

Developing a 3D Model of the Tongue and Mouth to Assess Pressure Generation When Swallowing

Midsemster Report

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Abstract

Our client Dr. JoAnne Robbins, is a specialist and one of the leading researchers in swallowing disorders. She has published multiple academic journals and articles about the swallowing process and the causes of this disease. Swallowing is one of the most unique and complex systems of muscle movements that our bodies do hundreds of times each day. The process is a fairly automatic process, one that people don't consciously think about unless something goes wrong. A useful piece of equipment that has yet to be developed is a mechanical tongue that mimics the complex dynamics of the swallow. This tongue could be used to measure pressure points in the mouth and eventually point to which muscle's deficiency leads to the inability to swallow. Using a complex system of motors and cables, this mechanical tongue can be constructed and accurately model the movement of the tongue during a swallow. We have designed a prototype to do this, and the team will use the remainder of the semester to build, thoroughly test, and eventually represent exactly what researchers in this field are looking for.

Table Of Contents

Abstract.....	2
Background.....	5
Client Description.....	5
Dysphagia.....	5
Problem Motivation.....	7
Current Devices.....	8
Robotic Dental Test Dummies.....	8
Animatronic Model of a Human Tongue and Vocal Tract.....	9
Design Requirements.....	9
Design Alternatives.....	11
The Air Muscle Model.....	11
Hydraulic Muscle System.....	11
Cable Model.....	12
Design Matrix.....	13
Functionality in Real Time.....	14
Accuracy and Precision of Motion.....	14
Durability.....	14
Force Generation.....	14
Ease of Coordination.....	15
Ease of Assembly.....	15
Part Replacement.....	15
Cost.....	15
Power System.....	16
Future Works.....	16

Works Cited.....18
Appendix.....20

Background

Client Description

Dr. JoAnne Robbins is one of the leading throat pathologists in the world. Her studies have been conducted over the last 40 years and have served as some of the most useful information in helping dysphagia patients. She has developed multiple techniques that are used in clinics to treat patients and have shown great promise in swallowing therapy. Her exercises have been proven to cure dysphagia as a result of sarcopenia, or the deterioration of the throat muscles over time. It is completely safe to assess Dr. Robbins as an expert in the area of swallowing and the complexities that come along with it.

Dysphagia

Dysphagia is the term that refers to the inability to properly swallow. According to Dr. JoAnne Robbins, “As many as 40% of adults aged 60 and older currently suffer from dysphagia, with an exponential increase in the total dysphagic population likely as the geriatric population grows” [1]. With such a growth in recent years, researchers like Dr. Robbins have been attempting to find ways to cure this disease and have made some significant advances. The type of dysphagia that will be focused on is oropharyngeal dysphagia, which related to nerve and muscle problems that can weaken your throat muscles and make it difficult to move food from your mouth into your throat. The other type is esophageal dysphagia, which refers to food getting stuck in the swallowing tube (esophagus) [4].

This disease develops due mainly to a couple of different causes: stroke and sarcopenia [1]. Stroke occurs due to a loss of blood flow to the brain and causes the inability for the victims’ brain to communicate with the throat and tongue muscles properly after having the

stroke. Patients who have suffered a cerebrovascular accident and aspirate are significantly more at risk of suffering from pneumonia than those who do not and also have a greater rate of mortality [1].

Sarcopenia, or the deterioration of muscles over time, is another leading cause of swallowing disorders. As people get older, everyone suffers some sort of muscle loss. Some receive this to a severe extent in their throat and tongue muscles, which then lead to problems during the swallow. The various pressures that the tongue and throat muscles need to supply in order to swallow are not achievable in a sarcopenia victim. Dr. Robbins has made some serious advancement in this area by developing exercises in order to strengthen the proper muscles in the mouth.

The effects of dysphagia such as malnutrition, dehydration, and especially pneumonia can be life threatening to the patient. Pneumonia occurs due to the liquids that seep into the lungs of a dysphagia victim through pulmonary aspirations. According to Dr. Robbins, “Of the deleterious dysphagia-related health outcomes, pneumonia may be the most devastating—the fifth leading cause of death in those aged 65 and older and the third leading cause of death in those aged 85 and older” [1]. Pneumonia is a fatal infection that can be prevented, beginning with the growing amount of dysphagia awareness and research. Malnutrition and dehydration are also serious effects of swallowing disorders and both results from the patient not being able to physically swallow liquids or solids. Both lead to another handful of serious diseases and illnesses.

Both sensory and motor information are necessary for the initiation of the swallow response. In the past, researchers always believed the swallow to be a reflex but it is now known

that it is also control by the brain stem, cortical input, and input from the muscle spindles [3]. Therefore, all of these could play a role in the inability to swallow properly. The signals to swallow are sent from our brain but are also controlled involuntarily by some reflex muscles in the throat.

The main driving force during a swallow is the tongue. The tongue is such a complex muscle because it is made up of four intrinsic and four extrinsic muscles, all playing a part in the movements of the tongue. All of these muscles move in such a complex fashion that it is hard for even the most advanced researchers to document the exact dynamics.

Problem Motivation

Dysphagia is a swallowing disorder that affects more than 18 million adults and millions of children in the U.S. alone. This disorder is often resulting from stroke or other degenerative neurologic disease. When left untreated, dysphagia can lead to more damaging and sometimes lethal complications including pneumonia, malnutrition, and dehydration. Lingual weakness has been identified as a critical underlying cause of dysphagia. In order to study and properly treat dysphagia, a phantom mouth model needs to be constructed that can accurately mimic the mechanical properties of the tongue and palate. The model will be used to compare pressure generation at various points in the oral cavity during swallowing and the impact of bolus flow in varying conditions. Due to the complexity of this design, this semester's work will focus on creating a functioning, mechanical tongue that will have the ability to realistically mimic swallowing motions of an adult, human tongue. The tongue and it's attachments to other oropharyngeal structures has a particularly critical role in the swallowing function, propelling a bolus of food, liquid or medication and saliva properly and efficiently through the oral cavity

into the esophagus. The tongue is a unique structure being a muscular hydrostat lacking a skeletal infrastructure.

Current Devices

Although Dysphagia is serious disorder, no device has been created to specifically studying its characteristics and effects. However, other animatronic devices have been created to study speech and practice dental performance. These devices possess particular qualities that are desired for the design of a synthetic tongue that will mimic swallowing mechanics and pressure distribution.

Robotic Dental Test Dummies

A new, life-like robot called the Showa Hanko 2 was recently released by Japan's Showa University. This is the latest in a long line of robotic developments. This particular model is the latest in a series of dental training dummies that mimics facial, as well as head and neck movements of a human. Particularly impressive is the human-like movements of the mouth and tongue and the ability of the robot to react to pain and fatigue similarly to a real life dental patient. Furthermore, this robotic test dummy has features includes the ability to blink, sneeze, cough, gage, and engage in simple conversation using basic voice recognition software. This model also displays a distinct human appearance being made of the latest synthetic skin. This device displays are great degree of desired life-like qualities; however, it only displays limited tongue movement. The robotic tongue only allows two degrees of motions, which is severely lacking the ability to

Figure 1. The Showa Hanko 2 robotic dental test dummy.



produce the complex movements and pressure distributions our client requests.

Animatronic Model of a Human Tongue and Vocal Tract

Robin Hofe and Roger K. Moore at the University of Sheffield in the United Kingdom have developed a functioning mechanical jaw, tongue, and vocal tract – named AnTon – in order to reproduce speech gestures. The model is comprised of moveable tongue and jaw models that are attached to the hyoid bone and a fixed skull base. Each moveable part is driven by servo motors in a particular sequence to mimic the desired movements. This device has all the desired components and features that are desired for the complete

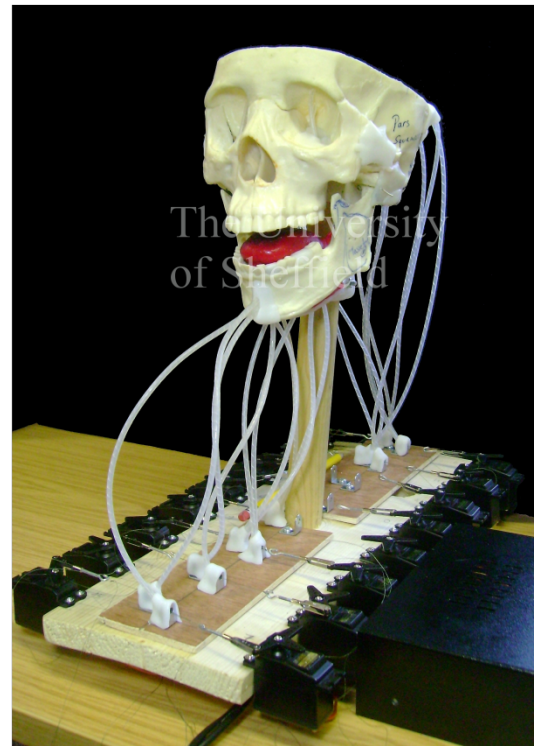


Figure 2. The AnTon Model of a Human Tongue and Vocal Tract.

design the client has requested. The animatronic tongue is particularly sought-after; however, it mimics speech movements and not swallowing movements.

Design Requirements

The client's work requires that the motions and forces generated by the animatronic tongue be as identical to the motions and forces of a true human tongue. As part of a longer term project, this tongue will eventually be placed inside a mechanically realistic mouth, and attached to a user interface that will include pre-programmed motions in addition to the ability to manipulate actuators individually. In order to create a tongue that can later fit this model and meet the client's needs effectively and thoroughly, some design requirements have been set

forward. Meeting these requirements will help assure that the final device is effective, reasonably priced, and user friendly.

The focus this semester will require a structure that can actuate a tongue structure such that they can be coordinated, and produce the necessary force to recreate the tongue's pressure. A typical healthy human can produce a pressure between 40 and 80 pKa with their tongue, measured against the palate. [8] The actuating fibers will be required to withstand the necessary forces to produce this pressure over repeated use and strain. To ensure their structural security actuators that fail at a minimum of 180 Newtons (approximately 40 pounds) will be chosen. To approximate the actual motion of a tongue, the actuators will be directed along the lines of action in a true tongue. This will also allow for an understanding of individual muscle contractions throughout the swallowing motion. The tongue itself must be made of temperature resistant, waterproof, pliable material that can return to its resting shape reliably. This will allow for use throughout its life time in studies involving liquids as well as hot or cold foods. Finally, the material should be easy to clean after exposure to food items or liquids. However, because this device will not be used on a patient, sterilization is a non-issue.

To ensure the safety of the operator, the tongue will not leave moving pieces unprotected. The actuators will be bundled into a tube or other construct that will protect hands from becoming caught in them while they are in motion. Furthermore, the materials chosen for this device will be non-allergenic so as to avoid potential complications from contact with an operator.

Design Alternatives

In order to meet the outlined requirements, the team considered three separate strategies for construction of a realistic animatronic tongue. The following design considerations come with their own unique advantages and disadvantages to be considered.

The Air Muscle Model

The first design that was considered would have utilized actuators that were constructed of air bladders enclosed by sturdy mesh which allowed for contraction, but maintained a fixed volume. A model air muscle can be seen in Figure 3. By pumping air into the bladder, the air muscle would “contract” and produce a force proportional to its size. The design would allow for realistic deformation in that a contracted “muscle” increases its



Figure 3: Air Muscles [9]

cross-sectional area much like a true muscle would. By anchoring the air muscles at realistic points, and building them to match the size of their corresponding muscles, a tongue could be constructed that closely matched a true tongue. To simplify the coordination and construction of the device, the air muscle groups would be attached to unique air compressors rather than a single compressor.

Hydraulic Muscle System

A second design consideration is a slightly modified air muscle system. This design would similarly utilize bladders and mesh as actuators. Instead of air power however, a closed fluid dynamic system would be utilized to increase maximum force and reduce noise emission. The

design would allow for scaling strength and realistic deformation much like the air muscle model. This device would utilize an array of liquid pumps to contract the “muscles.”

Cable Model

The third design considered would utilize a system of cables attached along the lines of action of the muscles of the human tongue. Because the actuators themselves are not creating the tongue shape as in the other models, a tongue structure would need to be built that the cables could actuate. A silicone mold or a latex coated segmented structure would be used to recreate the tongue’s shape and stiffness, and the cables would be run through the structure. The motion of the tongue will rely primarily on cable tension, but depending upon the stiffness of the cables, compression forces could also be applied. In future semesters, the cables will be attached to servo-motors.

Design Matrix

Category and Value	Air Muscle Model	Hydraulic System Model	Cable Model
Functionality in Real Time (20)	14	14	18
Accuracy and Precision of Motion (20)	15	15	18
Durability (15)	10	9	12
Force Generation (10)	8	9	7
Ease of Coordination (10)	6	6	8
Ease of Assembly (10)	8	7	9
Part Replacement (5)	2	2	2
Cost (5)	2	2	5
Power System (5)	1	3	5
Total Points (100)	66	67	84

Functionality in Real Time

This describes how closely the different systems could come to moving as fast as the tongue naturally does. The air and hydraulic models are rated slightly lower, because they require the bladders to fill or empty to drive movement. The cable system simply requires shortening or lengthening a cable, so has less time delay.

Accuracy and Precision of Motion

This is essential to our clients because they want to use this model for testing, so it has to work like an actual tongue. The bladder-driven systems change volume to make the movements, which differs from the tongue because it stays the same in volume. They also are likely to be less accurate, because their accuracy is determined by the size of the bladder, whereas the cable system's accuracy is determined by the number of cable attachment points.

Durability

Durability is important because the client intends to use the model a lot. Durability of hydraulic and air muscle systems is of concern if the hoses or bladders get punctured. This is especially of concern in the hydraulic system because if the hydraulic oil gets released, it would have to be replaced in the system. The cable system is mostly a concern at the attachment points, so as long as those are reinforced it should be less of a problem than the other two systems.

Force Generation

The amount of force generated by the model should closely resemble the amount of force generated by a real tongue. The maximum amount of force that a system can generate is a good

indicator of this, since the force can be lessened if necessary. Hydraulic systems have a very high maximum force generation, followed by air compressor systems. The cable system is low, because it would be based on how hard the people pulling the cables can pull. In the future, this will be made better with the servos or other mechanical drivers.

Ease of Coordination

This is how easy the system is to program or create certain movements. The ease of coordination is better for the cable system, because by shortening different cables any possible motion can be made. The hydraulic and air systems are a little more difficult to coordinate, because the movement is based on how much the bladders are filled.

Ease of Assembly

The system that's easiest to assemble is the cable system, because it does not require pumps or hydraulic oil. Also, the air compressor or hydraulic system would be bulky, and would require some sort of cover or cart to carry around.

Part Replacement

This could be an issue, because the system will be used often. Unfortunately, all of the systems have the same flaw; once the systems are assembled, all of the parts within the tongue are impossible to replace. The silicone rubber would have to be completely removed to access any parts, which would require a whole new tongue.

Cost

The cable system will be the most economical choice, because the only items that would need to be purchased would be some sort of cable and the attachment matrix. The other systems would

require multiple pumps or compressors, as well as the hose and bladders for the movement of the tongue, and the attachment matrix.

Power System

The power system is the worst for the air muscles because air compressors are large, heavy, expensive, and loud, and we would have to get multiple air compressors to move individual bladders. The hydraulic system would be similar to an air compressor in difficulty. The cable system, as it is currently, would not require any power, but it would have to be “driven” by people.

By adding up all these categories, the cable system is the best option. In fact, it outscores the other systems in 6 out of 8 categories.

Future Works

The next step is to order the materials we need for the cable system and its attachments, as well as a skull for mounting, and silicone rubber for making a covering for the tongue. Then the correct locations for the attachments have to be determined, and the parts have to be manufactured. Finally, the tongue has to be molded in silicone, and the system has to be mounted on the skull, with some sort of way to drive the tongue.

The clients eventually want a fully functional model of the mouth and upper esophagus that mimics swallowing. This semester the tongue itself will be built and in the future an automated system will be added to move the cables, with a program to mimic the movement of the tongue during swallowing. Other tissues and muscles will be added to the mouth and throat area to continue improving on the swallowing mechanism. Finally, testing will be done with the

different items the client wanted the model to be used for, to see if any improvements can be made.

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Appendix

Developing a 3D model of the Tongue and Mouth to Assess Pressure Generation When Swallowing

Donald Weier

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Function:

The device must be a physical 3D model of the tongue, mouth, and throat that closely mimics the mechanism of human swallowing. It will be used to test different pressure testing devices and also to determine the ease of swallowing different foods and liquids under different neuromuscular conditions.

Client requirements:

- A sturdy design to allow for daily use
- Waterproof material for liquid studies
- Easy to clean (Sterilization not necessary)
- A trap to catch foods or liquids after “consumption” that can hold 5-20 ml
- Ability to be swallow hot and cold samples
- Stain-protected material

Physical and Operational Characteristics

Performance Requirements:

The product will be demanded to perform the functions of the tongue, specifically the swallowing mechanism. In order to fully model and replicate swallowing fluid dynamics of the human mouth, the product will be required to: transport the bolus from the anterior to posterior

oral cavity for passage to the pharynx. In order to achieve this, functioning synthetic muscles and a functioning synthetic tongue are needed. Additionally, the product will need to perform these tasks on a daily basis and interact successfully with both hot and cold food, as well as being waterproof.

Safety:

The product should be made to be very user friendly. This requires all proper safety factors including safety guards for any hydraulic systems and smooth surfaces on exposed parts to prevent injury. All air compressed powered hydraulic and electrical systems need to properly labeled with necessary warnings. Additionally, non-allergen materials should be utilized.

Accuracy and Reliability:

This product will need to have a great deal of precision (repeatability) in the movements and replicated swallowing fluid dynamics it will provide. Furthermore, the product will need to accurately simulate the swallowing mechanism of the tongue. To model the most typical case, the design should mimic an adult's tongue as closely as possible.

Life in Service:

The product will need to be used daily for multiple demonstrations by various users. This continuous use should be able to persist for several years without any deterioration of materials and with sustained mechanical efficiency.

Shelf Life:

While in storage, the product should be able to withstand temperature changes from a range of 15° C – 40° C. The product will use air hydraulics and electricity to power its functions. Consequently, the shelf life of batteries and other powering sources do not need to be taken into consideration. The materials the product will be comprised of will need to have shelf life of 5 – 10 years, so the product can be cost effective and have proper usage.

Operating Environment:

The device will be exposed to a great deal of water and anything edible during its time of use. It will need to operate with both hot and cold food (15°C - 40°C). The product also be required to endure frequent contact with fluid (i.e. water, other consumable fluids, saliva), vibrations (i.e. air compressor), and specific parts of the model will need to endure pressure conditions due to the physiology of swallowing. During storage, the model will need to be able to be exposed to dust, dirt, humidity, and extended non-use. Because of the nature of this device the product will be exposed to extended handling and use.

Ergonomics:

This device will need to be very user friendly and easy to use. The forces of the power systems used will be similar to the force exerted by the typical human tongue muscles. Primarily, the product should be light enough to be easy and straightforward to transport by a single individual.

Size:

The size of the product should be similar to the dimensions of the typical human mouth and jaw, while being easy to transport. This will require a degree of portability and limitation of additional components besides the model mouth itself.

Weight:

The maximum weight of the product is 100 lbs. to ensure ease of transportation and there is no minimum weight for the design. A lighter product would be ideal; however, weight is very low on the priority list of the project design.

Materials:

Materials that resemble a tongue in stiffness and flexibility that will allow the same range of motion as a true tongue will be used.

Aesthetics, Appearance, and Finish:

The product should resemble an actual human tongue as much as possible. There should be the proper color and texture that will resemble flesh in order to disguise all mechanical parts. The client has requested to avoid red materials and utilize materials that do not absorb dye.

Production characteristics

Quantity:

The client has requested a single model for use in the lab. If the project is successful, more could be produced for labs elsewhere.

Target Product Cost:

The cost of the materials used to construct the prototype should not exceed 300 dollars, in order to fit the budget provided.

Miscellaneous

Standards and Specifications:

The device is not drug related so therefore doesn't have to be approved by the FDA, but could possibly have to undergo some other inspection in order to be used by businesses. Mainly the students building the model set the standards for this project.

Customer:

The product's most important use will be to serve as a testing subject for the other pressure sensors developed, The Madison Oral Strengthening Therapeutic (MOST) device and The Iowa Oral

Performance Instrument (IOPI). The main use of the device that will be focused on is recreating the pressure and swallowing motion created by the tongue. The highest priority for the customer is ensuring accuracy in this regard.

Patient-related Concerns:

Because its purpose is outside of clinical contact with human subjects, the device does not necessarily need to be sterilized between uses, but will need to be easily cleaned to avoid mold and rotting food particles building up.

Competition:

Currently there are few devices resembling the proposed design, and none meant to study swallowing. There is, however, one line of devices that will be considered while designing the prototype. The dental community has innovated several versions of mechanical, interactive robots for clinical practice. The animated robots are, in various combinations, capable of “feeling,” wincing, vomiting, and moving its tongue all in response to the practicing dentist’s ministrations. The device uses some of the same ideas put forth by this team in creating a replica of a human mouth, notably, air powered “muscles.” The most significantly similar technology is the functional tongue. It may not be capable of the fine motions necessary to mimic swallowing however.