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

Final Report

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Abstract

Swallowing is a unique and complex system of muscle movements that the body performs hundreds of times each day. The process is perceived as a fairly automatic motion that is usually only considered in the case of malfunction, such as choking or aspiration. These disorders and dysphagia in general are areas in need of further research. A synthetic hydrostat that can replicate the motions of a true tongue would be invaluable in advancing current knowledge of dysphagia. This mechanical tongue will be used to measure pressure distribution and pressure points in the mouth, and ultimately would be used to study the effects of specific muscle failure during the swallowing process. Using a complex system of cables and distributed forces, the model tongue has been constructed to accurately model the movement of the tongue throughout a healthy swallowing motion. Silicone is used to represent the overall structure of the tongue and nylon cables are embedded in the tongue to actuate the structure.

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Background

Client Description

Dr. JoAnne Robbins is one of the leadings throat pathologists in the world. Dr. Robbins' research interests focus on the effects of aging and age-related disease and the relationship between swallowing and speech production (dysphagia). Her studies have been conducted over the last 40 years and have served as some of the most useful information in helping dysphagia patients. In particular, Dr. Robbins' work using video fluoroscopy and magnetic resonance imaging is revealing the effects of aging on the relationship between swallowing physiology and the brain. 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. Most recently, her clinical research group is using MRI to quantify muscle in head and neck structures integral to swallowing. It can be safely assess that Dr. Robbins is an expert in the area of swallowing and its various complexities.

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 a growth in the number dysphagia patients in recent years, researchers like Dr. Robbins have been attempting to find ways to cure this disease and have been significant advances. The type of dysphagia that will be focused on is oropharyngeal dysphagia, in which various 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 of dysphagia is esophageal dysphagia, which refers to food getting stuck in the swallowing tube (esophagus); however, this will not be addressed [4].

This disease develops due to many different causes, two of which are 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. Patients who have suffered a cerebrovascular accident and aspirate are significantly more at risk of suffering from pneumonia and also have a greater rate of mortality than those who do not [1].

Sarcopenia, or the deterioration of muscles over time, is another leading cause of swallowing disorders. As an individual becomes older, he/she will suffer some sort of muscle loss. Some experience this muscle loss to a severe extent in their throat and tongue muscles, leading to problems and difficulties during the swallowing process. In particular, the various pressures that the tongue and throat muscles need to supply in order to swallow are not achievable in a sarcopenic individual. Dr. Robbins has made some major 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 when liquids seep into the lungs of a dysphagia sufferer 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 infectious 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 increasing the amount of dysphagia awareness and research. Malnutrition and dehydration also are serious effects of swallowing disorders and both result from the patient not being able to physically swallow liquids or solids. Both lead to many serious diseases and illnesses.

Many difficulties and complications arise due to the complexity of the swallowing process. 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 controlled by the brain stem, cortical input, white matter tracts, other CNS mechanisms and input from the muscle spindles [3]. Therefore, all of these factors 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 reflexive muscle responses in the throat.

The main driving force during the swallowing process is the tongue. The tongue is a complex structure, as it is comprised of four intrinsic and four extrinsic muscles, all involved in the movements of the tongue.

Problem Motivation

In order to study and properly treat dysphagia, a phantom mouth model will 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 a serious disorder, no device has been created to specifically study 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.

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

The robotic tongue only allows two degrees of motions, which is severely lacking the ability to 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 comprises 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 design the client has requested. The animatronic tongue is particularly sought-after; however, it mimics speech movements and not swallowing movements.

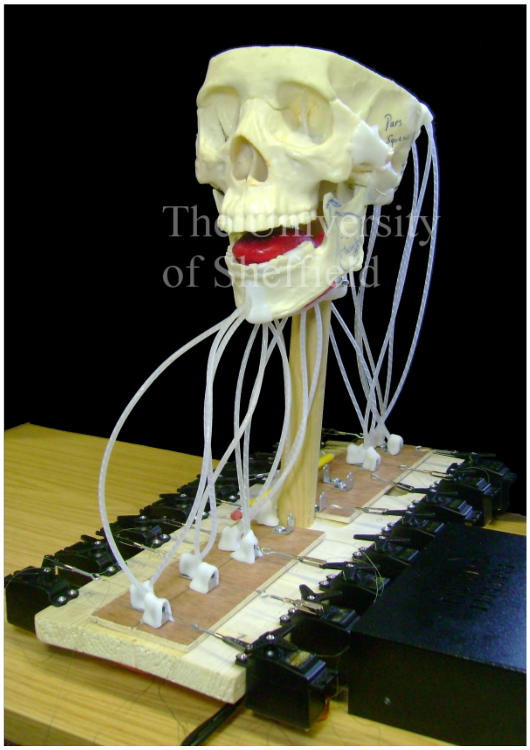

Figure 2: Anton was constructed for use in vocal studies, and includes as part of its design, a functional and complex tongue. [5]

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 with parts that 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 also will 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 cross-sectional area much like a true muscle behaves. 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.

Figure 3: Air Muscles [9]

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. Bladders are also likely to be less accurate, because their accuracy is determined by the size, 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.

Time Management

To accomplish the design, the team spent the first portion of the semester researching and learning about the structure and function of the tongue, as well as potential ways in which to construct a synthetic tongue. The pure research stage lasted approximately 1 month. After this time the team assembled a design matrix, comparing each of three potential designs. The matrix showed that a cable model would be the most effective way to recreate a tongue. With a design chosen, the team ordered materials and devised a molding system. Once the materials arrived, the team began the fabrication process, multiple molding templates were attempted to yield an effective four-stage process.

Final Design

To build a functional tongue, a four step molding process was devised. By filling a mold of the tongue in portions, it becomes possible to lay meshes that can then be molded over, embedding them in the structure. An illustration of the process can be seen in Figure 4. The placement of the meshes is based on the attachment points of the major extrinsic muscles of the tongue, and the cables are directed along the lines of their corresponding muscle. [10] The effect of the genioglossus was mimicked by the use of all three of the pictured meshes to make an anterior, central, and distal attachment point. The final device can be seen in Figure 5. The structure is reinforced by small sections of standard hardware store 1/8" tubing in places where the nylon cable pulled tight against the silicone (the distal portion of the genioglossus, for example, directs first towards the back of the tongue, then redirects approximately 130 degrees to exit at the distal base of the tongue). The tubing prevents tearing of the silicone over time due to the nylon cable. The cable used in this design is tested at 50 pounds to ensure durability of the tongue over time.

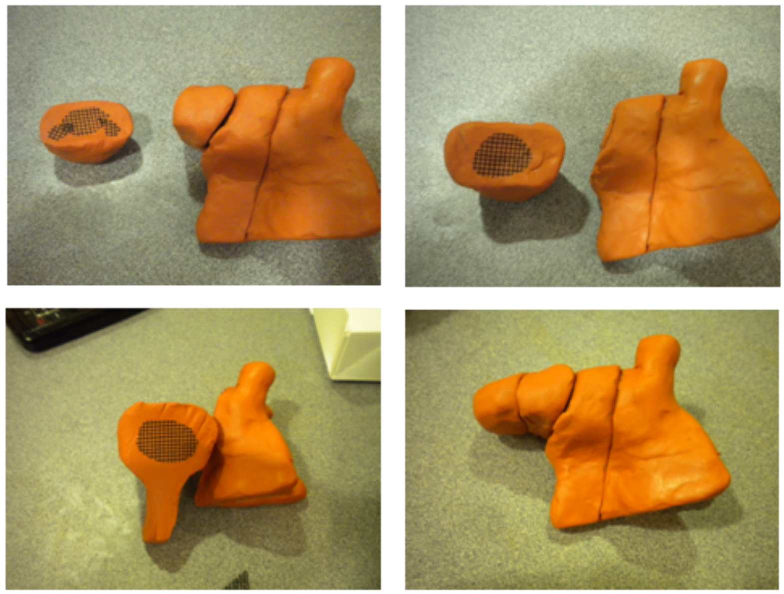

Figure 4: The molding stage was imagined with the aid of modeling clay. The sectioning of the tongue can be seen, as well as the placements of the meshes in the structure itself.

Discussion

The final design had some flaws that need to be addressed. One such flaw was in the silicon material itself. The material proved to be too dense and inflexible, restricting the motion of the tongue to a degree. Secondly, air bubbles accumulated in the silicone tongue mold. Air bubbles serve as weak points in the mold when the forces from the cables are applied, and have a negative effect on the aesthetics of the final product. The alginate used in the molding process degrades over time, a process that is accelerated at room temperature. Since the silicone required an environment greater than 63 degrees Fahrenheit, the alginate deteriorated as the molding progressed, leading to warping and volume loss from the intended shape.

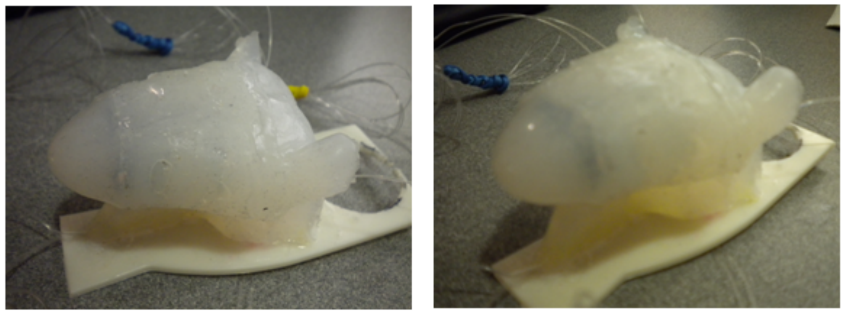

Figure 5: The final design mounted on a plastic base. The base was used as a stand in for the hyoid bone that the tongue will attach to in a final model.

The design did, however, prove the concept. Actuation of the device was achieved, and the muscles placed acted to produce the correct motions. With some adjustments to the molding process and the materials used, a more effective prototype can be made. The prototype serves as a solid part of the overall design process and its flaws provide valuable information when it comes to moving forward with the project. It can be concluded from the design that the attachment points of the mold worked properly in simulating some of the muscle movements during the swallow.

Future Work

The next step is to fix the problems from this semester's design, namely the stiffness of the silicone, and the problems with the manufacturing process. The stiffness of the silicone will be fixed by ordering a shore 0010 silicone from the manufacturer. In the manufacturing of the tongue, bubbles and degradation of the alginate were the two major problems. Silicone can be used for the mold, but was discounted this semester due to cost. In the future, this would be a good replacement for the alginate because it does not degrade and is easy to use. A silicone-based mold will allow for a longer molding process free of shrinkage. Another improvement would be to use a vacuum chamber to remove any bubbles from the mold as it is curing, because bubbles are unpredictable and cause a non-uniform matrix.

The clients eventually want a fully functional model of the mouth and upper esophagus that mimics swallowing. This semester the tongue itself was built. In the future an automated system will be added to move the cables, which will consist of servos and a program to coordinate common motions of the tongue during the act of swallowing. Other tissues and muscles will be added to the mouth and throat area to give the complete structure necessary in the swallowing mechanism. Finally, pressure testing will be conducted to determine the forces necessary to give an accurate reproduction of the swallowing process.

Works Cited

1. Robbins, J., Gangnon, R. E., Theis, S. M., Kays, S. A., Hewitt, A. L. and Hind, J. A. (2005), The Effects of Lingual Exercise on Swallowing in Older Adults. Journal of the American Geriatrics Society, 53: 1483–1489. doi: 10.1111/j.1532-5415.2005.53467.

2. Paik, Nam-Jong. *Dysphagia*. New York City: Medscape Reference, 2011. Web. <http://books.google.com/books/feeds/volumes?q=http://emedicine.medscape.com/article/324096-overview>.

3. McCaffrey, Patrick. "Neuropathologies of Swallowing and Speech." *The Neuroscience on the Web Series*. N.p., 2011. Web. 18 Oct 2011.

4. "Dysphagia." *Mayo Clinic*. Mayo Clinic, 2011. Web. 19 Oct 2011. <http://www.mayoclinic.org/dysphagia/>.

5. Hofe, Robin and Moore, Roger K.: *Towards an investigation of speech energetics using 'AnTon': an animatronic model of a human tongue and vocal tract*, Connection Science, 20 (4): 319-336, December 2008, DOI: 10.1080/09540090802413251.

6. "Robotic Doll Will Teach Dentists In Training." *[IAN] Today's Internet News: World, Showbiz, Sports, Technology, Politics, Business and Health*. Web. 19 Oct. 2011. <http://www.itsanews.com/2011/07/robotic-doll-will-teach-dentists-in.html>.

7. "Latest Dental News : Latest News in Dentistry : Stem Cells Research." *Dental Tourism:Advertising in Dental India:Latest in Dentistry*. Web. 19 Oct. 2011. <http://www.dentalindia.com/latnews.html>.

8. Iopi.info. Web. 19 Oct. 2011 <http://www.iopi.info/index.php? >.

9. Instructables.com. Web. 19 Oct. 2011 <http://www.instructables.com/id/How-to-make-air-muscles!/>

10. Takemoto, Hironiri. "Morphological Analyses of the Human Tongue Musculature for Three-Dimensional Modeling." *Journal of Speech, Language, and Hearing Research* 44 (2001): 95-107. Print.

Appendix

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

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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.