Mechanical Puppetry and Emotive Motion: Gasp and Wheeze

Fall 2020 ME 450 Team 12

Final Report

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Executive Summary

Professor Heidi Kumao from the University of Michigan STAMPS School of Arts and Design, has tasked the team to create a kinetic lung mechanism that will be embedded in her puppet sculpture. Based on Kumao's personal story of the loss of her loved ones, she would like the puppet to come across as "struggling" and provoke empathy from the audience at the exhibits.

The user requirements and engineering specifications were developed based on interviews the team had with Professor Kumao. The lung mechanism will be in the approximate shape of human lungs. To express emotions of "struggle," it would mimic the kinetic motions of sporadic coughing and wheezing. Additionally, the puppet will also have the ability to replicate the sounds of human breathing and coughing, along with the kinetic motions. To elicit empathy from the audience, the kinetic lung mechanism will be overlaid with random coughing and gasping patterns that will appear naturally as life-like. It also has the ability to interact with its audience based on proximity every day over the course of the month-long exhibits.

With the concept generation, development, and evaluation process, the team first started with brainstorming concept ideas within the three critical subsystems and two supplementary subsystems as the concept generation method, which exhibited divergent thinking. Then, we used heuristic cards and morphological charts to further develop new ideas and combinations of ideas. Going through the possible combinations of concepts, the team came up with top 8 concepts to be evaluated against criterias that are derived from user requirements, which exhibited convergent thinking. Narrowing down to top 3 concepts, the team then used Pugh Chart to select the final concept. At the end, we also provided an engineering justification for the final chosen design.

The engineering analysis and solution development process is done by diving deeper into the components of each of the subsystems and identifying the failure modes of the puppet. Then, three of the main challenges from the failure are identified to conduct engineering analysis. By understanding the quantitative data and behavior of the mechanism, we were able to develop a CAD design with all the components implemented.

Since the design involves non-uniform surfaced components, one of the anticipated challenges would be to perform engineering analysis through finite element analysis and appropriate simulation tools. While having a simulation motion demonstration is the minimum deliverable of this project, fabrication of subsystems of the prototype is performed for verifications.

This report will outline the details of identification, development, analysis process, and our solution result as well as future recommendations of the project.

Problem Description and Background

Background Information

Professor Heidi Kumao has sponsored a project to build a small-scale breathing motion simulator in order to be implemented in her kinetic sculpture puppet installations. Inspired by the breathing-related issues her father faced when he had lung cancer, she wants to create a motion activated sculpture that breathes and coughs irregularly when approached by museum-goers. This breathing motion simulator would also look like real lungs that expand and contract with each irregular breath. In her vast experience with kinetic sculpture installations, requirements like simplicity, ease of assembly, and maintenance have risen to the top of her project preferences. Her ideal solution is a durable and lifelike breathing robot that she can service herself and use in many different puppet designs for many years.

The lung mechanism will be in the approximate shape of human lungs. To express emotions of "struggle," it would mimic the kinetic motions of sporadic coughing and wheezing. Additionally, the puppet will also have the ability to replicate the sounds of human breathing and coughing, along with the kinetic motions. To elicit empathy from the audience, the kinetic lung mechanism will be overlaid with random coughing and gasping patterns that will appear naturally as life-like, based on Kumao's previous experience with imitating life-like behaviors in kinetic puppets. It also has the ability to interact with its audience based on proximity every day over the course of the month-long exhibits. The main goal of this puppet is to evoke empathy and sadness as an emotional experience when the audience interacts with this puppet.

Other kinetic sculptures by Kumao include her exhibit "Misbehaving Machines", in which two models of children's legs depict the active emotions "Protest" (left) and "Resist" right). Both robots respond to museum visitor proximity and exhibit random actions that look like stomping (left) and kicking (right).

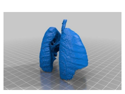

Figure 1. Exhibitions by Kumao in her "Mischievous Machines" Exhibit that depict childrens' legs kicking (right, "Resist") and stomping (left, "Protest"). The machines also respond to audience proximity.

Kinetic sculptures are meant to evoke emotion and interest in the audience, and Kumao's work focuses on simplifying human behavior that typically signifies a flood of emotion. In this project's case, Kumao seeks to simplify the complex action of labored human breathing to strip the concept bare for her audience.

Benchmarking and Existing Products

In order to understand the existing market for such a device, we have benchmarked similar lung/breathing simulation products. Most are not automated -- our definition of automation in this project is action that does not necessarily need an on-switch but that responds to human interaction/proximity. Most are also not capable of evoking the correct emotion in the audience; only the cat and the nicotine lung prototype do so, but it isn't the effect that Kumao wants.

Table 1: A comparison of five breathing/lung simulation products on the market as they fit the solution space for this project.

	Breath/ Cough Gesture	**3D Vol. Expansion**	**Simplicity**	**Noise/ Sound**	**Emotive Response**	**Price**	**Automated**
 Nicotine Lung Prototype	No	No	Yes	No	Yes	$10	No
 Pig Lung Kit	Yes	Yes	Yes	No	No	$380	No
 3D printed model	No	No	Yes	No	No	$10	No
 2D motion art	Yes	No	No	Yes	Yes	N/A	No
 del Perfect Petzzz mo	Yes	Yes	Yes	Yes	Yes	$30	No

It is apparent that the available solutions for this design problem are not able to meet the minimum requirements set by Professor Kumao; thus we have quantified the requirements that should be met in order for the solution to be considered successful in the following section.

Requirements and Specifications

In order to fully constrain this problem, the specifications were divided into categories. The requirements and specifications are divided into four categories: (1) geometric constraints and anatomy, (2) sound, (3) mechanical, and (4) general requirements. The geometric constraints and anatomy requirements cover the look and size of the mechanism, and by how much it is expected to expand. The sound requirements cover the volume pressure that the coughing should be based on research and the expected range of the mechanism's exhibit, and thus noise level of the mechanism's motions in order to preserve the sound of the cough. The mechanical constraint requirements covers how the random breathing patterns will be simulated mechatronically. The final section, general requirements, covers quality-of-life requests from Kumao as well as typical museum exhibit requirements, in order to ensure the breathing mechanism is an acceptable museum installation. Priority ratings are assigned to each requirement within each requirement category on a scale of 1 to 4, with 1 being the highest priority and 4 being the lowest priority. The team will prioritize a requirement with higher rating if there are different tradeoffs between requirements that need to take place.

Geometric Constraints and Anatomy

The project description specified that the lung mechanism should be 5-6 inches (12.7-15.2 cm) tall. To adequately depict lungs in a puppet, requirements for dimensions and volume expansions were listed below in Table 2. These dimensions were based on human-lung sizes and volumes and scaled accordingly to sponsor's requirements. The dimensions are listed in a range with decimals to accommodate for appropriate tolerances. It is important to note that the width and depth of the lungs do not change significantly when inhaling and exhaling but only the height changes by 10-15% [12]. Upper and lower bounds are provided for the minimum and maximum height. The percent change in volume is currently unknown and will be tested during the design phase, depending on the design choice. Dimensions were given a high priority because they were explicitly stated in the project description and reaffirmed by the sponsor.

Table 2: The user requirements, engineering specifications, rationale, and priority for geometric constraints and anatomy.

Requirements	**Engineering Specifications**	**Source**	**Priority**
Mechanical Dimensions	Min. Height (Lower Bound, Upper Bound): Right Lung: (10.8-11.4, 12.9-13.7) cm Left Lung : (10.3-10.9, 12.2-13) cm Max. Height: Right Lung:12.7-15.2 cm Left Lung: 12.1-14.4 cm Width:	Sponsor, Dr. Kumao; Kramer et al 2012 [11]; Foucand et al 2019 [12]	1

	Right Lung: 6.9-8.3 cm Left Lung: 6.1-7.2 cm Depth: Right Lung: 10.3-12.3 cm Left Lung: 10.3-12.3 cm		
Expansion Volume	Min. contracted volume of 3 Liters Right Lung: 2 Liters Left Lung: 1 Liter Max. expanded volume of 6 Liters Right Lung: 3 Liters Left Lung: 3 Liters	Konheim et al 2016 [9]; Kramer et al 2012 [11]	2

Sound Requirements

To replicate the coughing, breathing, and gasping sounds of human lungs, the lung model must fulfill a set of sound requirements that was requested by the sponsor, as listed in Table 3. The sponsor specified that coughing sound should be simulated as the lung model exhibits the coughing motion simultaneously. She has also specified to minimize unwanted noises, so that coughing sounds could be picked up by the audience without noise disturbance. These volume pressures were based on literature reviews on the volume pressures of human coughs.

Table 3: The user requirements, engineering specifications, rationale, and priority for sound.

Requirements	**Engineering Specifications**	**Source**	**Priority**
Minimizes unwanted noise from the mechanism	Volume of mechanism ≤ 40 decibels from 3 feet away	Chung 2006 [5]; Jones, Davis, Slater [15]; Dernie 2006 [16]	2
Produces a sound when simulating a cough that can be picked up by an audience	Volume of sound ≤ 65 decibels from 3 feet away	Chung 2006 [5]; Wallace, Macrae, and Huckabee 2020 [8]; Dernie 2006 [16]	3

Mechanical Requirements

The largest priorities regarding mechanical requirements relate to the seamlessness of the breathing animation. Prioritizing the breathing and coughing gestures is most important because having a mechanism that breathes autonomously and looks natural is most likely to elicit the proper empathic human response. Subtle, unnatural behavior will draw unwanted attention to the mechanism, rather than the behavior. To address these requirements, the study of breathing and coughing modeling for healthy and unhealthy lungs was conducted [10]. As shown in the figure 2 below, the breathing pattern follows a sinusoidal shape.

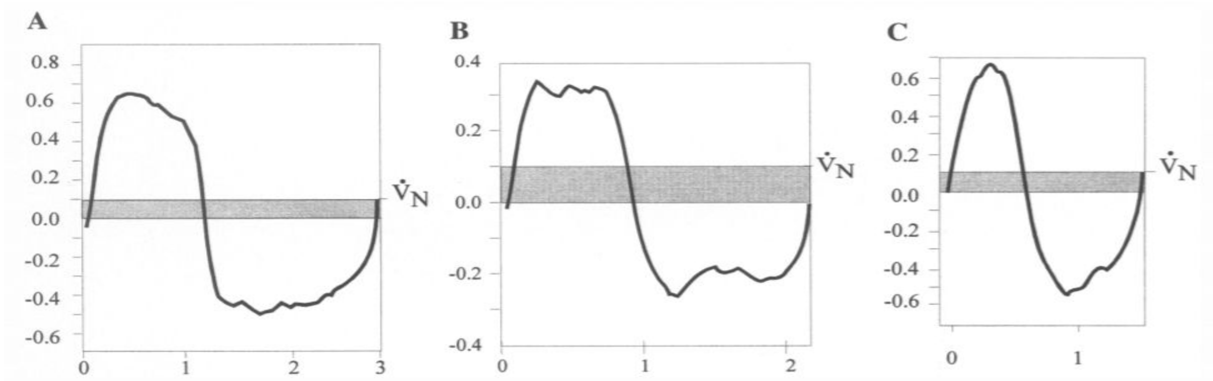


Figure 2: Breathing pattern taken from the data of three of the subjects. (A) Data from a 174-cm tall patient with normal lung function. (B) Data from a 139-cm patient with normal lung function. [10]

Coughing is defined as deep inspiration followed by rapid expiration [3]. To describe the deep inspiration cycle, a sinusoidal curve is used similar to breathing, but only defined for half of a period. The rapid expiration is characterized by a Pulse Width Modulation (PWM) signal. The Figure below shows a comparison between coughing patterns shown in studies and our replication of that pattern.

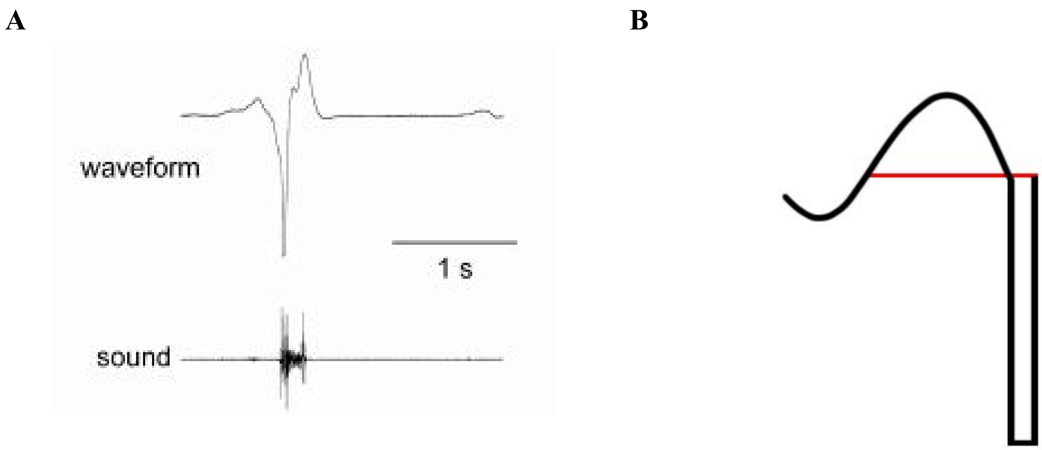


Figure 3: (A) Coughing pattern from Haji et al (2013) [3]. The horizontal axis represents time. The positive vertical axis represents inspiration and the negative vertical axis represents expiration. (B) Proposed coughing model. The red line indicates the coughing period. This model is characterized by half a sine period, followed by a PWM signal.

The mechanism trigger was requested by the stakeholder. Ultimately, this requirement will help save power and prolong the longevity of the mechanism from cyclic loading. Although automatic detection is favored, it is not as important as the actual motion of the mechanism. The full list of requirements are shown in Table 4, page 9 and 10.

Table 4: The user requirements, engineering specifications, rationale, and priority for Mechanics.

Requirements	**Engineering Specifications**	**Source**	**Priority**
Basic, repeated random breathing gesture	Let a breathing pattern be represented by a sinusoidal signal where: ➔ Amplitude: represents the % volume change and has range (8, 12) ➔ Frequency: represents the speed at which the volume changes and has range (0.3, 1) Hz ➔ Number of periods: represents the duration of the breathing pattern and varies from (1, 3) A breathing gesture is defined as a sequence of sinusoidal signals where no two adjacent signals are identical. There must be at least 20 unique signals in a breathing gesture.	Coates et al 1999 [3]; Levitzky 2017 [6] ; Tsunashima et al 2004 [10]	1
Consecutive impulse of coughing	Inspiration is modeled by half a period of a sine function where: ➔ Amplitude: represents the volume change and has range (8, 12) ➔ Frequency: represents the speed at which the volume changes and has range (0.3, 1) Hz Expiration is modeled by a negative PWM signal where: ➔ Magnitude: represents the volume change and has range -0.5L to -1L ➔ Duty Cycle: represents the ratio of duration between contraction and resting between 90 to 95% ➔ Duration: determines the speed of the cough between 0.2 to 0.5s.	Fanta 2018 [2]; Foucand et al 2019 [12]; Haji et al 2013 [13]; Lomauro and Aliverti 2019 [14]	1

Mechanism would be triggered to start automatically by detection of audience nearby	Angle 120 degrees of detection. At least 4 ft. range of detection. Mechanism starts within 5 seconds of detection automatically.	Dernie 2006 [16]	2

General Requirements

The general usability requirements cover the quality of the puppet, including the life cycle, weight, simplicity. As shown in Table 5 on page 10, these are specifically requested by the sponsor in order to easily operate the puppet easily throughout the entirety of the exhibition. There are also specific exhibition guidelines that require certain requirements for the quality of the puppet[16].

Table 5: The user requirements, engineering specifications, rationale, and priority for general usability.

Requirements	Engineering Specifications	Source	Priority
Life cycle	Continuously operable throughout a full 8 hour work day. Mechanism lasts more than 216,000 cycles.	Bendixen, Smith, Mead 1964 [17]	2
Light weight	Weighs under 10 lb.	Dernie 2006 [16]	2
Simple	Number of components under 15. Average person can disassemble/reassemble with an instruction manual and 3 tools under 30 minutes.	Dernie 2006 [16]	1

Concept Exploration

After conducting the initial investigation into the background and requirements for the project, we began to generate some preliminary ideas for the solution. Some techniques used to give better ideation results include, brainstorming, mind mapping, and morphological analysis. Using these we generated a list of potential ideas. Three of these preliminary ideas include an accordion like design, the infusion pump design, and an inflatable pig lung design.

Accordion Design

Since human lungs expand mostly in the vertical direction, with only slight variation in diameter, we proposed to create a scissor lift controlled by a motor. This would sit inside a membrane shaped like a set of lungs and be controlled via the motor by an arduino type microcontroller. A sketch of this concept can be seen in Figure 4, page 11.

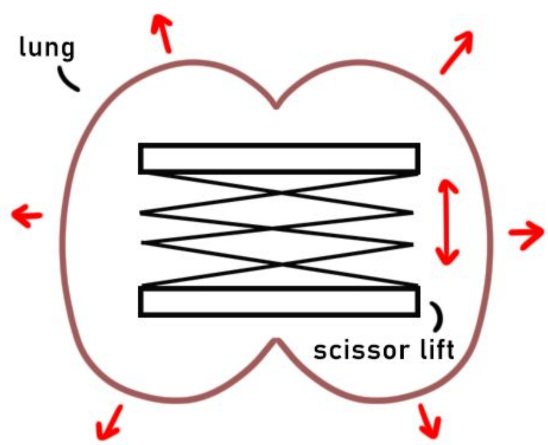


Figure 4: A sketch of the rough idea being described. It shows the "lung" membrane with a scissor lift mechanism embedded inside. This would be controlled by a motor via a microcontroller.

This design was the first preliminary design we thought about when going through some of the possible options. This design would be able to be controlled very easily due to being actuated by a motor. This would allow for very precise control of the lung movements allowing for more complex movements.

Infusion Pump Design

This design utilizes an infusion pump to inflate a pair of lungs. The pump is powered by a linear actuator and could easily be located outside the puppet itself. It would be connected to the lungs via a hose. The lungs are made of elastic material allowing for expansion and contraction. A sketch of this solution can be seen in Figure 5.

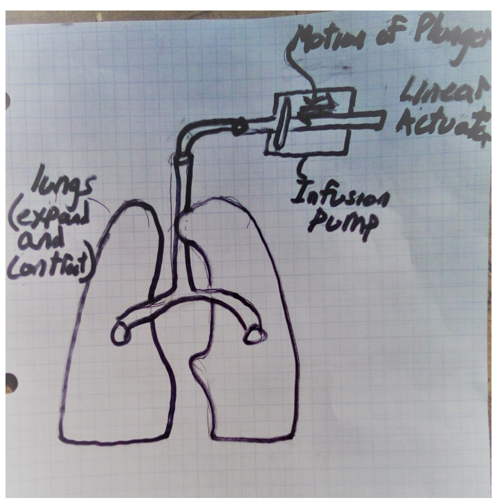


Figure 5: A sketch of the infusion pump lung expansion design*. It shows the infusion pump connected to the lung structure allowing for inflation and deflation.*

Pig Lungs
Through our research we found that there exists a teaching device that is a set of inflatable pig lungs. For this concept we proposed using the existing lungs and modifying them with some mechatronics to automate the process. The pig lung set can be seen in Figure 6.

Figure 6: A BioQuest inflatable lung comparison kit. The bellows system used to inflate the lungs can be seen on the left. This would be replaced with an automatic inflation system controlled by a microprocessor.

This design was thought up due to the suggestion of adapting existing rather than reinventing the wheel from the sponsor. The benefits of going down this path is that there is some work already done for us, however this design doesn't perfectly meet all of our criteria. There would need to be modifications made in the design in order to properly fit our requirements.

Concept Generation / Concept Development

The team started the concept generation process by splitting the concepts into three critical subsystems: lung, Actuator, Motion. The lung subsubsystem is defined as the mechanism that exhibits the lung expansion and contraction motion. The Actuator subsystem is defined as the mechanism that transfers the force from the source of motion to the lung mechanism. The motion subsystem is defined as the mechanism that generates the force to operate the motion of the prototype. These three critical subsystems are brainstormed at the same time because the functionality of these three subsystems are interdependent with each other.

Additionally there are three other supplementary subsystems that are also brainstormed: the electronic, sound, and audience detection subsystem. These subsystems are supplementary because they can be easily integrated into any concepts of the critical subsystems and do not depend on the functionalities of the critical subsystems. This section will detail some of the brainstormed concepts and concepts generated from Heuristics and Morphological methods, as well as the engineering thought process behind the generation process.

Brainstormed concepts
Lung subsystem: The team brainstormed this subsystem from feasible materials that could be used in the project. Since the sponsor has mentioned that she has widely adopted aluminum as one of her choices of design, we thought about lung structures made from aluminum. An expandable ribcage concept was generated, which was derived from the shape and structure of a head scratcher. An aluminum ribcage

design that is constructed as individual linkage bars is also something that was generated. Since 3D printed parts are lightweight and able to fabricate complex structures like lung and rib cages, that was a consideration as well, specifically a 3D printed rib cage and flexible TPU printed lungs constructed like spiderwebs. Other forms of polymers and membranes were also part of the consideration, such as balloons and existing products like bouncy balls, beach balls, and Perfect Petzzz (an existing pet toy product that imitates breathing of a sleeping pet).

Actuator subsystem: There were four main actuator design concepts that were generated from brainstorming. The cam and follower is a classic and well-researched mechanism that is considered. It is easy to mimic the sinusoidal motion of the breathing motion, which is why it is considered. The infusion pump is another possible concept, which pumps up an enclosed, elastic lung mechanism. Since the infusion pump is limited to its infusion abilities, it can only be paired with lung concepts such as balloons and inflatable polymer balls. There are also different fluids that can potentially model as a pump, such as air pump and water pump. Another concept is a scissor lift and power screw combination, which was suggested by our sponsor. The last concept is a simple linear actuator with one degree of freedom.

Motion subsystem: The purpose of the motion mechanism is to convert the power source into force and torque to drive the actuator and the lung system. The most straightforward way to accomplish this while also meeting the goal of being a precisely controlled device is to use a motor. We explored the option of using brushless metal gearbox motors with encoder and planetary gearbox motors. Another way to create motion is thermal pressure change. Since we have inflatable balloons as a preliminary concept, a mechanism that changes thermal pressure can potentially have interesting effects.

Electronic subsystem: A mechatronic system needs to be set up for the lung device so that breathing and coughing motions can be modelled precisely. Some of the options include Arduino, Raspberry Pi, and ESP32 /Teensy being the most commonly used control system. The team is also familiar with the platform of these systems. To connect the device to a control system, there are options of using a hardware connectivity, Wifi connectivity, and a bluetooth connectivity.

Sound subsystem: The sound subsystem is used to produce the gasping and wheezing sounds of the puppet. The most straightforward way to accomplish this is integrating an electronic speaker onto a mechatronic system so that the motion can match up to the sounds. Some of the speaker components include traditional loudspeakers and Piezo Speakers. The project sponsor had also suggested that the team can explore concepts that utilizes existing products such as slide whistles and wheezing toys.

Audience detection subsystem: The audience detection subsystem is used to fulfill the requirement to interact with the audience at the exhibit and trigger to start the lung device when the audience is in its proximity. Some of the existing and feasible audience detection components are motion/proximity sensors, Camera/face recognition (computer visioning), capacitance sensor, infrared vision, and sonic detection.

Heuristic and morphological methods

Besides brainstorming, the team also went about concept generation using more systematic concept generation tools such as heuristic cards and morphological methods.

Heuristic method: The team used various heuristics to generate more concepts. Using the scale up and layered heuristics, we thought about using many small balloons instead of only one single balloon for inflation., as shown in figure 7 below. This is also derived from an existing product called Bunch-O-Balloons. The justification for using many small balloons instead of one big balloon is to minimize the risk of bursting balloons from a low elastic modulus of rubber latex[31]. The less strain on the small balloons prevents the balloon from reaching the fracture toughness. This concept is also foreseeably adaptable for rapid prototyping for the project sponsor if she would like to use the existing product to explore this concept further.

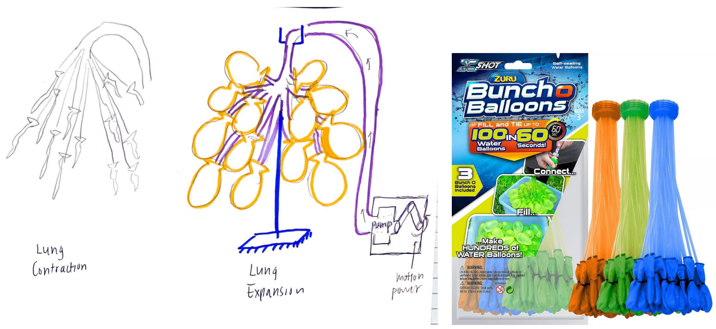


Figure 7. Layered, scaled up balloon concept, derived from the existing product “Bunch-O-Balloons”.

Another concept was to combine an inflatable balloon lung with the rib cage as one single lung mechanism, using the “compartmentalize” and “utilize inner spaces” heuristics. The concept is shown in figure 6, page 13. The justification for this concept is to have a more realistic depiction of the human lung, imitating the thoracic cavity and diaphragm. After consulting with the sponsor about this concept, the geometric and artistic alikeness of this concept was also one of the considering factors.

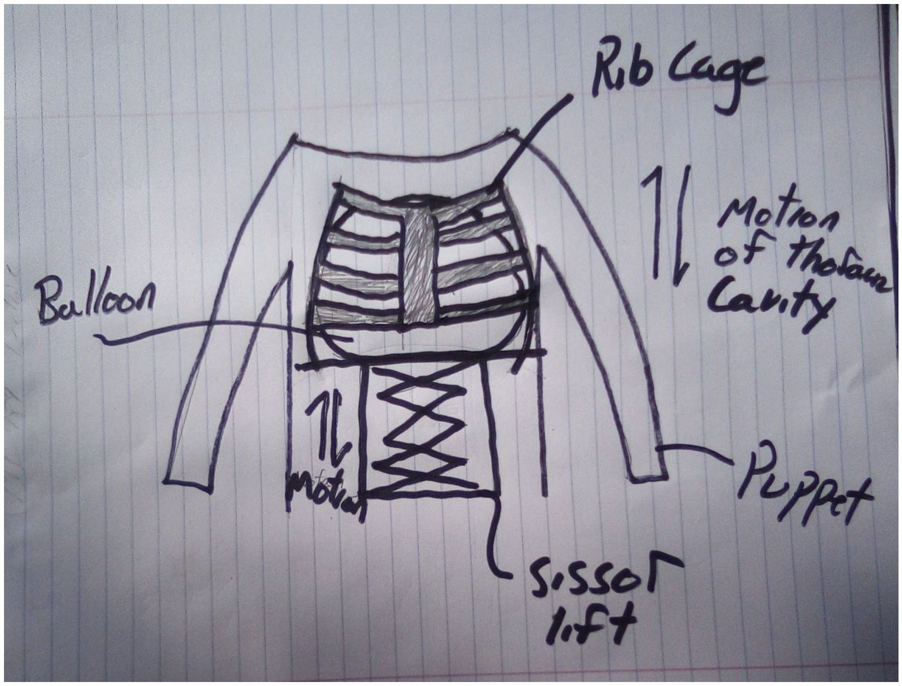


Figure 8. Combination of rib cage and balloon concept to depict the thoracic cavity and diaphragm of human lungs.

Morphological Method: Morphological method was also used as a way to create design components with deviation within each subsystems, providing more options for design choices. Since the ribcage design was something that was discussed extensively among the team and sponsor, this concept was explored deeper into different materials to create a rib cage structure. From initial brainstorming, the rib cage structure was intended to be aluminum, but we can also create a 3D printed rib cage with connecting joints. Another iteration was to create a rib cage with 3D printed resin with a spinal structure made out of aluminum. This was brought up because the sponsor has mentioned that she uses aluminum frequently to easily assemble her puppets. This concept is able to be more convenient for her while maintaining a light weight.

Idea development process

To develop fully fledged concepts, all the different subsystem ideas were combined into the different possible combinations. The three subsystems used were the actuator, lung, motion. Then one idea from each subsystem was picked and they were combined into one concept. This process can be seen below in Figure 9, page 16.

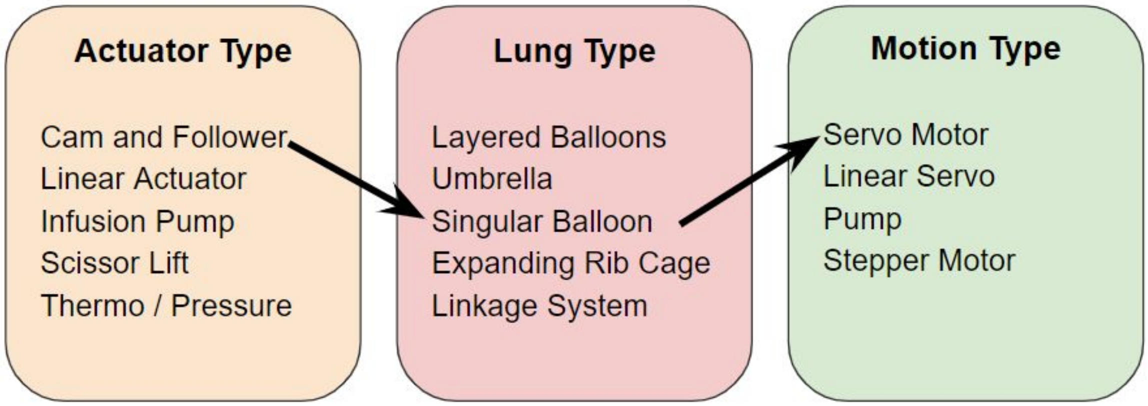


Figure 9. Flow of the ideas from the three subsystems were combined into different concepts.

From the above diagram, we can see the flow for generating the Cam and Follower with a singular balloon powered by a servo motor concept. This same methodology was used to generate the rest of the concepts for the initial list of concepts. For the initial generation unreasonable ideas were still kept and not filtered out until the next section.

Selection of top 8 concepts

In order to be able to properly evaluate the concepts, we did some preliminary narrowing down of the concepts. The first thing done was to take out the concepts that didn't make any sense, for example ones where a pump was meant to drive a mechanism. Then after the initial narrowing a gut check was done to eliminate some of the less feasible concepts to get a list of eight concepts to compare against each other. These concepts can be seen collected in Table 6.

Table 6: Preliminary filtering of ideas and selection of top 8 concepts.

Concept Number	Actuator Type	Lung Type	Motion Type
1	Cam and Follower	Linkage System	Servo Motor
2	Cam and Follower	Singular Balloon	Servo Motor
3	Infusion Pump	Single TPU Balloon	Linear Servo
4	Infusion Pump	Singular Balloon	Linear Servo
5	Infusion Pump	Layered Latex Balloon	Pump
6	-	Linkage system	Servo Motor
7	Linear Actuator	Linkage System	Linear Servo
8	Linear Actuator	Singular Balloon	Linear Servo

This list was then used for the comparisons in the following sections. The ideas that were eliminated from gut checking were done so by looking at the complexity and variability of the design. This meaning the top eight designs were the simplest most dynamic designs that would allow for the most range of motions.

Concept Evaluation/Selection

Criteria selection and definition

We separated our design specifications into simple requirements for us to judge the eight concepts on a rating scale of 1-5. These criterias were derived from the user requirements and engineering specification mentioned above. We judged these specifications based on engineering values. For example, in expandable criteria, we assessed the concept's elastic modulus, plasticity, and fracture toughness, to understand the risk factor and the ability of expansion for the concept. Another factor that was discussed with expandable ability is constraining forces from structures, such as rib cage structure preventing a balloon from expanding.

Table 6. The Criteria and their definitions, as well as an explanation of a 1 rating and a 5 rating.

Criteria	Definition	Rating
Expandable	Produces lung-like expansion based on material properties (fracture toughness, elastic properties), and force analyses[4][9]	1 - Inelastic material, material prone to failure when expanded 5 - Very elastic material
Breathing/Coughing gesture alikeness	Able to mimic sinusoidal coughing motion by analyzing the control system[11][12][17]	1 - Unable to produce nuance of sinusoidal wave, unable to expand and contract at different rates 5 - Very able to expand sinusoidally, capable of expansion at different speeds
Simplicity	# of parts, maintenance needs, practicality of materials, feasibility[8]	1 - More parts, more difficult maintenance, less practical materials, less feasible 5 - Fewest parts, least difficult maintenance, practical materials, very feasible
Lifetime/Durability	216,000 breathing cycles based on our estimate of the daily length of a museum exhibition and the average breathing cycles per minute of an unhealthy human adult.[8]	1 - Unable to function for this many cycles due to needing difficult maintenance or sustaining permanent wear 5 - Easily capable of reaching this many cycles with only simple repair or no wear at all.

Weight	Engineering specifications specified that device should weigh less than 10 lbs.[8]	1 - Weighing more than or close to 10 lbs 5 - Weighing much less than 10 lbs
Cost	We are given $400 in our budget to buy materials and components for our design.	1 - Costing more than or close to $400 5 - Costing less than $400

Selection of top 3 concepts

After the selection criteria were selected and defined, the top 8 concepts of the critical subsystems that were developed were rated against the criteria. Before rating the concepts, team members who are the most familiar with each of the top 8 concepts would present the pros and cons of the concept to the rest of the team. The team would then have a thorough discussion of the concept and assess (1) if there are other pros and cons of the concept that the rest of the team has not brought up, (2) to what extent does this concept fulfill the criteria need according to the engineering research, and (3) a unanimous agreement of a final rating for each of the criteria for a concept.

First, a discussion of pros and cons of each concept was carried out. For each of the concepts, the engineering assessment that was detailed in the criteria selection and definition subsection was assessed for each of the top 8 concepts. Other deciding factors for pros and cons of a concept also involve ability to integrate with the mechatronic systems. For example, we foresaw that a motor with an encoder paired with a linear actuator is the most straightforward way to integrate a device to a mechatronic system, whereas there might be potential challenges modeling a mechatronic system with the infusion pump. An open loop control system versus a closed loop control system is also something that needs to be considered with mechatronics systems for each design, which might add complexity to the overall design. For example, concepts with cam and follower might have to be a closed loop system, because the position of the cam might be a disturbance input and require feedback loop in order to create an appropriate behavior, which is also very geometry dependent. A linear actuator design might be easier, since the open loop system would just have to feed in certain commands.

Then, these criteria were rated a score from 1 to 5 for each concept, with 1 being the least suitable to fulfill said criteria and 5 being the most suitable to fulfill said criteria. As shown in Table 7 below, the team agreed on a unanimous rating for each criteria of each concept. The criterias for expandable abilities and breathing/coughing gesture alikeness were rated as the highest priority as identified between the sponsor and the team, which was assigned a weighting factor of 3. The criteria for simplicity was the next criteria with high priority, which was assigned a weighting factor of 2. The criteria for lifecycle/durability, weight, and cost were assigned a weighting factor of 1. After summing up a total rating score for each criteria and incorporated the weighting factors for each concept, the three following concepts have the highest total score and will be moving on to top 3 selection process: Cam and follower as the actuator with singular latex/spandex balloon and 3D printed ribs (concept 2), layered multiple balloon with infusion pump and linear actuator (concept 5), and linear actuator with singular latex/spandex balloon and 3D printed ribs (concept 8).

Table 7: Criteria rating matrix for each of the top 8 concepts. The specificity of the top 8 concepts according to their concept numbers can be referred back to the previous sections.

Concept number	Criteria						Total
	Expandable (weight: x3)	Breathing/ coughing gestures alikeness (weight: x3)	Simplicity (weight: x2)	life cycle/ durability (weight: x1)	Weight (weight: x1)	Cost (weight: x1)	
1	4	4	3	4	3	4	**41**
2	4	4	4	3	5	5	**45**
3	3	3	4	2	5	5	**38**
4	3	3	3	3	5	5	**37**
5	5	3	4	4	5	5	**46**
6	5	3	3	2	4	4	**40**
7	4	4	4	4	4	4	**44**
8	4	4	4	4	5	4	**45**

Selection of sound, audience detection, and electric subsystem

The selection of the three auxiliary systems -- sound, electric, and audience detection -- was not interdependent with the selection of the previous mechatronic systems, thus we left that choice to practicality, past experience, and cost.

Table 8: The choices we made for the three auxiliary systems and their rationales.

	Selection	Rationale
Electrical	Arduino	● Stakeholder has experiences using Arduino ● Great for rapid prototyping, simple to set up ● Robust
Sound	Traditional Loudspeaker	● Easily integratable to mechatronic system ● Cheap
Audience Detection	Proximity/Motion Sensor	● Stakeholder has experiences using

		proximity sensor ● Great for rapid prototyping ● Easily integratable to mechatronic system ● Cheap

Our team members have experience using Arduino controllers, thus we chose to use the Arduino to control the breathing mechanism. We also have felt that in terms of rapid prototyping capabilities and available literature, the Arduino is superior to other options in the market. In terms of sound system, we chose a physical speaker as it is the cheapest and most appropriate option for our application. A traditional loudspeaker is capable of many output volumes and is typically used in conjunction with an Arduino in similar implementations. Similarly, the audience detection mechanism we chose was a proximity/motion sensor as it is the most seamless version of the effect the stakeholder is looking for and it is a component she has used in the past, as opposed to a mechanical proximity sensor that may be more cumbersome and disrupt the effect.

Pugh chart and final concept

Upon the top three concepts that were selected in previous sections, these three concepts were further analyzed and benchmarked against each other. For the linear actuator with singular latex/spandex balloon and 3D printed ribs concept, the mechanism can be located outside of the puppet. With few components, the reduced complexity of the device is a big advantage. The open loop control system allows straightforward implementation of the mechatronic system. For the cam and follower as the actuator with singular latex/spandex balloon and 3D printed ribs concept, it is similar to the previous concept, except the cam and follower would warrant a closed loop control system for the mechatronics. For the layered multiple balloon with infusion pump and linear actuator concept, the air distribution for the balloons expanding lightly in the elastic stage makes it less likely for balloons to burst. It also provides an artistic depiction of lung airway structure.

These three concepts were then put into a Pugh Chart to be further compared, as shown in Table 9. The same weighting factors and criterias remained the same as the top 8 selection. The linear actuator with singular latex/spandex balloon and 3D printed ribs concept was used as a baseline benchmark and also has the highest total score, which allowed the team to proceed to finalizing this concept.

Table 9: Pugh chart for top 3 concepts.

		Linear Actuator	Cam and Follower	Infusion Pump
Requirement	Weight			
Expandable (↑)	3	0	0	+1
Breathing/ coughing gestures	3	0	-1	-1

alikeness (↑)				
Simplicity (↑)	2	0	0	-1
Life cycle/ durability (↑)	1	0	-1	0
Weight (↓)	1	0	0	0
Cost (↓)	1	0	+1	+1
Total		0	-3	-1

Solution Ideation

Single Balloon/ball with Linear Actuator

This final design concept consists of three components, a linear actuator, the thoracic cavity, and a balloon/ball. The device is seen in Figure 10.

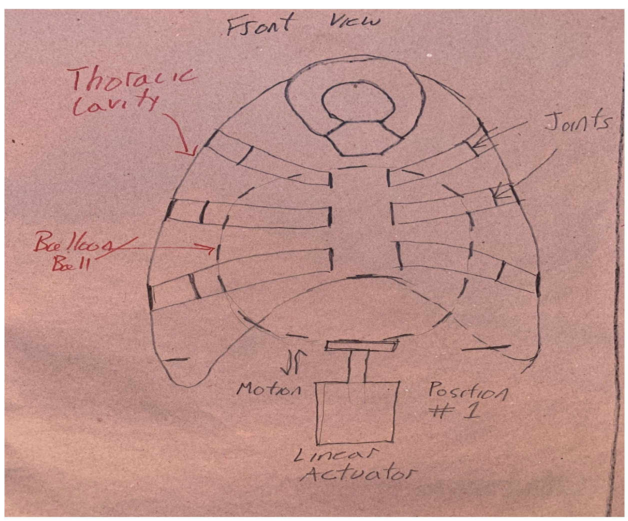


Figure 10. Single balloon/ball with a linear actuator

The mechanism mimics a breathing behavior when the linear actuator, operated by an arduino, asserts a force on the balloon/ball. The balloon/ball in turn asserts a force on the surrounding thoracic cavity. The thoracic cavity expands diametrically outward from the spinal column creating the illusion of breathing. The following three sections expand upon the three components of this mechanism and explore the rationale behind each design choice.

Linear Actuator

When compared with other actuators such as a scissor lift, the linear actuator was found to have fewer moving parts and would be quieter and simpler to design/ maintain. This fulfills the design requirement of being simple and quiet. When compared with a cam and follower, the linear actuator would be able to mimic breathing behavior more easily. The linear actuator would also have a quicker response time than the pump because changing the volume of a balloon/ball would take longer than simply displacing the balloon/ball.

The location of the linear actuator in relation to the balloon/ball was also considered. Figure 11 shows three possible locations when viewed from the side of the thoracic cavity.

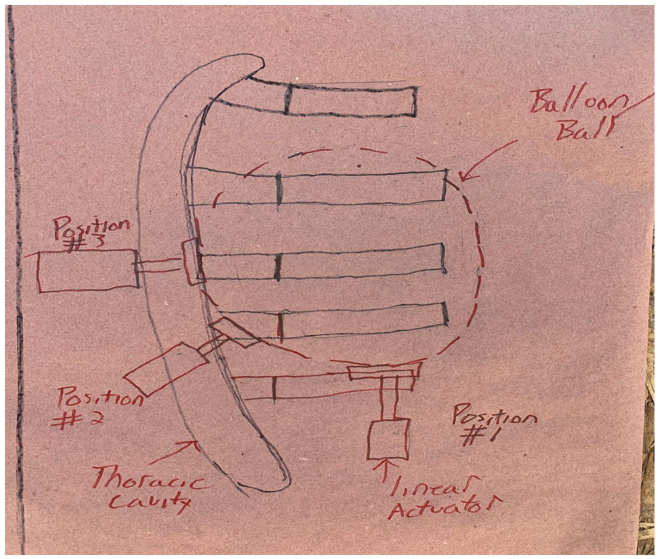


Figure 11: Possible Linear actuator positions.

Position 1 is directly beneath the balloon, while position 2 is at a 45 degree angle, and position 3 is located directly to the side of the balloon. The best choice is position 2 or 3 because the thoracic cavity expands visibly diametrically by 0.5 cm laterally and 1 cm deep (when viewed from the front of the thoracic cavity)(Bellemare, 2003) [2]**.** Locating it behind the puppet will save space and provide the displacement in the desired direction. This can be accomplished by locating the actuator in the cabinet the puppet will be sitting/laying on when on display in a gallery. This will save space and dampen the noise produced by the actuator.

The force required to displace/deform the balloon/ball has not yet been determined. To find the force vectors a more complex analysis will be done using Solid Works and ADAMS. A more general exploration of the force analysis was done using free body diagrams as shown Figure 12.

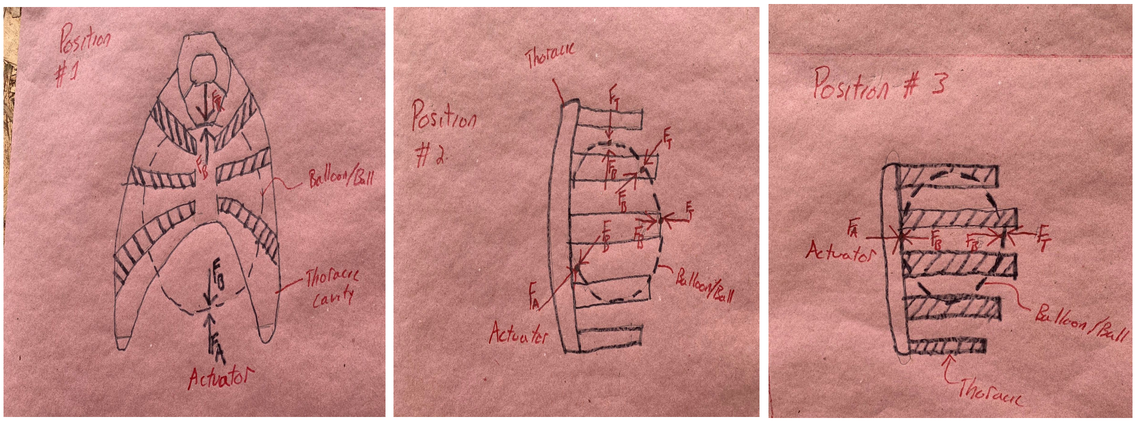
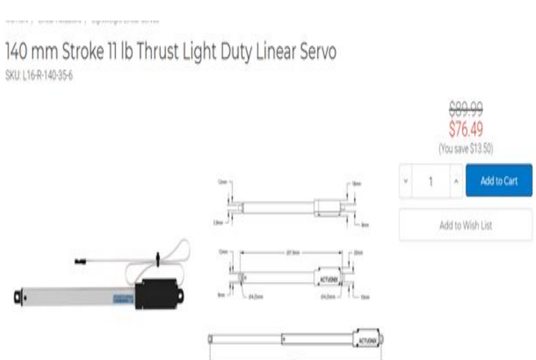


Figure 12: (Left) FBD for actuator in position 1. (Middle) FBD for actuator in position 2. (Right) FBD for actuator in position 3.

It is important to note that a plate is located at the end of the actuator to distribute the force on the balloon/ball over a larger area, thus decreasing the possibility of fracture. The fastest speed required by the motor is during coughing. The actuator needs to complete at least a 1 cm stroke between 0.2-0.5 seconds.

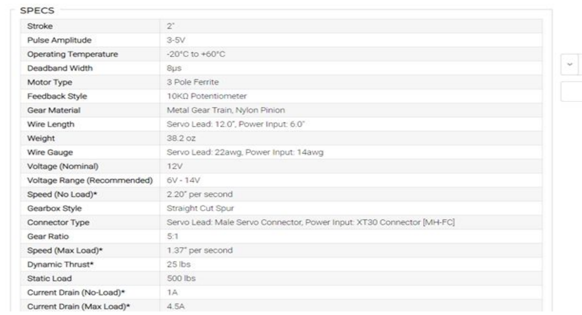
When considering the type of linear actuator to use, a rotary and servo linear actuator were considered. A servo was chosen because it can provide precise and fast displacements in comparison. Two types of linear servo motors were explored as seen in Figures 13 and 14.



SPECS

Stroke	5.5"
Pulse Amplitude	3 - 5 V
Operating Temperature	-10°C ~ +50°C
Motor Type	Brushed DC
Feedback Style	16 KΩ / inch
Wire Length	300 mm
Weight	3.65 oz
Wire Gauge	26 AWG
Voltage Range (Recommended)	4.5 - 7.5 V
Speed (No Load)*	32 mm per second
Connector Type	Male Servo Connector
Gear Ratio	35:1
Dynamic Thrust*	50 N
Static Load	250 N powered on, 31 N powered off
Current Drain (Stall)*	650 mA
IP Rating	IP54
Duty Cycle	20%
Potentiometer Linearity	Less than 2.00%

Figure 13: A 140 mm stroke 11 lb thrust light duty linear servo. The motor specs are shown to the right.


SPECS

Stroke	2"
Pulse Amplitude	3-5V
Operating Temperature	-20°C to +60°C
Deadband Width	8μs
Motor Type	3 Pole Ferrite
Feedback Style	10KΩ Potentiometer
Gear Material	Metal Gear Train, Nylon Pinion
Wire Length	Servo Lead: 12.0", Power Input: 6.0"
Weight	38.2 oz
Wire Gauge	Servo Lead: 22awg, Power Input: 14awg
Voltage (Nominal)	12V
Voltage Range (Recommended)	6V - 14V
Speed (No Load)*	2.20" per second
Gearbox Style	Straight Cut Spur
Connector Type	Servo Lead: Male Servo Connector, Power Input: XT30 Connector [MH-FC]
Gear Ratio	5:1
Speed (Max Load)*	1.37" per second
Dynamic Thrust*	25 lbs
Static Load	500 lbs
Current Drain (No-Load)*	1A
Current Drain (Max Load)*	4.5A

Figure 14: A heavy duty 2" stroke 25 lb thrust linear servo motor. The motor specifications are shown to the right.

The bigger motor is much more expensive at $254 compared to $76 for the light duty motor. The heavy duty motor should easily meet the force requirements. Both motors can be operated with an arduino and receive PWM signals. The power requirement will be met by a wall outlet which will be available in the gallery.

Balloon/Ball

A balloon/ball was chosen primarily for aesthetic reasons. It can easily create the illusion of being a lung and the thoracic cavity can be exposed. If for some reason it fails in creating this illusion, the thoracic cavity could be unexposed. Another possible option was having lungs that expand and contract mechanically. This approach was deemed too complicated and does not satisfy the requirement of keeping the mechanism as simple as possible.

When exploring materials to use for the balloon/ball, 3 different materials were considered as shown in Table 10.

Table 10: It was assumed that the balloon/ball will be spherical in shape, with a radius of 0.076 m (3 inches) and thickness of 0.001 m.

Material	Yield Strength (MPa)	Max Internal Pressure at yield strength(MPa)
Nylon	**45**	**1.179 (171 psi)**
PVC (DuraBalloon)	**55.2**	**1.4479 (210 psi)**
Latex (Standard party Balloon)	**18**	**0.469 (68 psi)**

The following calculations were made using Equation 1, the equation for a pressurized spherical vessel.

$$\sigma = \frac{pr}{2t} \qquad \text{Eq(1)[22]}$$

The PVC (DuraBalloon) was the strongest of the materials and could withstand a pressure of 210 psi before yielding. The latex was considered as a frame of reference to help the engineers intuitively understand the strength of the other materials considered.

Design for Rib Cage Expansion

The design for the expansion of the rib cage was inspired by our research into 3D printed prosthetic limbs. As shown in Figure 15, the rib can be segmented into separate components and joined by pin joints. The pin joints will allow for rotation between components.

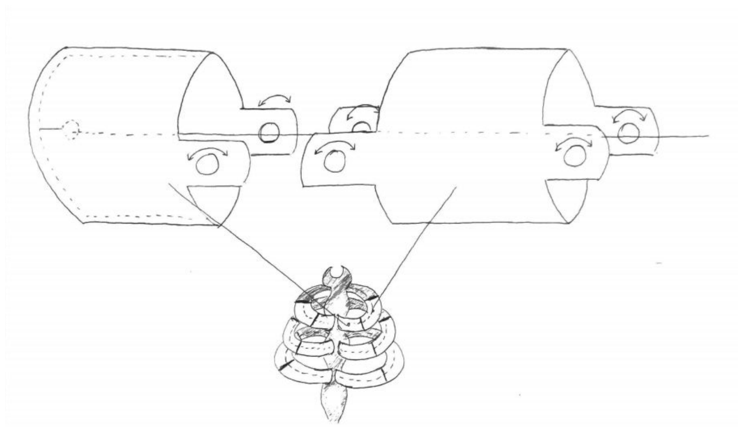


Figure 15. Design for the expansion and contraction of the rib cage. Rib is separated into individual, hollow 3D printed components joined by pin joints.

A string passes through the center of each component and allows for the rib cage expansion in one direction. The amount of expansions can be determined from the length of the string chosen. The segmented design is one way we can achieve the flexibility in the rib cage as the balloon pushes against it.

3D Printing Materials

3D printed materials were examined for the design of the rib cage and thoracic cavity over aluminum alloys for manufacturability and cost. Firstly, 3D printing and additive manufacturing allows for more complex structures to be printed that would be hard to achieve with CNC machines. The overall cost of 3D printing is also less expensive. Figure 16 shows a price comparison among three 3D printing materials our group considered, provided from Simplify3D [28]. For the small puppet dimensions of 5 to 6 inches, we can expect the weight to be much less than 1 kilogram from the material densities listed. Pricing for the two cheapest materials starts at only $10 per kilogram.

Compare Selected / Show All	ABS	PLA	Polycarbonate
	Learn More	Learn More	Learn More
Ultimate Strength	40 MPa	65 MPa	72 MPa
Stiffness	5 / 10	7.5 / 10	6 / 10
Durability	8 / 10	4 / 10	10 / 10
Maximum Service Temperature	98 °C	52 °C	121 °C
Coefficient of Thermal Expansion	90 µm/m-°C	68 µm/m-°C	69 µm/m-°C
Density	1.04 g/cm^3	1.24 g/cm^3	1.2 g/cm^3
Price (per kg)	\$10 - \$40	\$10 - \$40	\$40 - \$75
Printability	8 / 10	9 / 10	6 / 10

Figure 16. Properties of three 3D printing materials [28]. Areas of interest for cost calculations are density and price. For our design, the weight should never exceed 1 kg and should be under $10 to print.

The three materials in Figure 16 were also compared for the material properties. ABS has a low cost, good impact and wear resistance, as well as heat resistance. However, these parts can have heavy warping and a tendency to shrink. PLA is a popular and cheap material for printing, and also has a long shelf life. The main disadvantage of PLA is that the filament is brittle and prone to breaking. It is also unsuitable for sunlight exposure. Polycarbonate is the most expensive option we considered. It has the greatest flexibility among the materials compared. One major drawback aside from price is the tendency for the material to absorb moisture. This is unideal because the stakeholder will not be able to control all exhibits that the puppet is displayed in.

Engineering Analyses

Identification of Failure modes

After developing a rough draft of the final chosen design and understanding some of the design choices from the last design review, the team identified a list of possible design failures shown in Table 11 below. From the three critical subsystems aforementioned, a number of failure modes are identified based on the material properties, force transfer, deformation properties, dynamic properties of the subsystem.

Table 11: Possible failure modes identified according to each of the critical subsystems

Subsystem	Possible failure modes
Lung/balloon	● Popping/leakage ● Plastic deformation ● Fail to inflate ● Not properly supported ● Not properly contacted with rib cage (force transfer)
Ribcage	● Too stiff to move ● Failure with expansion and contraction ● Plastic deformation ● Fatigue ● Snapping between two joints
Mechatronics	● Inadequate input power ● Inadequate output torque ● Too loud ● Failure to imitate breathing/cough gestures ● Encoder value out of sync

Upon identifying possible failure modes of each of the subsystems, the team had a discussion on the failure outcomes of each of these failure modes to assess the severity, occurrence, and detectability of these failure modes. After the assessment, the team identified the three critical challenges: (1) the failure of force transfer between the linear actuator and the ribcage balloon structure, (2) the failure of the ribcage expansion and contraction., and (3) the failure to imitate breathing and coughing gestures from the control settings of the mechatronic system.

Top 3 critical challenges

The Top three failure modes were chosen to be further analyze through empirical, software, and theoretical analysis: (1) the failure of force transfer between the linear actuator and the ribcage balloon structure, (2) the failure of the ribcage expansion and contraction., and (3) the failure to imitate breathing and coughing gestures from the control settings of the mechatronic system. This subsection will go through the rationale on why these three were chosen and the thought process on choosing the appropriate engineering analysis.

First, we have chosen the failure of force transfer between the linear actuator and the ribcage balloon structure to be the most critical failure mode that we have to design against. The failure situation would be that the linear actuator would not be transferring enough force onto the balloon to expand the ribcage, while having the ribcage expand and the balloon ball to deform were two of the most critical requirements of this project. The severity of this situation would be high and occurrence if not designed properly would also be high, while the detectability of this failure is obvious. Since a numerical value for the force of the contact forces between the ribcage and the balloon/ball would be needed, a theoretical analysis was performed to model the relationship between each component in the dynamic system.

Then, we have chosen the failure of the ribcage expansion and contraction to be the next most critical failure mode that we have to design against in the ribcage subsystem. This failure situation would be that joints, structure material, or elastic band holding the ribcage constrained would be faulty or malfunction, not allowing the ribcage structure to expand and contract properly. This is related to one of our most critical requirements, which is to have expandable and contractible ribcages in the specified dimensions. The severity of this failure mode would be high, as it will not fulfill this critical requirement and also potentially cause structural breakage. The occurrence of this failure would be high if not designed properly. The detectability of this failure is high as it would be obvious. Since the elastic and material properties of the elastic band holding the structure together does not have any specifications, we would have to perform empirical analysis to better understand the behavior by acquiring experimental force displacement data. The 3D printed test rig structure would allow us to better inspect the 3D printed parts for any faulty components before final fabrication.

Last, we have chosen the failure to imitate the breathing and coughing gestures from the control settings of the mechatronic system as the last critical failure mode that we have to design against. The failure situation would be that the pairing between the input (audience detection/motion sensor) would not output an appropriate lung behavior as an output response to the linear actuator. This relates to one of our most critical requirements to design a lung mechanism that would exhibit coughing and breathing motion that is life-like. The severity of this failure mode would be medium high, as it might still expand and contract the structure just not in the appropriate behavior. The occurrence of this failure mode is high, as it is easy for mechatronic systems to be unstable and faulty. The detectability of this failure is medium, as sometimes it is unpredictable with unstable performances when it runs with the hardware. Since the mechatronic system largely relies on the program and systems development, a simulation test would be the most appropriate to study the input and output behaviors.

Engineering Analysis: Ribcage

An empirical analysis was performed on the rib cage structure. This is due to the rib cage structure's complexity to analyze the joint smoothness from the material and design and the lack of specification data for the elastic string of the structure. To best understand the behavior and obtain numerical data for the structure, we fabricated a 3D printed test rig of the rib cage structure and assembled it with elastic bands (Dritz Elastic Thread - 30 yards) bought from craft stores, shown in Figure 17. The 3D printed rib cage was fabricated using ultimaker 5 and FDM material.

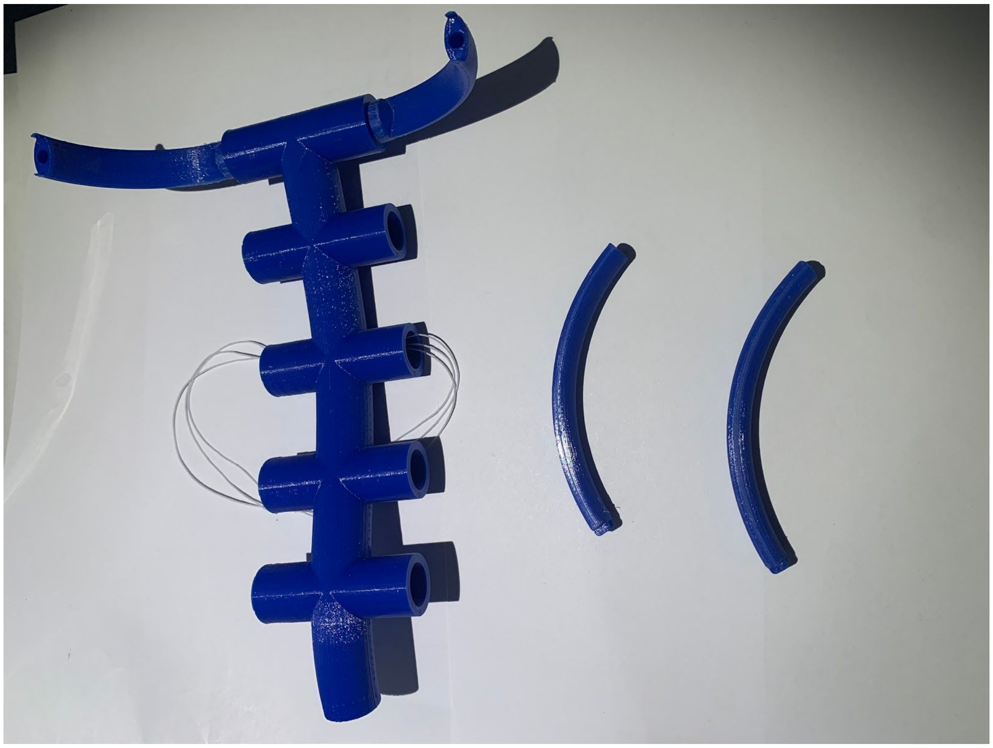


Figure 17: The FDM 3D printed test rig of the ribcage and elastic string

After 3D printing, we discovered that a critical challenge presents in the joint. The original design of the joint did not account for the capability of 3D printer layer size. While we designed to have a pin that goes through the joints to constrain, the joints were not printed properly to allow an appropriate assembly between the rib parts. Another challenge that was discovered with 3D printing rib cages was that the internal opening of the rib pieces were too small to allow the elastic string to go through. These design components will be redesigned for assembly.

Another thing that needed to be empirically tested regarding the expansion and contraction motion of the rib cage was the elastic band force displacement behavior. A string loop with a diameter of 10 cm was tied around the opening of the spinal cord 3D printed piece. With a ruler taped to the side of the table top to measure the force displacement, the elastic string was suspended by a piece of mass, as shown in Figure 18. By varying the suspended mass applied on string loop, the force displacement relationship can be obtained.

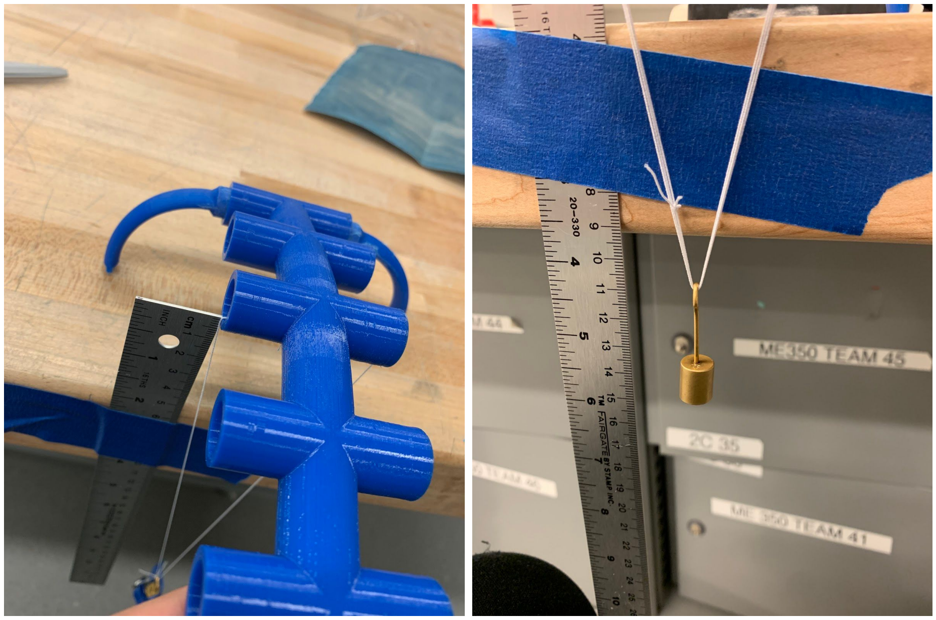


Figure 18: The top of the loop was held against the 0cm mark throughout all the test (left), mass is suspended off of the string and displacement is measured.

A 10 gram, 20 gram, 30 gram, 60 gram suspended mass were tested with 3 trials. The reasoning for conducting the force displacement test like this is because the gravitational constant and force are considerably precise when measuring the opposing force, which is the tension force of the spring in this case. The free body diagram of the setup is shown below in figure 19.

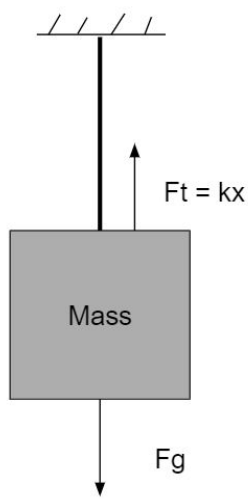


Figure 19: Free body diagram of the suspended mass acting on the elastic string as gravitational force.

The tension force of the elastic string can be modeled as a spring with a spring constant *k*. The force of elastic string would then be *k***x*. The equal and opposite forces between tension force and gravitational force allows us to obtain displacement force using equation set (2):

$$Ft = Fg \qquad \text{Eq(2)}$$
$$Ft = k * x,\ Fg = g * m$$
$$Ft = k * x = g * m$$

where Ft is the tension force of the elastic string, Fg is the gravitational force of the suspended mass, k is the spring constant in N/cm when the tension force is modelled as a spring force, x is the displacement distance in cm, g is the gravitational constant 9.8 N m^2/kg^2, m is mass in kg.

The displacement values are documented and averaged for each of the mass values. The relationship between displacement and force was graphed. The slope indicates the spring constant k, which is calculated to be 0.0206 N/cm. The graph is shown in Figure 20. Since the diameter of the elastic string loop is 10 cm, the displacement has an offset of about 10-15 cm in the graph.

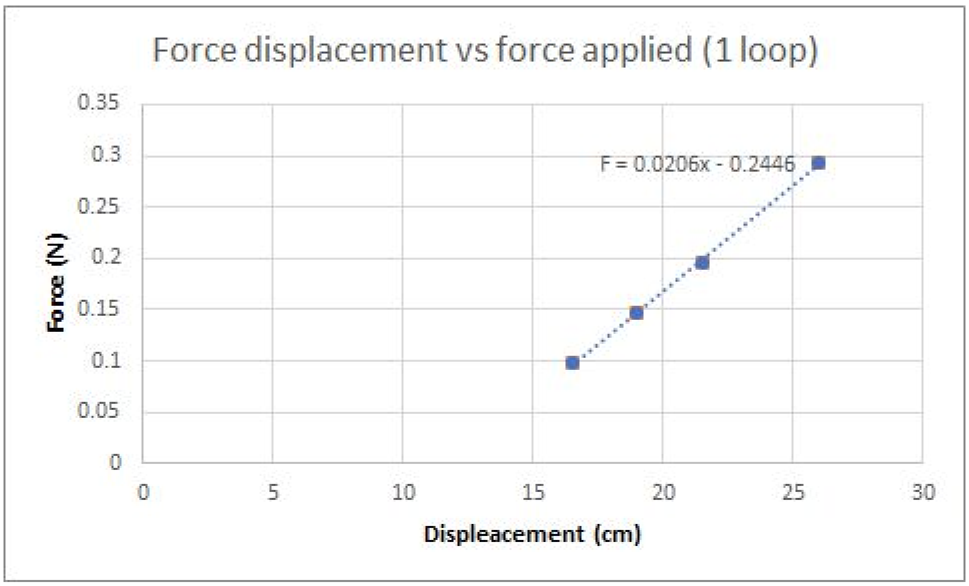


Figure 20: The relationship between force displacement and force applied onto the elastic string. The relationship between the displacement and force has an r value of 0.99 which has a strong linear relationship. The spring constant value k is calculated to be 0.0206 from this linear relationship.

Based on the requirements, the rib cage should displace by 2 cm. This means that the elastic string force would exhibit a force of F = 0.0206 N/cm * 2 cm = 0.0412 N, which is a small value for the force we might need. Because of this, similar tests were conducted with the elastic strings forming 2 loops and 3 loops. This would allow an increase in spring constant to have a higher force value for the elastic string force. Figure 21 and 22 show the relationship between force and displacement with 2 loops and 3 loops of the string respectively.

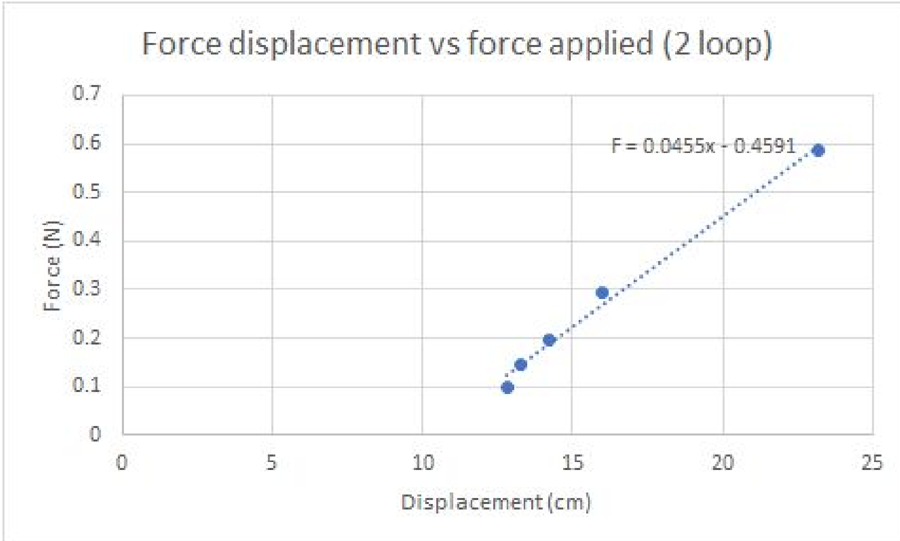


Figure 21: The relationship between force displacement and force applied onto the elastic string with 2 loops. The relationship between the displacement and force has an r value of 0.98 which has a strong linear relationship. The spring constant value k is calculated to be 0.0455 from this linear relationship.

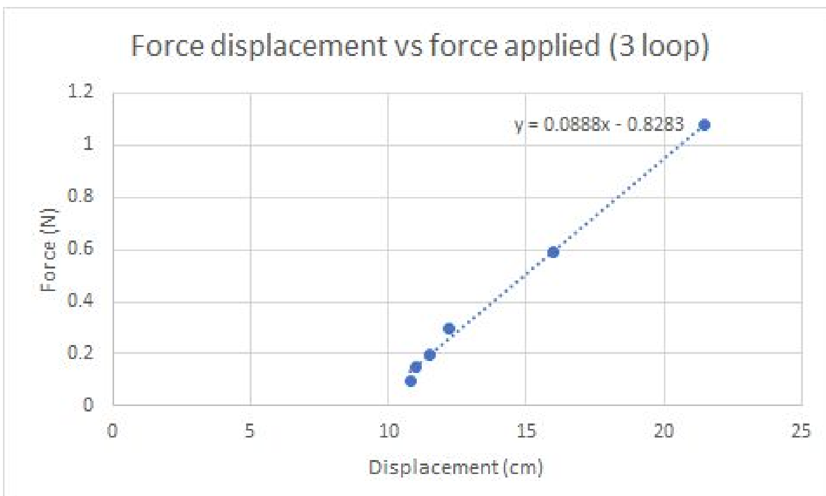


Figure 22. The relationship between force displacement and force applied onto the elastic string with loops. The relationship between the displacement and force has an r value of 0.98 which has a strong linear relationship. The spring constant value k is calculated to be 0.0888 from this linear relationship.

For the elastic string with 2 loops, the elastic string force would exhibit a force of F = 0.0455 N/cm * 2 cm = 0.091 N. For the elastic string with 3 loops, the elastic string force would exhibit a force of F = 0.0888 N/cm * 2 cm = 0.18 N. Both of these values are speculated to be relatively too small for the needs of the structure, which will be explained in the next section. An alternative elastic string would need to be sourced in order to have the performance of what is needed for this structure.

Engineering Analysis: Force Transfer

To analyze the transfer of force between the servo motor, ball and the rib cage, a free body diagram (FBD) was created, and an equation of motion derived from it. The FBD is shown in Figure 23.

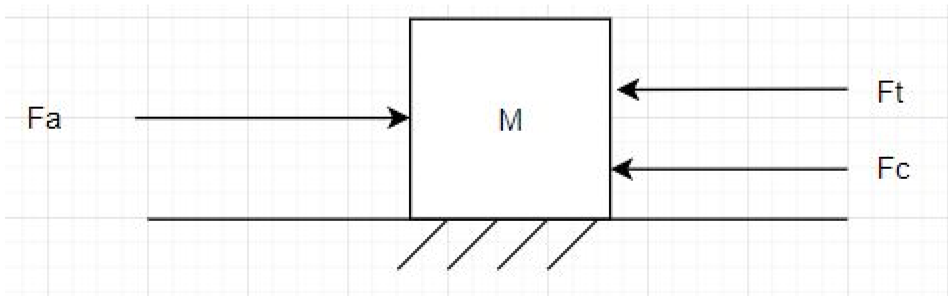


Figure 23: Fa is the force due to the servo motor, Ft is the force due to tension, Fc is the force due to compression and M is the mass of the ball and ribs.

In defining the model the engineers considered what information they desired to procure from it. They desired to know the ideal material for the ball and the force required by the servo to displace the ribs. To solve for these parameters it was helpful to have the mass include the ball and ribs. This allowed the engineers to internalize any interactions between the two masses and therefore not have to account for them in the equation of motion. In accounting for the compressive force, there was the possibility of treating it as a spring force (kx) and mathematically equating it to a modulus (E) via

$$k = E * \frac{A}{L} \quad \text{Eq (3)}$$

Where k is the spring constant, A is the cross-sectional area and L is the length. However, the modulus of many foams aren't given but rather psi for % compressed. The engineers desired a 25% compression and multiplying psi by an area gave us the force absorbed due to compression. Some assumptions taken into consideration when creating the model were:

1. The force of friction is negligible

2. The force exerted over the ball will only be over the area of the servo plate (4 in^2).

3. All the ribs are in contact with the ball at all times

Concerning assumption 1, there will be forces of friction between the ball and thoracic cavity and at the joints of each rib but these were treated as negligible. Concerning assumption 2, the thoracic cavity will exert a force on the ball over an area, but these forces are indeterminable as of now. Using the free body diagram one can observe that the majority of the force transferred from the ball will be in the direction of the hinged ribs, which is the direction accounted for. Concerning assumption 3, the ball/ribs are not experiencing a constant force due to tension all the time. It changes with time. Calculations were made using the maximum force exerted on the ribs/ball due to tension.

The equation of motion for the FBD is:

$$MA = Fa - Fc - Ft$$

Eq (4)

Mass (M) and force of compression (Fc) are material dependent parameters. Acceleration (a) can be solved using the mechanical requirements from Problem Definition. Force of tension (Ft) can be solved empirically but can also be changed depending on need. Force due to the servo (Fa) is a function of the other parameters.
To Solve for Fc and M variables, the engineers chose McMaster-Carr Super Cushioning Foam Ball. This material choice provided the desired compressive value of 25% when 0.5 psi is applied. It also is manufactured as a sphere which means it requires no additional manufacturing. The diameter of the sphere is 4 inches, its density is 1.5 lbs/ft3, and its volume is 0.0194 ft3. Using these values Fc and M can be calculated.

$$Fc = 0.5\,psi * \frac{6894.76Pa}{1\,psi} * \frac{1\frac{N}{M^2}}{1Pa} * \frac{1M^2}{1550\,in^2} * 4in^2 = 8.89\,N$$

Eq (5)

$$M = 1.5\frac{lbs}{ft^3} * \frac{4.448\,N}{1\,lbs} * \frac{1kg * 9.81\frac{M}{s^2}}{9.81\,N} * \frac{1}{9.81\frac{M}{s^2}} * \frac{ft^3}{1728\,in^3} * 33.5\,in^3 = 0.0132\,kg$$

Eq(6)

Fc was found to be 8.89 N while M was found to be 0.0132 kg. To solve for acceleration the fastest response time required by the servo, which is during a cough, was used.

$$x = 0.5at^2 + ct + c$$

$$@t = 0\,, x = 0\,,$$

$$c = 0$$

$$x = 0.5at^2$$

$$@t = 0.1\,, x = 0.02\,m$$

$$a = 4\frac{m}{s^2}$$

Eq (7)

A full stroke of 4 cm happens between 0.2-0.5 seconds which means the largest acceleration value is 4 m/s^2 . To solve for tension the empirically derived values were going to be used. It was found that these values were too low because the force of tension must be greater than the force of compression, otherwise the ball won't compress but only displace. The force of compression was calculated to be 8.89 N so the minimum value of tension must be approximately 9 N. By using an elastic material with a higher modulus this value can be achieved. Using the previous calculated values, the force required by the servo can be calculated.

$$Fa = Ma + Fc + Ft$$

$$Fa = 0.0132\ kg * 4\frac{m}{s^2} + 8.89\ N + 9 = 17.94\ N\ (4\ lbs)$$

Eq(8)

The force required by the servo was found to be 4 lbs. The engineers have a confidence level of about 25% in the results they found. This is because there may be forces accounted for in the assumptions that are significant and they are not accounted for in the equation of motion.

Engineering Analysis: Mechatronic System

Research for this section was largely influenced by the team's concerns for failure related to mechatronics. The code for the microcontroller was developed to be used in empirical testing to further tweak the specific parameters in the code. The code output to the linear servo will be a repeating position command based on the code using sine waves and pulse width modulation (PWM) signals. The servo can travel to a specific analog position upon receiving the command. This will address the critical failure "unable to imitate coughing/breathing gestures". The code can also be used in conjunction with additional empirical testing to see if the encoder value will fall out of sync. Ultimately, the structure of the code defines input as a person within 3 ft of proximity sensor. The output is defined as the linear servo moving by 10% or 20% of its resting length.

Figure (24) below is the first prototype of the Arduino code.

```
// import packages. initialize variables.
#include <Servo.h>
Servo myServo;
int sensorPin = 0;
int pos = 127;
int amplitude = 127*0.1;
float frequency = 0.2;
int[1/frequency*1000] sinArray; // average breath is 5 seconds ms
void setup(){
```

```
        mySerVo.attach(9); // attach servo to pin
        Serial.begin(9600);
        for(int time = 0; time < sinArray.length; time++){
              sinArray[time] = amplitude * sin(2*pi*frequency*time/1000)+127;
        }
}
void loop(){
        // if proximity sensor is active, run a breathing simulation
        if(analogRead(sensorPin) > 3/5 * 1023){
              breathe();
        }
        else if (pos != 127){
              pos = 127;
              mySerVo.write(pos); // reset puppet if sensor is not activated
        }
}
void breathe(){
        for(int i = 0; i < sinArray.length; i++){
              pos = (int) sinArray[i];
              mySerVo.write(pos);
              if(random(1, 10) == 5 && i < sinArray.length/4){ // 10% chance to cough during inhalation
                    int numCoughs = (int) random(1,4); // between 1 and 3 coughs
                    for(int i = 0; i <= numCoughs; i++){
                          cough();
                    } break;
              } delay(1);
        }
 }
 void cough(){
        pos = 127-(127*0.8)*140/255;
        mySerVo.write(pos);
        delay(200);
        pos = 127;
        mySerVo.write(pos);
        delay(200);
 }
```

Figure 24. First prototype of Arduino code.

Packages are imported and variables are initialized in lines 1 to 8. In line 6, the amplitude is determined as 10% of the resting linear servo position. In line 6, the frequency is determined to be 0.2 Hz, based on our research that indicated an average breath duration was 5 seconds. In line 8, an array of length 5000 is instantiated to store the sine position at every millisecond.

In lines 12-15, the sine values used to represent the natural breathing pattern are calculated and stored using the array. The formula is based on $Asin(2\pi\omega t) + B$, where A is the amplitude, ω is the frequency, t is the time, and B is the initial displacement.

In line 18, the position of the proximity sensor is checked. The sensor has a range of detection of 5 feet, but we want to trigger the breathing function at 3 feet. analogRead() has a range of 0 to 1023. The ratio $3/5 \cdot 1023$ represents the scaled voltage reading for detection. In lines 21 to 25, the linear servo is reset to its default position if there is no detection.

Lines 26 to 37 represent the breathing function. Values from the sine array are retrieved every millisecond. In line 30, there is a 10% chance to cough during an inhalation. An inhalation is defined as a part on the sine wave that has a positive value and a positive first derivative. If the chance for coughing was successful, a random number of coughs between 1 and 3 inclusive are performed.

Lines 38 to 45 represent the coughing function, which is modeled by a PWM signal. In line 39, the analog position of the servo is calculated to contract by 20% of its original resting length. The lung remains contracted for 0.2 seconds before resetting to its natural position, and waits another 0.2 seconds.

Risk Assessment

In performing risk analysis, three main areas with risk for functionality of the design were identified. These were the balloon/ball system popping, the rib joints failing to fatigue, and the mechatronics not properly emulating human breathing. From these failure modes, the balloon/ball popping was selected as the highest risk due to it being the most likely to happen, combined with rendering the design completely nonfunctional if it fails. The balloon has a fairly high likelihood of failing, due to being in a high cycle movement as well as being pressurized. If it fails, the ribs would no longer expand as the linear actuator pushes out, which would cause the motion to stop completely.

In order to mitigate the risk of the balloon popping, several possible design changes were looked at. After comparing the different changes, we decided to change from using a fluid filled balloon/ball, to using a piece of spherical foam. This completely eliminates the problem of the balloon popping as well as making the part much more durable in fatigue. This change eliminates the popping concern and only leaves fatigue left. Due to the foam ball being extremely durable in this application, it is now more than acceptable for the expected wear.

Solution developments

Component finalization

Once the basic structure of the circuit was determined through analysis, the components themselves were able to be selected. The most important piece of the design, the microcontroller, was chosen to be the Arduino Uno, as it outmatched its competitors for price and flexibility. The design team also has experience using it. The second most important piece, the proximity sensor, was chosen to be the same model that the stakeholder typically uses in order to increase the usability of the design. The model, the Maxbotix Ultrasonic Rangefinder - LV-EZ1, has a range of 6in to about 20ft, making it a great choice for our design because museum exhibit sizes change drastically from building to building. Finally, we decided to use a linear servo instead of a linear actuator, as the linear servo is fundamentally identical to the actuator; it just comes with slightly more circuitry in order to make it respond to positional commands instead of commands to extend or retract. This reduces the extra components we will need to complete the circuit.

CAD Model Development

In the development of the CAD model, the system was first developed as the general shape. To do this the spine was first designed to be the correct height, and to allow for easy assembly and disassembly of the rib pieces. The rib pieces were then designed to mimic human ribs, while being symmetrical and with simple geometry. This preliminary design can be seen below in Figure 25.

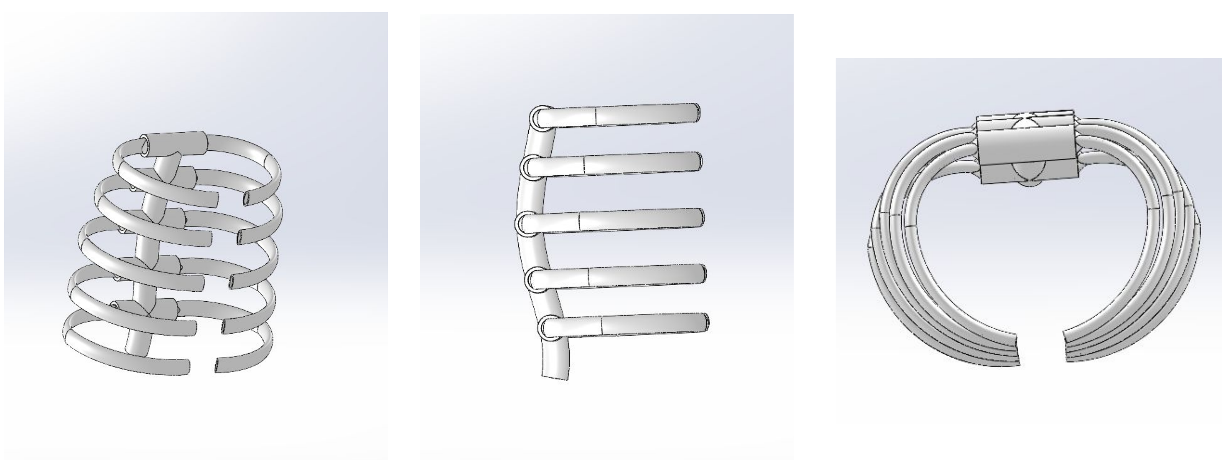


Figure 25. Multiple views of ribcage CAD design.

After the preliminary design for shape, the motion mechanism was then added to the CAD. Using a joint design similar to the one shown in Figure 15, the ribs were split into two parts being joined by the joint. The joints connect the ribs at the middle, with only one per rib allowing one degree of freedom. This joint design can be seen in Figure 26.

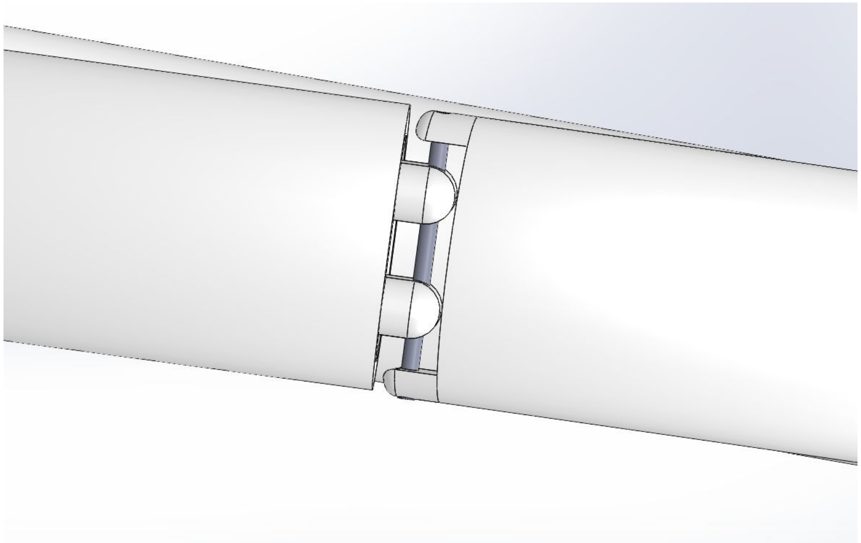


Figure 26. Close up of the first joint design.

After the joints were added the mount for the linear actuator was added, based on the actuator selection from above. The foam ball chosen from McMaster Carr was also added to the CAD model, as well as the mounting plate to attach it to. This updated CAD can be seen in Figure 27.

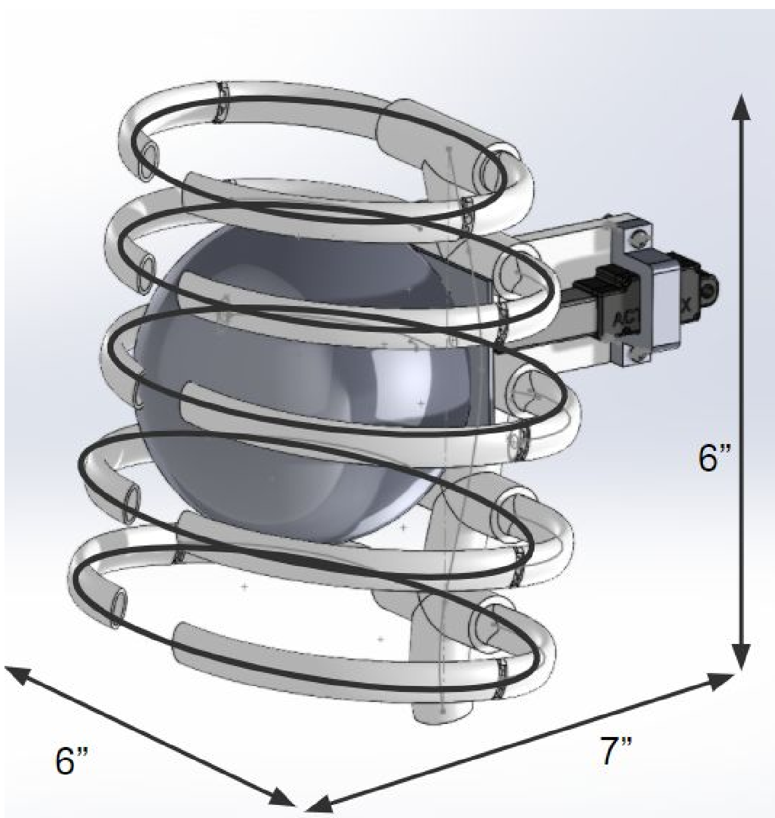


Figure 27. Picture of final CAD model with linear actuator and foam ball added.

This is the penultimate design, with small changes coming before the final. The bands going around each ring of the ribs represents an elastic band that will be used to contract the ribs after the foam ball pushes on them. The foam ball is adhered to a plate at the end of the linear actuator, which supplies an end for the ball to contract between, the other being the ribs. The linear actuator is mounted to the back of the spine using the given mounting brackets. The joints were not ideal to 3D print, so there will be a design change on them before the final design. The first iteration of these new joints was designed, however without the ability to empirically test them, there is risk in using them directly in a final design. These joints can be seen below in Figure 28.

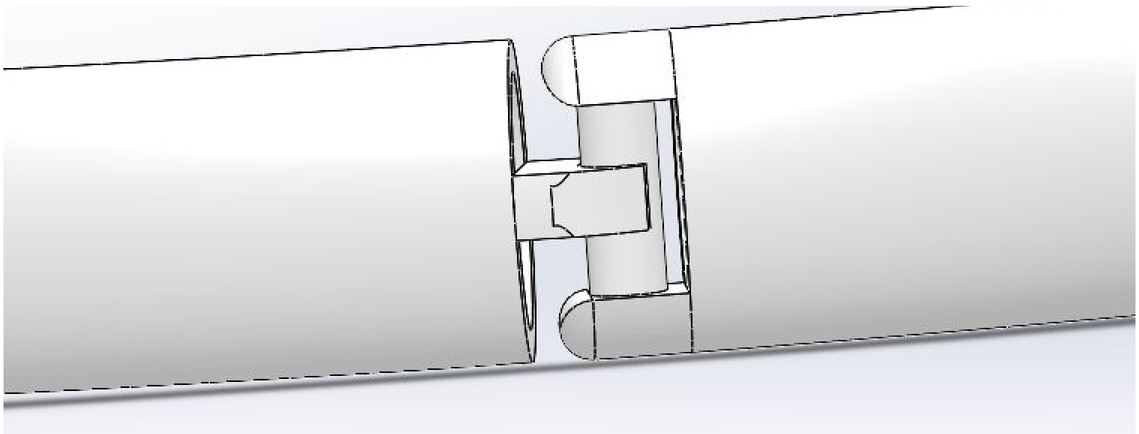


Figure 28. Modified joint for easier 3D printability.

This second iteration of joints involves less parts by rigidly attaching the pins to one end of the ribs, as well as should make the parts printable, because all dimensions were scaled up and the hole that wasn't printing was completely removed. However, because it can't be tested without printing, the possibility of it needing more redesigns is a concern.

Detailed Design Solution

Rib Cage Structure

This section presents the final design for the Rib Cage Structure. The rib cage was modeled to emulate human ribs while being durable enough to withstand the cyclic load while being on display. The structure also had to be around 6 in. tall, and capable of expanding the lung volume at least 50% increase from the resting state. The rib cage is entirely printed out of PLA plastic to save weight and ease of manufacturing the complex geometry. There are elastic bands running as loops through each set of ribs which allows for proper retraction. An image of the rib cage structure can be seen in Figure 29.

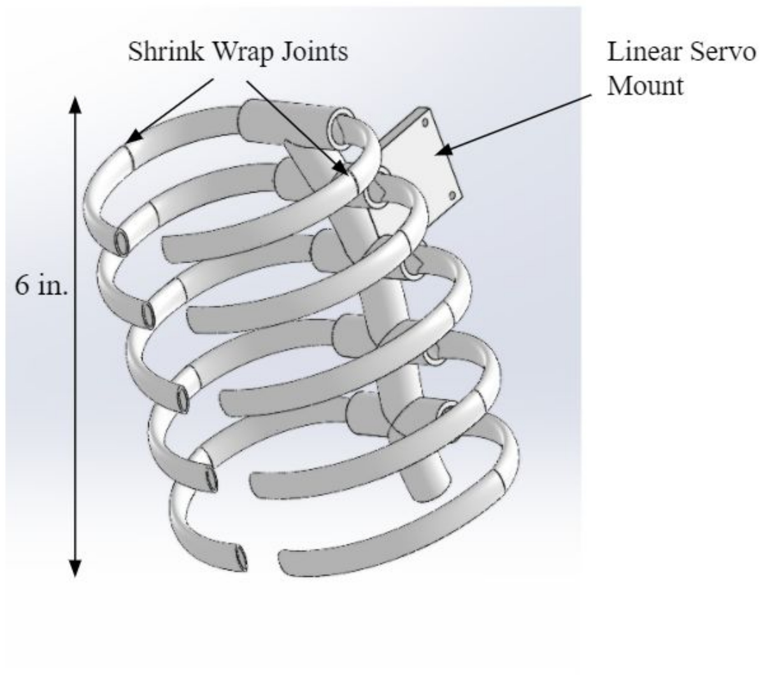


Figure 29. Isometric view of rib cage CAD model.

In order to have the joints consistently 3D printable, the printed joints were removed in favor of a shrink tube joint design. This allowed for the ribs to be printed on the desired scale, without the joint failing due to the resolution limits in the available 3D printers. This design involves using a clear electrical shrink tube to combine the two halves of each rib, which completely erases the tiny complex parts of the joint that cause 3D printing issues. An image showing a zoom in of this design can be seen in Figure 30.

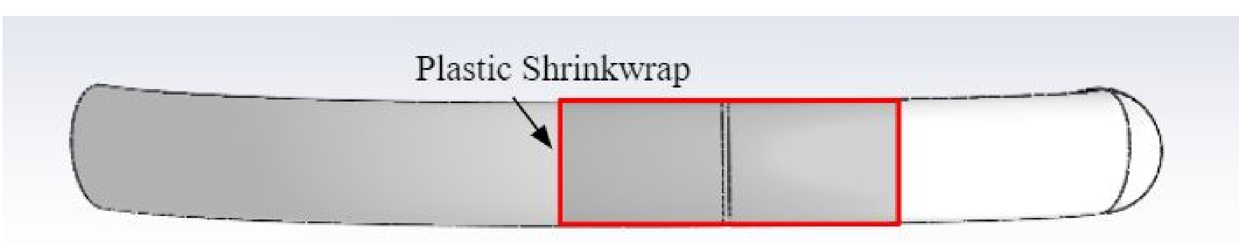


Figure 30. Zoom in of the joint design highlighting the shrink tube joining design.

Linear Servo Subsystem

This section describes the design behind the actuating motion subsystem. This design was chosen due to its simplicity, as well as its minimal amount of moving parts. The basic principles of the design are a foam ball is attached to the linear servo by a plate to disperse the load. The foam ball is sourced from McMaster and is attached using adhesive on the face that touches the actuator plate. The linear servo can then be extended pushing the ball against the ribs and causing an expansion effect. This system needs to be able to force the ribs out far enough to expand at least 50% increase in volume, and needs to be able to produce a 9N force at its maximum. This system also needs to be able to move at least 25 mm/s in order to properly emulate coughing. An image of this system can be seen in Figure 31.

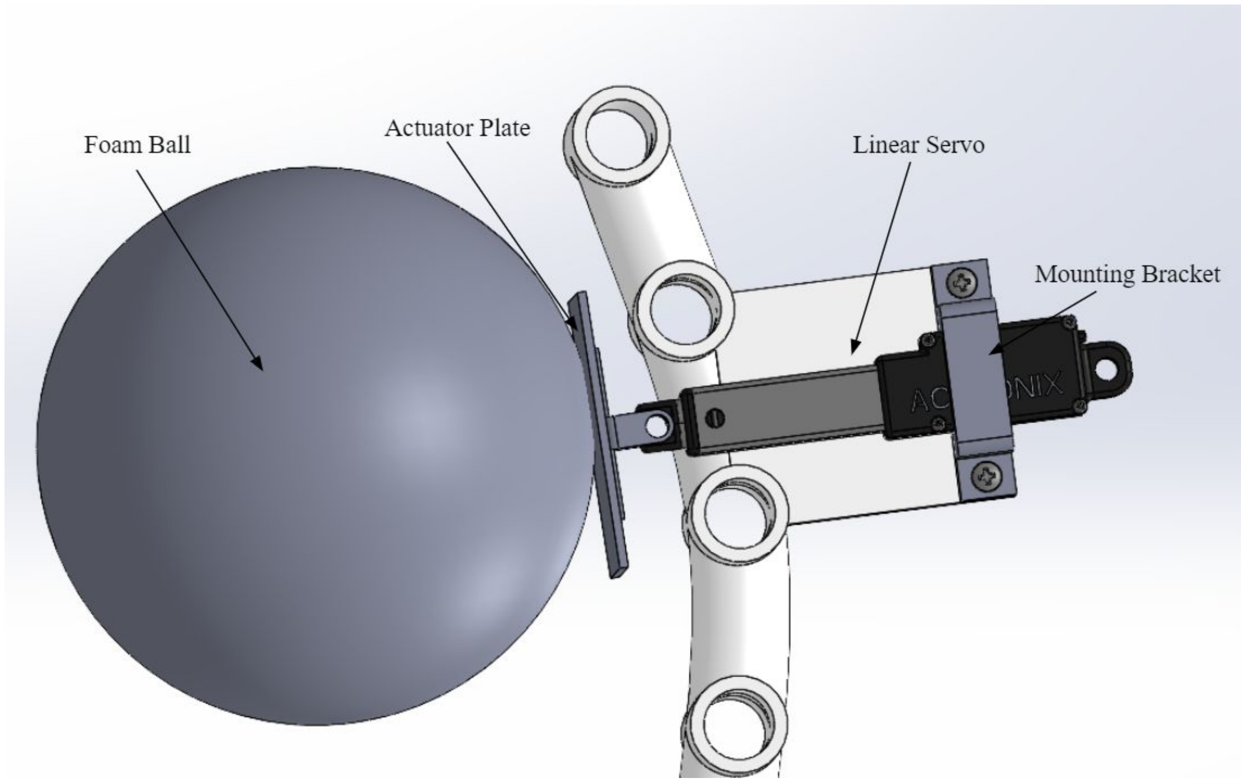


Figure 31. Highlights the linear servo system, showing how motion is transferred to the foam ball.

In Figure 31 above, the mounting bracket used to connect the linear servo is the stock one that comes with it, and is connected to a plate that is a part of the 3D printed spine structure. The actuator plate is 3D printed, and connected to the linear servo using the stock bolt to secure it. The linear servo moves slightly offset to the spine, to avoid any interference between the arm of the servo and the spine structure.

Mechatronics System

The mechatronics system consists of an Arduino Uno, the Actuonix L-12-R linear servo, a McMaster Foam ball, and a Maxbotix Ultrasonic Rangefinder proximity sensor. The code for the arduino is explained in depth starting on pg. 48 as a part of the verification section, which dictates how the logic behind the breathing. The system is always running, however motion is only activated when the proximity sensor receives a signal in the desired range. This system is run as an open-loop due to the controlled environment it is run in. The basic flow of the system can be seen in Figure 32.

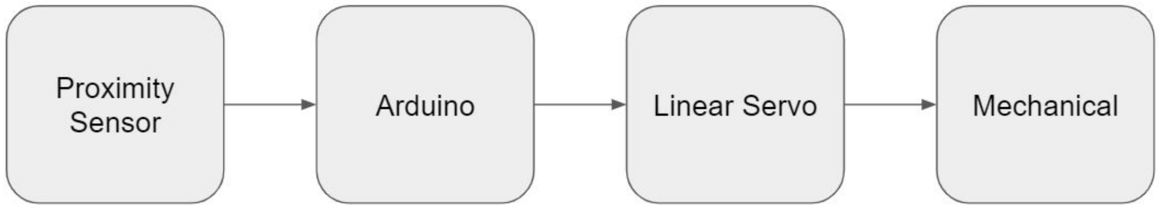


Figure 32. Flow showing the basic parts controlling the mechatronic system.

Verification

Foam Ball model

The engineers desired to model the interaction between actuator, actuator plate and foam ball, to observe how this subsystem would perform and if the calculations and design choices made so far were appropriate. Unfortunately, due to Covid, only particular aspects of this subsystem could be modeled. A model/experiment was created to determine the pressure required to compress the foam ball and these experimental values were then compared to the values given by the manufacturer. There was some concern that the values given by the manufacturer did not take into consideration the geometrical shape of the sphere. An empirical model would be able to resolve this question.

It is hypothesized that to convincingly imitate breathing behavior, the servo motor must exert a force on the servo plate, such that the foam ball is compressed between the servo plate, the hinged ribs and other parts of the thoracic cavity. The desired compression value is 25% of the foam balls diameter. This means that by compressing the spherical foam ball, which has a 101.6mm (4 in) diameter, by 25% it will change the compressed diameter to 76.2 mm (3 in). To model this interaction an experiment was performed with the goal of determining the pressure required to compress the foam ball for a range of percent compressed values. Due to Covid, limitations were placed on what the experiment could accomplish. The following experiment cannot take into account the area over which the hinged ribs and other portions of the thoracic cavity exert a force on the foam ball. It also cannot take into account the magnitude and direction of the forces exerted by the hinged ribs and other portions of the thoracic cavity on the foam ball.

Procedure: An experiment was conducted to measure the pressure required to compress the Ultra Soft Foam Ball by 12.5%, 25% and 37.5% which is equivalent to 12.7 mm (0.5 in), 25.4 mm (1 in) and 38.1 mm (1.5 in) change in diameter. This change in diameter is later referred to as displacement. The foam ball was placed on top of a scale and its initial height was recorded. A force was then exerted on it by a clamp, over an area of 2580 mm^2 (4 in^2), in the vertical direction. The foam ball was compressed to a specified final height corresponding to a percent compressed value. The final height, the reading on the scale, and the area of contact between the compressed ball and scale were recorded. Ten trials were conducted for each percent compressed value. The following figure illustrates the experimental setup.

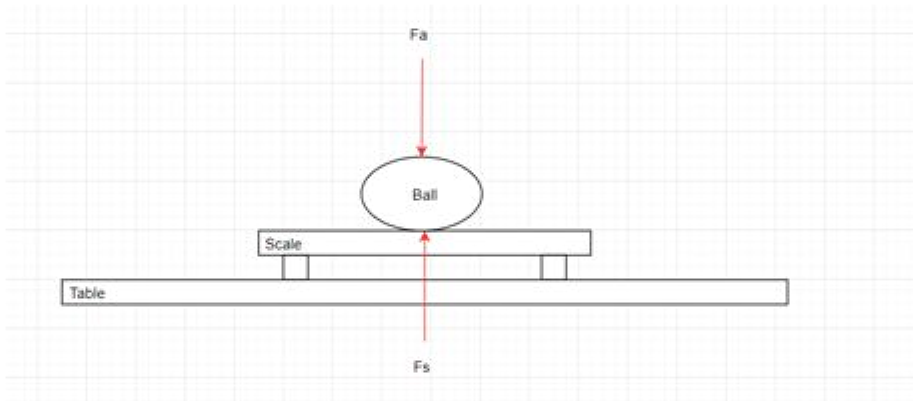


Figure 33: The FBD diagram illustrates the experimental setup and the forces exerted on the foam ball due to Fa (force due the servo plate) and Fs (force due to the scale). In the figure, the foam ball is in a state of compression.

The following two figures are diagrams of the actual experimental setup.

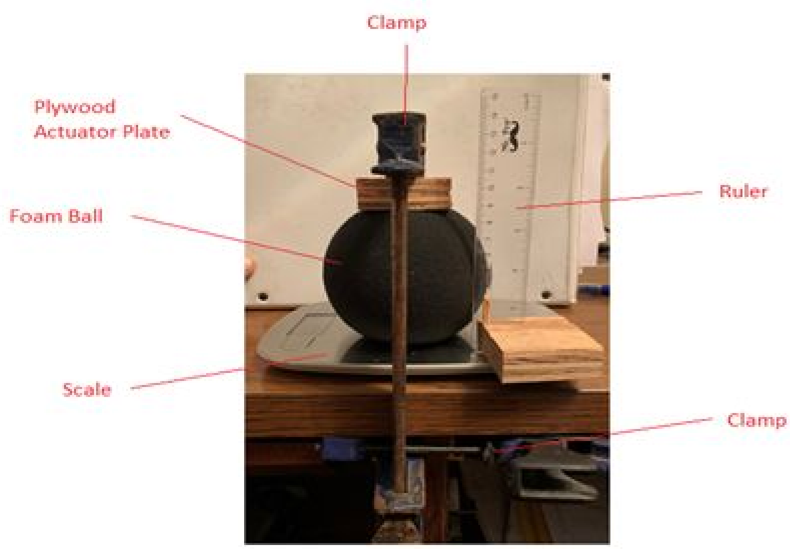


Figure 34 and 35: The actuator plate is glued to the vertical clamp and the ball is centered under the actuator plate. The vertical clamp exerts a force downward and compresses the foam ball to a height corresponding to a specific percent compressed value.

Aspects of the experiment that may have led to imprecise measurements is the distance of approximately 1 inch between the ruler and the servo plate. This potential inaccuracy may have influenced the displacement values. Another aspect that may have led to inaccuracy is the hysteresis of the scale. The scale demonstrated a decrease in histersis at lower forces and an increase at higher forces. To obtain some consistency in measurements, values were only recorded when a duration of 1 second passed before a value changed on the scale. The hysteresis of the scale influences the experimenter's confidence in this model.

Results: The average force on the scale when the foam ball was compressed by an average displacement of 14 mm (13.75%), 27.8 mm (27.5%) and 40.9 mm (40.25%) was 4.5 N, 8.2 N, and 14.1 N respectively. The average displacement values do not correspond exactly with a 12.5%, 25% and 37.5% compression values due to the lack of precise instruments. Figure X plots all the displacement values and the corresponding force on the scale.

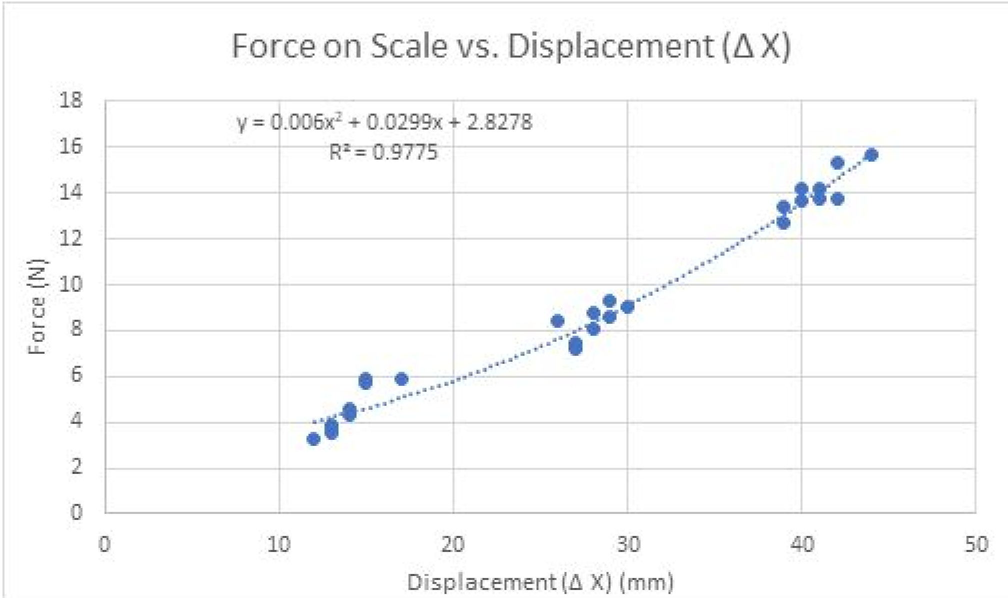


Figure 36: A line of best fit runs through the data points to allow for values to be calculated that lie between the data points. The lack of precise measurements can be attributed to the hysteresis in the low quality scale.

The area of contact between the ball and scale when the foam ball was compressed was 1,963 mm^2 (3.04 in^2), 3,318 mm^2 (5.14 in^2) and 4300 mm^2 (6.67 in^2) for their respective displacements.

To solve for the pressure required to compress the foam ball by 25%, the forces on the foam ball must be solved for using the equation of motion derived from the FBD and the empirical data, where *M* is mass and *a* is acceleration.

$$Ma = Fs - Fa$$

$$a = 0$$

$$Fs = Fa$$

Eq (9)

The equation for the line of best fit was then used to solve for the Fs

$$Fs = 0.006x^2 + 0.0299x + 2.28278$$

Eq (10)

$$x = 25.4\ mm$$

$$Fs = 7.46\ N$$

Eq 2 is then used to solve for the pressure at 25% compression ($P_{25\%}$)

$$P_{25\%} = \frac{Fs}{A_a} + \frac{Fa}{A_s}$$

$$P_{25\%} = \frac{7.46\ N}{2580\ \mathrm{mm}^2} + \frac{7.46\ N}{3318\ \mathrm{mm}^2} = 5140\ Pa = \ 0.75\ psi$$

Eq (11)

Where A_a and A_s are the areas of contact for the servo plate and scale respectively.

Conclusion: These results differ from the manufactures value of 0.5 psi for a 25% compression although a direct comparison is difficult to make. Using the line of best fit, the empirical value differs from the manufacturer's value by 50%. This could be attributed to imprecise instrumentation or the manufacturer's value may not take into account the geometry of the sphere. Their value could be based on testing a rectangular test sample composed of the same foam material. If this were the case, one would expect that the value for the rectangular sample would be higher than a spherical test sample. This would mean the data collected by this experiment is even more inaccurate. Action will be taken to contact McMaster-Carr to determine how the foam balls specifications were determined. Whether the manufacturers specifications or this experiments data reflect the true compressive values, it is clear that the Ultra Soft Foam Ball will be suitable for the artificial lung mechanism.

Thoracic cavity prototype

The thoracic cavity prototype went through the second round of 3D printing fabrication. All parts of the thoracic cavity are fully printed with modified and finalized design. Some of the modifications made were simplifying the joint design after multiple rounds of evaluation on risks and design for assembly (DFA), as well as improving tolerancing of the spinal cord opening to allow the close fit between the rib pieces and the spinal cord to be better fitted. Figure 37 below shows the fully assembled prototype. The prototype is 3D printed using Ultimaker 5 with FDM technology. The printed material is PLA.

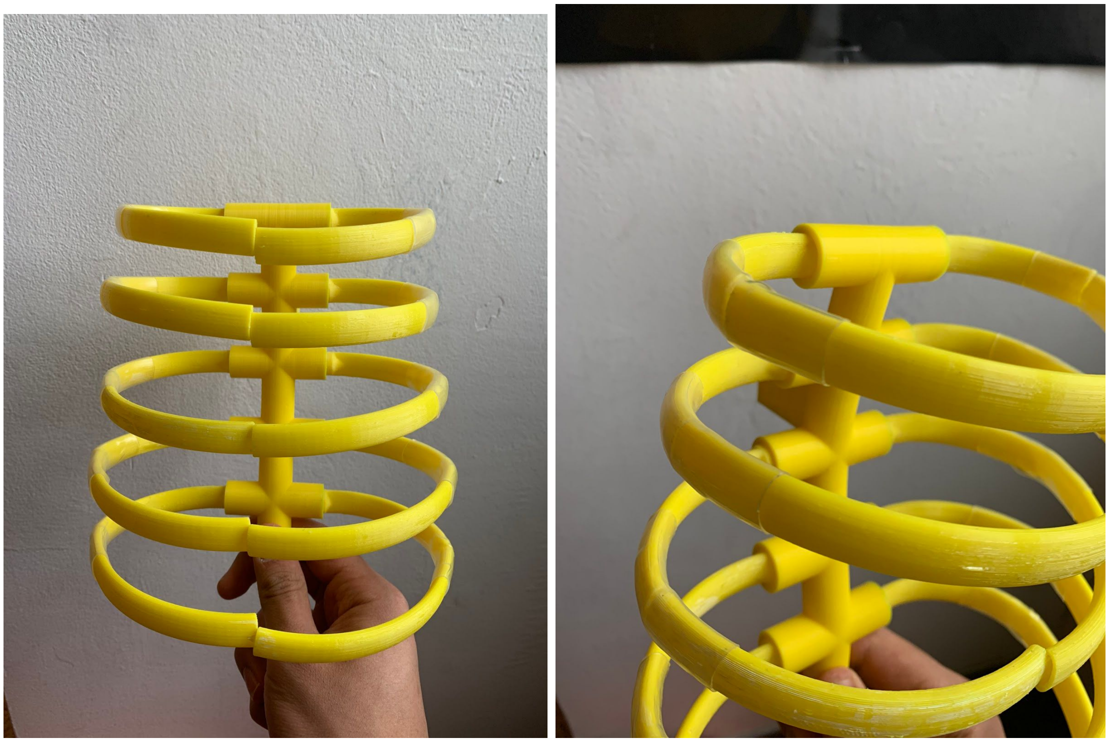


Figure 37: Fully assembled prototype of the 3D printed thoracic cavity. Heat shrink tubings were used to join two rib pieces together (right).

First, the joint design between two rib pieces went through the third design iteration change. This design decision was made because the resolution of the 3D printer would not allow anything less than 0.4 mm tolerance for FDM printing. The intricate details of the original joint design would require at least 0.1 mm resolution to be able to achieve the quality of detail for a potentially functional joint. On top of that, the joint has a high risk of failing or fracture because of how small the joints are compared to the rib parts itself. Based on all the reasoning above, joints are ultimately eliminated altogether. Plastic heat-shrink tubings (McMaster Carr Heat-Shrink Tubing ID: 0.5 to 0.25 after shrink, transparent) were used to join the two rib parts together instead, as shown in Figure 37. An industrial heat gun was used to heat shrink these heat shrink tubings at 250℉, as required by the specifications provided by McMaster Carr.

The design justifications for using heat shrink tubing as our final design choice for joining between two rib pieces is mainly based on the requirements of simplicity, expandability, and reliability of the mechanism. First, the elimination of the joints allows more clearance for the elastic band to run through the interior of the thoracic cavity structure as well as eliminating the potential of assembling failure or complications with previous designs. Second, the material of the heat shrink tubes is Polyolefin Plastic, which allows movement at the joints to perform the expansion and contraction motion of the thoracic cavity.

Another design modification made on the final prototype of the thoracic cavity system was using nylon cords (0.8mm Fun Pack Stretch Cord) instead of elastic cotton threads to bind each set of the rib cages together with a higher elastic tension force. Since this design change was made after the semester has transitioned to fully online due to COVID-19, a verification test to acquire force displacement data could not be conducted due to the lack of test setup at home and the closing of in-person labs. By observation, the nylon cords do have a higher elastic tension force than the elastic cotton threads that were previously tested. The nylon cords also satisfy the design requirements of holding the thoracic cavity together and allow expansion and contraction movement from its elastic properties.

Arduino/motor interface

Figure 38 illustrates the most current version of the Arduino program.

```
#include <Servo.h>

Servo myservo;

int pos;
float per;
float pos_sin;
int sensorPin = 0;

void setup() {
  myservo.attach(7);
}

void loop() {
      // if proximity sensor is active, run a breathing simulation
      if(analogRead(sensorPin) > 3/5 * 1023){
            breathe();
      }
      else if (pos != 90){
            myServo.write(90); // reset puppet if sensor is not activated
      }
}

void breathe(){
  int randomDelay = (int) random(20, 40);
  for (pos = 0; pos <= 100; pos ++){
    per = 2 * PI * pos / 100;
    pos_sin = sin(per);
    myservo.write(90 + (90 * pos_sin));
    if(random(1,50) == 5 && pos < 25){
      int numCoughs = (int) random(1,4);
      for(int i = 0; i <= numCoughs; i++){
        cough();
      } break;
    }
    delay(randomDelay);
```

```
37    }
38  }
39
40  void cough(){
41    myservo.write(0);
42    delay(200);
43    myservo.write(180);
44    delay(200);
45    myservo.write(90);
46    int randomDelay = (int) random(100, 400);
47    delay(randomDelay);
48  }
```

Figure 38: Modified Arduino program. Updates made to the calculation of retrieval of sine values and period of breathing. Servo `write()` values were updated to accommodate a continuous servo motor.

The Arduino program is modified so that sinusoidal values are no longer stored and retrieved from an array, but are calculated during the breathing method. This change was performed because retrieving values from an array resulted in a jerky motion, rather than a smooth acceleration. This calculation is performed on lines 27-29. Additionally, the period of each sine wave is determined by a random delay on lines 25 and 36.

Due to constraints from the pandemic on shipping, the linear servo we wanted to test for the prototype did not arrive on time. However, this code was tested using a continuous servo motor. Thus, modifications were made to the code to accommodate this change. Notably, the `write()` method on the continuous servo behaves differently compared to a standard linear servo. For a continuous servo, `write(90)` represents no movement. `write(0)` rotates the motor at full speed in one direction, and `write(90)` rotates the motor at full speed in the opposite direction.

From physical testing, one potential improvement that was observed occurred during the coughing motion. As shown in lines 40 to 48, a PWM signal is still being used. However, the coughing motion was perceived to be too slow and therefore unnatural, even with the motor operating at full speed in both directions. One potential solution could be using a separate motor with a faster gear reduction.

Minimum viable deliverable

Due to COVID-19 class plans, the minimum viable deliverable had to be adjusted accordingly. After discussing between the team and sponsor, we have agreed on having an engineering simulation video to be the minimum viable deliverable by the end of this class. Unfortunately, two of our teammates currently do not reside in Michigan, which makes prototype fabrication challenging. Although building a functionable prototype is not within the scope of this project anymore, the team still plans on purchasing selected components to assemble some of the subsystems as a reach goal. If time allows, the team is prioritizing building the lung subsystem first, as it is the most experimental and considerably challenging subsystem. By doing so, we hope to present this preliminary concept to our sponsor. Then, the rest of the subsystems can also be implemented if there is extra time by the end of this semester.

Project Plan

Project overview

To plan out and track our progress throughout the project, a gantt chart outlining the major milestones was created. This will be used to ensure we meet all of our deadlines and to keep us aware of upcoming milestones. This map of very high level how we expect the project to go this semester can be seen in Figure 39.

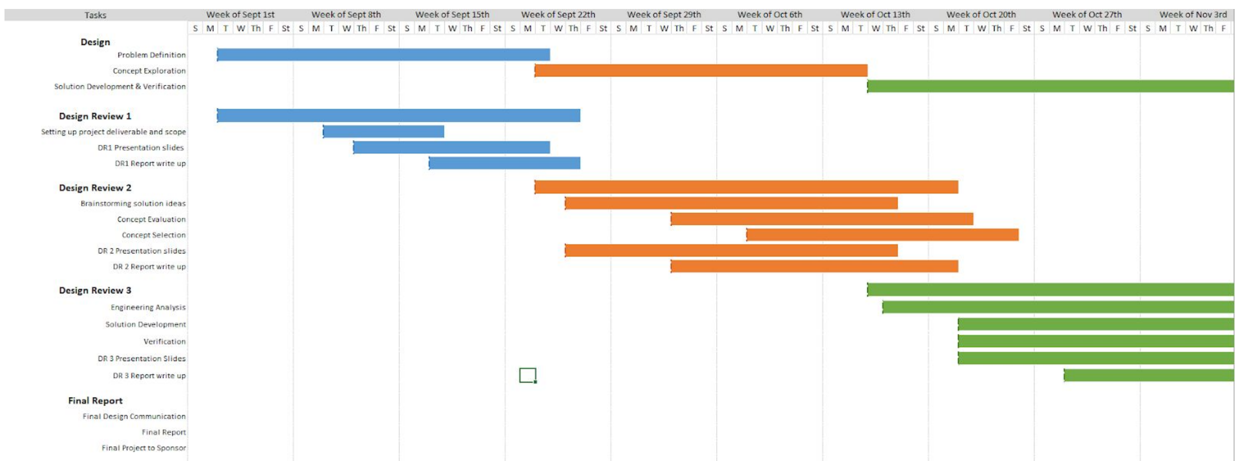


Figure 39: This is the outline of what we need to get done by the end of this project. It holds all the major deadlines currently known to us. The different colors represent the different stages of development. Blue is problem definition, orange is concept generation, and green is solution development.

The project overview is then taken and split into the subtasks for each of the major tasks from Figure 39 above. This breakdown is done using Asana which allows us to create as many subtasks as necessary while being able to assign internal deadlines and divy out the responsibilities. An example of some of these breakdowns can be seen in Figure 40.

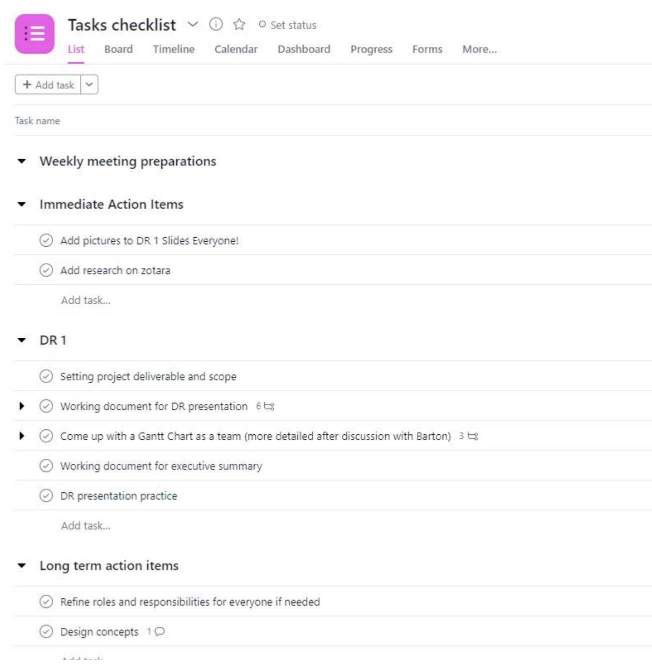


Figure 40: Shows an example of how tasks are being broken down with Asana. This allows us to easily determine who's doing what and when everything needs to be done by.

Using these breakdowns, we were able to establish a plan for the project's immediate future. A more detailed breakdown of design, testin , and verification of major milestones is presented in table 12.

Table 12: List of soft due dates for design, testing, verification major milestones.

Program	Start Date	End Date	Primary Team Members
CAD Model	10/20/2020	10/27/2020	Peter, Tanvi, Richard
Engineering Analysis	10/29/2020	11/03/2020	Richard, Joe, Sam
Final Material Selection	11/03/2020	11/05/2020	All
Adams Simulation	11/05/2020	11/07/2020	Tanvi
3D printed part manufacturing (Optional)	11/07/2020	11/24/2020	Joe, Peter, Sam
CAD Model Finalization	11/14/2020	11/20/2020	Sam, Joe
Validation Simulation	11/18/2020	12/03/2020	Richard, Tanvi, Peter
Animation	11/18/2020	12/03/2020	All

Discussion and Recommendations

To improve on the current design, the engineers would need more input from the task holder to direct their efforts. The engineers were only able to meet with the task holder twice, at the beginning of the project and during Problem Definition, due to busy schedules and COVID-19. If the engineers could have met three more times with the sponsor -- two more times during Concept Exploration and another during Solution Development and Verification -- the final design could have met more of the sponsors desires/needs. A meeting during Concept Exploration would have allowed the sponsor to share her opinion regarding the actuator location and using a sphere for the lungs. A meeting during Solution Development and Verification would have allowed the design team to use remaining time in the semester to make final changes and further meet the needs of the sponsor.

Some strengths of the design are its simplicity and the breathing emulating a real person. The design is also very easy to maintain and manufacture, making any issues that come up in long term use easier to solve. The benefits of the simplicity of the design are twofold; it makes less room for any failure to happen while operating at an event, and it is very simple for the sponsor to add or modify the design to tailor to any future uses or as her artistic vision changes. This simplicity is also part of the reason the design is able to have smooth and lifelike breathing, which is one of the most important aspects of the design. Due to the project being more creative in nature, the ability to adapt to whatever needs the sponsor has is vital to the longevity of the design.

In the case that the sponsor or later 450 teams work more on this design, there are a few topics that should be revised or addressed that were not originally covered in the problem scope. In the case of this report, we were tasked with creating a ribcage approximation that can appear to breathe and cough, with code that can be integrated with a proximity sensor. Given more time and more access to in-person/on-campus facilities, our first recommendation would be to fully assemble all subsystems (actuator, sensor, arduino, ball, and ribcage) and observe and tune the parameters of the code to more closely simulate coughing and wheezing. Were we capable of doing this, our code would most likely look much different.

Beyond this, we suggest altering the top and bottom of the spine of the rib cage slightly to better integrate to the sponsor's idea of a full puppet. Depending on her vision of how it should be positioned (seated, standing, or lying down) and also of how she wishes to actually fabricate the head and legs, a few small adjustments to the puppet should be made. Cosmetically, the foam ball may also be cut and shaved into an oblong shape to more closely resemble lungs, and potentially bought or spray-painted a more anatomically accurate color than black. The sponsor also mentioned having the actuator positioned flush with or parallel to the spine using a simple 90-degree force transfer, and if this is still something that she wishes to incorporate, we would recommend looking into bevel gears or simple linkages in order to achieve this.

The sponsor would also like the mechanism to be durable over cyclic loading that the rib pieces undergo over the course of the exhibition. The team went through a few iterations of joint designs and came down to the heat shrink tubing solution. A more thorough discussion on making elegant joint designs using components like torsion springs would be worth exploring. Despite this project's scope as a single use, custom art piece, we also suggest pursuing avenues of fabrication for the ribcage that do not use 3D-printed plastic, since if this piece did end up being replicated on a larger scale, the manufacturing cost, time, and sustainability would become a concern. As it stands, this method is perfect for a custom design.

In preliminary observations of the linear actuator and the code, it seemed that the actuator we chose may not move fast enough to simulate a realistic cough once everything is assembled. We recommend being mindful about the limitations of the actuator and potentially sourcing a better one if full-system tuning cannot mitigate this issue. Alternatively, different mechanisms for contraction and expansion could be explored. For example, direct mechanization of the elastic string inside of the rib joints could produce the desired speed of contraction and expansion. The continuous servo was also noticeably loud. While the linear servo would be quieter, the quietest option would likely be a brushless DC motor with an encoder. In this case, a custom design would need to be created to turn rotational motion into linear motion. One idea for this could be to attach a pinion gear to the motor to move a rack translationally.

Conclusion

The project sponsor, Professor Heidi Kumao from the University of Michigan STAMPS School of Arts and Design, has tasked the team to create a kinetic lung mechanism that will be embedded in her puppet sculpture. The user requirements and engineering specifications were developed based on interviews the team had with Professor Kumao, including the geometric constraints, mechanical constraints, sound constraints and general usability. Since the project scope covers the intersection of arts, humanities, and engineering, one of the biggest challenges would be to quantify the metrics of the kinetic puppet in engineering terms to satisfy the needs for a piece of art, which could be subjective based on Professor Kumao's artistic design choices. The engineering analysis and solution development process is covered in this design review. From the rough draft of the final design presented from the last design review, the team dived deeper into the components of each of the subsystems and identified the failure modes of the puppet. Then, three of the main challenges from the failure are identified to conduct engineering analysis. By understanding the quantitative data and behavior of the mechanism, we were able to develop a CAD design with all the components implemented. The team will move onto finalizing the simulation for the last two weeks of the project.

Acknowledgements

The team would like to express gratitude towards our project sponsor, Professor Heidi Kumao, for allowing us to have such an amazing opportunity to work on such a unique and interdisciplinary project that expanded our learnings across engineering, arts, and humanities. We are thankful for the support and guidance throughout this project.

We would also like to thank our faculty mentor, Professor Kira Barton, for the support and guidance throughout this project, from providing helpful feedback to challenging the team to think more critically and become better problem solvers. This project would not have been possible without the technical advice and your help.

The ME machine shop staff, Charlie, Jon, and Don, have been so accommodating this semester despite the difficulties faced due to COVID-19, especially when the team had to place a huge 3D design order right before thanksgiving break. Thank you for your diligence and commitment to help students like us succeed. Our prototypes would not have been possible without the help of the machine shop staff.

The UM ME 450 Librarian, Joanna Thielen, has been a huge help for pointing us in the right direction with library resources, databases, and literature research. Thank you for your help and support throughout the semester and stopping by our Design Expo to communicate on the library resource feedback.

Finally, we would like to acknowledge the hard work of ME 450 instructional staff for making the senior capstone a valuable learning experience and being so accommodating, despite difficulties of online learning.

References

[1]Altose, Murray D. "Pulmonary Mechanics." *Fishman's Pulmonary Diseases and Disorders*, edited by Michael A. Grippi et al., 5th ed., McGraw-Hill Education, 2015, accessmedicine.mhmedical.com/content.aspx?aid=1122354876.

[2]Bellemare, François, et al. "Sex Differences in Thoracic Dimensions and Configuration." *American Journal of Respiratory and Critical Care Medicine*, vol. 168, no. 3, Aug. 2003, pp. 305–12, doi:10.1164/rccm.200208-876OC.

[3]Bendixen, Henrik H., et al. "Pattern of Ventilation in Young Adults." *Journal of Applied Physiology*, vol. 19, no. 2, Mar. 1964, https://journals.physiology.org/doi/abs/10.1152/jappl.1964.19.2.195?casa_token=aBStY3UBJUAAAAAA%3AG3Z_VdC2nVUZXdNX4FMR-LcLN7R90pT81-M4uboCrBHreXmme1YTccPeJIf7agRx8ZfUQB22qCBi&.

[4]Brandon, Kären E., and Rebecca M. Goldberg. "A Kinetic Sculpture Intervention for Individuals Grieving the Deaths of Family Members." *Journal of Creativity in Mental Health*, vol. 12, no. 1, Jan. 2017, pp. 99–114, doi:10.1080/15401383.2016.1184114.

[5]Chung, K. F. "Measurement of Cough." *Respiratory Physiology and Neurobiology*, vol. 152, no. 3, July 2006, pp. 329–39, doi:10.1016/j.resp.2006.02.001.

[6]Coates, Allan L., et al. "Do Sinusoidal Models of Respiration Accurately Reflect the Respiratory Events of Patients Breathing on Nebulizers?" *Journal of Aerosol Medicine*, vol. 12, no. 4, 1999, pp. 265–73, doi:10.1089/jam.1999.12.265.

[7]Dernie, David. *Exhibition Design*. 2006, https://books.google.com/books?hl=en&lr=&id=CalHMBYjdpoC&oi=fnd&pg=PA6&dq=museum+installation+kinetic+sculpture+design&ots=RLTi3WWY0y&sig=V5VjUyn4agHsT_PnDG-BkQSzBJU#v=onepage&q&f=false.

[8]Engineering ToolBox. https://www.engineeringtoolbox.com/. Accessed 8 Oct. 2020.

[9]EORGE SIMON, LYNNE REID, J. M. TANNER, H. GOLDSTEIN, and BERNARD BENJAMIN. “Growth of Radiologically Determined Heart Diameter, Lung Width, and Lung Length from 5-19 Years, with Standards for Clinical Use.” *The Department of Experimental Pathology, Instituttе of Diseases of the Chest, the Department of Growth and Development, Institute of Child Health, Guilford Street, and Civil Service College, London*, https://adc-bmj-com.proxy.lib.umich.edu/content/archdischild/47/253/373.full.pdf.

[10]Fanta, Christopher H. “Cough.” *Harrison’s Principles of Internal Medicine*, edited by J. Larry Jameson et al., 20th ed., McGraw-Hill Education, 2018, accessmedicine.mhmedical.com/content.aspx?aid=1155942996.

[11]Foucaud, Laurent, et al. “Modulation of Protective Reflex Cough by Acute Immune Driven Inflammation of Lower Airways in Anesthetized Rabbits.” *PLOS ONE*, vol. 14, no. 12, Dec. 2019, p. e0226442, doi:10.1371/journal.pone.0226442.

[12]Haji, Akira, et al. “A Model of the Central Regulatory System for Cough Reflex.” *Biological and Pharmaceutical Bulletin*, vol. 36, no. 4, 2013, pp. 501–08, doi:10.1248/bpb.b13-00052.

[13]Hong, Hyeon, and Areum Han. “A Systematic Review on Empathy Measurement Tools for Care Professionals.” *Educational Gerontology*, vol. 46, no. 2, Feb. 2020, pp. 72–83, doi:10.1080/03601277.2020.1712058.

[14]Kramer, Gary, et al. “LINEAR DIMENSIONS AND VOLUMES OF HUMAN LUNGS FROM CT IMAGES.” *Health Physics Society*, vol. 102, no. 4, Apr. 2012, pp. 378–83, doi:10.1097/HP.0b013e31823a13f1.

[15]Lee, Hyuk Jin, et al. “A Built-up-Type Deformable Phantom for Target Motion Control to Mimic Human Lung Respiration.” *Review of Scientific Instruments*, vol. 91, no. 5, May 2020, p. 054106, doi:10.1063/5.0003453.

[16]Levitzky, Michael G. “Alveolar Ventilation.” *Pulmonary Physiology*, 9th ed., McGraw-Hill Education, 2017, accessmedicine.mhmedical.com/content.aspx?aid=1160936072.

[17]---. “Mechanics of Breathing.” *Pulmonary Physiology*, 9th ed., McGraw-Hill Education, 2017, accessmedicine.mhmedical.com/content.aspx?aid=1160935887.

[18]LoMauro, Antonella, and Andrea Aliverti. “Respiratory Muscle Activation and Action during Voluntary Cough in Healthy Humans.” *Journal of Electromyography and Kinesiology*, vol. 49, Dec. 2019, p. 102359, doi:10.1016/j.jelekin.2019.102359.

[19]Morton, David A., et al. “Lungs.” *The Big Picture: Gross Anatomy*, 2nd ed., McGraw-Hill Education, 2019, accessmedicine.mhmedical.com/content.aspx?aid=1158276797.

[20]*MOTION - Linear Actuators - Heavy Duty Linear Servos - ServoCity*. https://www.servocity.com/heavy-duty-linear-servos/. Accessed 8 Oct. 2020.

[21]*Motor Noise and Product Sound | AccessEngineering | McGraw-Hill Engineering*. https://www-accessengineeringlibrary-com.proxy.lib.umich.edu/content/book/9780070359710/chapter/chapter9#/p2000aed49970344001.

[22]Potter, Merle C. *Schaum's Outlines: Strength of Materials*. Seventh edition, McGraw-Hill Education, 2020.

[23]"Predictive Equations for Lung Volumes from Computed Tomography for Size Matching in Pulmonary Transplantation." *The Journal of Thoracic and Cardiovascular Surgery*, vol. 151, no. 4, Apr. 2016, pp. 1163-1169.e1, doi:https://doi.org/10.1016/j.jtcvs.2015.10.051.

[24]"Respiratory System | AccessMedicine | McGraw-Hill Medical." *Respiratory System | AccessMedicine | McGraw-Hill Medical*, https://accessmedicine-mhmedical-com.proxy.lib.umich.edu/MultimediaPlayer.aspx?MultimediaID=17723708. Accessed 15 Sept. 2020.

---. https://accessmedicine-mhmedical-com.proxy.lib.umich.edu/MultimediaPlayer.aspx?MultimediaID=17723708. Accessed 15 Sept. 2020.

[25]Terry, Mark, et al. "Estimation of Loudness by Questionnaire." *US : American Psychological Association*, vol. 68, no. 2, May 1983, pp. 273–77, https://www-scopus-com.proxy.lib.umich.edu/record/display.uri?eid=2-s2.0-0020755695&origin=resultslist&sort=r-f&src=s&st1=%22estimation+of+loudness%22&st2=&sid=f4b9cc85cb97549f825f32e87c32a262&sot=b&sdt=b&sl=39&s=TITLE-ABS-KEY%28%22estimation+of+loudness%22%29&relpos=3&citeCnt=1&searchTerm=.

[26]*The Routledge Companion to Puppetry and Material Performance*. Routledge Handbooks Online, 2014, doi:10.4324/9781315850115.

[27]Tsunashima, Yoshikazu, et al. "Correlation between the Respiratory Waveform Measured Using a Respiratory Sensor and 3D Tumor Motion in Gated Radiotherapy." *International Journal of Radiation Oncology*Biology*Physics*, vol. 60, no. 3, Nov. 2004, pp. 951–58, doi:10.1016/j.ijrobp.2004.06.026.

[28]*Ultimate 3D Printing Material Properties Table*. /support/materials-guide/properties-table/. Accessed 19 Oct. 2020.

[29]Wallace, Emma, et al. “Objective Measurement of Acoustic Intensity of Coughing for Clearance of Penetration and Aspiration on Video-Fluoroscopy.” *International Journal of Speech-Language Pathology*, vol. 0, no. 0, July 2020, pp. 1–8, doi:10.1080/17549507.2020.1784280.

[30]Zhang, Tan, et al. “Robotic Dynamic Sculpture: Architecture, Modeling, and Implementation of Dynamic Sculpture.” *IEEE Robotics Automation Magazine*, vol. 21, no. 3, Sept. 2014, pp. 96–104, doi:10.1109/MRA.2014.2312842.

[31]Zheng, Q. J., et al. “Finite Element Analysis of the Contact Forces between a Viscoelastic Sphere and Rigid Plane.” *Powder Technology*, vol. 226, Aug. 2012, pp. 130–42, doi:10.1016/j.powtec.2012.04.032.

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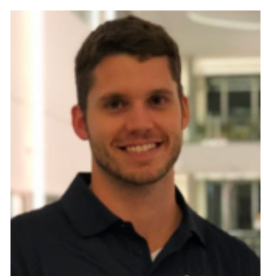

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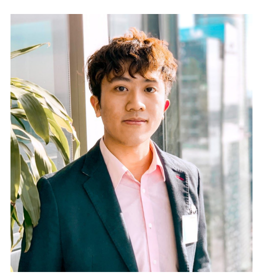
Sam is a senior in Mechanical Engineering, with a minor in multidisciplinary design. Outside of the classroom, he is a photographer who takes graduation and group portrait photos. Sam is also involved in MeasHER, a medical device start-up from GHDI working towards commercialization. After graduation, he plans to be a product designer/manager in the healthcare/tech industry.



Appendix A - Design concept generation

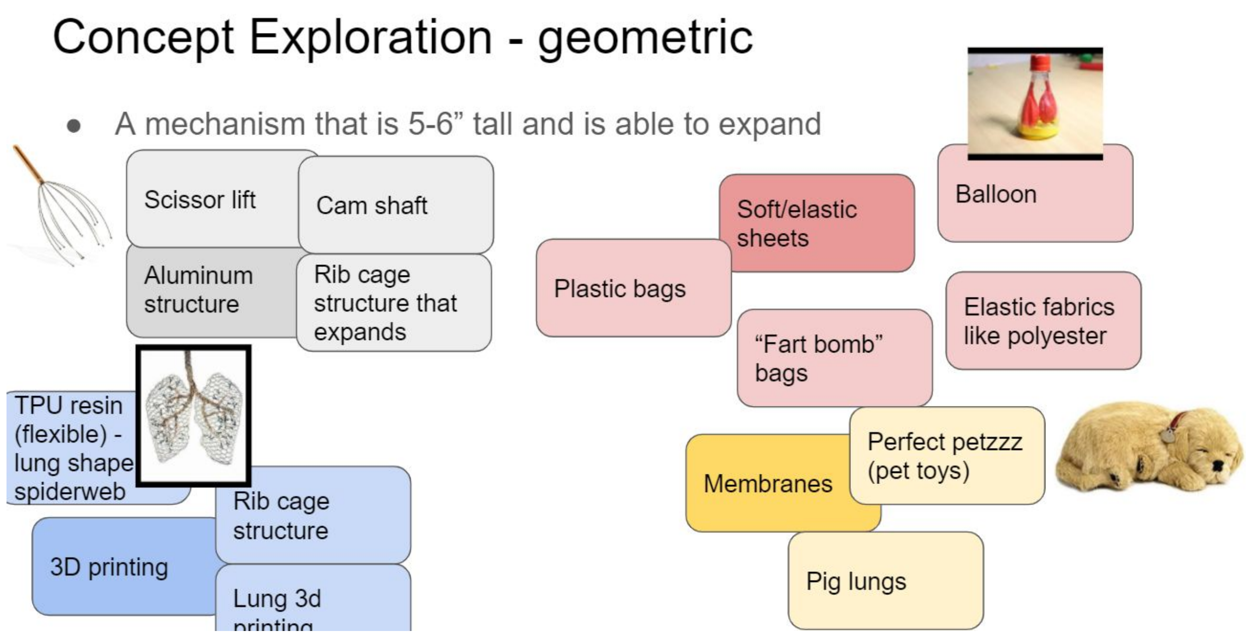


Figure A.1: Brainstorming mind map for concept generation

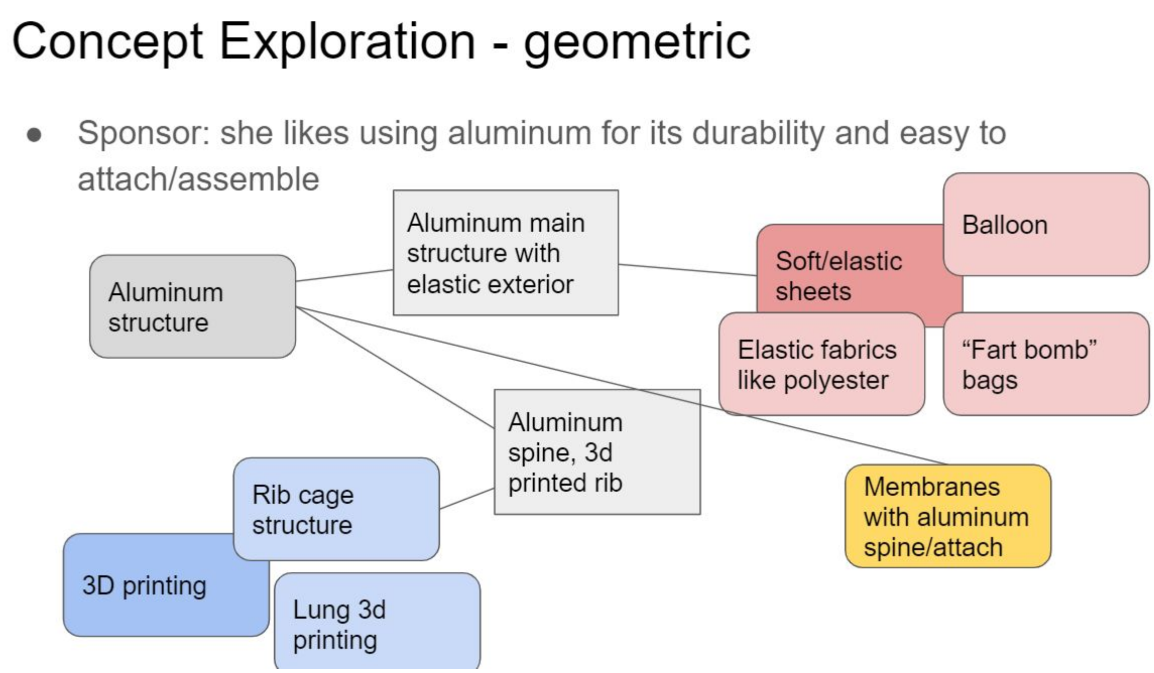


Figure A.2: Concept generation with combining concepts from brainstorming

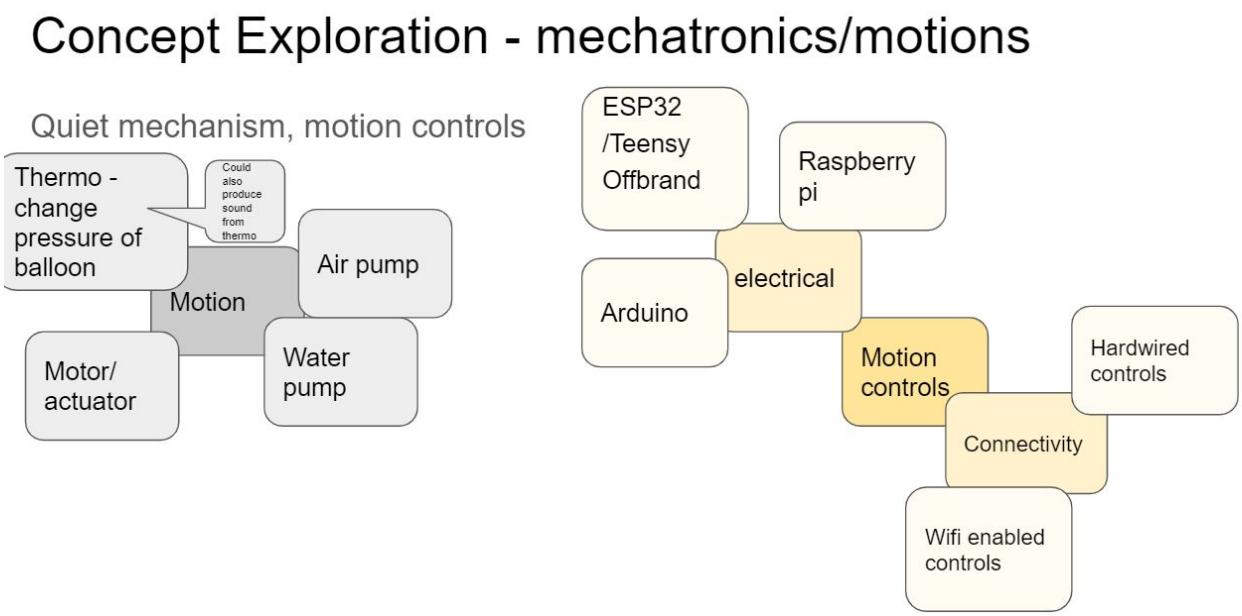


Figure A.3: Mechatronic system brainstorming mind map

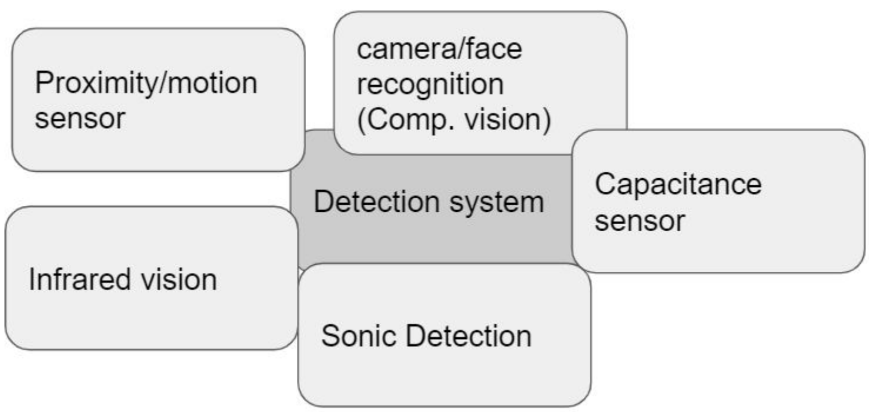


Figure A.4: Audience detection system brainstorming mind map

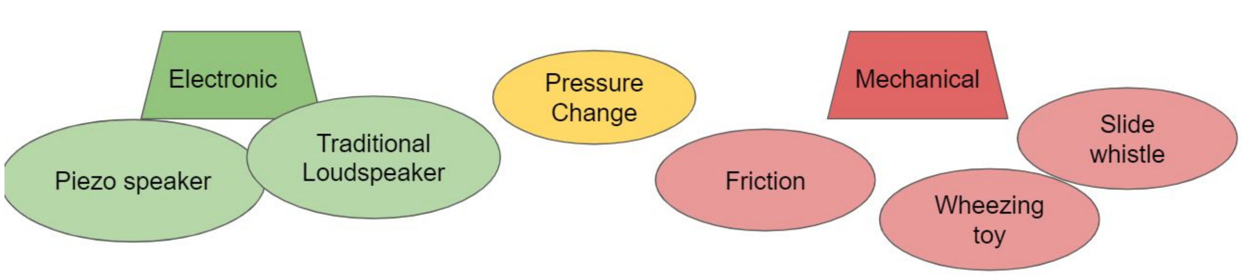


Figure A.5: Sound system brainstorming mind map

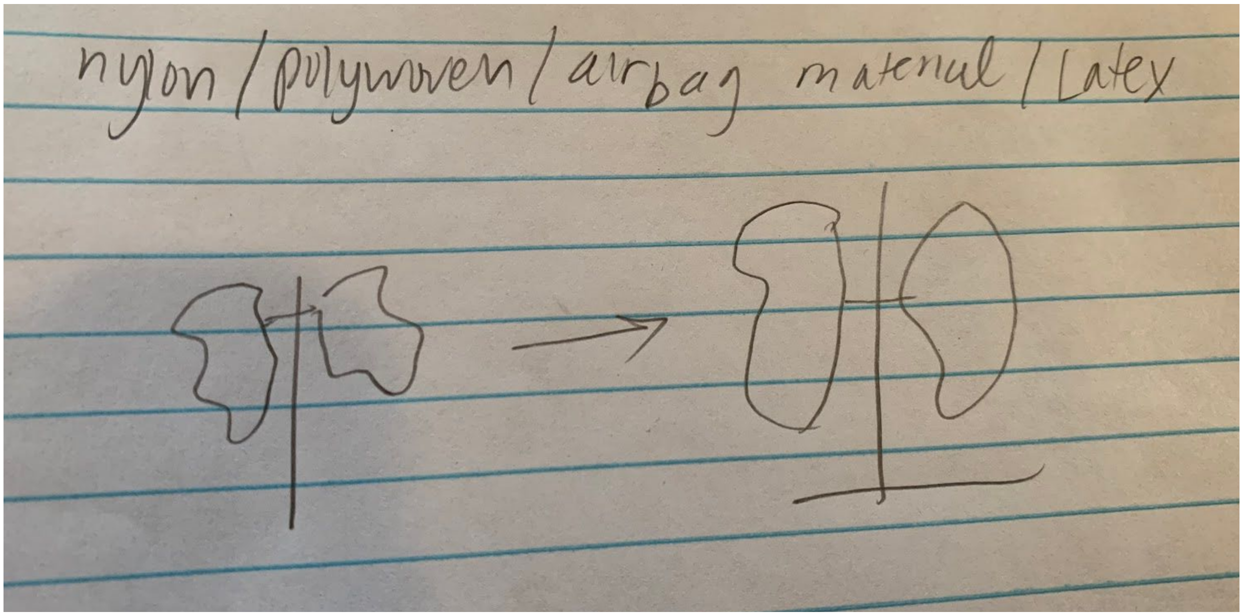


Figure A.5: Different elastic material for expandable lung

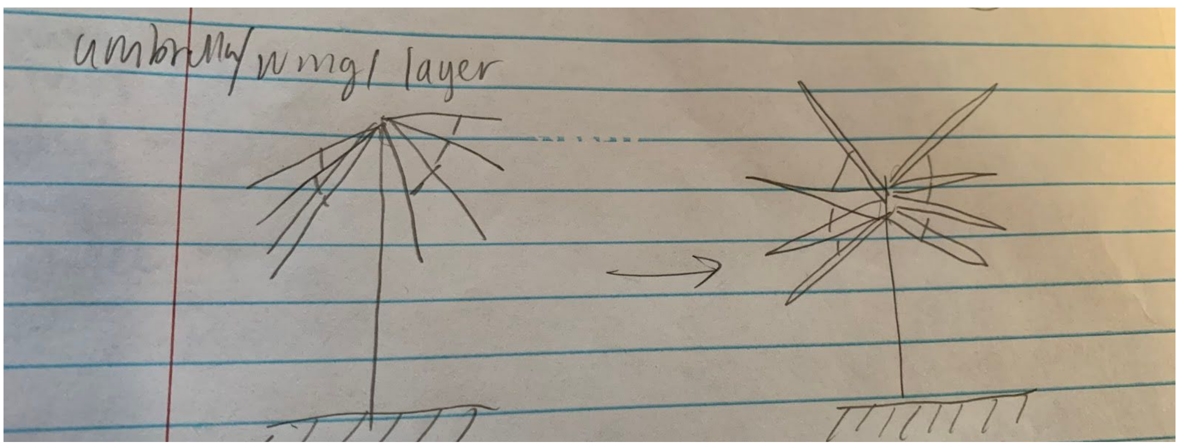


Figure A.6: Umbrella/wing lung design from heuristics

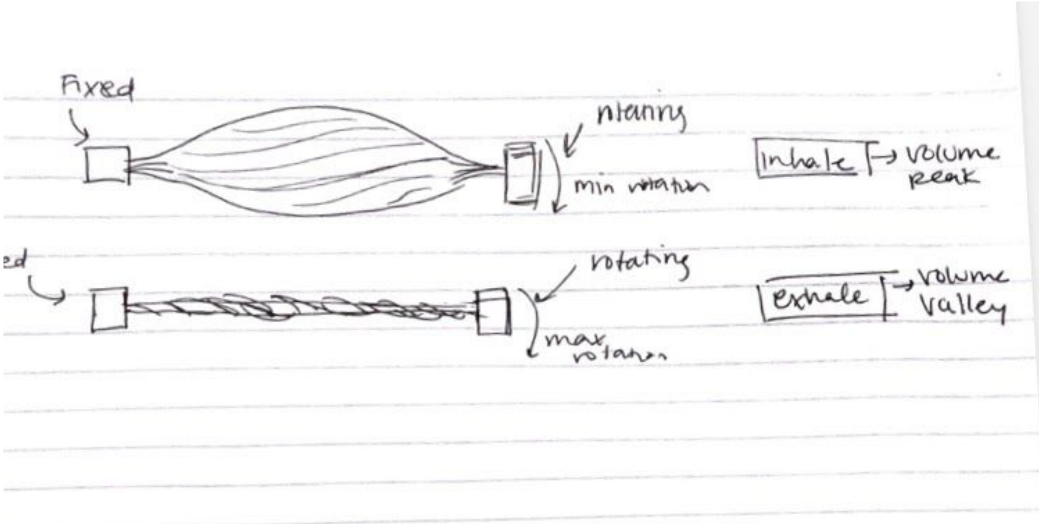


Figure A.7: Twisted ball as a lung mechanism to imitate inhale/exhale motion from heuristics

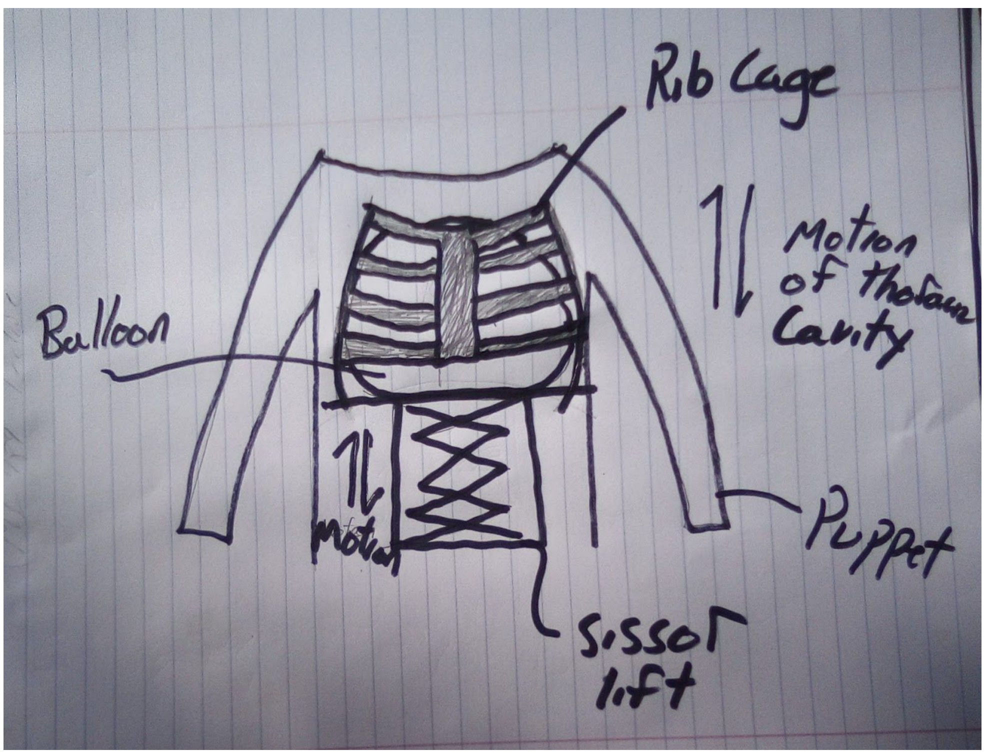


Figure A.8: Thoracic cavity ribcage with a balloon, actuated by scissor lift concept

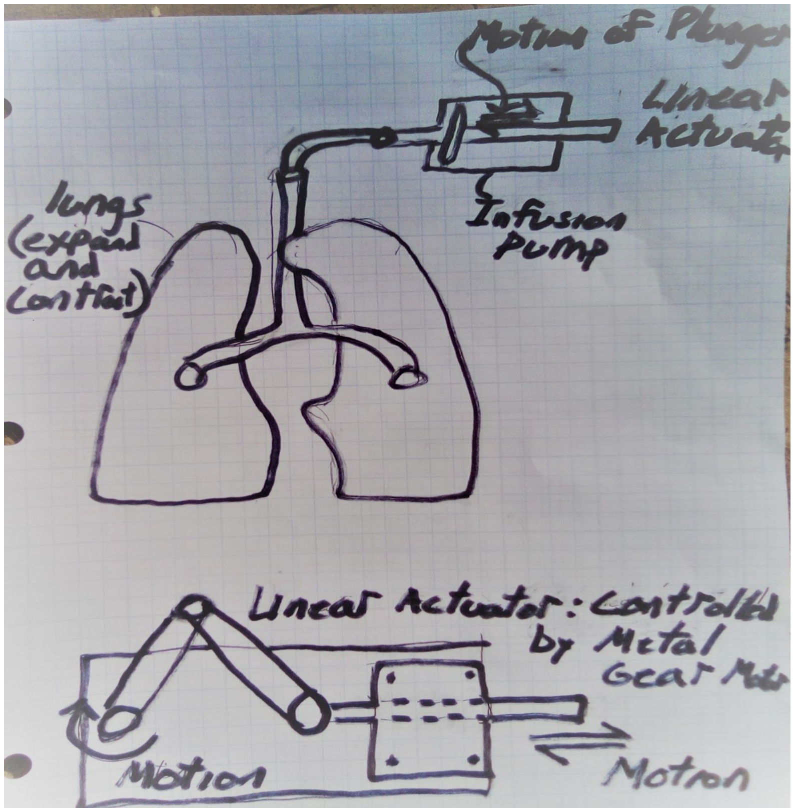


Figure A.9: Infusion pump with expandable and elastic lung mechanism linked by tubing concept

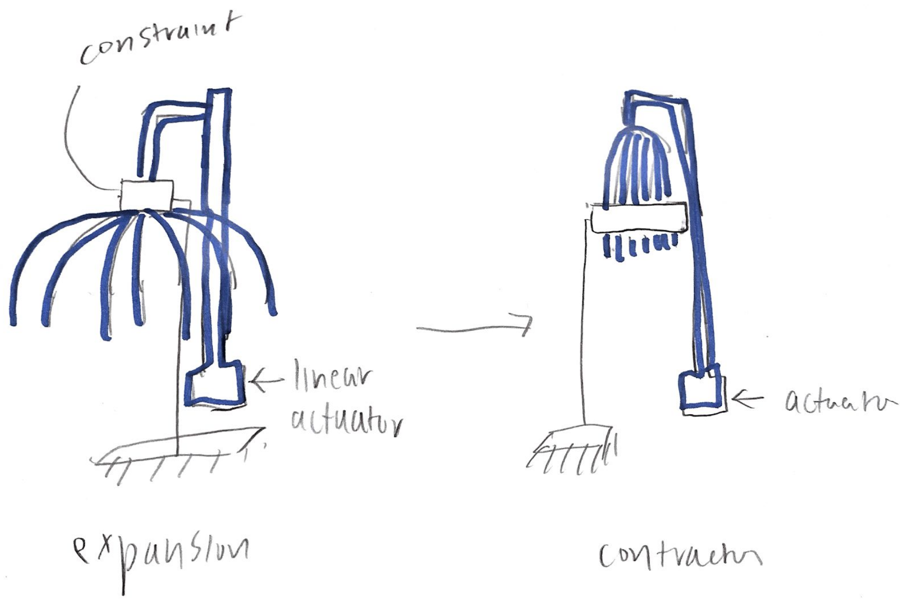


Figure A.10: Expandable structure concept derived from hair scratcher

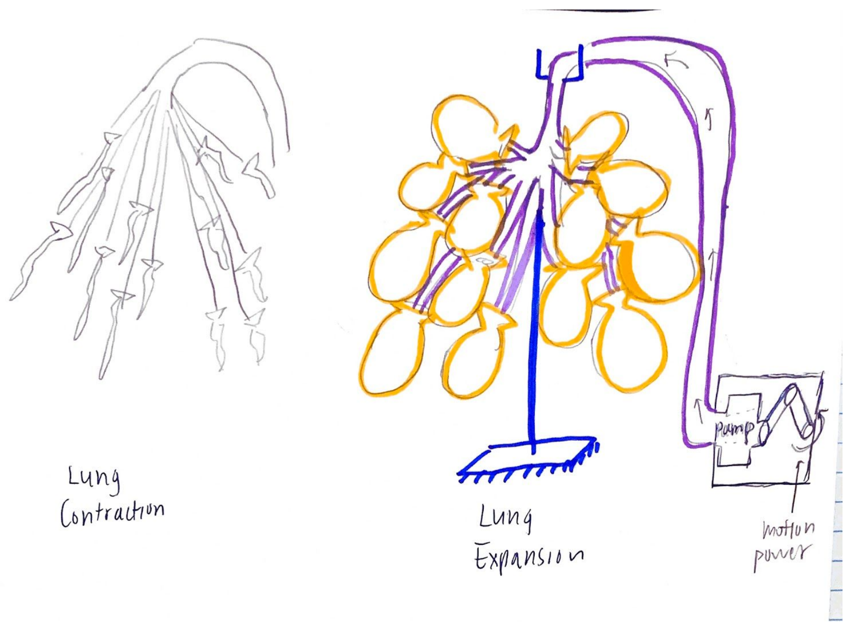


Figure A.11: Multiple inflatable balloon driven by infusion pump concept

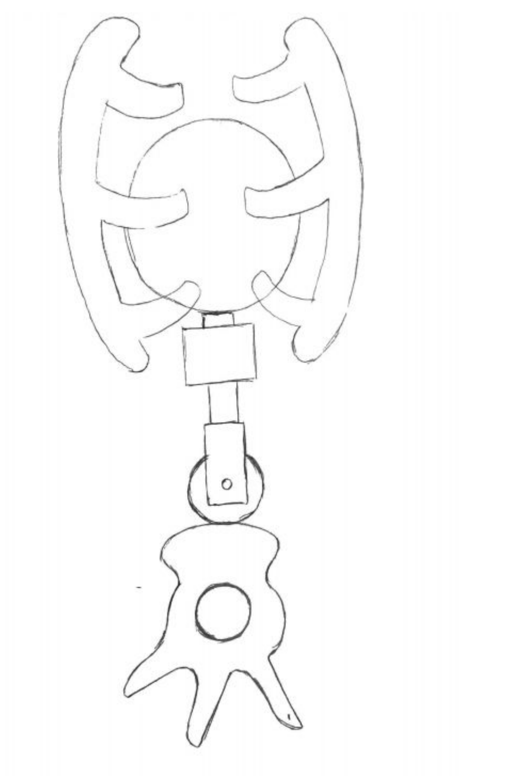


Figure A.12: Thoracic cavity and single balloon driven by cam and follower concept

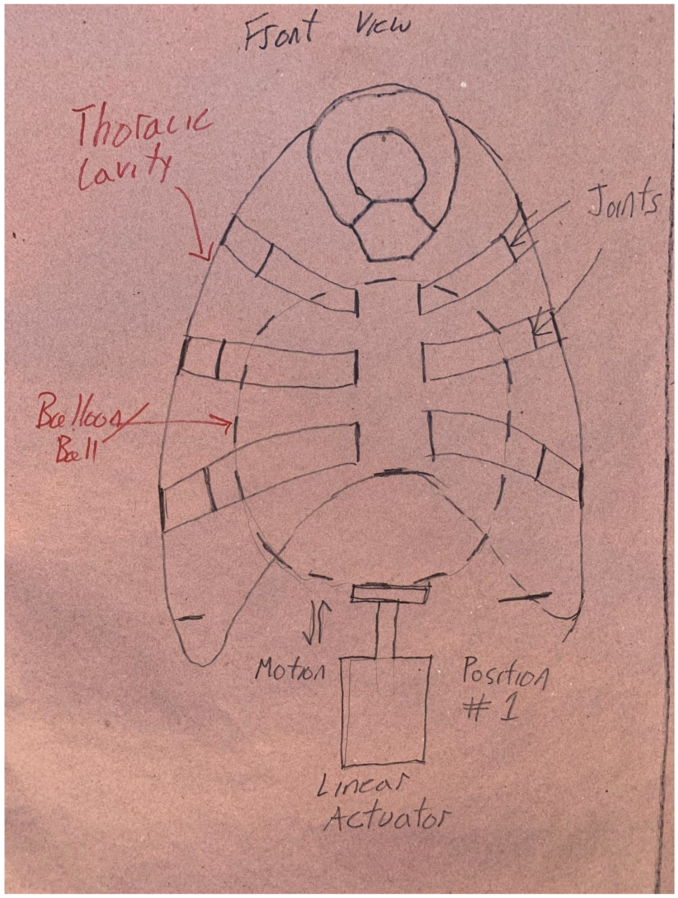


Figure A.13: Thoracic cavity and single balloon driven by linear actuator concept

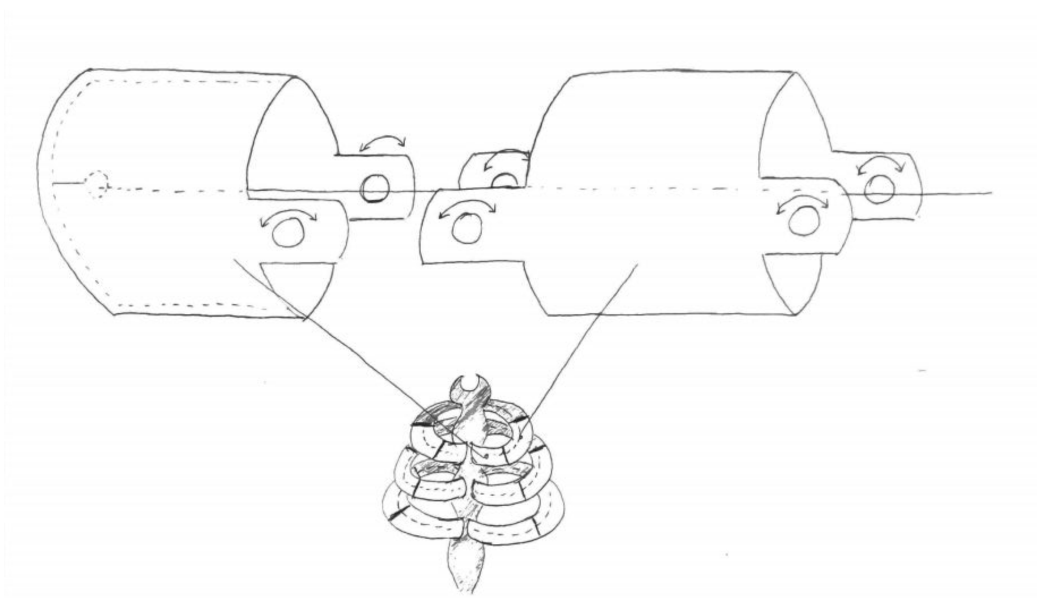


Figure A.14: Design for rib cage joints concept

Appendix B - Supplemental Analyses

B1. Engineering Standards

Since there are no technical definitions or guidelines regarding this mechanism, engineering standards are not applicable.

B2. Engineering Inclusivity

Inclusivity in engineering and the identities of stakeholders and design engineers alike can heavily influence the success of a project. In our design team's case, our personal identities appeared very similar -- we are all students of similar ages and educational backgrounds -- but the difference between us and our stakeholder's identities as a professor in a nontechnical field and a celebrated artist/sculptor made it imperative for us to keep in mind the social and power frameworks discussed in the engineering inclusivity block.

First and foremost, we acknowledged the obvious institutional power that our stakeholder holds over us, and resolved to be respectful but confident in our meetings with her to convey our understanding of her prestigious position while also maintaining the image of competence. We took extra care to write our questions out beforehand for our first meeting with her so that we could focus on her artistic talent and deeply understand her motivation for creating this project, thus including her in the project more concretely. Without diving too deep into technical knowledge, we asked her about her background and learned that she has experience creating mechanical sculptures. Learning this, we were able to communicate with her effectively, keeping in mind the balance between using layman's terms and her previous knowledge of the subject matter.

One thing that could have been improved was the number of meetings we had with her and understanding how she planned to implement the design. In earlier meetings we asked her in what positions and overall set up the ribcage would be used and she was concerned mostly with its flexibility in multiple positions. Due to the busy nature of her schedule, we were unable to have many follow-up meetings with her in the final stages. If we had, we could have made more informed decisions about how the rib cage needs to be secured in place and in what positions the puppet would be coughing in, as she had given more thought to those answers towards the end. Despite this, our design honored her request for simplicity and ease of maintenance, and in these areas and others, she was satisfied with our solution.

B3. Environmental Context Assessment

Since this is an art installment that is a one-and-only custom made mechanism, some of the typical engineering contexts such as mass production and distribution are not fully applicable for this project, thus requiring a set of unique environmental assessments for this specific scenario. Some of the environmental contexts to consider for the future of this project is to think about power usage and carbon footprint of this art exhibit experience.

First to consider the power usage of this exhibition, although the power usage to motorize a mechatronic system for a small-scaled structure is insignificant, some of the environmental considerations can still be considered, such as using renewable energy sources to power the device. If there is enough solar light present in the exhibition setting, solar panels can be considered to be the energy source that powers the mechanism to minimize carbon consumption. Considering that the exhibit could take place over months, this might have a positive impact regarding energy consumption. On top of that, the sponsor's requirement of using a proximity sensor as a trigger to start the mechanism when detecting the audience also allows energy savings. When the audience is not detected within proximity, the mechanism would not start, thus not consuming any power.

Second, an innovative way to think about carbon footprint in the context of art exhibition is to minimize paper usage for pamphlets. Based on University of Michigan Campus computing and planet blue initiative, color printing consumes 0.02 kgCO2 per color print (data was collected using a test print on campus). Suppose turnout for the exhibition averages 200 people per day and all visitors receive a one-page pamphlet that explains the context of this puppetry, that is about 480 kgCO2 for a four months span of exhibition. Instead, if a speaker or a projector is used to present the information of the exhibition using solar power, that would be a minimization of carbon footprint on this project.

B4. Social Context Assessment

Similarly to the Environmental Context Assessment, this project is unique in that it is not meant to be mass produced or even, really, to be sustainable at all. This is a custom work for a kinetic art sculpture, so the point of the project is to be unique and not intended to be replicated by anyone but the artist. However, in the broader context of a functioning rib prototype, this could be marketed towards any prop maker for films or animation studios, or a theater prop, or even used for classroom demonstrations on anatomy if the design were reworked to be more accurate to the human body.

In this specific case, though, the impact that the puppet may have on an audience is limited to abled individuals. If an audience member is vision impaired, then the effect is lost. This could be mitigated by adding auditory components like a recording of a person coughing and adding an audio recording of the description of the exhibit as well as a braille caption. For people with mild vision impairment or auditory impairment, a projector showing a blown up simulation of the coughing could be used to supplement the puppet. For wheelchair users, the height of the puppet’s display could be at eye level for those sitting and standing. In these ways, the reach of the project could be expanded to include more of society, and to emphasize the importance of this inclusion, especially given the theme of helplessness and decreased health in the sculpture itself.

B5. Ethical Decision Making

The development of this mechanism required few ethical decisions. The design choices and manufacturing processes did not compromise people, the environment or markets. The only ethical decision the engineers had to consider was the emotional and psychological effect creating a piece of art can have on the viewer. Would the creation of this mechanism/ artwork cause viewers to see themselves or others negatively? Would this mechanism cause the viewer to hurt themselves or others? Upon considering these questions, the engineers understood that the mechanism is intended to create empathy and provide insight into individuals struggling to breathe. The intended effect is a positive and does not compromise the engineers ethical standards.

Appendix C - Process Roadmaps

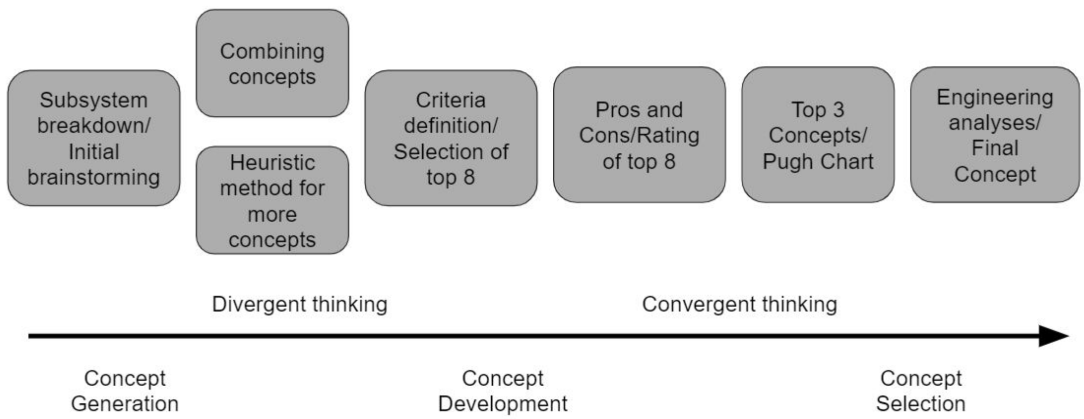


Figure C-1. Design concept generation development and selection thinking process roadmap.

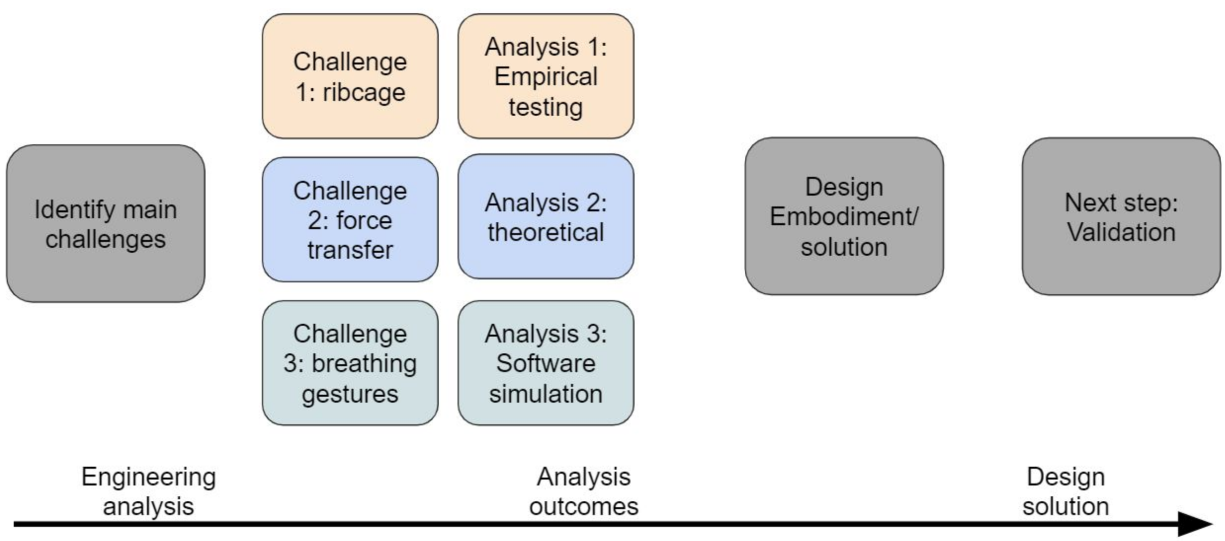


Figure C-2: Flow chart of the team's engineering analysis and design solution development process.