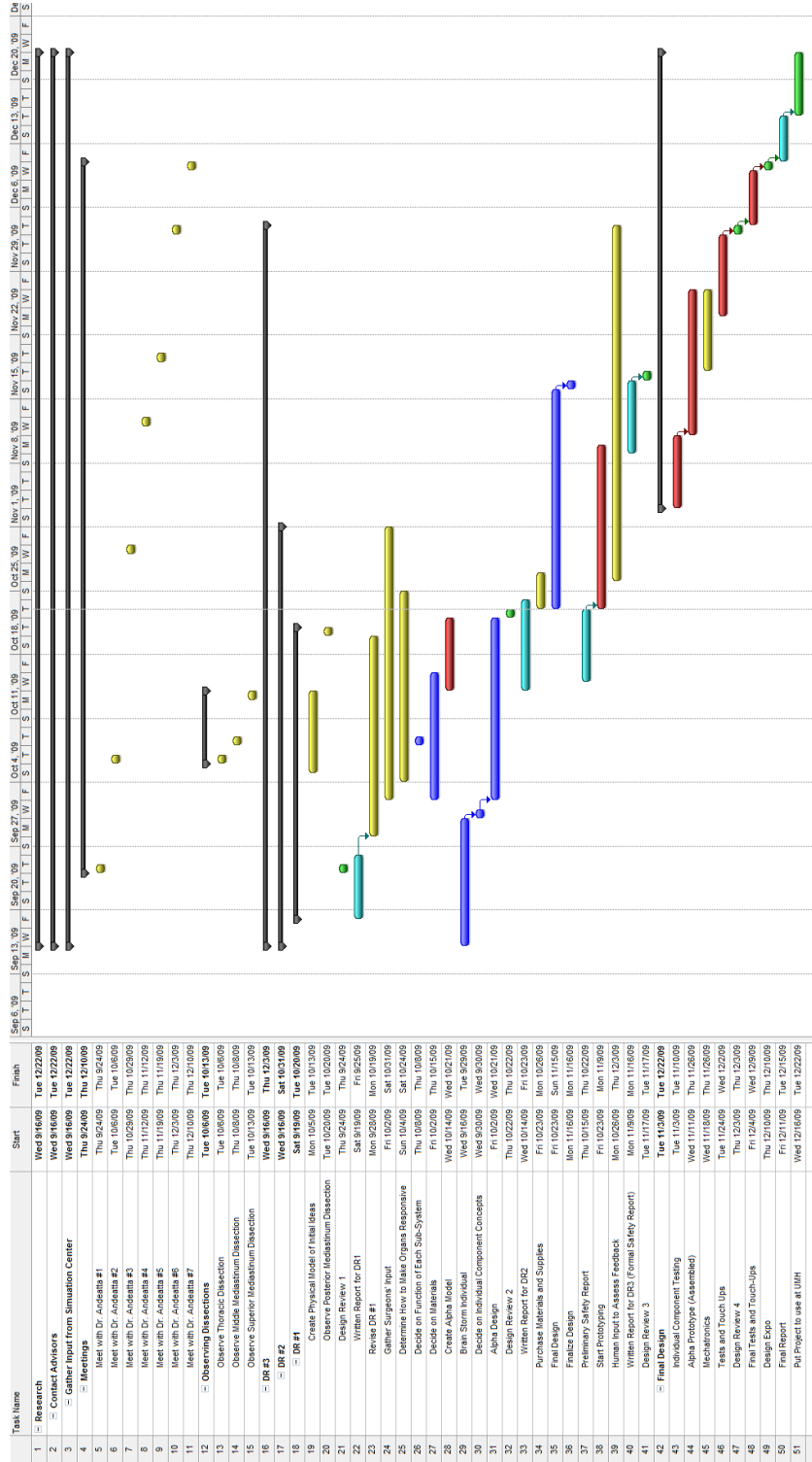
Summary and Conclusion

We need to provide an emergency thoracotomy simulator with a beating heart and breathing lungs, as well as develop a way to provide evaluative and instructive feedback to the trainees. After consulting with our project mentor, we have come up with a list of user requirements and engineering specifications. We have categorized key components of the thoracic cavity and made use of research based on medical journals, medical personnel interviews and anthropological data to select materials for the simulator components. We have also used engineering fundamentals to define the various dimensions of the thoracic components and determined the mechanical and electrical design that will provide effective visual and tactile feedback for the heart. We have also developed a CAD model and a physical three dimensional sample model of the thoracic cavity to visualize the design concept.

We have used engineering parameter design analysis, experimentation and user feedback to further narrow down our ideas and we currently have selected all of the materials and components we need to build a working prototype. We created a completed model of our design and displayed it at the Design Expo. The next step is to continue testing and validating, and revamping our design.

Appendix E

Gantt Chart



Brainstorming Ideas

Skin:

Materials

- Plastic Covering (Halloween Costume) N
- Ballistics Gel Y
- Leather Y
- Rubber Y
- Wet Suit Material Y
- Cardboard N
- Paper N
- Towels/cloth Y
- Netting N
- Silk Pajamas N
- Sponge N
- Styrofoam N
- Saran wrap N
- Latex (band-aid material) N
- Taffy N

Ways to open/close

Openings

- Zipper
- Velcro
- Magnets
- Buttons/snaps
- Flap/door (hinged)
- Slide/accordion
- Spring loaded N
- Press correct button to open correct incision N
- Slits
- Laces
- Zip-lock

Malleable

- Use a replaceable square to cut
- Use glue/tape/caulk/putty to reseal
- Use old trauma man skin

Ribs:

Materials

- Plastic
- Wood: Plywood/balsa wood, popsicle sticks/twigs
- Rubber/belts
- Epoxy
- Pre-made

- Paper Mache
- Clay
- Bacon
- Glass
- Ballistics Gel
- PVC
- Plexi-Glass
- Carbon fiber
- Metal
- Plaster of Paris
- Noodles
- Styrofoam
- Sponge
- Rope
- Can

Open

- Torsional springs
- Hinges
- Rubber
- Slide on a track
- Rack and pinion
- Spring/accordion loaded
- Pneumatics

Pleura/Pericardium:

Material

- Plastic bag
- Silly putty
- Saran wrap
- Bubble wrap
- Touchable bubbles
- Balloons
- Paper
- Rubber
- Aluminum Foil

Lungs:

Material

- Nerf ball
- Sponge
- Jell-O
- Plastic bag
- Balloon
- Wet suit material
- Dead fish

- Cloth
- Canvas
- Leather
- Ballistics Gel
- Foam

Breathing

- | | |
|--------------------------------------|---|
| - Pneumatics | Y |
| - Electric Pump | Y |
| - Hand pump | Y |
| - Ventilator | Y |
| - Balloon | |
| - Whoopee Cushion | |
| - Marshmallows + microwave radiation | N |
| - Vibrator | N |
| - Expandable ball toy | N |
| - Roti | N |
| - Internal combustion engine | N |
| - Turbine | N |

Heart:

Whole Ideas:

- 1) Ballistics Gel and Gauze & Mini Motor w/ Cam & Packets of Liquid System
- 2) Ballistics Gel & Balloon & Keyboard Buttons
- 3) Rubber & Pneumatics & Teeter-totter Switch
- 4) Latex w/ Dots & Hand Pump & Bubble wrap
- 5) Balloon & Electric Air Pump & Marbles
- 6) Cloth & Pocket Pump & Piezo Sensors

Material

- | | |
|---------------------|---|
| - Nerf ball | N |
| - Sponge | N |
| - Jell-O | N |
| - Plastic bag | Y |
| - Balloon | N |
| - Wet suit material | Y |
| - Dead fish | N |
| - Cloth | N |
| - Canvas | N |
| - Leather | N |
| - Ballistics Gel | Y |
| - & Gauze | |
| - Latex | Y |
| - Pre made | Y |
| - Marshmallows | N |

Problems

- Rupture
- Slit
- Tear
- Puncture
- Bruise/edema

Beating

- Pneumatics Y
- Motor Y
- Pocket pump Y
- Manual pump Y
- Balloon
- Whoopee Cushion
- Marshmallows + microwave radiation N
- Vibrator N
- Expandable ball toy N
- Roti N
- Internal combustion engine N
- Turbine N

Blood Flow:

- Colored water
- Oil
- Hand pump
- Electric pump
- Plastic tubes
- Go through the lungs/chemical reaction/change colors
- Rubber tubes
- Straws

Feedback:

- Color ribs to indicate correct location
- Measure blood loss
- Timer
- Heart/respiration rate
- Pressure sensor H
- Heat H
- Lights H
- Sirens/buzzers
- Change colors H
- Vision
- Smell
- Taste
- Haptic
- Hear

- Bubble Wrap H
- Packets of Liquid H
- Shapes H

Arduino Mega Microprocessor Code

```
#include <Servo.h>

const int ledPinA = 31;      // LEDs connected to digital pins
const int ledPinB = 33;
const int ledPinC = 35;
const int ledPinD = 37;
const int ledPinE = 39;
const int ledPinF = 41;
const int ledPinG = 43;
const int ledPinH = 45;
const int ledPinI = 47;
const int ledPinJ = 49;
const int ledPinK = 51;
const int ledPinL = 53;

int ACount=0;               //Time count for each sensor
int BCount=0;
int CCount=0;
int DCount=0;
int ECount=0;
int FCount=0;
int GCount=0;
int HCount=0;
int ICount=0;
int JCount=0;
int KCount=0;
int LCount=0;

const int sensorInA = 0;   //Sensors connected to analog pins
const int sensorInB = 1;
const int sensorInC = 2;
const int sensorInD = 3;
const int sensorInE = 4;
const int sensorInF = 5;
const int sensorInG = 6;
const int sensorInH = 7;
const int sensorInI = 8;
const int sensorInJ = 9;
const int sensorInK = 10;
const int sensorInL = 11;

int valA=0;                //Measures voltage generated by each sensor
int valB=0;
int valC=0;
int valD=0;
int valE=0;
int valF=0;
int valG=0;
int valH=0;
int valI=0;
int valJ=0;
int valK=0;
```

```

int valL=0;

Servo myservo;

void setup()
{
  myservo.attach(9);           //attaches the servo on pin 9 to the
                               servo object

  Serial.begin(9600);
  pinMode(ledPinA, OUTPUT);    //Defines LED digital pins as outputs
  pinMode(ledPinB, OUTPUT);
  pinMode(ledPinC, OUTPUT);
  pinMode(ledPinD, OUTPUT);
  pinMode(ledPinE, OUTPUT);
  pinMode(ledPinF, OUTPUT);
  pinMode(ledPinG, OUTPUT);
  pinMode(ledPinH, OUTPUT);
  pinMode(ledPinI, OUTPUT);
  pinMode(ledPinJ, OUTPUT);
  pinMode(ledPinK, OUTPUT);
  pinMode(ledPinL, OUTPUT);
}

void loop()
{
  myservo.write(180);

  valA=analogRead(sensorInA); //Reads the sensor voltage
  if (valA>1022 || valA<500)   //Threshold voltages defined
  {
    if (ACount>=200)           //Defines time threshold
    {
      digitalWrite(ledPinA, HIGH); //Turns on LED
    }
    ACount=ACount+1;           //Increase time
    valA=analogRead(sensorInA); //Reread sensor voltage
  }

  valB=analogRead(sensorInB);
  if (valB>1022 || valB<375)
  {
    if (BCount>=200)
    {
      digitalWrite(ledPinB, HIGH);
    }
    BCount=BCount+1;
    valB=analogRead(sensorInB);
  }

  valC=analogRead(sensorInC);
  if (valC>1022 || valC<175)
  {

```

```

    if (CCount >= 200)
    {
        digitalWrite(ledPinC, HIGH);
    }
    CCount = CCount + 1;
    valC = analogRead(sensorInC);
}

valD = analogRead(sensorInD);
if (valD > 1022 || valD < 300)
{
    if (DCount >= 200)
    {
        digitalWrite(ledPinD, HIGH);
    }
    DCount = DCount + 1;
    valD = analogRead(sensorInD);
}

valE = analogRead(sensorInE);
if (valE > 1022 || valE < 300)
{
    if (ECount >= 200)
    {
        digitalWrite(ledPinE, HIGH);
    }
    ECount = ECount + 1;
    valE = analogRead(sensorInE);
}

valF = analogRead(sensorInF);
if (valF > 1022 || valF < 300)
{
    if (FCount >= 200)
    {
        digitalWrite(ledPinF, HIGH);
    }
    FCount = FCount + 1;
    valF = analogRead(sensorInF);
}

valG = analogRead(sensorInG);
if (valG > 1022 || valG < 300)
{
    if (GCount >= 200)
    {
        digitalWrite(ledPinG, HIGH);
    }
    GCount = GCount + 1;
    valG = analogRead(sensorInG);
}

valH = analogRead(sensorInH);
if (valH > 1022 || valH < 300)

```

```

{
  if (HCount >= 200)
  {
    digitalWrite(ledPinH, HIGH);
  }
  HCount = HCount + 1;
  valH = analogRead(sensorInH);
}

valI = analogRead(sensorInI);
if (valI > 1022 || valI < 300)
{
  if (ICount >= 200)
  {
    digitalWrite(ledPinI, HIGH);
  }
  ICount = ICount + 1;
  valI = analogRead(sensorInI);
}

valJ = analogRead(sensorInJ);
if (valJ > 1022 || valJ < 300)
{
  if (JCount >= 200)
  {
    digitalWrite(ledPinJ, HIGH);
  }
  JCount = JCount + 1;
  valJ = analogRead(sensorInJ);
}

valK = analogRead(sensorInK);
if (valK > 1022 || valK < 300)
{
  if (KCount >= 200)
  {
    digitalWrite(ledPinK, HIGH);
  }
  KCount = KCount + 1;
  valK = analogRead(sensorInK);
}

valL = analogRead(sensorInL);
if (valL > 1022 || valL < 300)
{
  if (LCount >= 200)
  {
    digitalWrite(ledPinL, HIGH);
  }
  LCount = LCount + 1;
  valL = analogRead(sensorInL);
}
}

```

Medical Simulator Evaluation Form

Date: _____

Name: _____ Department: _____

Vendor: _____ Product: _____

Please mark the scale associate with each item to indicate your assessment of the simulator.

	Strongly Disagree	Disagree	Not Sure	Agree	Strongly Agree
The authenticity of the simulator reflects the actual medical environment					
Using the simulator feels like I am actually doing the procedure(s)					
The directions for using the simulator are clear and direct					
The interface of the simulator is easy to use					
The simulator accurately represents the actual equipment and tools for the procedure(s)					
The simulator will help me practice specific techniques in my specialty					
The simulator will help me learn new procedures in my specialty					
The performance measurements accurately assess the users abilities					
I would use this simulator to develop my skills if I were learning to perform the task(s) it supports					
I would use this simulator to train HOs and other hospital personnel					
The value of this simulator for UMHS/UMMS is high					
The simulator compares favorably with other simulators I have used					
I recommend purchasing this simulator					

The following specialties could benefit from this simulator:

- | | | | |
|---|---|--|---|
| <input type="checkbox"/> Anesthesiology | <input type="checkbox"/> Internal Medicine | <input type="checkbox"/> Oral Maxillofacial | <input type="checkbox"/> Plastic Surgery |
| <input type="checkbox"/> Cardiology | <input type="checkbox"/> Nephrology | <input type="checkbox"/> Orthopaedic Surgery | <input type="checkbox"/> Psychiatry |
| <input type="checkbox"/> Dermatology | <input type="checkbox"/> Neurology | <input type="checkbox"/> Otolaryngology | <input type="checkbox"/> Radiation Oncology |
| <input type="checkbox"/> Emergency Medicine | <input type="checkbox"/> Nursing | <input type="checkbox"/> Pathology | <input type="checkbox"/> Radiology |
| <input type="checkbox"/> Family Medicine | <input type="checkbox"/> Obstetrics &
Gynecology | <input type="checkbox"/> Pediatrics | <input type="checkbox"/> Surgery |
| <input type="checkbox"/> Gastroenterology | | <input type="checkbox"/> P M & R | <input type="checkbox"/> Urology |
| <input type="checkbox"/> Geriatric Medicine | <input type="checkbox"/> Ophthalmology | <input type="checkbox"/> Pharmacology | <input type="checkbox"/> Vascular Surgery |

What specific problem or challenges do you think this simulator would help you address?

How does this simulator compare to other methods of training this particular skill set?

What are the main advantages this simulator would provide to your specialty/department?

Additional Comments:

Thank you!

References

- (1)http://img.diytrade.com/cdimg/604184/7917203/0/1233810576/steel_door_hinge.jpg
- (2)*1079064_metallic.colors.balloons.jpg (JPEG image, 361x433 pixels)* Retrieved 10/23/2009, 2009, from http://wb4.itrademarket.com/pdimage/64/1079064_metallic.colors.balloons.jpg
- (3)*19589.jpg (JPEG image, 400x320 pixels)* Retrieved 10/23/2009, 2009, from <http://www.nlm.nih.gov/medlineplus/ency/images/ency/fullsize/19589.jpg>
- (4)*22711.jpg (JPEG image, 400x320 pixels)* Retrieved 9/25/2009, 2009, from <http://www.drugs.com/enc/images/images/en/22711.jpg>
- (5)*9968_en.jpg (JPEG image, 400x320 pixels)* Retrieved 10/23/2009, 2009, from http://www.mdconsult.com/das/patient/body/166513569-2/0/10041/9968_en.jpg
- (6)*Air properties* Retrieved 11/20/2009, 2009, from http://www.engineeringtoolbox.com/air-properties-d_156.html
- (7)Alciatore, D. G., & Hestand, M. B. (2003). *Introduction to mechatronics and measurement systems* . Boston: McGraw-Hill.
- (8)*Animal testing and ethics* Retrieved 10/6/2009, 2009, from <http://www.scu.edu/ethics/publications/iie/v1n3/cures.html>
- (9)*Animation of human heart beating* Retrieved 11/18/2009, 2009, from http://www.nhlbi.nih.gov/health/dci/Diseases/hhw/hhw_pumping.html

- (10) *Aorta_scheme.jpg* (JPEG image, 521x630 pixels) Retrieved 9/25/2009, 2009, from http://upload.wikimedia.org/wikipedia/commons/9/91/Aorta_scheme.jpg
- (11) *Atlas of human cardiac anatomy* Retrieved 10/23/2009, 2009, from <http://www.vhlab.umn.edu/atlas/ex/anterior/index.shtml>
- (12) Berne, R., & Levy, M. (2008). In Koeppen B. M., Stanton B. A. (Eds.), *Physiology* (6th ed.). Philadelphia, PA: Mosby Elsevier.
- (13) Bia, D., Armentano, R., Zócalo, Y., Grignola, J., & Ginés, F. Aortic and pulmonary arterial distensibility, elastic modulus, and pulse wave velocity, during active and passive systemic and pulmonary acute hypertension.
- (14) Black, J., & Hastings, G. W. *Handbook of biomaterial properties* London ; Chapman & Hall, 1998.
- (15) *Blood velocity and turbulence* Retrieved 9/24/2009, 2009, from <http://www.rwc.uc.edu/koehler/biophys/3e.html>
- (16) *Blood-supply-of-thoracic-wall.jpg* (JPEG image, 706x499 pixels) Retrieved 10/23/2009, 2009, from <http://anatomytopics.files.wordpress.com/2009/01/blood-supply-of-thoracic-wall.jpg>
- (17) *Boiology 2404 digestive system* Retrieved 10/23/2009, 2009, from <http://science.tjc.edu/Course/BIOLOGY/2404/2404 Digestive.htm>

- (18) *The british journal of radiology*. Retrieved 9/24/2009, 2009, from <http://bjr.birjournals.org/cgi/reprint/71/850/1018.pdf>
- (19) *Bronchoscopy simulator - UVa medical simulation center* Retrieved 10/23/2009, 2009, from <http://www.healthsystem.virginia.edu/internet/simulation/BronchSim.cfm>
- (20) Bull, R., Edwards, P., & Dixon, A. (1998). CT dimensions of the normal pericardium. *The British Institute of Radiology*, , 923.
- (21) *c2cec7cf-6ead-4323-9128-0c3b85d623a2.jpg (JPEG image, 700x391 pixels)* Retrieved 10/23/2009, 2009, from <http://www.fofato.co.uk/include/images/products/c2cec7cf-6ead-4323-9128-0c3b85d623a2.jpg>
- (22) Carter, Y. M., & Marshall, M. B. (2009). Open lobectomy simulator is an effective tool for teaching thoracic surgical skills. *The Annals of Thoracic Surgery*, 87(5), 1546-50; discussion 1551.
- (23) Cardiac output.(May 2000). *Encyclopedia Britannica Article*,
- (24) *Case study: Medical simulation corporation* Retrieved 9/24/2009, 2009, from <http://www.medsimulation.com/SocietyCaseStudy.asp>
- (25) Cooper, J. B., & Taqueti, V. R. (2008). A brief history of the development of mannequin simulators for clinical education and training *Postgraduate Medical Journal*, 84(997), 563-570. doi:10.1136/qshc.2004.009886

(26)Curtis, H. (1989). *Biology*

(5th ed.). New York: Worth.

(27)*Diameters of the thoracic aorta throughout life as measured with helical computed*

tomography -- hager et al. 123 (6): 1060 -- the journal of thoracic and cardiovascular surgery Retrieved 9/24/2009, 2009, from

<http://jtcs.ctsnetjournals.org/cgi/content/full/123/6/1060>

(28)Diode Characteristic Curves Tutorial & Circuits - Diode Characteristics - The Diode -

Electronic Hobby Projects, 2009, 11/20/2009,

http://www.hobbyprojects.com/the_diode/diode_characteristic_curves.html

(29)*Dive_Rite_Surgical_Tubing_Black.jpg (JPEG image, 264x400 pixels)* Retrieved 10/23/2009,

2009, from http://www.divecourses.co.uk/acatalog/Dive_Rite_Surgical_Tubing_Black.jpg

(30)Dowling, N. E. Mechanical behavior of materials.

(31)Feliciano, D. V., Mattox, K. L., & Moore, E. J. *Trauma (trauma (moore))* McGraw-Hill

Professional.

(32)*FemoraLineMan system / simulab corporation* Retrieved 10/23/2009, 2009, from

<http://www.simulab.com/product/ultrasound-trainers/femoralineman-system>

(33)*GCRME: Harvey: Major changes* Retrieved 9/24/2009, 2009, from

<http://www.crme.med.miami.edu/#/harvey-major-changes>

- (34)Gierada, D. S., Hakimian, S., Slone, R. M., & Yusen, R. D. (March 1998). MRAnalysis of LungVolume and thoracic dimensions in patients with emphysema before and after LungVolume reduction surgery.(170), 707.
- (35)Gordon, C. C., Churchill, T., Clauser, C. E., Bradtmiller, B., McConville, J. T., Tebbetts, I., et al. (September 1989). 1988 ANTHROPOMETRIC SURVEY OF U.S. ARMY PERSONNEL: METHODS AND SUMMARY STATISTICS.
- (36)*Gray112.png (PNG image, 436x600 pixels)* Retrieved 9/25/2009, 2009, from <http://en.wikivisual.com/images/8/88/Gray112.png>
- (37)*Group takes aim at university of michigan's use of dogs to train doctors in medical procedures | ann arbor news - - MLive.com* Retrieved 10/6/2009, 2009, from http://www.mlive.com/news/ann-arbor/index.ssf/2009/01/group_takes_aim_at_university.html
- (38)HeartDebakey, M., & Gotto Jr., A. M. (1997). The new living heart., 23.
- (39)*Human patient simulator HPS - sem lampotang personal* Retrieved 10/23/2009, 2009, from <http://vam.anest.ufl.edu/sem/ip.html>
- (40)*Illustrations. fig. 505. gray, henry. 1918. anatomy of the human body.* Retrieved 9/24/2009, 2009, from <http://www.bartleby.com/107/illus505.html>
- (41)*image503.gif (GIF image, 700x576 pixels)* Retrieved 10/23/2009, 2009, from http://scapula.pl/anatomia/duze_rys/image503.gif

- (42) *Imaging of pleural effusions in adults* Retrieved 9/24/2009, 2009, from <http://www.uptodate.com/patients/content/topic.do?topicKey=~9gaOHSBXGIPdLQ>
- (44) *Lumbar vertebrae with sacrum model | simulab corporation* Retrieved 10/23/2009, 2009, from <http://www.simulab.com/product/orthopedic/lumbar-vertebrae-sacrum-model>
- (45) *Lung_infection.jpg (JPEG image, 400x300 pixels)* Retrieved 9/25/2009, 2009, from http://www.asa3.org/ASA/topics/Youth page/Lung_infection.jpg
- (46) *Mediastinal tumor resection - beth israel deaconess medical center* Retrieved 10/23/2009, 2009, from <http://www.bidmc.org/YourHealth/MedicalProcedures.aspx?ChunkID=239522>
- (47) *Medical simulation « UNE SimLog* Retrieved 10/23/2009, 2009, from <http://robotodd.wordpress.com/category/medical-simulation/>
- (48) *MSDS - nomaco inc.* Retrieved 11/20/2009, 2009, from <http://www.nomaco.com/capabilities/msds>
- (49) Munson, B., Young, D. F., & Oklishi, T. H. *Fundamentals of fluid mechanics.*
- (50) *Neoprene sheeting - product information and background* Retrieved 10/23/2009, 2009, from <http://www.algeos.com/html/products/neoprene.htm>
- (51) Nilayam.in, S. (2009). *Heart special Heart Special,*
- (52) *Plastic-bag-2.jpg (JPEG image, 450x338 pixels)* Retrieved 10/23/2009, 2009, from <http://sustainabledesignupdate.com/wp-content/uploads/2008/05/plastic-bag-2.jpg>

- (53) *PP_1a.jpg (JPEG image, 400x400 pixels)* Retrieved 11/20/2009, 2009, from http://www.teamskyline.com/productImages/PP_1a.jpg
- (54) *Reality check: Medical training goes virtual - medicine at michigan summer 2007* Retrieved 9/24/2009, 2009, from <http://www.medicineatmichigan.org/magazine/2007/summer/clinsim/default.asp>
- (55) *Respiratory research | full text | measuring the lung function in the mouse: The challenge of size* Retrieved 11/20/2009, 2009, from <http://respiratory-research.com/content/4/1/4>
- (56) *Resusci@Anne CPR-D - www.laerdal.com* Retrieved 9/24/2009, 2009, from <http://www.laerdal.com/doc/1850971/Resusci-Anne-CPR-D.html>
- (57) Roberts, J. R., & Hedges, J. R. (2004). *Clinical procedures in emergency medicine*, 4th edition.
- (58) *ScienceDirect - journal of dermatological science : In vivo data of epidermal thickness evaluated by optical coherence tomography: Effects of age, gender, skin type, and anatomic site* Retrieved 10/23/2009, 2009, from http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6T87-4M6SBK5-1&_user=99318&_coverDate=12/31/2006&_alid=1060593617&_rdoc=1&_fmt=high&_orig=search&_cdi=5079&_sort=r&_docanchor=&view=c&_ct=100169&_acct=C000007678&_version=1&_urlVersion=0&_userid=99318&md5=d8641306c87d38b1a4c4dd52d3860cf6
- (59) Selthofer, R., Nikoli, V., Mrcla, T., Radi, R., Lekan, I., Rude, I., et al. (November 17, 2005). *Morphometric analysis of the sternum*.30, 43.

- (60) Sherwood, L. (2006). *Fundamentals of physiology: A human perspective*. Belmont, Calif.: Thomson Brooks/Cole.
- (61) SHEVI. Retrieved 10/23/2009, 2009, from http://www.shevi.org.il/xhtml/articles/animal_abuse/vivisection/07_life-education.html
- (62) *Simulation in medicine - a knol by dianesliwka* Retrieved 9/24/2009, 2009, from http://knol.google.com/k/dianesliwka/simulation-in-medicine/QmrUYGrF/CM0QhQ#Types_of_Simulators
- (63) *Society for academic emergency medicine > home* Retrieved 9/24/2009, 2009, from www.saem.org/SAEMDNN/.../0/SAEM%20Obj_3a_Summary.pdf
- (43) SparkFun electronics - piezo vibration sensor - large with mass Retrieved 11/20/2009, 2009, from http://www.sparkfun.com/commerce/product_info.php?products_id=9197
- (64) SparkFun Electronics - Servo - Full Rotation, 2009, 11/20/2009, http://www.sparkfun.com/commerce/product_info.php?products_id=9347
- (65) *SpringerLink - journal article*. Retrieved 9/24/2009, 2009, from <http://www.springerlink.com/content/n250218626208852/fulltext.pdf>
- (66) *StateMaster - encyclopedia: Pulmonary trunk* Retrieved 9/24/2009, 2009, from <http://www.statemaster.com/encyclopedia/Pulmonary-trunk>
- (67) *The sternum* Retrieved 9/25/2009, 2009, from <http://www.yorku.ca/earmstro/journey/sternum.html>

- (68) *An ultrasound study of the phrenic nerve in the posterior ce... : Regional anesthesia and pain medicine* Retrieved 10/23/2009, 2009, from http://journals.lww.com/rapm/Abstract/2008/11000/An_Ultrasound_Study_of_the_Phrenic_Nerve_in_the.6.aspx
- (69) *University of michigan health system - clinical simulation center* Retrieved 9/24/2009, 2009, from <http://www.med.umich.edu/umcsc/equipment/index.html>
- (71) *The university of the west indies* Retrieved 11/20/2009, 2009, from http://www.eng.uwi.tt/depts/elec/staff/rdefour/ee33d/s2_vichar.html
- (72) *VACUTAIN-TOURNIQUET.jpg (JPEG image, 352x247 pixels)* Retrieved 10/23/2009, 2009, from http://4.bp.blogspot.com/_hxdmntF5Nso/SYJ_c0YU0tI/AAAAAAAAAB4I/mGsxAdVi2qE/s400/VACUTAIN-TOURNIQUET.jpg
- (73) *Why simulation works - medicine at michigan summer 2007* Retrieved 9/24/2009, 2009, from <http://www.medicineatmichigan.org/magazine/2007/summer/clinsim/clinsim-02.asp>
- (74) *Willow fabrics siesta embroidery hoops* Retrieved 11/18/2009, 2009, from http://www.willowfabrics.com/acatalog/Siesta_embroidery_hoops.html
- (75) *Your-heart.jpg (JPEG image, 440x300 pixels)* Retrieved 9/25/2009, 2009, from <http://away.com/images/outside/200708/your-heart.jpg>
- (76) *YouTube - medical animation beating heart* Retrieved 11/18/2009, 2009, from http://www.youtube.com/watch?v=FRd3K6LkhWs&feature=player_embedded

(77) http://www.sparkfun.com/commerce/product_info.php?products_id=9197

(78) <http://arduino.cc/en/Main/ArduinoBoardMega>

(79) <http://web.mit.edu/rec/www/workshop/voltage-divider.gif>

(80) http://www.sparkfun.com/commerce/product_info.php?products_id=8532-datasheet

Bios

Josh Rollins



Ever since I was old enough to move around I was interested in how things worked. Whether it was me trying to take apart the dish washer with a screw driver at age 4 or figuring out how to open the emergency window in kindergarten (my escape was foiled at the last moment), figuring out how the world around me was put together has always been my passion. I would take apart anything I could get my hands on and put them back together (with mixed resulted), as well as try to combine different devices and see if I could improve on the design.

I chose mechanical engineering because I didn't want to be limited to one degree of expertise. I wanted to be able to have the option to change my mind and what I was working on in the workforce without having to get another degree. Mechanical engineering is perfect for me because it give me a taste of everything and allows me to not only develop a sense of how all aspects of engineering are related, but also gives me the freedom to specialize if I find a particular area of interest. Pursuing my degree has allowed me to meet and work with people from the US and abroad, and get far away from my small town of Farmington, MI.

In the immediate future, I plan on finding a job, though I don't know with whom yet, and develop a better understanding of what I want to concentrate on as a career. I plan on eventually getting a master's degree, hopefully sooner rather than later, and exploring the rest of what this world has to offer.

Ofra Rybak



I am from West Bloomfield, Michigan, though I spent most of the early years of my life in Southfield, Michigan. I think my interest in Mechanical Engineering stemmed from my involvement in my high school's robotics team. Going to a robotics tournament was always a blast; everyone was so enthralled in the competition, it was almost like going to a sports match. It was amazing what some of the teams created as well, considering all of the teams were made up of young teenagers. As for my future plans, I intend on going to graduate school to get my Masters in Mechanical Engineering next year. If everything works out correctly, I will be doing the Sequential Graduate Undergraduate Studies (SGUS) program at the University of Michigan's College of Engineering and I will be able to finish my Masters in one year. Outside of engineering, my passion is vocal performance, thus I am very involved in the Dicks & Janes co-ed a cappella group on campus.

Wajiha Shahid



I was born in Karachi, Pakistan and have spent almost my entire life there so far. I have always been fascinated by problem solving and I actively pursued this passion during high school days by organizing and participating in several in-state mathematics and physics science competitions. My motivations in the area of mechanical engineering particularly control systems developed when I started researching for sources of time delays in network controlled systems at the Center for Reconfigurable Manufacturing Systems. After graduation, I intend to pursue a PhD degree in mechanical engineering and look forward to return to my country as an instructor/researcher. In my spare time, I enjoy running, swimming and cooking.

Carly Schiffer



At the age of 6 all I wanted for Christmas were Legos. When I was 10 I drew blueprints of the fort that I then built with my father. On my 12th birthday I was given a broken down 1965 Honda 55cc motorcycle, in two weeks I was riding it around. According to my parents I have always been an engineer, and it's what I enjoy. My name is Carly and I am from Ovid Michigan, population 1,514. The majority of people in my town are farmers, not only crop but also dairy farmers. My father is a crop-duster and led my younger brother and I to solo in a J-5 cub on our 16th birthdays. Our local high school was combined with the town just north of it to form Ovid-Elsie High School. There wasn't really much to do in Ovid so I was involved in many extra-curricular activities, through the school and other organizations. Such as Mathletes, Science Olympiad, and Odyssey of the Mind. I was also very involved in the musical community around the area. All four years of my collegiate career, I have pole vaulted as a Big-Ten athlete on varsity track and field team here at the University of Michigan. The University has been one great learning experience with all of the down falls to boot. I can only it finishes up the same way.