Pennsylvania State University
PSU MNE 2
Human Chest Expansion Simulator
Final Report

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Figure 1 (Chest Energy Harvester Design)

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No - Intellectual Property Rights Agreement
No - Non-Disclosure Agreement
Executive Summary

The main goal of this project is to design and build a system that simulates expansion of the human chest during breathing. Currently, the Mechatronics Research Laboratory is designing a wearable chest energy harvester shown on the cover page. Testing on human subjects has not yielded accurate results. The purpose of this project is to create a torso simulator that can replace the need for an actual human subject when testing the wearable chest energy harvesters. In order to achieve this goal, a six stage process was implemented. The first step was to research how to measure chest displacement due to breathing during low, medium, and high activity levels. Following the measurement stage, an actuator method will be selected to expand the chest simulator, keeping in mind maximum frequencies needed, the scale of the displacements required, and the ease of use of the actuator. The chosen actuator will then be placed into a housing that resembles a human chest, such as a mannequin torso. Designing the outer part of the artificial chest will allow the mannequin to compress like human soft tissue. For the design of the artificial outer body, thickness and stiffness specifications for human muscle, fat, and skin will allow the mannequin to actually mimic the compression of human soft tissue. Furthermore, the goal is to design a simulator that has the ability to adjust the soft tissue compression characteristics to mimic different body types. Finally, using the chest expansion data profiles from the first step, the simulator will be controlled by generating continuous, repeatable breathing motion. The simulator will be able to replicate the breathing of different people during different levels of activity. The final model can then be used by the Mechatronics Research Laboratory to improve development of wearable chest energy harvesters.
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3
1.0 Introduction

The goal of this project is to design a system that simulates human chest expansion due to inspiration and expiration. The model will be able to mimic breathing of a human at low, medium and high activity levels. The activity levels will respectively replicate rest, walking, and running. In the future, the simulator should be able to simulate coughing and wheezing. Chest displacement of the model should change depending on the activity level.

The chest simulator will be used to test wearable chest energy harvesters like the one shown in Figure 1. The Mechatronics Research Laboratory currently has wearable devices that are capable of converting the mechanical work created by breathing into electrical energy. The lab is testing prototypes that are capable of absorbing the mechanical energy exerted by breathing. Eventually, the goal is to create a shirt lined with biosensors for subjects to wear that will be capable of measuring vital signs. The shirt will be self-powered through the harvesting of mechanical energy stemming from inspiration/expiration of the wearer.

![Figure 1 (Chest Energy Harvester Design)](image_url)

1.1 Initial Problem Statement

The Mechatronics Research Laboratory possesses multiple chest energy harvesting devices that have unknown efficiencies. Tahzib Safwat has been tasked with testing these devices, and in order to do so he needs an emulator of the human chest that simulates breathing patterns. This project will assist Tahzib by creating a life-size model of the chest that is capable of simulating breathing patterns at various levels of exercise, as well as emulating the mechanical and physical properties of the tissues surrounding the chest cavity.
1.2 Objectives

Chest displacement versus time data will be measured at different activity levels to drive the model’s function. The data will determine the maximum frequencies and displacements. The optimal actuator, as well as the number of actuators, will be selected based on the chest displacement experiment. A model of a chest will be designed to mimic breathing of a human using the actuator. The artificial chest will have the same mechanical properties as human soft tissue. The tissue will take into account the viscoelastic and mechanical properties of skin, fat and muscle. The simulator will then be able to generate continuous repetitive signals that mimic breathing stemming from the contraction of the diaphragm in humans.

2.0 Customer Needs Assessment

Customer input is important in designing to ensure client satisfaction. The needs can then be weighted to determine, which ones are more important during concept selection. A hierarchical method was used to calculate weighting from the customer needs given.

2.1 Gathering Customer Input

The customer needs for this project depend on the specific needs of the Mechatronics Research Laboratory. They will be using the chest simulator to test their energy harvester prototypes. Customer input was gathered through conversations with Tazhib to understand the most important elements of the project. Then this information was discussed within the team to organize his points.

The criteria includes how accurately the model simulates human breathing. In addition, other criteria are safety, durability of the model, ease of use, and portability of the torso emulator. Factors that affect the building of the model include ease of manufacturing, cost, and time to assemble. Realistic criteria refer to how closely the model resembles a human chest soft tissue. Manipulation refers to how easy it is to change the breathing type to coughing or wheezing.

2.2 Weighting of Customer Needs

The analytic hierarchy process (AHP) model, shown in Table 1, is used to determine the importance of each criterion. A scale of one to four was used to rate each criteria against the others. To find the weight of each criterion, the sum of the criteria inputs was divided by the sum of the matrix. The criteria with the highest weights included evaluations of manipulation, realistic, and accuracy.
Table 1: AHP Comparison Chart to Determine Weighting for Main Objective Categories

<table>
<thead>
<tr>
<th></th>
<th>Accuracy</th>
<th>Safety</th>
<th>Cost</th>
<th>Durability</th>
<th>Portability</th>
<th>Ease of Mfg</th>
<th>Ease of Use</th>
<th>Time to Assemble</th>
<th>Realistic</th>
<th>Manipulate</th>
<th>Total</th>
<th>Weight</th>
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</thead>
<tbody>
<tr>
<td>Accuracy</td>
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<td>1.00</td>
<td>2.00</td>
<td>2.00</td>
<td>4.00</td>
<td>3.00</td>
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<td>1.00</td>
<td>1.00</td>
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</tr>
<tr>
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</tr>
<tr>
<td>Time to Assemble</td>
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<td>0.50</td>
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<td>24.01</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Total 139.7 1.0

4.0 Engineering Specifications

For the project, there was a discussion with the sponsor to find out what he wanted as a final product. Interesting specifications were obtained through this conversation. The findings of these customer needs helped to determine which concepts to pursue.

4.1 Establishing and Relating Target Specifications to Customer Needs

First, the sponsor requested a torso that could mimic the movements of breathing in different levels of activity. To complete this task, research was used to find the best way to simulate the expansion and compression of the chest. The sponsor has provided the idea to use linear actuators to complete this task. These actuators needed to be small enough in length to fit inside the body of the torso itself. Materials needed to replicate the human body including skeletal muscle tissue, fat, and skin were the next task. To accomplish these specifications, research into the different values pertaining to each part of the human body was helpful. The values found are shown in Appendix A [1,2]. The values include, but are not limited to, the ultimate tensile strength, ultimate percent elongation, and the shear modulus based on the background of each person. Finally, the sponsor suggested to create a program that will communicate with the system to adjust the breathing to each level of activity. In
this case, using an Arduino was considered to obtain the measurements and transfer the results into a MATLAB array. The movements of the simulator can be controlled using a microcontroller. Further information is needed to accomplish this final decision.

**5.0 Concept Generation and Selection**

For concept generation, a black box model was created to help identify each input and output associated with the project. From there, a subfunction diagram was made to determine the mechanisms that will be involved in the final model. After brainstorming concepts, a Pugh concept scoring matrix used the weighted customer needs to select the concept.

**5.1 Problem Clarification**

A black box model was created, as shown in Figure 2. The black box is used to visualize the inputs and outputs for the chest expansion simulator. The inputs include chest displacement data during low, medium, and high activity levels, linear actuators, microprocessor, structure casing, mannequin, and material to mimic skin, fat, and muscle tissues. By including these items in the design of the chest expansion simulator, the outputs should be a torso structure that simulates the expansion of the chest due to breathing during low, medium, and high activity levels and voltage for the chest energy harvesters. These inputs and outputs help the team gain a better understanding of what needs to be considered when designing the chest expansion simulator.

![Figure 2: Black Box Model for Chest Expansion Simulator](image)

Additionally, the inputs and outputs can be categorized in a sub-function diagram to organize the process even further. The sub-function diagram shown in Figure 3, displays what affects the simulation of chest expansion and compression, what provides the voltage for the chest energy...
harvesters, and what creates the torso structure. The first input necessary to achieve the expansion and compression simulation is the chest displacement data during low, medium, and high activity levels. The interpretation of this data will require reference to the literature with respect to magnitude of displacement during exercise [3] and effects that the harness might have on displacement data due to the compressive forces exerted on the chest by the harness [4]. This data will then be provided to a microprocessor, which delivers the information to the linear actuators. The linear actuators will simulate expansion and compression of the chest during these activities. This expansion and compression simulation will provide voltage for the chest energy harvesters. Lastly, the torso structure will provide a casing around the linear actuators and create a shape similar to the size and structure of the chest. The torso structure will be composed of a structure casing to hold the linear actuators in place, a mannequin to emulate the shape of the chest, and material that mimics the mechanical properties of skin, fat, and muscle. The sub-function diagram allows the team to understand what each sub-function directly affects and how the sub-functions work together to create the chest expansion simulator and its outputs.

Figure 3: Sub-function diagram for Chest Expansion Simulation

### 5.2 Concept Generation

For the concept generation phase, three ideas were developed to deal with the positioning and placement of the linear actuators in the system. Most of the ideas stemmed from a paper written by Mead and Loring in which the mechanics of breathing were distilled down to a conservation of volume concept [5]. The first idea, shown in Figure 4, has the two actuators placed next to each other and parallel to the the front part of the chest plate. This idea accounts for the expansion of the chest laterally but fails to account for the expansion of the chest anterior/posterior. The second and
third ideas shown in Figure 5 have the linear actuators criss-crossed within the chest structure. This criss-cross positioning will account for the lateral and anterior/posterior expansion of the chest. The second idea has the actuators angled upwards which will account for the expansion of the upper chest. The third idea has them positioned straight with the chest which will allow for expansion of the middle chest. The current plan is to pursue the third idea. However, when the team gathers the data on chest expansion during activity, the final idea will be chosen.

![Figure 4](image)

Figure 4: Drawing of potential positioning of the actuators placed straight with a plate

(A)
5.3 Concept Selection

Table 2 presents a Pugh Concept Scoring chart used to decide among the three different possible positions for the actuators. The concept scoring matrix is based on a scale of five, with one as the lowest score and five as the highest. The chosen selection criteria used to rank the concepts were: safety, ease of use, ease of manufacturing, accuracy, durability, portability, time to assemble, realistic, and manipulation. All of the options have the same safety, cost, durability, manipulation, and portability scores. Option three is more realistic than the other two options, while option one is the easiest to manufacture. Option two will take the longest to assemble. Option three came out with the highest score.
Table 2: Pugh Concept Scoring

<table>
<thead>
<tr>
<th></th>
<th>Straight with the Chest Plate</th>
<th>Criss Cross and Angled</th>
<th>Criss Cross and Straight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Score</td>
<td>Weighted Score</td>
<td>Score</td>
</tr>
<tr>
<td><strong>Accuracy</strong></td>
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<td>0.14</td>
<td>5</td>
</tr>
<tr>
<td><strong>Safety</strong></td>
<td>5</td>
<td>0.1</td>
<td>5</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>5</td>
<td>0.09</td>
<td>5</td>
</tr>
<tr>
<td><strong>Durability</strong></td>
<td>5</td>
<td>0.11</td>
<td>5</td>
</tr>
<tr>
<td><strong>Portability</strong></td>
<td>2</td>
<td>0.03</td>
<td>2</td>
</tr>
<tr>
<td><strong>Ease of Manufacturing</strong></td>
<td>4</td>
<td>0.05</td>
<td>2</td>
</tr>
<tr>
<td><strong>Ease of Use</strong></td>
<td>2</td>
<td>0.1</td>
<td>2</td>
</tr>
<tr>
<td><strong>Time to Assemble</strong></td>
<td>3</td>
<td>0.07</td>
<td>1</td>
</tr>
<tr>
<td><strong>Realistic</strong></td>
<td>2</td>
<td>0.16</td>
<td>3</td>
</tr>
<tr>
<td><strong>Manipulate</strong></td>
<td>3</td>
<td>0.17</td>
<td>3</td>
</tr>
<tr>
<td><strong>Total Score</strong></td>
<td>3.28</td>
<td>3.62</td>
<td>4.13</td>
</tr>
<tr>
<td><strong>Rank</strong></td>
<td>3</td>
<td></td>
<td>2</td>
</tr>
</tbody>
</table>

6.0 System Level Design

Information from previous steps are needed to move forward in the project. For example, the reaction of simulated body materials against different actuator voltages needs to be known to choose the right actuator to do the job. However, components have been included that have been discussed and agreed upon to use in the final product. The chest measurement system, shown in Figure 6, was redesigned multiple times as problems continued to arise. The final product for the measurement system uses a harness to hold a string potentiometer (A) in place, via Velcro strips (B). A string has been attached to the end loop (C) to extend the potentiometer to fit every body type, whether male or female. As the string wraps around the body, it will use a hook through the hole at the other end of the potentiometer (D) to keep it firmly in place. As breathing occurs, the string will expand and contract to give the opportunity to measure the displacement to calculate the force and resistance. To collect the data continuously, an Arduino microcontroller was chosen as shown in Figure 7. The Arduino was connected through a USB port connect to a computer and 5V from the Arduino will be used. The data taken from the Arduino was then transferred into a MATLAB code that can be adjusted to control the linear actuator, shown in Figure 8. The linear actuator shown is not the final actuator chosen for the product as it is too lengthy to fit within our system and requires 12V to run. An actuator similar in shape with a smaller length and driving voltage to accommodate our specifications will be used.
Figure 6: (A) Harness to hold string potentiometer, (B) String potentiometer held in place via velcro strips, (C) String attached to end loop of string potentiometer, (D) String tied through the hole on the other side of the string potentiometer.

Figure 7: Arduino System

Figure 8: Linear Actuator similar to the actuators the team will use in the final design.
7.0 Special Topics

There is a limited budget for this project. Therefore, it is important to keep track of the spending. Another critical part of the project is to stay within the timeline of a semester. A Gantt chart was made to stay on target. A risk plan was also created to ensure that major setbacks are minimized throughout the length of the project. Ethics and the environment will also be important considerations during the design process. Lastly, this section covers communication with the sponsor.

7.1 Preliminary Economic Analyses

The total budget for the project is $1000. The budget will be spent mostly on materials to prototype and build the chest expansion simulator. The sponsors for this project are from Penn State. Therefore, money does not need to be spent on travel. The sponsors work in a lab on campus where they provide the equipment to create the prototypes and final simulator, so only a small portion of money needs to be used for equipment. The total estimated material cost will include items to gather chest expansion data during activity, items to build the structure of the torso, and items to create the simulation of the chest expansion and compression during breathing. The amount of the budget that will be set aside for contingency will be around 15% of the budget. This is approximately the cost of a linear actuator, the most expensive item, so if something happens to the one that is purchased, extra money in the budget will be set aside for a backup. Finally, the poster will be a cost that is listed in the budget. The total budget and details can be seen in Appendix B. The Bill of Materials shown in Appendix C describes items already bought and future purchases. The Bill of Materials can be found in Appendix C. By keeping track of the budget from the start of the project, overspending should not occur.

7.2 Project Management

The Gantt chart shown in Figure 9 displays the anticipated progress throughout this project. By creating a Gantt chart, the overall project goal can be decomposed into smaller tasks, so that progress can be tracked. The timeline allows the team and sponsor to assess if the project is making adequate progress to reach certain goals by the indicated due dates and milestones. The two biggest milestones indicated are the final presentation on December 5, and the Design Showcase on December 7. By following the timeline and completing the tasks displayed on the Gantt chart, the project will be completed on time.

The Gantt chart tracks the progress, while the management and technical skills help to fulfil the customer’s needs. The management skills will keep the team organized and give each member certain responsibilities. Every week each member is to complete a certain task that will help further the progress of the project. These tasks will be separated so that each member has an equal amount of work to complete. Furthermore, the weekly meetings with the sponsor ensures the project is meeting customer needs. If a team member misses a meeting or does not finish their task for the week, then they will be disciplined accordingly. The technical skills team members have
accumulated through classes and activities will help fulfill the customer needs. Everyone in the team has engineering backgrounds, two in biomedical engineering and three in mechanical engineering. Through the coursework certain concepts have been learned that will be useful in completing the project and meeting customer needs. The management and technical skills will help the team design a final project to meet the customer needs of our sponsor.

Figure 9: Gantt chart for the project

7.3 Risk Plan and Safety

The critical path for the project is displayed in Table 3. The tasks are organized so that the ones that need to be completed first are located at the top of the list, while ones that are to be completed later are lower in the list. Furthermore, this list displays what tasks need to be completed before moving onto another task. For example, the first task is “obtain string potentiometer” and the second task is “take chest expansion measurements.” These two need to be completed in this order because we need the string potentiometer to take the chest expansion measurements. However, some tasks could be overlapped, also. For example, to complete the last task, “write the report,” can be worked on while the team is designing and building the chest expansion simulator. The start and end dates provided show which tasks need to follow a specific order and which tasks can be worked on at the same time. The critical path provides clarification to the steps needed to be completed to reach the final product.
Table 3: Critical Path for the Project

<table>
<thead>
<tr>
<th>Milestone(s)</th>
<th>Description</th>
</tr>
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<tr>
<td>21/07/2017</td>
<td>Presentations</td>
</tr>
<tr>
<td>22/07/2017</td>
<td>Showcase</td>
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</tbody>
</table>

<table>
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<th>Duration [Min]</th>
<th>Start Date</th>
<th>End Date</th>
<th>Description</th>
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<td>09/11/2017</td>
<td>09/11/2017</td>
<td>09/17/2017</td>
<td>Obtain Single Potentiometer</td>
</tr>
<tr>
<td>7</td>
<td>09/18/2017</td>
<td>09/18/2017</td>
<td>09/24/2017</td>
<td>Take chest expansion measurements</td>
</tr>
<tr>
<td>7</td>
<td>09/11/2017</td>
<td>09/11/2017</td>
<td>09/17/2017</td>
<td>Research Tissue Properties (skin, fat, muscle)</td>
</tr>
<tr>
<td>7</td>
<td>09/11/2017</td>
<td>09/11/2017</td>
<td>09/17/2017</td>
<td>Research Actuators (size, type, etc.)</td>
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<td>5</td>
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<td>09/24/2017</td>
<td>Select Best Activation Method</td>
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<td>10/18/2017</td>
<td>Design Housing for Actuator</td>
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<td>10/31/2017</td>
<td>10/31/2017</td>
<td>Design outer material (skin of system)</td>
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<tr>
<td>14</td>
<td>11/01/2017</td>
<td>11/14/2017</td>
<td>11/14/2017</td>
<td>Design other layers within the system (fat, muscle)</td>
</tr>
<tr>
<td>12</td>
<td>11/15/2017</td>
<td>11/26/2017</td>
<td>11/26/2017</td>
<td>Mimic Other Body types (male vs. female) if time allows</td>
</tr>
<tr>
<td>7</td>
<td>09/11/2017</td>
<td>09/11/2017</td>
<td>09/17/2017</td>
<td>Learn how to use a microprocessor</td>
</tr>
<tr>
<td>7</td>
<td>09/28/2017</td>
<td>10/04/2017</td>
<td>10/04/2017</td>
<td>Implement measurements into actuator using microprocessor</td>
</tr>
<tr>
<td>61</td>
<td>09/27/2017</td>
<td>11/26/2017</td>
<td>11/26/2017</td>
<td>Assemble the system</td>
</tr>
<tr>
<td>7</td>
<td>11/27/2017</td>
<td>12/03/2017</td>
<td>12/03/2017</td>
<td>Test the system</td>
</tr>
<tr>
<td>14</td>
<td>11/20/2017</td>
<td>12/03/2017</td>
<td>12/03/2017</td>
<td>Create Poster</td>
</tr>
<tr>
<td>31</td>
<td>10/10/2017</td>
<td>11/20/2017</td>
<td>11/20/2017</td>
<td>Write Report</td>
</tr>
</tbody>
</table>

Additionally, a risk plan was created for the project. This risk plan was prepared for any issues that may arise. The risks are described in Table 4. The table displays the risk, level of likeliness for it to occur, actions to minimize the likeliness, and a fall back strategy. A low level risk is unlikely to happen, while a high level risk is very likely to happen. Necessary actions will be taken to minimize the likelihood of the risks occurring. These actions are presented in the “Actions to Minimize” column. Lastly, in case the risk does occur, there is a fall back plan. This fall back plan will help the team stay on track if a risk does occur. The risk plan is used to prepare ways to avoid risks and ways to correct risks if needed.
Table 4: Risk Plan for our Project

<table>
<thead>
<tr>
<th>Risk</th>
<th>Level</th>
<th>Actions to Minimize</th>
<th>Fall Back Strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change in customer needs</td>
<td>Moderate</td>
<td>- Involve sponsor in process of refining specifications &lt;br&gt;- Meet with sponsor weekly to discuss project expectations and goals</td>
<td>- Add time to schedule for that particular task &lt;br&gt;- Additional budget required</td>
</tr>
<tr>
<td>Schedule delays</td>
<td>High</td>
<td>- Constantly track project progress with the Gantt chart &lt;br&gt;- Look for ways to accelerate activities</td>
<td>- Build in safety time &lt;br&gt;- Re-allocate resources or staff</td>
</tr>
<tr>
<td>Delays in delivery of items</td>
<td>Moderate</td>
<td>- Make sure parts are in stock &lt;br&gt;- Order items ahead of time, in case there are delivery delays &lt;br&gt;- Communicate with the ME department about all purchases</td>
<td>- Make substitutions with items we can find on campus or near State College</td>
</tr>
<tr>
<td>Product does not function properly</td>
<td>Low</td>
<td>- Test early and often &lt;br&gt;- Be aware of risks of new technology &lt;br&gt;- Create multiple prototypes to be able to choose best design</td>
<td>- Alternative design &lt;br&gt;- Different material, technology, etc.</td>
</tr>
<tr>
<td>Customer is not satisfied with final product</td>
<td>Moderate</td>
<td>- Understand the customer’s needs (voiced and non-voiced)</td>
<td>- Discuss ways to fix the problem</td>
</tr>
<tr>
<td>Go Over Budget</td>
<td>Low</td>
<td>- Know the budget total of $1000 &lt;br&gt;- Create a budget with all expenses accounted for &lt;br&gt;- Create a Bill Of Materials &lt;br&gt;- Have contingency money</td>
<td>- Do not make as many prototypes before the final design &lt;br&gt;- Different material or structural pieces</td>
</tr>
</tbody>
</table>

7.4 Ethics Statement

The data produced from experimentation and measurements will be reported as recorded. Budgets and receipts will be tabulated to provide to the sponsor. All ideas and concepts appended from other sources will be given due credit.

7.5 Environmental Statement

Materials needed will be used judiciously. Specifically those with the propensity to cause harm to the environment, like synthetic polymers used to mimic human soft tissue, and plastic shards created from mannequin torso alterations, will be disposed of properly and not wasted.
7.6 Communication and Coordination with Sponsor

The main form of communication with the sponsor is through email. The emails can include questions on the project, due dates of tasks, and rescheduling of meetings. Weekly emails are sent out on Monday during normal business hours to summarize progress and billable hours. In addition, weekly meetings are held on Thursdays at 4:30pm with Tazhib to discuss ideas and tasks for the upcoming week.

8.0 Detailed Design

Section 8.0.1 Modifications to Statement of Work Sections
Revisions to the Proposal Sections 1 through 7 are listed as 8.0.1.7:
8.0.1.1. Introduction - No change
8.0.1.2. Customer Needs – No change
8.0.1.4. Engineering Specifications - No change
8.0.1.5. Concept Generation and Selection - The primary design concept has been modified to use a motor instead of linear actuators as previously stated. A detailed reasoning, explanation, as well as SolidWorks models of the motor intended to be used is found in section 8.1.
8.0.1.6. System Level Design - A revised exploded view of the system is shown in Appendix H. The final design has been updated to include a motor. The manufacturing process of the motor as well as the casing is detailed in section 8.1.
8.0.1.7. Special Topics - An updated version of the budget and Bill of Materials is shown in Appendix B and discussed in section 8.7.

8.1 Manufacturing Process Plan

Our complete design includes a pre-purchased motor that uses connections to operate successfully, a structure to stabilize the motor, a urethane polymer to simulate human tissue, and a mannequin torso.

8.1.1 Actuation Method
A general concept is shown in Figure 10. The motor will be connected to a circular plate such that the plate rotates with the same angular velocity as the motor. The plate will then be attached to two main arms with attachment points sitting anteriorly and posteriorly with respect to their positioning in the mannequin torso. This positioning is to ensure arm extension upon rotation of the motor in the counterclockwise direction (looking down from the neck of the torso). These main arms will have branch points where two more extending arms will be coupled to the main arm with another bolt. These extending arms will be the contact points to the interior of the torso and will affect change in the torso through mechanical load driven by the torque supplied by the rotary motor. The material, size, and summarized operation of the main arms, extending arms, motor, and bolts used to secure the overall fixture, are shown in Table 5.
8.1.2 Stabilizing Structure
The stabilizing structure will fix the motor with respect to the torso cavity such that the restoring force of the torso against the small motor arms does not displace the motor itself. The apparatus will be constructed using aluminium bars that are easily affixed to one another with screws. The motor will be positioned in the caudal portion of the torso, supported by the aluminium stabilizing structure in the form of an X or a square (yet to be determined), which will be affixed to the bottom of the torso via screws. The motor stabilizing structures material, size, and summarized operation are shown in Table 5.

8.1.3 Torso
The mannequin torso was procured from an outside vendor and is shown in Figure 11. The torso was modified with strategically placed cuts to allow for maximum compliance of the plastic. Cuts were shaped in the form of a “Y,” and placed anteriorly, near the ribcage, and medially. Additionally two straight cuts were made in the back to allow for the slight posterior expansion associated with inspiration. VytaFlex 10 will be purchased from Smooth-On to simulate human tissue. The mixtures will be combined according to Smooth-On protocol, the non-adhesive spray will be applied to a flat surface surrounded by a barrier, and the mixture will be poured onto the flat surface. Once the mixture is partially cured, it will be draped over the mannequin torso so it may form fit the curvature. The surface area of the mold will be made slightly larger than that of the torso such that there is some overlap in the back to allow for permanent attachment to the torso. The torso’s material, size, and summarized operation are detailed in Table 5 below.
Figure 11: Front, back, and side view of mannequin
Table 5: Manufacturing Process Plan Rudiments

<table>
<thead>
<tr>
<th>ASSEMBLY NAME</th>
<th>MATERIAL TYPE</th>
<th>RAW STOCK SIZE</th>
<th>OPERATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor</td>
<td>NA</td>
<td>12 cm diameter</td>
<td>N/A</td>
</tr>
<tr>
<td>Main arms</td>
<td>Steel</td>
<td>7 cm x 2 cm x 1 cm</td>
<td>Bolted to Motor</td>
</tr>
<tr>
<td>Extending arms</td>
<td>Steel</td>
<td>7 cm x 2 cm x 1 cm</td>
<td>Bolted to main arms</td>
</tr>
<tr>
<td>Bolt</td>
<td>Steel</td>
<td>1 cm diameter</td>
<td>Used to connect arms to motor and each other</td>
</tr>
<tr>
<td>Motor Stabilizer</td>
<td>Aluminium</td>
<td>To be determined</td>
<td>To be determined</td>
</tr>
<tr>
<td>Torso mannequin</td>
<td>Heavy Plastic Polyethelene</td>
<td>25.2” height 38” chest/bust circumference 30.3” waist circumference</td>
<td>Cuts made anteriorly, on rib cage, along side in “Y” shape, and straight cuts made in the back alongside the spine.</td>
</tr>
<tr>
<td>Smooth on</td>
<td>Vitaflex - 10</td>
<td>9 lbs</td>
<td>Mixed according to Smooth-on instructions and draped on torso mannequin</td>
</tr>
</tbody>
</table>

8.1.4 Rudiments

Table 5 above presents more details of the process plan rudiments for the manufacturing of the human chest expansion simulator. The table presents the material type, size, and operation of each of the assembly parts. It includes specifications for all necessary parts used in the assembly line, including bolts and arms, which will be attached to the motor, as well as the skin like material that will cover the mannequin.

8.2 Analysis

The analysis of chest displacement is necessary to design the chest expansion simulator. The team designed and conducted an experiment to get chest displacement data while sitting and standing, as well as during low, medium, and high activity levels. The results will be implemented into the final design of the chest expansion simulator. The experiment and the results are further explained in this section.
8.2.1 Chest Displacement Analysis
To determine chest displacement, the harness explained in Section 6.0 System Level design was used to measure the displacement of subjects. As stated previously, a spring potentiometer is attached to measure the displacement around the chest and its variable resistance is placed in series with a known resistor. The Arduino reads the voltages from the voltage divider and passes it directly to MATLAB. The MATLAB code used along with the experimental procedure can be found in Appendix D.

Before the experiment could be done, a calibration experiment was completed. The spring potentiometer was pulled out one centimeter at a time and the voltage exported from MATLAB was recorded. The maximum displacement from chest displacement was three centimeters, which is why measurements were taken from one to five centimeters. Figure 11 shows the plot of displacement versus voltage. A regression analysis was run to determine the equation that described the relationship between voltage and displacement. The MATLAB code within Appendix D represents the voltage to displacement conversion. This allows the Arduino to output the voltage to the computer and MATLAB converts this data into displacement.

![Figure 11: Displacement versus Voltage plot for spring potentiometer calibration](image)

The chest displacement experiment used five subjects for different activity levels. The different activity levels tested were sitting, standing, low, medium, and high levels of activity. The data was exported into Excel and plotted. Graphs of chest displacement vs time for each subject are shown in Appendix E. Each subjects graph includes the different activity level. Appendix G show the graphs separated by activity level. From the graph each peak to valley displacement and time was calculated. The peaks to valley averages were taken for each subject at that activity level. The frequency for each subject level was calculated by taking the inverse of the time difference. The angular frequency is determined by multiplying the frequency by two pi. Table 6 shows the peak to valley averages for each subject at the respective activity level. The RPM was calculated by converting frequency in Hz to rotations per minute. The maximum RPM of 69 will be used to size the motor.
From these averages, a sine wave will be used to simulate the activity level on the model. The amplitude will equal the average displacement of the subjects for that activity level. The angular frequency will correspond to the average angular frequency across all subjects. Table 7 shows the equations that will be used for each respective activity level.

<table>
<thead>
<tr>
<th>Activity Level</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sitting</td>
<td>0.53sin(4.15°t)</td>
</tr>
<tr>
<td>Standing</td>
<td>0.61sin(5.46°t)</td>
</tr>
<tr>
<td>Low</td>
<td>1.54sin(4.5°t)</td>
</tr>
<tr>
<td>Medium</td>
<td>1.65sin(5.03°t)</td>
</tr>
<tr>
<td>High</td>
<td>2.38sin(7.17°t)</td>
</tr>
</tbody>
</table>

**8.3 Material and Material Selection Process**

The team conducted a skin hardness experiment and compared the results to the type of material offered by Smooth-On. This section explains the experiment and material selection criteria in more detail.

**8.3.1 Skin Hardness Selection**

Smooth-on product VytaFlex-10 was chosen to replicate skin, muscle, and fat of the chest. Some of the reasons that Smooth-On was chosen for the outer layer of the model is location, availability, and quality of their products. Smooth-On has a distributor located in Pennsylvania. Because of the proximity of their distributor to Penn State, the shipping for their products takes less than a week. In addition, Smooth-On is known for its quality and strength of materials. The only downside to Smooth-On, is that the material is expensive.

To determine which specific polymer to use, the elastic modulus of the chest where the displacement measurements were taken was determined. The experiment procedure and analysis can be found in Appendix G. The elastic modulus can be converted into a hardness value, which Smooth-On lists in a material property table. Shore A hardness test is used for Smooth-On products. The experiment used a force gauge to determine the amount of force to compress the tissue around the torso. Figure 12 displays the belt wrapped around the subject. The length of the belt with no force was marked on the belt. Then the force gauge was pulled left as seen on Figure 12. The force shown on the gauge and the corresponding displacement of the belt from the marked position were recorded. Force and displacement were logged until the forces became too high to be solely compressing tissue. The strain of the each point was determined by dividing the displacement by the original length of the belt.
belt with no force applied. All experimental data for skin hardness can be found in Table 8 below. The stress was calculated by dividing the force by the surface area of the belt. Figure 13 shows the stress versus strain plot calculated for subject 1, 3, 4, and 5. The linear portions of the graph’s slope corresponds to the elastic modulus of the skin, muscle, and fat of the subject.

Figure 12: Force gage attached to belt to measure skin hardness

Table 8: Skin Hardness Experiment Data

<table>
<thead>
<tr>
<th>Subject</th>
<th>Original Length (m)</th>
<th>Original Length (m)</th>
<th>Change Length (m)</th>
<th>Change Length (m)</th>
<th>Force (N)</th>
<th>Width (m)</th>
<th>Thickness (m)</th>
<th>Width Thickness (m^2)</th>
<th>Circumference Area (m^2)</th>
<th>Circumference Area (m^2)</th>
<th>Strain (unitless)</th>
<th>Hoop Stress (Nm^-2)</th>
<th>Internal Pressure (N)</th>
<th>Force Internal Pressure (N)</th>
<th>Internal Stress (Nm^-2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lucila</td>
<td>0.77724</td>
<td>0.7742</td>
<td>0.0034</td>
<td>0.0034</td>
<td>3.28</td>
<td>2</td>
<td>1.27E-03</td>
<td>5.42E-05</td>
<td>59.7</td>
<td>0.039</td>
<td>0.003</td>
<td>60232.92</td>
<td>0.120</td>
<td>13911.17</td>
<td>40.59</td>
</tr>
<tr>
<td>Bree</td>
<td>0.77724</td>
<td>0.7742</td>
<td>0.0034</td>
<td>0.0034</td>
<td>3.28</td>
<td>2</td>
<td>1.27E-03</td>
<td>5.42E-05</td>
<td>59.7</td>
<td>0.039</td>
<td>0.003</td>
<td>60232.92</td>
<td>0.120</td>
<td>13911.17</td>
<td>40.59</td>
</tr>
<tr>
<td>C gerne</td>
<td>0.77724</td>
<td>0.7742</td>
<td>0.0034</td>
<td>0.0034</td>
<td>3.28</td>
<td>2</td>
<td>1.27E-03</td>
<td>5.42E-05</td>
<td>59.7</td>
<td>0.039</td>
<td>0.003</td>
<td>60232.92</td>
<td>0.120</td>
<td>13911.17</td>
<td>40.59</td>
</tr>
<tr>
<td>Dand i</td>
<td>0.77724</td>
<td>0.7742</td>
<td>0.0034</td>
<td>0.0034</td>
<td>3.28</td>
<td>2</td>
<td>1.27E-03</td>
<td>5.42E-05</td>
<td>59.7</td>
<td>0.039</td>
<td>0.003</td>
<td>60232.92</td>
<td>0.120</td>
<td>13911.17</td>
<td>40.59</td>
</tr>
<tr>
<td>Rand i</td>
<td>0.77724</td>
<td>0.7742</td>
<td>0.0034</td>
<td>0.0034</td>
<td>3.28</td>
<td>2</td>
<td>1.27E-03</td>
<td>5.42E-05</td>
<td>59.7</td>
<td>0.039</td>
<td>0.003</td>
<td>60232.92</td>
<td>0.120</td>
<td>13911.17</td>
<td>40.59</td>
</tr>
<tr>
<td>Samantha</td>
<td>0.77724</td>
<td>0.7742</td>
<td>0.0034</td>
<td>0.0034</td>
<td>3.28</td>
<td>2</td>
<td>1.27E-03</td>
<td>5.42E-05</td>
<td>59.7</td>
<td>0.039</td>
<td>0.003</td>
<td>60232.92</td>
<td>0.120</td>
<td>13911.17</td>
<td>40.59</td>
</tr>
<tr>
<td>Pascale</td>
<td>0.77724</td>
<td>0.7742</td>
<td>0.0034</td>
<td>0.0034</td>
<td>3.28</td>
<td>2</td>
<td>1.27E-03</td>
<td>5.42E-05</td>
<td>59.7</td>
<td>0.039</td>
<td>0.003</td>
<td>60232.92</td>
<td>0.120</td>
<td>13911.17</td>
<td>40.59</td>
</tr>
<tr>
<td>Average</td>
<td>0.77724</td>
<td>0.7742</td>
<td>0.0034</td>
<td>0.0034</td>
<td>3.28</td>
<td>2</td>
<td>1.27E-03</td>
<td>5.42E-05</td>
<td>59.7</td>
<td>0.039</td>
<td>0.003</td>
<td>60232.92</td>
<td>0.120</td>
<td>13911.17</td>
<td>40.59</td>
</tr>
</tbody>
</table>
The elastic moduli for each subject is shown in Table 9. Each elastic modulus (E) was converted to a Shore A hardness (S) using Equation (1). All the elastic moduli were averaged to determine the average total. This average was then converted to shore A hardness resulting in a value of 11.04. The Smooth-on product with the closest hardness was VytaFlex-10.

\[
S = 100 \times \text{erf} \left( 3.186 \times 10^{-4} E^{1/2} \right)
\]  

(1)

Table 9: Conversion from Elastic Modulus to Shore A Hardness

<table>
<thead>
<tr>
<th>Subject</th>
<th>1st Slope (Pascale)</th>
<th>Shore A Hardness</th>
<th>2nd Slope (Pascale)</th>
<th>Shore A Hardness</th>
<th>3rd Slope (Pascale)</th>
<th>Shore A Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>61383.98</td>
<td>8.89</td>
<td>156721.15</td>
<td>14.16</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>2</td>
<td>22583.74</td>
<td>5.40</td>
<td>82303.14</td>
<td>10.28</td>
<td>22805.25</td>
<td>5.42</td>
</tr>
<tr>
<td>4</td>
<td>30469.21</td>
<td>6.27</td>
<td>381966.80</td>
<td>21.93</td>
<td>145770.23</td>
<td>5.47</td>
</tr>
<tr>
<td>5</td>
<td>35963.34</td>
<td>6.81</td>
<td>104584.46</td>
<td>11.59</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Average</td>
<td>37600.07</td>
<td>6.96</td>
<td>181393.89</td>
<td>15.22</td>
<td>84287.74</td>
<td>10.41</td>
</tr>
<tr>
<td>Avg Total</td>
<td>94959.21</td>
<td>11.04</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

8.4 Components and Component Selection Process

There are two main parts to be considered for the design of the chest expansion simulator. The two parts include the device used to simulate expansion and the material to mimic the skin, fat, and muscle tissues. These parts have been decomposed further and components for each main part have been selected or are currently in the selection process.

For the device used to simulate expansion of the chest, the team had two ideas. The first idea was to use two linear actuators. These linear actuators would be criss-crossed and placed within the torso structure. The team planned to input data from a MATLAB code to communicate to the linear actuators how much to expand and contract. However, the team realized the linear actuators would not have a fast enough expansion and contraction rate to account for high, intense activity level breathing. Due to this drawback of the linear actuators not having the correct speed, the team thought of a new way to create the chest expansion simulation. The current idea is to use a rotary motor in the chest expansion simulator. For the selection of what motor to purchase, the team has to consider the size of the torso, the strength needed to expand the torso, the speed of the motor, and the control
of the motor. The type of motor being considered is a DC gearhead motor with a sensor. For the control of the motor, the team has decided to use a power board because it is cheaper option than an external controller for the motor. Additionally, the team is designing parts to attach to the motor. These parts will attach to the outer torso to create the chest expansion simulation. Overall, the team believes the choice to use a motor for the device to simulate expansion will be beneficial to the final design.

For the material to mimic the skin, fat, and muscle tissue, the team has decided to use a product from Smooth-On. This decision to use Smooth-On was made in the early stages of the project. Through research, the team found that Smooth-On was accurate in mimicking human tissue. The selection of what type of Smooth-on material to use had to be determined. The team conducted the skin hardness experiment to gather data on the actual compressive hardness of the tissues, and to analyze the differences in skin, fat, and muscle tissue hardness. The team considered if multiple Smooth-On products should be purchased to mimic each tissue, or if one Smooth-On product should be purchased based off the average of the tissues. The final decision was to purchase one Smooth-On product that had a hardness value close to the average of the skin, fat, and muscle hardness levels. This decision was made because the cost of purchasing one Smooth-On product as opposed to three was more cost effective. Furthermore, the one product will still provide an accurate replication of the tissues. The Smooth-On product that has the closest value to the average of skin, fat, and muscle tissue is the VytaFlex-10. The team believes the Smooth-On material selected will mimic the tissues well.

**8.5 CAD Drawings**

CAD drawings were created to get a better view and understanding of how the final motor design will simulate chest expansion and compression. The motor design is made up of multiple parts including bolts, clamps, sliders, extendable bars, and the main motor. Individual CAD drawings of these parts are provided in Appendix H. The sliders are placed within the motor. A bolt connects the main extendable bars to the slider and motor and a clamp connects the main extendable bar to the two outermost extendable bars. These outermost bars will be attached to plates, which will make direct contact with the torso. The torso is represented as an ellipse-like casing in the CAD drawing. The final design has the motor powering the extended bars to move back and forth as the motor rotates to create the expansion and compression simulation. The final design is shown in Figure 14. The top view of the design with a casing around it demonstrates how the bars will push against the casing to make it expand.

In addition, a simulation of the expansion and compression of the chest is being created by integrating the SolidWorks model into COMSOL, which is a multiphysics software. This simulation will allow the team to see how each part of the motor design works together to create expansion. Furthermore, it will help the team evaluate the final design to see if there is a more efficient way to build the device. Both the CAD drawings and COMSOL simulation have given and will provide the team with a better understanding of the final motor design.
8.6 Test Procedure

The most important customer needs defined in Section 2 were accuracy, realistic, and manipulation. Accuracy was defined on how well the model simulated the displacement of the chest. To evaluate this feature, the chest displacement experiment will be replicated on the final mannequin. The experimental procedure for this experiment can be found in Appendix D. The test will be done for each corresponding activity level. The same analysis mentioned in Appendix D will be carried out to determine the response sine wave. This sine wave will be compared with the results in Table 5.

Another important customer need is for the model to be realistic. The term realistic is defined on how well the model compresses similar to skin, fat, and muscle. The skin hardness was determined by the experiment in Appendix G. The compression test using a force gauge and displacement data can be converted into a stress strain graph. The elastic modulus is calculated from the slope of the line. The elastic modulus can then be converted into a shore A hardness value. The average shore A hardness from this experiment was approximately 11. The closer the models hardness is to 11 the more realistic it will be.

The manipulation, or manipulability, of our model is also an important aspect of our model. The motor must be able to switch readily from various levels of exercise and possibly incorporate a coughing feature. This requires a adaptable code that is capable of being easily edited, or having multiple loops that correspond to each desired setting. Additionally, having it in code format will also allow for additional modes to be added, like the putative coughing mode discussed in early meetings with Tahzib. Before this code can be composed, a motor must be selected that is compatible with an Arduino and capable of communicating with the Arduino via changes in polarity to alter motor direction (CCW to CW) and to alter desired exertion mode.
8.7 Economic Analyses - Budget and Vendor Purchase Information

The budget has been updated to account for the changes in the final design of the device made within the past couple weeks. The total budget for the project is $1000. The budget is mostly spent on materials to build the final chest expansion device and materials to gather data to input into the device. The biggest difference in the material purchases is the two linear actuators in the design have been replaced with a motor. Additional changes include specific prices for smooth-on and the mannequins, and the inclusion of materials used to gather data. The sponsors are from Penn State, so no money will be spent on travel. Equipment to build the prototypes and final device is provided by the sponsor’s lab and Penn State resources. The team decided to have 15% of the total budget to be set aside for contingency. Finally, the poster is included in the final budget. The total budget and bill of materials can be found in Appendix B and Appendix C. The team is able to avoid overspending by keeping track of the budget.

9.0 Final Discussion

Section 9.0.1 Modifications to Statement of Work and DDR Sections
Revisions to the Proposal and DDR Sections 1 through 8 are listed as 9.0.1.X:

9.0.1.1. Introduction - no change
9.0.1.2. Customer Needs – no change
9.0.1.3. External Search – no change
9.0.1.4. Engineering Specifications – no change
9.0.1.5. Concept Generation and Selection – no change
9.0.1.6. System Level Design – no change
9.0.1.7. Special Topics - Budget and bill of material changed shown in Appendix B, C respectively
9.0.1.8 Detailed Design - Updated manufacturing process plan in 9.1

9.1 Construction Process

There are four main systems in our model, which are the mechanism, stabilizing structure, smooth on, and motor. The mechanism will push out onto the mannequin, which will mimic the expansion of the chest. As shown in Figure 15 a rod comes up from the motor to rotate the plate. This pushes the arms forward and the sheet metal hits the torso. The stabilizing structure is to ensure the rod does not move in the xy-plane. Smooth-on is the material used to replicate skin that is wrapped around the mannequin. Lastly, the motor provides the desired rotation and torque required to mimic breathing pattern at different activity level. The updated manufacturing process plan is shown in Table 10.
Figure 15. Mechanism supported by stabilizing structure.

<table>
<thead>
<tr>
<th>ASSEMBLY NAME</th>
<th>MATERIAL TYPE</th>
<th>RAW STOCK SIZE</th>
<th>OPERATIONS</th>
</tr>
</thead>
</table>
| Arms          | Steel         | Flat bar 36x1x1/8” | Cut pieces of size 6.8”, 5.9”, 5.7”, 3”  
All pieces drill ¼” hole 0.5” from edge  
All pieces drill two 0.5 holes next to each other ¼” from the edge  
Deburr |
| Bolt          | Steel         | ¼”-28 x 1-½” hex  | Used to connect arms to motor |
| Nuts          | Steel         | ¼”-28             | Used to connect arms to motor |
| Plate         | 6061 Aluminum| ¾” thick 5” wide ½" long | Cut plate done to 4.8x4.8”  
Drill ¼” holes in locations shown in Appendix I  
Drill three holes #8-32 in locations shown in Appendix J  
depth ½”  
tapped 32 thread |
<table>
<thead>
<tr>
<th>Material/Component</th>
<th>Material/Size/Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sheet metal</td>
<td>Aluminum 18x6x21”</td>
<td>Cut sheet metal 6x4.5” Two hole size #8 punched into the center</td>
</tr>
<tr>
<td>Pipe Hanger</td>
<td>Cooper 3/4”</td>
<td>Loop through arms (two holes drilled next to each other) and screw into the sheet metal</td>
</tr>
<tr>
<td>Lightweight keyed rotary shaft</td>
<td>2024 Aluminum 1/2” diameter 12” long</td>
<td>Cut rod to 8”</td>
</tr>
<tr>
<td>Flange Mount Shaft Collar</td>
<td>2024 Aluminum 1/2” diameter</td>
<td>Attaches rod to Plate</td>
</tr>
<tr>
<td>Low Profile Mounted Ball bearing (self-aligning)</td>
<td>52100 Steel Two bolt 1/2” Shaft</td>
<td>Attach rod to stabilizing structure while allowing rod to spin freely</td>
</tr>
<tr>
<td>Stabilizing Structure</td>
<td>Wood 2 3x7” 2 6.5x7” 1 3x6.5”</td>
<td>Wood was cut into the pieces described under stock size. Hole in middle of 3x6.5” for Low profile mounted ball bearing attachment. Box put together with wood glue and nails.</td>
</tr>
<tr>
<td>Torso mannequin</td>
<td>Heavy Plastic Polyethylene 25.2” height 38” chest/bust circumference 30.3” waist circumference</td>
<td>Cuts made anteriorly, on rib cage, alongside in “Y” shape, and straight cuts made in the back alongside the spine.</td>
</tr>
<tr>
<td>Smooth on</td>
<td>Vitaflex - 10 9 lbs</td>
<td>Mixed according to Smooth-On instructions and draped on torso mannequin in sections.</td>
</tr>
<tr>
<td>Base</td>
<td>Wood 17x12.5”</td>
<td>Bottom shape of the mannequin was extruded from a rectangular piece of wood. Extrusion was made half way through the wood in order to place the mannequin on top of the wood, serving as a base.</td>
</tr>
</tbody>
</table>
9.1.1 Mechanism
The mechanism will use extendable arms that stem from a centre-piece plate to push up against aluminium sheet metal against the interior chest wall of the mannequin. This will simulate the expansion and compression of the chest. The mechanism was built through various machining processes and was based off of a SolidWorks design shown in Appendix H.

The first step was to measure out the length of the arms by using the mannequin interior circumference. The arms were cut by using a rotary saw. A mill was then used to drill a $\frac{1}{4}$” hole in each piece for the bolt to fit through. On the other side of the pieces, two holes were drilled $\frac{1}{4}$” from the edge. The two holes intersect creating enough space to loop through the pipe hanger. All sides that were machined were then deburred.

The next piece to be machined was the plate. The sides needed to be cut from 5x6” to 4.8x4.8” using a bandsaw. The machined sides were then milled down using a mill. Before milling, the sides of the piece need to be zeroed out. This process ensures the sides will be shaved off to the right depth. Then two $\frac{1}{4}$” holes were drilled all the way through the piece in the locations shown in Appendix I. These holes are to connect the arms to the plate with a bolt. Before drilling the hole, a countersink needs to be done to mark the hole placement. After the holes were drilled through, three #8 holes were countersinked and drilled using the same method described. The locations are shown in a table in Appendix J. This time the holes were only drilled to a distance of $\frac{1}{2}$” depth. Then the holes were tapped to a thread of 32. This will allow the flange mount shaft collar to be screwed into the plate.

The other pieces that needed to be machined are the rod and sheet metal. The rod was cut by a bandsaw to a length of 8”. An allen wrench was used to tighten the flange mount shaft collar around the rod. The sheet metal was cut into pieces of size 6x4.5” using manual cutting machine. Then two holes of size #8 are cut out using a hand punch.

The assembly can begin with the plate and collar connection. The rod was already attached to the collar. The collar was placed on the plate and three bolts were screwed in with a screwdriver. The following assembly for the arms will be repeated for each arm individually until it is attached to the plate. The pipe hanger was looped through the long hole in the arm. Then the bolts were pushed through the hanger and sheet metal, which then were tightened together with a nut. Two arms are connected on top of each other to one hole in the plate. The arm plate connection from top to bottom respectively: bolt, washer, arm, arm, bearing, plate, washer, nut. A top view of the assembled mechanism is shown in Figure 16.
9.1.2 Stabilizing Structure
The second main system in the model is the stabilizing structure. When the mechanism is pushing out against the inner mannequin wall, the unstable rod will most likely move in the xy-plane. The stabilizing structure’s main purpose is to ensure the rod does not move, while still allowing it to rotate the attached plate with the same angular velocity as the motor.

Using a table saw, two 3x7” pieces of ¾” thick wood were cut to serve as the two side walls of the box. From the same wood, two 6.5x7” pieces were cut for the front and back support of the hollow box. As shown in Figure 17, a smaller rectangle was cut from the back wood piece in order to have the motor cables coming out towards the power supply. To add a roof to the box, a 3x6.5” piece of the same wood was cut. A band saw was used to make an extrusion to that top wood piece. The extrusion was located in the very center of the rectangle and had the same diameter as the low profile mounted ball bearing, two smaller holes were done on both sides of the large extrusion. The low profile mounted ball bearing was placed on the middle hole and secured with one bolt on each side. All four walls of the box and the top piece were glued together using wood glue and then reinforced with a nail gun.
9.1.3 Smooth-On
The volume of VytaFlex 10 required was determined by multiplying the surface area of the mannequin by the thickness of the tissue required in the sternum vicinity of the chest. The calculation of the surface area was done by measuring the height of torso and the circumference of the cavity. Their product was then multiplied by the thickness of tissue found in the sternum region, which is about (on average) 0.2 inches [6].

The application of the polyurethane polymer to the exterior of the mannequin was accomplished by exploiting the inherent adhesive properties of polyurethane. The mix was half-cured in a cookie sheet and then applied directly to the surface of the exterior of the mannequin. Multiple cookie sheets were required to cover the entirety of the mannequin. These sheets were then adhered together with the addition of more polymer, creating a uniform polymer coat around the mannequin. Lastly, the application of baby powder to the exterior layer of tissue removed the slightly tacky texture.

9.1.4 Motor
A rotary stepper motor was decided upon after deliberation with our sponsor and application engineers at Pittman. The final purchase was made from Lin Engineering due to their more affordable prices and expedited shipping timetable. The strength of the motor was determined by manually operating the actuation apparatus with a torque wrench. The torque required to achieve the maximum displacement observed in our breathing data was compared to torque ratings on the Lin Engineering website to decide which motor was best for the design. The rotary stepper motor was connected to a driver provided by Dr. Sommer, and a script in Arduino was utilized to alter the angular displacement, frequency, and delay of the motor’s change in
direction. All breathing levels were able to be simulated with this code outside the confines of the mannequin.

9.2 Test Results and Discussion

The chest expansion simulator functioned in expanding the chest at a constant rate. The team believes the simulation created a displacement and expansion rate at a sitting activity level. However, the team was unable to test the chest expansion simulator to get results due to a lack of time. During the project, the team decided to switch the simulating mechanism from linear actuators to a motor. This led to a setback in progress and put the team behind on the gantt chart timeline. Additionally, all the necessary parts of prototype were not acquired until the final week of the project timespan. Due to these setbacks, the team did not have time to test the chest expansion simulator. The test procedure outlined in section 8.6 should be done to determine the efficacy of the final design.

10.0 Conclusions and Recommendations

Through various discourses with the sponsor, the three needs associated with the design of the simulator were, accuracy, realisticness, and manipulability. Speaking first about the manipulability of the final design, the code can be adjusted to change the rate and angle at which the motor will turn. Additionally, the design includes a hole in the back of the mannequin as well as the stabilizing structure for easy access to the motor in case adjustments have to be made. The realistic aspect of the design can be noted in the choice of polymer to mimic the human tissues. Because of the self-adhesion properties of polyurethane, adjustments to the tissue thickness to mimic different body types can be easily accomplished. Unfortunately, accuracy has yet to be tested. Potential improvements to the design would include a more sophisticated motor-control mechanism by purchasing a driver and controller from Lin Engineering. Another improvement would be conferring more stability to the torso. During preliminary testing, the motor was unable to run at higher angular displacements and frequencies because it would shake the mannequin as opposed to just pushing against it. This is due to the nature of the stepper motor partially, but also because the mannequin was not fixed to the wooden base properly. Additionally, a computational model of the actuation method would prove to be useful for optimization of force transducing properties of the apparatus.

11.0 Customer Needs Assessment

Our customer needs are shown in Table 11. They are listed in descending order with the most important customer need at the top and the least important customer need at the bottom.

11.1 Manipulation

The top customer need is manipulation. Manipulation refers to how easy it is to adjust the prototype to account for a different breathing displacement and rate for each activity level. The hole placed in the back of the mannequin and stabilizing structure allows for easy adjustments to be made to the motor during testing. Additionally, the script written in Arduino allows the user to tune angular displacement, frequency, and delay between changes in direction. However, the structural stability of
the mannequin did not allow higher angular displacements and frequencies to be reached. Based on these considerations, the team gave manipulability a 5 for meeting the customer need.

11.2 Realistic
Our next customer need is realistic. Realistic refers to how closely the model resembles soft tissue in the human chest. Vytaflex 10, was chosen based off of experimental results and recommendations. Vytaflex 10 provided a realistic feel and look to the prototype. Due to this, the prototype received a 9 for the customer need, realistic.

11.3 Accuracy
The third customer need is accuracy. Accuracy refers to how accurate the device is at simulating the specific displacements of the chest during the different activities and the rate at which the chest cavity expands and contracts. The prototype simulated the displacement and rate of expansion and contraction for sitting only. However, the team did not have time to test how accurate this simulation was at mimicking the displacement and rate of breathing. Therefore, the accuracy customer need is yet to be determined.

11.4 Durability
The next customer need is durability of the prototype. This received an 8 for meeting customer needs because it is made up of durable and sturdy materials including hard plastic, aluminum, and steel.

11.5 Ease of Use
The fifth customer need is ease of use. The team pre-programmed the microprocessor, to make the simulation process easy for the user. The prototype received an 8 for meeting the ease of use customer need.

11.6 Safety
Next, was the safety of the prototype. A slightly unsafe part of the prototype is the edges of the plates attached to the mechanism are a little sharp. Due to this small concern, the prototype received a 9 for the safety customer need.

11.7 Cost
The next customer need is cost. For this project the team was given a budget of $1000. The team delivered a final product and stayed within this budget, therefore the cost customer need was completely met and received a 10.

11.8 Time of Assembly
The next customer need was the time it took to assemble the device. The parts needed to assemble the prototype are the mannequin, mechanism, stabilizing structure, motor, arduino, driver, and breadboard. The average time to assemble the whole prototype is 10 minutes. Therefore, the time to assemble customer need received an 8.

The ease of manufacturing customer need depends on the proficiency and skills of the person making the device. If the person is proficient in machining, the manufacturing of the device should
be simple. However, if the person is a novice, it may take more time to learn the machining processes. Due to the differing levels of experience with machining people have, the ease of manufacturing customer need received a 6.

11.9 Portability
The last customer need is portability. Overall the weight of the simulator is light, weighing approximately 10 pounds. However, the size of the simulator is big and the additional components need to be carried separately. The portability customer need received a 6 due to the weight, size, and number of parts associated with the simulator.

Table 11: Customer Needs Assessment of Final Prototype

<table>
<thead>
<tr>
<th>Customer Needs</th>
<th>How Well Customer Needs are Met</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manipulate</td>
<td>5</td>
</tr>
<tr>
<td>Realistic</td>
<td>9</td>
</tr>
<tr>
<td>Accuracy</td>
<td>To Be Determined</td>
</tr>
<tr>
<td>Durability</td>
<td>8</td>
</tr>
<tr>
<td>Ease of Use</td>
<td>8</td>
</tr>
<tr>
<td>Safety</td>
<td>9</td>
</tr>
<tr>
<td>Cost</td>
<td>10</td>
</tr>
<tr>
<td>Time to Assemble</td>
<td>8</td>
</tr>
<tr>
<td>Ease of Manufacturing</td>
<td>6</td>
</tr>
<tr>
<td>Portability</td>
<td>6</td>
</tr>
</tbody>
</table>
References

Appendix A. Mechanical Properties of Different Tissues

SKELETAL MUSCLE TISSUE

- Pectoralis major (chest muscle) (20-39 year olds) (3)
  - Ultimate Tensile Strength: 13 g/mm²
  - Ultimate Percentage Elongation: 90%
- Women (2)
  - Shear modulus: 9 kPa

BONES

- Thoracic Vertebrae (bones in ribcage) (20-39 year olds) (3)
  - Upper Thoracic Vertebrae:
    - Tensile Breaking Load: 173 +/- 18.9 kg
    - Ultimate Tensile Strength: 0.37 +/- 0.01 kg/mm²
    - Ultimate Percentage Elongation: 0.86 +/- 0.11%
  - Lower Thoracic Vertebrae
    - Tensile Breaking Load: 336 +/- 13.2 kg
    - Ultimate Tensile Strength: 0.38 +/- 0.03 kg/mm²
    - Ultimate Percentage Elongation: 0.87 +/- 0.07%
- Ribs (3)
  - Elastic modulu: 13.9 GPa
  - Ultimate Tensile Strength: 100 MPa

SKIN IN THORAX (CHEST) REGION

- 30 - 49 year olds (3)
  - Tensile Breaking Load per Width: 3.2 kg/mm
  - Ultimate Tensile Strength: 1.47 kg/mm²
  - Ultimate Percentage Elongation: 112%
- Average (3)
  - Tensile Breaking Load per Width: 2.7 kg/mm
  - Ultimate Tensile Strength: 1.32 kg/mm²
  - Ultimate Percentage Elongation: 87%
- Women (age 30) (2)
○ Tensile Strength 20 MPa
○ Elastic modulus: 0.2-3 MPa

FAT
• Panniculus adiposus - fatty layer of subcutaneous tissues (pigs) (3)
  ○ Ultimate Tensile Strength: 8 +/- 0.4 g/mm²
  ○ Ultimate Percentage Elongation: 26 +/- 0.7%
  ○ Ultimate Expansive Strength per unit thickness: 0.71 +/- 0.02 kg/cm²/mm
• Adipose (women) (2)
  ○ Shear Modulus: 0.5-25 kPa
Appendix B. Team Budget for the Project

<table>
<thead>
<tr>
<th>BUDGET:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>TRAVEL</td>
<td>$0</td>
</tr>
<tr>
<td>TOTAL ESTIMATED EQUIPMENT COST</td>
<td>$0</td>
</tr>
<tr>
<td>TOTAL ESTIMATED MATERIAL COST</td>
<td>$785.80</td>
</tr>
<tr>
<td>% CONTINGENCY</td>
<td>$150</td>
</tr>
<tr>
<td>POSTER</td>
<td>$50</td>
</tr>
<tr>
<td>TOTAL</td>
<td>$985.80</td>
</tr>
</tbody>
</table>
Appendix C. Bill of Materials for the Project

<table>
<thead>
<tr>
<th>ITEM</th>
<th>PRICE</th>
<th>QUANTITY</th>
<th>TOTAL PRICE</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-Bridge</td>
<td>$9.48</td>
<td>1</td>
<td>$9.48</td>
</tr>
<tr>
<td>Smooth-On</td>
<td>$105.43</td>
<td>1</td>
<td>$105.43</td>
</tr>
<tr>
<td>Motor</td>
<td>$206.70</td>
<td>1</td>
<td>$206.70</td>
</tr>
<tr>
<td>Mannequin</td>
<td>$35</td>
<td>2</td>
<td>$70</td>
</tr>
<tr>
<td>Smooth - on</td>
<td>$51.84</td>
<td>1</td>
<td>$51.84</td>
</tr>
<tr>
<td>Smooth - on</td>
<td>$40.83</td>
<td>1</td>
<td>$40.83</td>
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<tr>
<td>Velcro</td>
<td>$5</td>
<td>2</td>
<td>$10</td>
</tr>
<tr>
<td>Shoulder/Chest Straps</td>
<td>$10</td>
<td>1</td>
<td>$10</td>
</tr>
<tr>
<td>Fish Hook (Scale)</td>
<td>$4.44</td>
<td>1</td>
<td>$4.44</td>
</tr>
<tr>
<td>Plate attach motor to arms</td>
<td>$25.70</td>
<td>1</td>
<td>$25.70</td>
</tr>
<tr>
<td>(6061 Aluminum, ¾” thick x 5” wide, ½ ft long)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extending arms</td>
<td>$4.86</td>
<td>2</td>
<td>$9.72</td>
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<tr>
<td>(Flat bar steel)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Nuts for arms</td>
<td>$0.07</td>
<td>2</td>
<td>$0.14</td>
</tr>
<tr>
<td>(hex nut ¼” -28)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bolts for arms</td>
<td>$0.24</td>
<td>2</td>
<td>$0.48</td>
</tr>
<tr>
<td>(¼” -28 x 1-½” hex bolt)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Washers for arms</td>
<td>$0.24</td>
<td>2</td>
<td>$0.98</td>
</tr>
<tr>
<td>(¼” flat washer)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum sheet metal</td>
<td>$10.17</td>
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<td>$10.17</td>
</tr>
<tr>
<td>(18x6x21)</td>
<td></td>
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<tr>
<td>Pipe hanger</td>
<td>$4.25</td>
<td>1</td>
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<tr>
<td>(¾” copper 2h)</td>
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<td>Mcmasters</td>
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<td>Poster</td>
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<td>$50</td>
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</table>

Total: $785.80
Appendix D. Chest Displacement Experimental Procedure

Chest Displacement Experimental Procedure

Material List

- Back correcting brace
- Arduino
- Bread board
- Spring potentiometer
- String
- Access to MATLAB program

MATLAB Procedure

1. Open ‘Arduino_data_collection.m’ file in MATLAB
2. Duration is set at ten seconds. Take the amount of seconds you want the code to run and divide by 0.2. Then take that value and replace 50 for i.
3. The voltage to displacement conversion should be changed if a different spring potentiometer is used.
   a. Pull the spring potentiometer out 1 cm
   b. Use the Arduino to get the voltage
   c. Repeat from 2 to 5cm in increments of 1cm
   d. In excel, run data analysis → regression.
      i. Voltage x value, Displacement y value
      ii. Intercept is the value of the y-intercept
      iii. X-variable is the value multiplied by voltage
   e. Replace the equation under voltage to displacement conversion with the values from dii and diii.

Activity Levels

- Sitting: Subject sits on a chair with good posture
- Standing: Subject stands in place
- Low: Box steps at a rate of 60 beats per minute
  o Set a metronome to 60 beats per minute
  o Subject should take a step with the beat
  o Subject place entire right foot on box. Then steps up to place their left foot next to their right. Steps back down one foot at a time.
- Medium: Box steps at a rate of 80 beats per minute
  o Set a metronome to 80 beats per minute
Following steps listed under low activity level

- High: Box steps at a rate of 120 beats per minute
  - Set a metronome to 120 beats per minute
  - Following steps listed under low activity level

**Experimental Procedure**

1. Tie string to the retractable string on the potentiometer.
2. When the string is wrapped around the subject, make sure there is a gap between the potentiometer and the stopper. To ensure the length of the string can increase and decrease. Since it is unknown what part of the breathing cycle the subject it in.
3. Knot the excess string in the hole located on the side of the spring potentiometer. Or wrap the string around the spring potentiometer.
4. The subject should be at the level of activity desired for at least one minute before the data is taken.
5. On the MATLAB file change the name the file will be saved as. This is the last line in the code: `save ('name of file.mat', 'voltage', 'displacement').`
6. After a minute, press run on MATLAB at random time so the subject is unaware.
7. The test will last around ten seconds. The time will be displayed on the screen when the code has completed.
8. Repeat steps 2–6 for desired activity levels

**Analysis**

1. Create a time value (t) in MATLAB
   a. For the original code: `t = linspace (0, 10, 50)`
2. Copy variables t and displacement value of mat file into excel
3. Graph Displacement vs time
4. Calculate the difference between each peak and valley for displacement and time
5. Calculate average delta displacement in between peaks and valleys
6. Calculate average delta time in between peaks and valleys
   a. Take the inverse of this value to get the average frequency of the graph
7. Repeat for number of trials for the activity level
8. Average the delta distance and frequency for each trial
9. Create a sine wave to stimulate the activity level
   a. Sitting = (average delta distance)*sin(2*pi*(delta frequency)*t)

**MATLAB Code for Chest Displacement Experiment**

```matlab
% ************************************************************
file name: Arduino_data_collection.m
programmer name: Thomas Randolph Blanda
date created: 9/28/17
date of last revision: 10/1/17
```
clear,clc

%Initializing Arduino
a=arduino();

%Start timer
tic

%Loop to acquire voltage data
for i=1:50
    voltage(i)=readVoltage(a,'A0');
    pause(0.2)
    i=i+1;
end

%End timer
toc

%Voltage to displacement conversion
displacement=-9.969*voltage+24.028;

%Initializing time vector
t=1:i-1;

%Plotting voltage values
figure;
plot(t,voltage)
title('Voltage vs. Time')
xlabel('Time (sec)')
ylabel('Voltage (V)')

%Plotting displacement values
figure;
plot(t,displacement)
title('Displacement vs. Time')
xlabel('Time (sec)')
ylabel('Displacement (cm)')

save ('voltage_sammie_high.mat','voltage','displacement')
Appendix E: Chest Displacement vs Time Graph Sorted by Subject
Appendix F: Chest Displacement vs Time Graph Sorted by Activity Level
Appendix G. Skin Hardness Experimental Procedure

Skin Shore A Hardness Experimental Procedure

Material List
- Force Gage with hook
- Tape Measure
- Marker
- Belt
  - Or create belt
    - Seatbelt material
    - Buckle
    - Needle and thread
    - Knife/scissors
- Excel

Creating the Belt
1. Measure with a tape measure the length of the subject's torso on the ribcage
2. Add 10 inches to the length
3. Cut seat material to the length from step 2
4. Loop the belt around the buckle (about 2 inches).
5. Sew the belt around buckle
6. On the other end of the belt use the knife/scissors to create a hole. (This allows the hook on the force gauge to attach to the belt)

Experimental Procedure
1. Wrap the belt around the subject and loop the material through the buckle
2. Attach the hook on the force gage to the hole in the belt
3. Pull the force gage around the bar in a horizontal plane
4. Find the tightness of the belt where there is no force measured from the gage
   a. Use a marker to mark the part of the belt that wraps around the bar
   b. This mark indicates the original length
5. Pull the force gage horizontal away from the subject until the mark is 1/4 inch away from the bar using the tape measure to determine the distance
   a. Record the displacement
   b. Record the force in Newtons from the force gage
6. Pull the force gage ¼ inch further than in step 5
   a. Record the displacement
   b. Record the force in Newtons from the force gage
7. Repeat steps 5 – 6 until the subject says the belt is too tight
8. Take the belt off the subject
9. Measure the length of the belt to the original length mark
10. Repeat 1 – 9 for multiple subjects
11. Measure the thickness of the belt

Analysis
1. Open excel
2. For each point
   a. Find the surface area of the belt applying pressure on the subject
      i. \( A = \text{Thickness} \times (\text{Original length} - \text{displacement}) \)
   b. Convert area from inch squared to meter squared
   c. Calculate strain
      i. \( e = \frac{\text{displacement}}{\text{original length}} \)
   d. Calculate stress
      i. \( o = \frac{\text{Force (N)}}{\text{Area (m}^2)} = \text{Pascals} \)
3. Graph stress vs strain for each subject
4. For each linear portion of the graph find trendline
   a. The slope of each trendline equals the elastic modulus (E)
5. Convert elastic modulus into Shore A hardness
   a. \( S = 100 \times \text{erf}(3.168 \times 10^{-4} \times \text{ElasticModulus}^{(1/2)}) \)
<table>
<thead>
<tr>
<th>PART</th>
<th>CAD DRAWING</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOLT</td>
<td><img src="image1" alt="Bolt" /></td>
</tr>
<tr>
<td>SLIDER</td>
<td><img src="image2" alt="Slider" /></td>
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<tr>
<td>CLAMP</td>
<td><img src="image3" alt="Clamp" /></td>
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<tr>
<td>Component</td>
<td>Image</td>
</tr>
<tr>
<td>-----------</td>
<td>-------</td>
</tr>
<tr>
<td>EXTENDABLE BAR</td>
<td><img src="image1.png" alt="Image" /></td>
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<tr>
<td>MAIN EXTENDABLE BAR</td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>MOTOR</td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
</tbody>
</table>
Appendix I: Locations of holes that were drilled on plate for arm attachment seen from above
Appendix J: Locations of holes drilled and tapped into plate for collar attachment seen from below

<table>
<thead>
<tr>
<th>Point (x)</th>
<th>Location (x,y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(2.209, 3.374)</td>
</tr>
<tr>
<td>2</td>
<td>(3.398, 2.275)</td>
</tr>
<tr>
<td>3</td>
<td>(2.507, 2.471)</td>
</tr>
</tbody>
</table>