Developing a 3D model of the tongue and mouth to assess pressure generation and predict bolus flow when swallowing

Marie Greuel (Team Leader), Tyler Lieberthal (Communicator),
Kelly Hanneken (BWIG), Denise Wong (BSAC)

University of Wisconsin-Madison - Biomedical Engineering Department
Clients: Dr. JoAnne Robbins and Jacqueline Hind
Advisor: Mitch Tyler

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1. Abstract

Swallowing is an essential part of our lives; unfortunately, a large segment of the geriatric population suffers from dysphagia, which is a disorder characterized by difficulty in swallowing. A 3D mouth model is needed for research and educational purposes in order to fully understand normal and abnormal swallowing. Dr. JoAnne Robbins will continue to supervise this third semester project. Building upon the tongue prototype developed by previous teams, the team will build a stable base to support the tongue and act as the pharyngeal wall. A mouth cavity is also needed to be compatible with pressure sensors. Three designs were evaluated based on accuracy, ease of fabrication, modifiability, client preference, durability, and cost. The Polycarbonate Enclosed Cavity Design was selected as the optimal design; the team will proceed to manufacture the model and test its functionality.

2. Introduction

2.1 Physiology of the Swallow

The action of swallowing is one that is often overlooked and underappreciated. Swallowing is a complex mechanism that consists of three phases: oral, pharyngeal, and esophageal. [1] The anatomy involved in the swallowing process can be found in Figure 1.

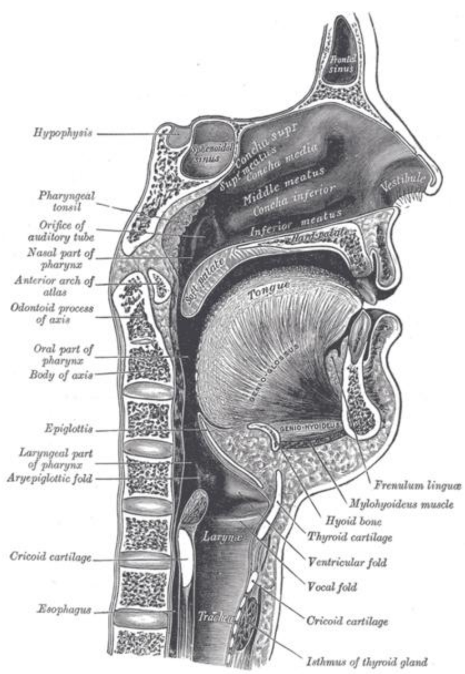

Figure 1: Anatomy involved in Swallowing[3]

The oral phase is a voluntary process in which food is chewed and moistened with saliva to form the bolus. After the bolus is formed, it is pushed to the back of the mouth cavity. The anterior portion of the tongue depresses down while the posterior portion on the tongue lifts up and generates pressure against the hard palate. As soon as the bolus reaches the pharyngeal wall, the next phase, the pharyngeal stage, begins.[1]

The second phase of the swallow, the pharyngeal phase, is an involuntary process and begins with the plunger force of the tongue propelling the bolus into the pharynx. The palatopharyngeal folds pull together medially to create a slit in the pharynx that the bolus can slide through. The soft palate also raises and closes the nasopharynx passage to prevent bolus entry into the passage. To prevent bolus re-entry into the oral cavity, the tongue is retracted. Next, three actions happen simultaneously to protect the airway. The first action is the upward and forward motion of the larynx and the hyoid bone to enlarge the pharynx and create a vacuum in the hypopharynx that pulls the bolus downward. The second action is the adduction of the true and false vocal folds. The third action consists of the epiglottis dropping down over the top of the larynx to protect the airway and divert the bolus into the esophagus. There are four factors that cause food to move down the pharynx during the rest of the pharyngeal stage, these include the driving force of the tongue, the stripping action of the pharyngeal constrictors, the presence of negative pressure in pharyngeal stage, and finally, gravity.[1]

Once the bolus enters the esophagus, the last stage, the involuntary esophageal stage, begins. In this phase, the bolus is moved down the esophagus via peristaltic wave motion assisted by gravity.[1]

Dysphagia, or difficulty swallowing, arises after injury, neurodegenerative disease, or stroke. It affects quality of life as well as physical health of an estimated 15%-40% of Americans over the age of 60.[2] Therefore, it is important that the physiology of swallowing be studied and understood to correct the problems that arise to cause dysphagia.

2.2 Project Motivation

Currently, there are no models that replicate the human swallow. A model that could duplicate the physiology of the human swallow would be a great teaching tool as well as a way to measure the forces generated between the hard palate and the tongue during both a normal and an abnormal swallow. The prototype tongue that has been fabricated by previous semesters also has motivated our design. We aim to improve upon this design by replacing the unstable cardboard base with a plastic mechanism that would double as the anatomy of the neck and throat. In addition, to assess the tongue movement already programmed, we aim to construct a hard palate that would be compatible with the Madison Oral Strengthening Theraputic (MOST) device, a device already used in human subjects to measure pressure generated by the tongue against the hard palate. Dysphagia can severely limit the quality of life as well as threaten it. It often leads to malnutrition, dehydration, and aspiration pneumonia, which is among the leading causes of death in the elderly.[4] For these reasons, it is essential that dysphagia be studied and understood further, and this model will aid in achieving that goal.

2.3 Problem Statement

JoAnne Robbins, Ph.D., the director of the UW/VA Swallowing Speech and Dining Enhancement Program (SWAL-ADE) will supervise this project concerning dysphagia, or difficulty in swallowing, which affects many adults and children in the U.S. It often is a result of stroke or degenerative neurologic disease. This project will focus on developing a 3D model of the tongue and mouth that will be used to assess pressure generation within the oral cavity during swallowing. This is a third semester project, and we will concentrate on creating a stable base that doubles as a pharyngeal wall, and designing a mouth cavity compatible with pressure sensors (MOST device).

2.4 Previous Design

This is a third semester project; therefore, there is a prototype, as seen in Figure 2, that is available to improve upon. Currently, the design consists of a moving silicone tongue. The movement of the tongue is generated through a JAVA program written by previous teams. The JAVA program controls eight servos that move eight corresponding metal rods, which move up and down to generate tongue movement. We are currently satisfied with the tongue movement, but wish to conduct testing to determine its accuracy in modeling human tongue movement during swallowing. At present, the tongue rests upon a cardboard base. This base needs to be manually held down while the tongue is moving, and this is another aspect of the design that we hope to improve.

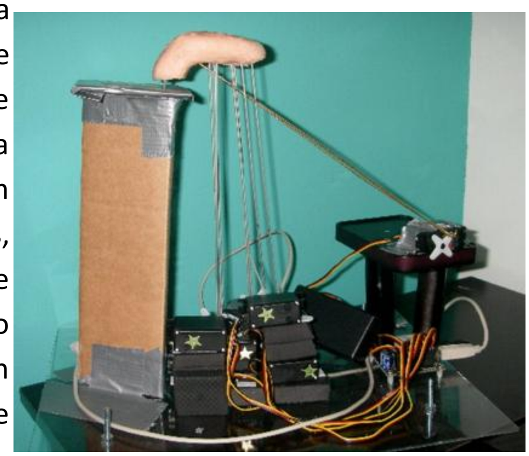

Figure 2: Previous Prototype - tongue constructed of silicone is moved with 8 rods that connect to 8 servos, cardboard base acts as support for tongue

2.5 Design Specifications

Specific design requirements can be found in the Product Design Specifications located in the appendix.

3. Designs

3.1 Design Options

3.1.1 Design 1: Polycarbonate Enclosed Cavity Design

The Polycarbonate Enclosed Cavity Design incorporates transparent polycarbonate as the material of the main structure to maintain visibility while still including the anatomical aspect of a closed mouth cavity. Toward the bottom right side of the design in Figure 3 to the right, there is a small tube used to represent the trachea. This tracheal tube will be also be transparent, and within it there is a servo connection to

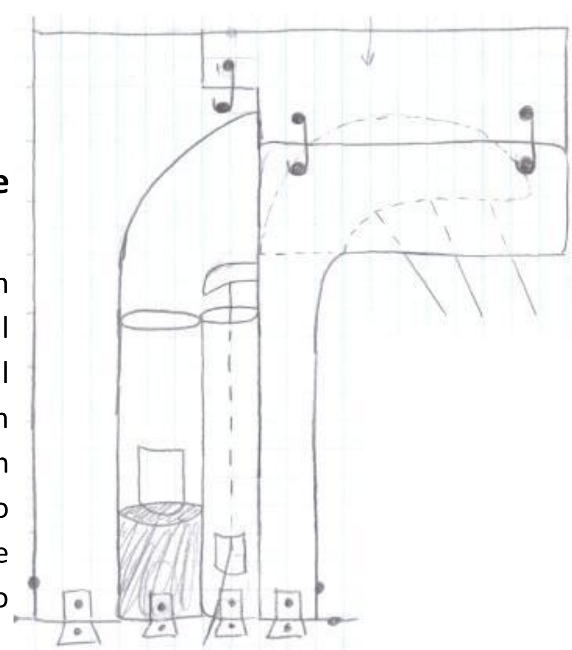

Figure 3: Profile view of the Polycarbonate Enclosed Cavity Design - two clear plastic tubes represent trachea and esophagus, epiglottis is activated by servo

the epiglottis silicone piece above. The servo acts to pull the epiglottis down as a bolus flows over it when the swallowing mechanism is running. The bolus will then enter the tube directly to the left of the trachea that functions to represent the esophagus. The esophageal tube has a filler and cut out toward the bottom so the user can easily remove the bolus after swallowing has occurred.

Directly next to the esophagus is the main base support for the design that is also used to represent that back of the pharynx. The base structure extends all the way towards the top, and has a hook along its side and indentation toward its end for a hard palate connection point. This hard palate is essentially a polycarbonate block that has unique features in order to induce functionality and anatomical correctness. First, it is indented and carved out on its underside with ridges to allow for realistic tongue interaction. It should be carved out such that the tongue can reach it easily enough to create pressures against it. Next, it also is removable from the base and jaw portions so that the user can insert a bolus directly onto the tongue. Finally, small circular extensions are left on the underside outer rim of the hard palate block that fit into holes on the top portion of the lower jaw piece.

The lower jaw piece has been designed to maintain the movement of the tongue, along with creating a support for the tongue to rest upon. As seen in figure 4 to the right, the lower jaw has been hollowed out so that the existing servos still have access to the tongue. Toward the back of the jaw, there is also a flat region where the tongue sits. This flat region eventually extends down to be fixed to the floor of the structure.

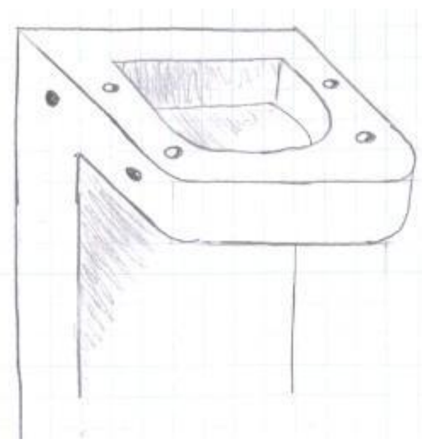

Figure 4: Angled view of the lower jaw portion of the Polycarbonate Enclosed Cavity Design – hollowed out jaw for servo access

Overall, the design can be seen as polycarbonate blocks that have been carved out to surround the tongue and permit current tongue and servo interaction. The design is unique in that it mimics the closed cavity of a real mouth cavity, while still maintaining visibility for the user. The enclosed cavity is an important aspect of the design, because it could potentially be beneficial when analyzing pressure generations of the tongue on the hard palate while the model is conducting its swallowing mechanism.

3.1.2 Design 2: Purchased Oral Cavity

The Purchased Oral Cavity design is much like the Polycarbonate Enclosed Cavity design, but varies slightly in its pharynx and hard palate details. As the figure 5 below shows, the trachea, epiglottis, and esophagus features are the same as the Polycarbonate Enclosed Cavity, yet the back support and pharynx differ slightly. This back support can be made of a material that is rigid yet durable, and will be attached to a purchased hard palate via a screw. Directly behind the hard palate, there is an access that has been drilled out for a servo to connect to a silicone soft palate. When swallowing is occurring, the servo will be programmed to retract its line in order to bring the soft palate back far enough to touch the pharynx. This portion of the design has been included to display the function of the soft palate, as well as adding more anatomical correctness to the model.

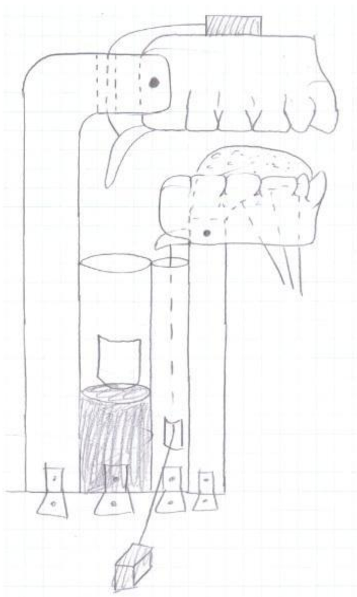

Figure 5: Profile view of the Purchased Oral Cavity Design – Purchased models used for upper and lower jaw, two plastic tubes for trachea and esophagus, servo activated epiglottis

As stated previously, the hard palate within this design will be purchased off the internet, and is expected to have physical qualities such as teeth and ridges in its underside. The lower jaw portion will also have teeth, but the team will work to hollow out its underside to allow for the servo to tongue attachments. This lower jaw is screwed to a front support that will include a flat region for the tongue to rest, as seen in the figure 6 to the right.

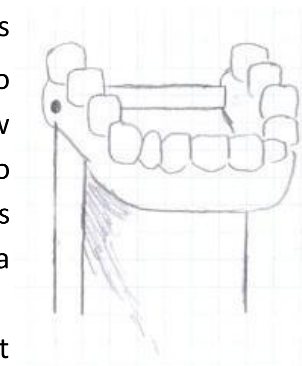

Figure 6: Angled view of the lower jaw portion of the Purchased Oral Cavity Design – purchased lower jaw would rest on base

This design includes a bit more anatomical correctness to it, but the fact that it is not an enclosed mouth cavity makes it less likely to be as functionally accurate as the Polycarbonate Enclosed Cavity Design.

3.1.3 Design 3: Wood Base Design

Because the client intends to use the model to measure lingual pressure, the model must feature a secured base to which the other model components will be attached. In order to avoid structural failure of the model components, the "Wood Base" design, seen in Figure 7, includes a posterior pharyngeal wall and hard palate that are worked into a continuous block of wood, which serves as a base.

Based on feedback given by the client, this design includes a dynamic soft palate, which improves on the rigidity of previous mathematical models. The soft palate's

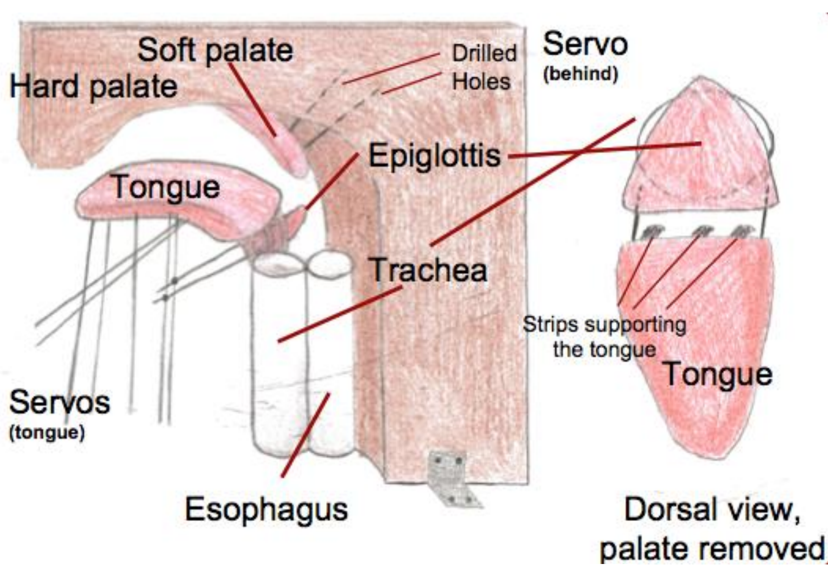

Figure 7: Design 3 - Wood base. A continuous block of wood serves to stabilize the model and provide the surfaces for the palate and posterior pharyngeal wall. The right-hand side image displays the dorsal view of the tongue and epiglottis

posterior movement (mainly retraction to block the nasopharynx) is regulated by an additional servo (not seen). The soft palate servo originates behind the base and attaches to the soft palate through holes drilled in the base. During swallowing, the soft palate servo retracts while the bolus enters the oropharynx.

The movement of the epiglottis to cover the opening of the tracheal tube does not, however, require an additional servo. Instead, this movement is coupled with the movement of the tongue so that the elevation of the tongue is concurrent with the blocking action of the epiglottis. This is accomplished through a lever-type system in which the metal rods attached to the epiglottis are also fixed to the vertical servos of the tongue. The attachment point allows rotation; it is the fulcrum of the lever. As seen on the right-hand side of Figure X, the metal rods that attach to the epiglottis are positioned around the wires that support the base of the tongue.

3.2 Design Matrix

Categories	Weight	Design 1 - enclosed cavity	Design 2 - purchased oral cavity	Design 3 - wood base
Functional Accuracy	**25%**	**4**	**4**	**3.5**
Anatomical Accuracy	**20%**	**4**	**3**	**3**
Ease of Manufacturing	**15%**	**5**	**3.5**	**2.5**
Modifiable in Future	**15%**	**4**	**4**	**4**
Client Preference	**10%**	**4**	**2**	**3**
Durability	**10%**	**4**	**3**	**4**
Cost	**5%**	**3**	**2**	**4**
Total:	**100%**	**4.1**	**3.325**	**3.35**

***Table 1. Design Matrix.* The three designs were evaluated by seven weighted criteria.**

The success of the model is ultimately determined by how accurately it can imitate actual swallowing. Therefore, functional accuracy is of primary concern to the team's design. Because the team recognized problems with the way the epiglottis and soft palate would function in Design 3 (wood base), the design received a lower score. The first two designs are similar in design regarding functional accuracy.

A distinction must be made between functional accuracy and anatomical accuracy; the client would like to use the model to integrate with the MOST device and would also like to use the model as an educational tool. For the model to be used to elucidate the swallowing process and disorder, it must be anatomically (visually) correct. All designs feature the same anatomical features and dimensions; however, only Design 1 (polycarbonate enclosed cavity) displays the anatomically correct sealed oral cavity, while Design 2 (purchased oral cavity) and Design 3 (wood base) have open oral cavities. Therefore, Design 1 was scored higher.

Due to the complexity of the model, the difficulty of fabrication was accounted for in selecting a final design. Determining whether a design would be easy or difficult to build depended on the materials that would be used to construct the model. Although many of the biomimetic materials for all designs have not been selected (e.g. the soft palate, tracheal and esophageal tubes), each design includes the material for which the base is constructed. Designs 1 and 2 are mainly composed of polycarbonate. These designs are much more compatible with other materials; subsequently, the team will look into 3D printing as a potential method of fabrication, which would dramatically decrease the difficulty of manufacturing the model. Instead, Design 3 has a base of wood, which must be modified by hand to fit the dimensions of the oral cavity.

This semester's team anticipates considerable future work for a complete, functioning model. Thus, the ability of all three designs to be modified in the future was a criterion for selecting an optimal design. However, because this semester's high-priority goals include fabrication of a sturdy base and hard palate, there will be opportunities within all designs for modifications.

Initial designs were presented to the clients; based on feedback from those meetings, the team was able to extrapolate the feedback, along with previous expectations, to evaluate the three designs based on client preference. The clients expressed concern regarding the second design's stability, particularly in the pharyngeal area. From this feedback, the polycarbonate enclosed cavity was created, which improved upon the stability and included other innovative features. Similarly, a predecessor to the wood base design (3) that included a hard/soft palate and base constructed with wood was met with criticism: its rigidity did not greatly improve upon the parallel-plate mathematical model used to analyze fluid dynamics of bolus flow. Accordingly, modifications to the design resulted in the addition of a soft palate and controlling servo.

When the model is fully functional, various pressures will be subjected to it that reproduce the forces generated during swallowing. Consequently, the model must be durable—both in resisting structural failure and material deterioration. The structural integrity of design 2 was questioned by the client and recognized as a potential weak point. Design 2 was therefore scored lower than the other two designs.

Finally, cost of the materials involved was considered. Because the raw materials involved will not be expensive, cost was not highly weighted. Design 2 and 3 incorporate purchased model parts and wood respectively; these designs are the most expensive and least expensive designs, respectively, while the first design is between the two.

4. Future Work

With the Polycarbonate Enclosed Cavity Design would as the final decision, the team would continue on choosing an ideal material for the mouth cavity. CAD files of the model would be prepared using SolidWorks so that the model could be manufactured through 3D printing. Testing of the model's functionality could then be carried out. The team plan to test the model's stability using the vibration simulation tool available in SolidWorks.[5] The pressure generated against the hard palate could also be simulated using SolidWorks. After that, the data collected would then be analyzed and compared to literature.[6] Finally, the model would be ready to be tested with MOST device.

Project Schedule:

Task	September				October				November				Dec.	
	9	16	23	30	7	14	21	28	4	11	18	25	2	9
Project R&D														
Background Research	X	X												
Design Brainstorm		X	X	X	X	X								
Final Design Selection					X	X	X							
Manufacturing														
Testing														
Deliverables														
Progress Reports	X	X	X	X	X	X	X							
PDS		X				X								
Midsemester Presentation					X	X								
Midsemester Paper					X	X	X							
Final Poster														
Final Paper														
Meetings														
Team	X	X	X	X	X	X	X							
Advisor	X	X	X	X	X	X	X							
Client	X	X		X	X									
Website														
Updates	X	X	X	X	X	X	X							

**X indicates a worked on or completed task. Shaded boxes indicate projected timeline*

Table 2: Project Schedule

We have only had a few deviations from the projected timeline. Design brainstorming went longer than projected due to continuous creative insight. Also, due to our client involvement and dedication to our project we met with her more than expected.

5. Conclusion

Dysphagia is a growing health care concern and is affecting six hundred thousand people yearly.[7] It is necessary to develop a 3D mouth model to better understand it. With the tongue developed from the previous semesters, the team would be building a stable base, which also plays the role of a pharyngeal wall, and a mouth cavity compatible with pressure sensors. After evaluating three design ideas, the team decided that the Polycarbonate Enclosed Cavity Design would be the most ideal design. It would be manufactured and tested by the team.

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7. Appendix

7.1 Project Design Specifications

Developing a 3D model of the tongue and mouth to assess pressure generation in predict bolus flow when swallowing

Project Design Specifications

Marie Greuel (Team Leader), Tyler Lieberthal (Communicator),
Kelly Hannenken (BWIG), Denise Wong (BSAC)

October 24, 2012

Function: JoAnne Robbins, Ph.D., Director of the UW/VA Swallowing Speech and Dining Enhancement Program (SWAL-ADE) will supervise this project concerning dysphagia, or difficulty swallowing, which affects many adults and children in the U.S. It often is a result of stroke or degenerative neurologic disease. This project will focus on developing a 3D model of the tongue and mouth that will be used to assess pressure generation within the oral cavity during swallowing. This is a third semester project, and we will concentrate on designing a mouth cavity compatible with pressure sensors (MOST device), and a stable base that will also represent the pharynx, esophagus and trachea.

Client requirements:

Our client requires a model that fulfills these requirements:

- Develop a mouth cavity with a hard palate:
  - Compatible with force sensors (MOST device)
  - That supports realistic pressure generations
- Develop a pharynx to allow for controlled bolus flow
- Programmed tongue movements that simulate various forms of dysphagia

Design requirements:

1. Physical and Operational Characteristics

a. *Performance requirements*: The design should allow for full tongue movement (posterior/anterior), be compatible with sensors that are able to detect a range of pressures (MOST device), and permit realistic pressures during testing.

b. *Safety*: This model would not be in direct contact with patients; therefore, typical medically ethical issues do not need to be considered. However, the model's electrical components should be contained as to not harm the operator.

c. *Accuracy and Reliability*: Our model should mirror the physiology and anatomy of healthy and unhealthy swallowing mechanisms found in humans as accurately as possible.

d. *Life in Service*: Our model is expected to last for many years, with continual updates to electrical components as technology advances.

e. *Shelf Life*: Our model will need to be stable on a flat surface and portable.

f. *Operating Environment*: The model should be able to maintain structural integrity when handled and if dropped.

g. *Ergonomics*: Our model is not a hand-held device and so ergonomics does not apply directly.

h. *Size*: Model should be consistent with typical human size. Mouth cavity: ~15 cm x ~15 cm.

i. *Weight*: Model (including electronics) should not exceed 4.5 kg.

j. *Materials*: Tongue is currently made of silicone. Hard palate and lower jaw should be constructed using a hard plastic (polycarbonate). Pharynx should be build of a rigid material. The soft palate should be constructed out of silicone.

k. *Aesthetics, Appearance, and Finish*: Model should accurately represent the appearance of a human mouth, and allow for user visibility when running.

2. Production Characteristics

a. *Quantity*: At least one functional prototype is needed. Design should be conscious of possible replication.

b. *Target Product Cost*: Device costs should not exceed 500 dollars.

3. Miscellaneous

a. *Standards and Specifications*: Model will not be in direct contact with patient; only basic safety specifications will be considered.

b. *Customer*: Functionality is a priority to the client.

c. *Competition*: Currently there are no devices that model the swallowing mechanisms of dysphagia.

d. *Modification for the Future*: The design should be conscious of future modifications that will benefit its performance and anatomical correctness.