Curriculum Vitae

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University of Maryland School of Dentistry
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Doctor of Dental Medicine, May 2013

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Bachelor of Science in Biochemistry and Bachelor of Arts in Biology

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Research Specialist
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Bethesda, MD
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University of Virginia, Department of Neurobiology
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American Dental Association
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University of Pennsylvania School of Dental Medicine
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Academic Dean's List
University of Virginia
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2012

United Community Clinic
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2011 – 2012

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People's Emergency Center & Jane Addams Place, Philadelphia, PA
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University of Virginia Medical Center - Thoracic Cardiovascular Post-Operative Unit
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Abstract

Purpose: The purpose of this study was to compare the tongue muscle activity of glossectomy patients and normal controls and to determine which of the following factors – palate height, palate width, and tumor size (T1 vs. T2) – might influence muscle activity after glossectomy.

Methods: Muscle shortening within the hemi-tongue of 12 controls and 9 glossectomy patients was measured during the elevation and retraction of the tongue from /s/ into the /uk/ of the word "a souk" using cine-MRI and tagged-MRI. The muscle length measurements were performed on the following five tongue muscle segments: 1) genioglossus posterior (GGp), 2) geniohyoid (GH), 3) transverse anterior (Ta), 4) transverse middle (Tm), and 5) transverse posterior (Tp).

Results: The controls demonstrated significant asymmetric Ta and Tp muscle shortening with the larger side shortening more than the smaller side. The patients showed relatively symmetric muscle shortening on the native and the resected sides. High palate subjects showed greater GH shortening, while wide palate subjects showed greater GH and Ta shortening. No significant interaction was found between the effects of palate dimension and glossectomy on muscle shortening. A significant positive correlation between shortening was found in five pairs of muscles in controls' both sides and in one pair (Ta and Tm) in patients' native side. The T2 patients showed less shortening than T1 patients on both the native and the resected sides for Ta and Tm.

Conclusion: There were no statistically significant differences in muscle shortening between the controls and the patients, suggesting that patients were unable to adapt to an easier, asymmetric muscle activity as in controls during multiple repetitions of speech task. The effects of palate height and width were independent of the surgical effects. In controls, the muscles functioned synergistically in order to elevate the tongue by decreasing its length and width. In patients, the Ta and Tm worked in concert to decrease tongue width and create a compensatory behavior during tongue elevation. The lesser muscle shortening in T2 than T1 patients suggested greater impairment and limited muscle activity in T2 patients.

The Effects of Glossectomy and Palatal Dimension on Activity of the Tongue Muscles: A Quantitative MRI Analysis

by
Ji Youn Lim

Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, Baltimore in partial fulfillment
of the requirements for the degree of
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2016

Acknowledgements

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I. Introduction

The human speech production is a complex and precise mechanism involving highly coordinated movements of various tongue musculatures. The tongue plays a central role in speech formation due to its ability to generate a wide range of movements and surface deformations[1]. Physiological approach for understanding the function of the tongue during speech aims at studying the activity of the extrinsic and intrinsic tongue muscles, because they produce the local compressions and expansions required for tongue movements and surface deformation[2,3,4]. The purpose of this study is to compare the tongue muscle activity of the glossectomy patients and the normal controls and determine which of the following factors – palate height, palate width, and resection size (T1 vs. T2) – might influence the muscle activity after glossectomy.

A. Literature Review

Role of the Tongue

The tongue plays critical roles in vital functions such as mastication, swallowing, and speech. Studying the function of the defective tongue by examining the change in activity of the intrinsic and extrinsic tongue muscles can help us understand the role of the tongue in normal speech production, as well as, the phenomenon of compensatory and adaptive mechanisms in disordered speech. Changes that occur within the hemi-tongue may be particularly important in glossectomy patients since only one half of the tongue is primarily affected by the tumor and subsequent resection. Examination of both sides of the tongue would provide more information on the degree of impairment on the affected side. The unaffected side could either serve as a comparison to the affected side or allow studying the compensatory mechanism to produce articulatory function.

Moreover, if the post-operative functions of the tongue in glossectomy patients could be precisely predicted, it would greatly contribute to designing better surgical procedures.

Oral & Oropharyngeal Cancer

Oral and oropharyngeal cancer accounts for 2.5% of all malignant diseases and 1.4% of all cancer deaths in the United States[5]. Every year approximately 1 in 5000 people in the United States develop carcinoma of the tongue and floor of the mouth. Oral cancer is more common in male (5:1) at ages between 55 to 64 years, and among those with a history of tobacco or heavy alcohol use, and individuals infected with human papillomavirus (HPV)[6]. It is estimated that approximately 30-40% of oral cancers originate in the tongue, 17% in the lip, and 14% in the floor of mouth[3]. The tongue is the most common site for oral squamous cell carcinoma (OSCC), which is associated with significant morbidity and mortality[7,8]. The areas that are commonly affected by OSCC are ventral and lateral borders of the tongue. Tumors of the tongue and floor of the mouth are slow-growing, however if it is not diagnosed early, it can infiltrate surrounding structures including the lymph nodes.

Effects of Glossectomy on Post-Operative Tongue Function

Different treatment modalities are used to treat tongue cancer depending on the size, location, and type of the lesion, and the preference of the surgeon[9]. Currently, the primary treatment approach is surgical resection (glossectomy) of the tumor, which may be combined with flap reconstructions or adjuvant radiation therapy[10]. During glossectomy, the surgeon removes the malignant tissue as well as a margin of surrounding normal tissue and musculature. Resection size is the amount of tongue tissue that has been surgically removed, and it reflects the initial tumor size plus an additional border of tissue surrounding the tumor. In order to eradicate the tumor, an additional 1-1.5 cm border of healthy tissue is typically removed, including any cells that may have invaded the surrounding tissue that are only apparent on a microscopic level[11].

Glossecotmy is an effective procedure to treat patients with oral cancer, however it may deteriorate the functions of the tongue. In most cases, efforts are made by the surgeon to preserve the tongue tip as much as possible, however at times, it is encroached upon in order to provide an appropriate malignancy-free margin of tissue in the resection. Consequently, the resected side is primarily affected as the tissue mass and motor innervation are reduced and/or eliminated. Following partial or total glossectomy, patients may exhibit varying degrees of speech and swallowing impairments as well as other problems related to tongue mobility, which may ultimately have a negative impact on quality of life. The most common disturbances include limited tongue mobility and impaired glossopalatal and glossopharyngeal seal[12]. The defects and dysfunctions of the tongue due to a tumor and its surgical resection can be attributed to the altered mechanical properties such as the shape, stiffness, and viscosity of the tongue musculature[10].

Due to a considerable variation in the post-operative speech quality, the outcomes of glossectomy are difficult to predict. Previous studies[10,13,14,15] reported that glossectomy patients had difficulties producing the tongue shapes required for accurate vowel production and presented limited tongue adjustments necessary to achieve precise articulation. Skelly et al.[15] have found a limited range of tongue movement along the anterior-posterior dimension during vowel production by speakers with partial glossectomy. They hypothesized post-glossectomy speakers might have difficulties producing the tongue shapes and muscle contraction required for accurate speech production, because the intrinsic and/or extrinsic muscles responsible for tongue protrusion and retraction might have been damaged by resection. On the other hand, Mckinstry et al.[9] have indicated that patients with partial glossectomy were able to achieve reasonably intelligible speech post-surgically due to the development of compensatory techniques. These authors proposed that partial glossectomy patients were able to achieve appropriate tongue elevation, because the muscles responsible for tongue elevation and depression had been preserved or the individuals developed effective compensatory adjustments.

Effects of Resection Size

Tumors can be classified according to the TNM staging system used by the American Joint Committee on Cancer. The T describes the size or extent of the primary tumor – the higher the T number, the larger the tumor. The T staging for tumors of the oral cavity defines T1 tumors as 2 cm or less in their greatest dimension and T2 tumors as more than 2 cm but not more than 4 cm in their greatest dimension[8].

Several factors have been reported to influence the functional outcome in post-glossectomy patients. A number of studies[4,9,16,17,18] have shown that the extent of the articulatory impairment following glossectomy depends on the amount and location of tissue resected. Sun et al.[16] examined the patients who underwent glossectomy to determine the factors that may influence post-surgical speech intelligibility. They found that size of the tumor, as well as site and extent of the excision may be key factors in determining the post-operative articulation intelligibility. Likewise, McKinstry et al.[9] and Borggreven et al.[17] reported that the size of the defect might be an influential factor determining the quality of post-operative speech. They both found that patients with larger tumors experienced more speech difficulties than those with smaller tumors. Nicolettie et al.[18] found that the patients with larger resections had decreased quality of speech that was rated via self-assessment, a conversational understandability test, and a computer-digitized speech analysis. Similarly, Matsui et al.[19] found higher speech function in glossectomy patients with smaller resection as measured through self-assessment, a speech intelligibility test, and a conversational understandability test.

On the contrary, the studies done by Michiwaki et al.[20] and Bressmann et al.[21] showed that there was no significant relationship between tumor size and the degree of post-operative speech impairment. They found that patients with very extensive surgery might have near-normal speech, while patients with limited surgery might have largely unintelligible speech. Their studies also revealed that post-surgical functional level varied widely among patients who have undergone the same type and size of resection. In a study by Ikema et al.[22], speech intelligibility scores of glossectomy patients with tumors in the anterior tongue were found to be significantly lower than those with tumors in the middle or posterior tongue. The patients with preservation of the tongue tip had higher intelligibility scores than those without preservation. Overall, these studies suggest that resection size and tumor location may influence the post-glossectomy articulatory function, although considerable individual variability exists.

Effects of Flap Reconstruction

Closure procedure refers to how the resulting surgical wound is closed following resection of the tumor and surrounding border of non-malignant tissue. Depending on the size of the tumor, the resulting surgical defect is closed using the following methods: 1) healing without closure (secondary intention), 2) closure with sutures and no graft (primary intention), and 3) reconstruction using graft or free flap. In primary closure, the wound edges are approximated and sutured together, which results in a reduced tongue mass and healing with scar formation. In flap reconstruction, the resected tongue tissue is replaced with a mass of tissue with its own blood supply that is harvested from a distant location on the patient's body. This often results in increased tongue mass and weight and some scarring[23]. Flap reconstruction is usually chosen when the resulting surgical defect in the tongue would result in significant loss of function.

Recent progress in reconstructive surgery has offered new therapeutic options suitable for the complex anatomy and function of the tongue. Surgeons can now restore the contour of the lost tongue by various free autogenous grafts for reconstruction and speech rehabilitation of the glossectomy patients[16]. The use of innervated flaps, i.e. myocutaneous flaps, improves reception of sensory stimuli, such as temperature, touch, and sensor separation[24]. Radial forearm free flaps have become the preferred method of reconstruction for larger soft tissue defects in the oral cavity because of their thin, pliable characteristics, which are suitable for reconstruction of dynamic structures of the tongue and yield favorable post-operative speech intelligibility[25].

Although one may expect the considerable volume of free flap to compensate for the excised part of the tongue, the studies have proven otherwise. Matsui et al.[19] and McConnel et al.[26] tested the speech intelligibility in post-glossectomy patients and found that the type of flap reconstruction had no effect on functional outcomes, including overall speech intelligibility. This is because a flap is mainly used to sustain and reform the contours of the tongue, not to mobilize the residual tongue. In addition, the immobile bulk and scar formation of the reconstructive flap may impede the mobility of the residual tongue, thus intensifying the speech impairment after surgery. In some cases with larger defects, the lost tongue volume cannot be properly restored solely by using the flap, resulting in significantly compromised post-operative speech function[25].

In agreement with the aforementioned studies, several other studies[27,28,29,30,31] have shown that speech quality, including intelligibility and articulation, was better in patients with primary closure. The results suggest that, for glossectomy patients without the flap, the tongue can move more freely than with flap reconstruction after the surgery. These authors also agreed that the speech quality after glossectomy is more a function of tongue mobility than volume, because they found that the flap reconstruction patients with greater tongue mobility have better consonant intelligibility.

Effects of Radiation Therapy

A study done by Shin et al.[32] concluded that the functional speech outcome was negatively influenced by post-operative adjuvant radiation therapy. Post-surgical radiotherapy may induce late complications such as subcutaneous fibrosis, mucosal edema, trismus, and salivary gland atrophy, all of which may have a detrimental effect on speech in glossectomy patients. Deficiency of saliva, which acts as a lubricant, may aggravate speech dysfunctions. However, Pauloski et al.[33] demonstrated that radiation treatment in post-glossectomy patients did not influence articulation or speech intelligibility. Despite the difference in the study designs, most studies suggest that the size and location of the tumor, size of the defect after surgical resection, and method of closure and reconstructive techniques are important factors in determining the post-operative functional outcomes, mobility, and articulation in glossectomy patients.

Anatomy & Functions of the Tongue Muscles

Tongue is one of the few organs in our body that is entirely composed of muscle tissue, allowing high flexibility and extensive range of movement. The tongue consists of a complex network of interwoven skeletal muscle fibers. These muscle fibers function together to produce a vast array of functional deformations, which contribute mechanically to speech production. There are ten muscles responsible for the movement of the tongue, including 4 intrinsic muscles (superior longitudinal, inferior longitudinal, transverse, vertical), 4 extrinsic muscles (genioglossus, hyoglossus, styloglossus, palatoglossus), and 2 floor muscles (geniohyoid, mylohyoid) (Figures 1 & 2). Although the musculature is bilateral and symmetric, the muscles can be activated asymmetrically to produce asymmetric tongue movements. Motor innervation for all muscles of the tongue is supplied by efferent motor nerve fibers of hypoglossal (CN XII) nerve with the exception of the palatoglossus, which is innervated by vagus nerve (CN X).

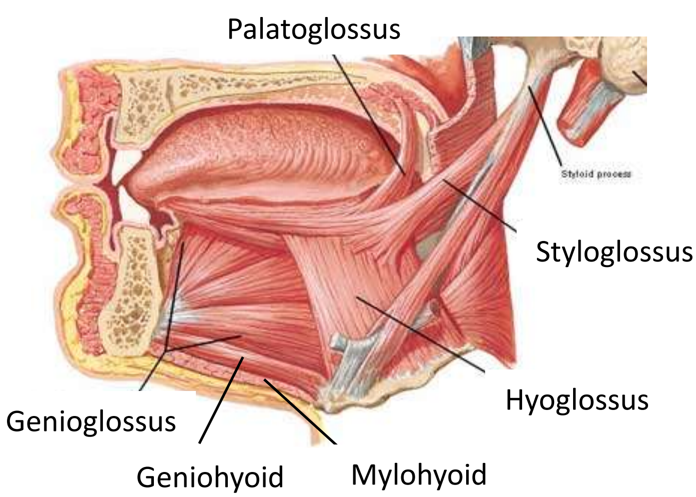

Figure 1. Extrinsic muscles of the tongue and floor muscles (Sagittal view)

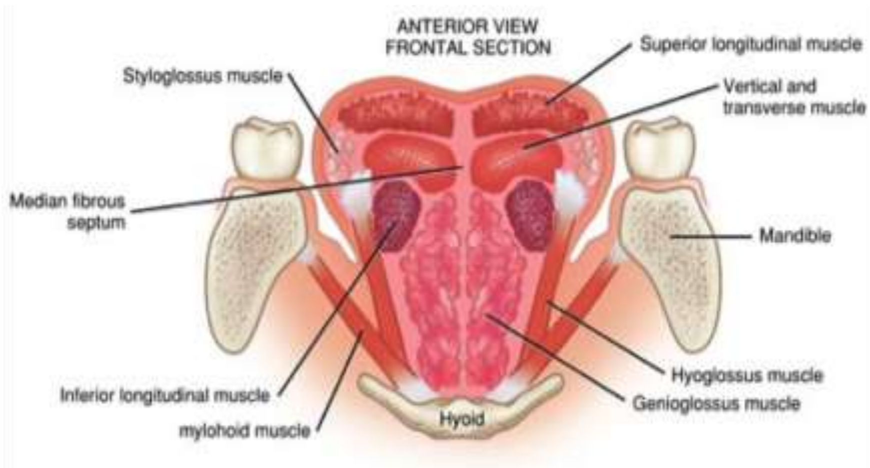

Figure 2. Extrinsic and intrinsic muscles of the tongue (Coronal view)

The muscles of interest for the present study include the posterior part of genioglossus, the geniohyoid, and the 3 subunits (anterior, middle, posterior) of transverse, all of which play a key role in elevation and retraction of the tongue. The tongue body is elevated and retracted in the mouth during production of a raised back vowel (i.e. /u/). During production of a velar consonant (i.e. /k/), the back of the tongue is raised to make contact with the soft palate and create a complete closure (Figure 3).

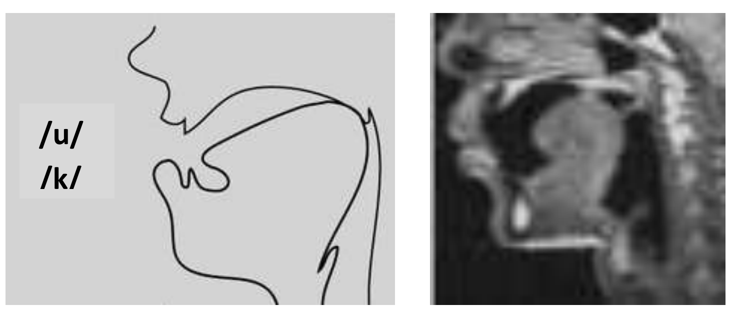

Figure 3. Tongue position during production of the /u/ and /k/

The genioglossus (GG) muscle is the largest and strongest tongue musculature, which lies near the midline. It arises from the mental spine on the inner surface of the mandibular symphysis above the origin of the geniohyoid muscle. From its origin, the fibers spread mid-sagittally in a fan shape in the medial part of the tongue. GG is arranged as 3 functional subdivisions - anterior (GGa), middle (GGm), and posterior (GGp) in dynamic control (Figure 4). The anterior fibers course superiorly, anteriorly, and laterally to project toward the dorsum near the tip. The middle fibers fan out antero-posteriorly and slightly medio-laterally and radiate towards the dorsum. The posterior fibers attached to the root of the tongue and body of the hyoid bone. The posterior fibers are thicker, stronger, and wider at the base of the tongue than the anterior fibers. The GGp is bound by a line from the mental spine, dorsum of the tongue, and upper ridge of the body of the hyoid bone. GGm-GGp boundary is the line that extends along the orientation of the short tendon of the GG, which is seen as a bright line arising from the mental spine of the mandibular symphysis in the MRI (Figure 6B)[34].

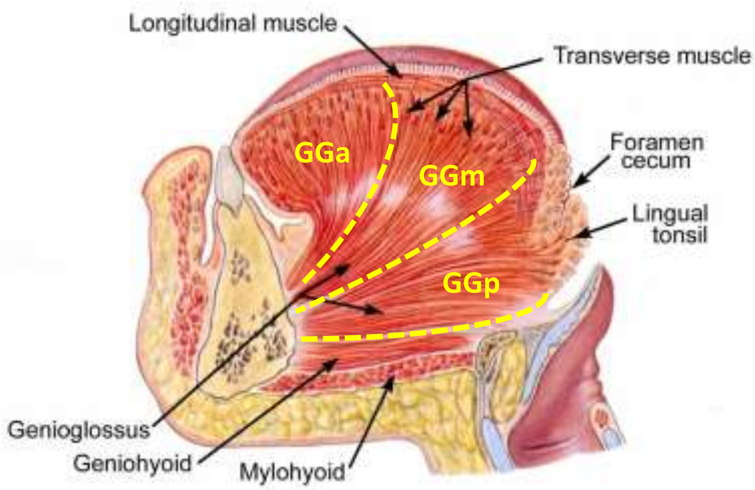

Figure 4. 3 Functional subunits of the genioglossus: Anterior (GGa), Middle (GGm), Posterior (GGp)

Takano et al.[34] examined the functions of extrinsic tongue muscles in vowel production by measuring the muscle length and tongue tissue deformation using MRI. They found that the contraction and relaxation of the GG is the primary driving force for protrusion, retraction, and depression of tongue body and it plays a dominant role in forming tongue shapes for vowels. The GGp has a major effect on the entire tongue, because it is the largest subdivision of the GG, capable of generating the greatest amount of force. Studies of tongue motion using EMG and velocity pattern of tissue deformation revealed that muscles in the tongue body were activated individually and the GGa, GGm, and GGp fibers functioned differently[3]. Contraction of the GGp allows formation of raised back vowels (i.e. /u/) and velar consonants (i.e. /k/) by producing a forward motion of the tongue base, which in turn causes elevation and arching of the tongue dorsum due to tissue displacement and compression (Figure 3).

The geniohyoid (GH) arises from the inferior mental spine on the posterior surfaces of mandibular symphysis, and projects backward and slightly downward to insert into the anterior surface of the body of the hyoid bone (Figure 1). When the hyoid bone is held steady, the GH depresses the mandible during mastication and speech. When the mandible is held steady, the GH contraction drives the hyoid bone upward and forward, elevating the tongue body and contributing to production of raised vowels such as the /u/.

The transverse (T) is composed of a series of thin laminae in the body of the tongue, and its fibers arise from the median fibrous septum and pass laterally to the tongue margin. The muscle fibers are subdivided into transverse anterior (Ta), transverse middle (Tm), and transverse posterior (Tp), corresponding to the anterior, middle, and posterior thirds of the tongue (Figure 5). The laminae of T and GG are intermeshed in an ordered manner from the apex to base to make a bulk of the tongue. The motion of the tongue to produce raised vowels and velar consonants, such as /u/ and/k/, is mainly achieved by internal deformation of the tongue tissue for compression of the tongue body medially. Contraction of the T causes lateral compression of the tongue body, making the tongue narrow and elongated aiding the elevation required for the production of the /u/ and /k/.

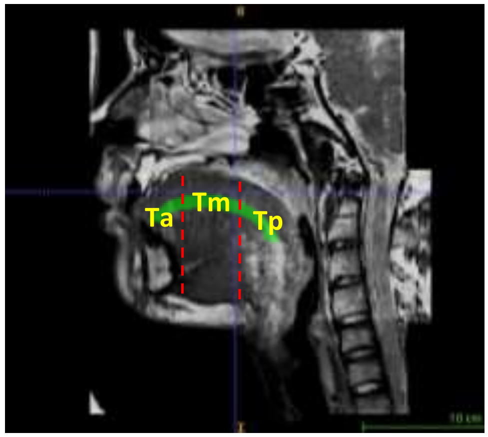

Figure 5. 3 Subdivisions of the transverse: Anterior (Ta), Middle (Tm), Posterior (Tp)

Mechanisms of Tongue Motion during Speech

Speech production requires a highly controlled movement of the tongue produced by coordination of different muscles within the oral cavity. The tongue, which has no internal skeleton, moves by activating the internal muscles inserted at all locations on the surface of the tongue. Active muscle contraction causes muscle shortening, which in turn produces local deformation that deforms and moves the tongue. The tongue also interacts precisely with various intra-oral structures such as the teeth, alveoli, and palate to perform articulatory function. Therefore, function of the tongue is greatly influenced by the individual muscle activity as well as different structures within the oral cavity.

The currently accepted model of the tongue is that of a ‘muscular hydrostat’ in which movement is created by displacement of soft tissue while overall volume is preserved[35]. The tongue body is considered to be incompressible soft tissue, therefore a force loaded in a specific direction would cause a compression in one direction and an expansion in the perpendicular direction. Tongue elevation is a finely controlled motion in which simultaneous compression of vertical and horizontal fibers allows fine tuning used in muscular hydrostat control. Simultaneous contractions in the antero-posterior and lateral directions produce reduction in tissue length and width, as well as, tissue elevation in the vertical direction. Contraction of the GGp and GH causes the tongue to decrease in length, while contraction of the T causes decrease in width. Thus, the synchronized activity of the GGp, GH, and T produce dorsal elevation of the tongue.

Methods for Studying Tongue Motion

Measuring the tongue movement during speech involves several challenges because: 1) the tongue is enclosed and concealed within the oral cavity and moves deep within the vocal tract, 2) tongue motion has a high number of degrees of freedom, and 3) tongue motion is rapid during speech[36]. First, the tongue is attached to various hard tissue structures within the oral cavity. Because the soft (i.e. tongue, lips) and hard tissues (i.e. maxilla, mandible, teeth) have different tissue consistency, they produce different fluid deformation that results in significantly different complexity of movements[37]. Second, the interaction between the muscles causes major measurement problems because the tongue consists of several intrinsic muscles with their fibers intermeshed together. Some articulatory behaviors are highly correlated, and distinguishing the contributions of each player can be quite difficult. In addition, the tongue is a very flexible and deformable organ that moves by highly coordinated local compression and expansion of functional segments. These local deformations yield a change in the shape of the tongue surface, which in turn modifies the airway space between the tongue surface and the palate to produce different sounds during speech. Therefore, studying tongue motion requires techniques that are capable of distinguishing hard and soft tissue structures within the oral cavity, as well as to examine superficial and deep structures of the tongue.

A variety of techniques, including electromyography (EMG) and various imaging techniques, have been used for measuring articulatory function and the change in surfaces and internal structures of the tongue during speech. Until a few decades ago, the functions of the tongue muscles in speech production have been discussed mainly based on anatomical features and EMG data[38]. EMG studies examine the activities of individual muscles during speech based on muscle action potentials. EMG requires instruments that are entered and positioned in the oral cavity directly, which may affect the speech articulation. An EMG study by Maeda et al.[39] proposed an antagonistic activity of the tongue muscles in which vowels are controlled by two orthogonally arranged pairs of muscles. Although these anatomical studies and EMG data provide reliable knowledge of the tongue muscle and useful information for estimating muscle functions, they do not explore the mechanism of the 3-dimensional deformation of the tongue tissue. Anatomical descriptions alone offer little insight into mechanisms of 3D deformation, and EMG data alone fail to explain the quantitative contributions of individual muscle to speech production.

Recently, various imaging techniques have gained popularity because they provide information on local tissue movement without directly contacting the structures and impinging upon normal movement patterns of the tongue. Imaging techniques also allow studying the internal structures of the vocal tract and inter-structure relationships. Four well-known imaging techniques used in speech study include X-ray, ultrasound imaging, computed tomography (CT), and magnetic resonance imaging (MRI)[17]. The 2-

dimensional (i.e. sagittal, coronal) X-ray images have been used to record the lengthwise and cross-sectional views of the oral cavity. Evaluation of soft tissue structures such as tongue using X-rays is difficult because of highly radiopaque bony structures obscuring more radiolucent soft tissues in the coronal view and lateral structures overlapping with midline structures in the sagittal view. Additionally, collection of large quantities of X-ray data increases the risk of potential overexposure.

Two-dimensional representation of the tongue is often unsatisfactory because it cannot give a complete representation of complex, non-rigid, three-dimensional structure. Three-dimensional ultrasound, CT, and MRI have been used as main tomographic techniques in speech research to visualize the three-dimensional tongue surface and contour[21]. CT uses X-rays to image tissue slices as thin as 0.5 mm or less, and the tissue slices can be collected rapidly and simultaneously from the rotating scanner[17]. CT produces the composite X-ray image by digitally summing a series of scans, thus allowing higher resolution and more distinct tissue definition. The major limitation of CT is the greater radiation exposure compared to traditional X-ray, because it images thinner slices that are scanned several times to collect multiple images. Although CT can be used to image the vocal tract at a high spatial and temporal resolution, it is not the instrument of choice for speech research.

Magnetic Resonance Imaging (MRI)

MRI has replaced X-ray for many speech research applications such as studying the shape of articulatory organs and assessing tongue motion, because it provides fairly accurate isolation of the tongue surface and reconstruction of 3D tongue volume with no known harmful effects[40]. MRI uses a magnetic field and radio waves rather than X-rays to record the density of hydrogen in tissue. Different types of MRI (i.e. high-resolution MRI, diffusion tensor MRI, and functional MRI, cine MRI, tagged MRI) exploit different features of the relationship between the hydrogen proton, magnetic fields, and radio waves[17]. MRI scanner consists of electromagnets that create a magnetic field in order to detect the presence of hydrogen atoms, which are present in human tissues in varying proportions. The magnetic field created by the electromagnets cause protons that are spinning about randomly oriented axes to align to the long axis of the body and perpendicular to the magnetic field[1]. When the protons realign to the magnetic field, they emit a weak radio signal that is detected by the scanner. Because the proton emissions are weak, the process is repeated many times and the radio signals are summed to reconstruct a single image. The resulting data are constructed into an image that reflects the various hydrogen contents of different tissues. Since both water and fat have high hydrogen content, tissues high in water or fat (i.e. tongue, soft tissue, maxilla, mandible) appear white, whereas tissues without water (i.e. teeth, vocal tract) appear black. MRI also allows characterization of different types of soft tissue, therefore is quite successful in identifying soft tissue pathology such as tumors.

Recently, MRI has been recognized as a method for visualizing and quantifying the spatio-temporal relationships among articulators during speech production. 3D physiological model of the tongue based on MRI data can be used to analyze the internal tongue motion and local deformations within the tongue musculature, as well as to study the changes in movements of the tongue before and after partial glossectomy. Two types of MRI used particularly to characterize tissues are high-resolution MRI (hMRI) (Figure 6) and diffusion tensor MRI (DTI). The intrinsic and extrinsic muscles of the tongue can be adequately visualized and characterized using hMRI (Figure 7). Both hMRI and DTI are excellent in evaluating tongue structures at rest, however they require relatively long data acquisition period and the image resolution can be affected by the movement of subject during image acquisition process. Although static MRI reveals the detailed anatomy of structures in the vocal tract including the airway, it is limited to modeling static features and cannot represent the tongue in motion.

Figure 6. High-resolution MRI (hMRI): Axial (A), Sagittal (B), Coronal (C)
*Short tendon of the genioglossus (Red arrow)

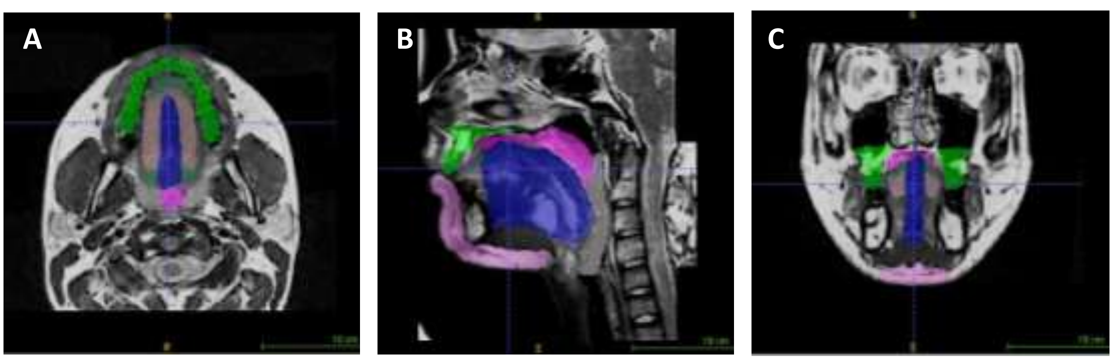

Figure 7. Segmentation of the tongue muscles using hMRI: Genioglossus (Blue), Transverse (Green)

Recently, cine-MRI and tagged -MRI were introduced to study the surface and internal aspects of the tongue[41,42]. The introduction of cine- and tagged-MRI allowed non-invasive, dynamic in vivo visualization of the surfaces and internal deformation of the tongue during speech. Cine-MRI acquires a time series of images in multiple orientations that can be used to study the motion of the tongue (Figure 8). Cine images are collected by having the subject repeat a speech task multiple times and summing the data from each frame across repetitions. While the motion of soft tissue organs can be captured, hard tissue structures such as teeth are almost invisible due to lack of mobile hydrogen atoms[43]. The biggest limitation for this technique is that the subject must produce the repetitions very precisely to prevent image blurring[44]. Cine-MRI does not produce the level of anatomic details seen in hMRI or DTI, however, it remains very popular in studying tongue motion during speech.

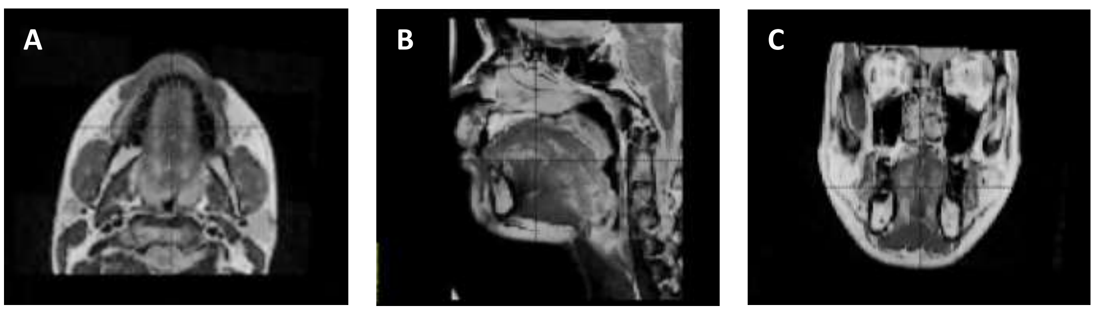

Figure 8. Cine-MRI: Axial (A), Sagittal (B), Coronal (C)

Although cine-MRI is useful in studying dynamics of the tongue surface, it does not provide enough information about deformation of the muscles within the tongue body. This drawback has been overcome by tagged-MRI, which temporarily marks or "tags" a plane of tissue within the tongue (Figure 9). Since its initial application in imaging deformation of contracting cardiac muscles, tagged-MRI has been successfully used to study motion of the tongue during speech. Tagged-MRI utilizes tissue tags that are created by demodulating the spinning protons in alternating planes in order to apply a spatial gradient to the tissue. The planes of tissue are magnetized by placing temporary markers or "tags" prior to the collection of cine-MRI sequence. A grid of tags is created by applying the tags in horizontal and vertical planes. In the demodulated planes, the protons spin out of phase from the rest of the tissue, making them invisible to the detector and appear as black stripes on the resulting image. The tags deform to exactly the same extent as the tissue during speech motion because magnetization stays within the tissue[17,41,42]. The resulting checkerboard deformation from tagged-MRI reflects local expansion and compression within the tissue, therefore the internal deformation of the tongue can be observed as the movement of the tags, which can be traced and subsequently used to study the tongue muscle activity. The combination of cine-MRI and tagged-MRI allows tracking of the internal tissue points throughout the entire period of the speech (Figure 10).

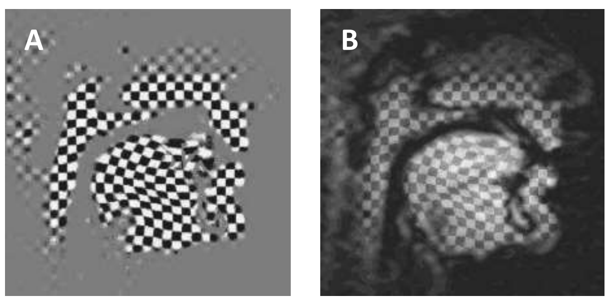

Figure 9. Tagged-MRI (A), Tagged Cine-MRI (B)

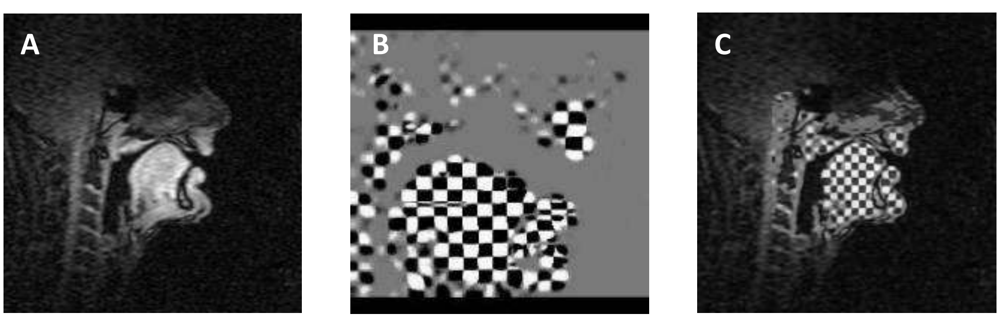

Figure 10. Cine-MRI (A), Tagged-MRI (B), Tagged Cine-MRI (C)

3D Tracking of Tissue Points & Measurement of Muscle Length

A 3-dimensional tracking of internal tissue-point motion patterns among subjects allows determining the common features in muscle compression and control mechanism used to create the same speech sound[45]. Stone et al. [46] used tagged cine-MRI to examine the internal deformation of the tongue during speech and found the link between internal tissue strain and surface deformation. In order to perform 3D muscle tracking during speech, a series of tagged cine-MRI of the tongue needs to be collected in 3 slice orientations (sagittal, coronal, and axial) during repetitions of the word. In tagged-MRI acquisition and analysis, Harmonic Phase MRI (HARP-MRI) allows processing of the tagged images to calculate the displacement and velocity at every tissue point within the tongue. HARP-MRI is an automatic tag tracking technique that estimates motion and deformation at every pixel in a tagged image[47,48,49]. It involves tracking of handpicked tissue points and calculating the stretch between two hypothesized muscle endpoints. HARP-MRI is capable of generating sequences of velocity fields that provide highly detailed patterns of different types of motion measurements as the tongue moves from one time frame to the next[50,51]. Information from sagittal, coronal, and axial tags are combined to completely characterize the 3-dimensional motion of the tongue during the production of speech sounds. This method serves as a great tool for investigating the function of intrinsic and extrinsic tongue muscles.

The muscles of the tongue undergo volume-preserving deformations. Incompressible Deformation Estimation Algorithm (IDEA) allows reconstruction of the 3-dimensional displacement field and the estimated motion field from tagged-MRI[52]. The orientations of both the MRI slices and their tags should be coordinated properly in order to interpolate 3D motion of the tongue. First, the 3D displacement vectors on the selected tissue points are computed from the tagged-MRI using HARP processing and in-plane motion tracking. At each imaged time frame, the tagged images are first processed to determine components of the displacement vector at each pixel relative to the reference time. Then, IDEA applies a smoothing vector projection to compute to the velocity fields by integration of the reconstructed displacement field.

3D Tracking Errors

Accurate tag tracking is critical to measurement reliability and 3D analysis. “Tag jumping” occurs when the motion between time-frames is larger than the distance between tags. Tag jumping is a likely problem with HARP-IDEA motion analysis of the tongue, when the tongue undergoes greater deformation than the distance between tags. A refinement algorithm attempts to minimize this phenomenon. The algorithm tracks a single, user defined point of minimal motion, in the tongue through all the time frames and uses the successfully tracked point as the “seed” point that is least likely to have a jump occur. The user can observe the tracking and choose a different point if jumping is apparent (Figure 11). The four points adjacent to the “seed” point are then tracked and this region is then grown outward from these points in a similarly conservative manner until the entire image is covered. The algorithm prevents large increases in motion relative to the previously tracked points to minimize tag jumping. This newly developed technique allows reliable 3D tracking of tongue tissues, mostly overcoming the problem of tag jumping[52].

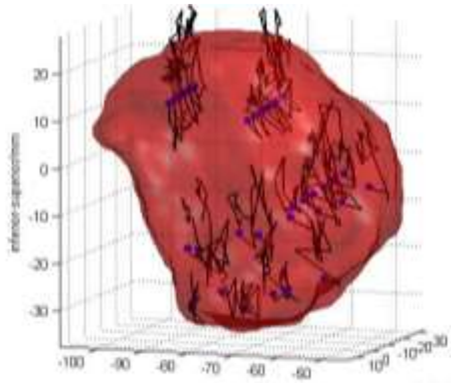

Figure 11. Tag jumping during 3D tissue point tracking

As with all instruments, MRI has several drawbacks. Cine-MRI and tagged-MRI require summation of multiple, very precise repetitions for optimal images quality. Another major limitation of MRI is the width of the tissue section. MRI sections are usually 5-10 mm thick, whereas CT sections are less than 1 mm thick. Narrower thickness in MRI sections are possible, however require longer exposure time. Also, metal objects such as tooth crowns and dental implants quench the signal creating a diffuse dark spot surrounding the metal. Lastly, the subject must be lying in a supine position, which changes the gravitational effect on tongue structures and normal agonist-antagonist muscle interactions[34,42]. Despite these drawbacks, the advantages of MRI make it an imperative instrument to study the tongue motion during speech.

B. Goals & Hypotheses

The aim of this study is to quantitatively analyze the muscle activity during tongue elevation and retraction in normal controls and glossectomy patients in order to examine how the post-surgical defect affect the motion of the tongue during speech. The study will also determine which of the following factors – palate height, palate width, and resection size (T1 vs. T2) – may influence the muscle activity after glossectomy. This will allow us to better understand the muscular dysfunction, mechanism of motor control, and the ability to adapt to altered tongue structure in post-glossectomy speakers. The % muscle shortening of 5 tongue muscles – 1) the Posterior Genioglossus, 2) the Geniohyoid, 3) the Transverse Anterior, 4) the Transverse Middle, and 5) the Transverse Posterior – during elevation and retraction of the tongue from /s/ to /uk/ will be examined. The change in muscle length within the hemi-tongue among the 4 subject groups – 1) Control larger side, 2) Control smaller side, 3) Patient native side, and 4) Patient resected side – will be compared to identify statistically significant difference between the groups. The effect of palate height and width on muscle shortening will be investigated to identify the presence of potential interaction between the palate dimension and surgical effects. The relationship between the percent shortening among all measured muscles will also be examined to identify the positive or negative correlation. The goals and hypotheses are summarized in the following outline.

Goal 1: Determine the effect of subject group (control vs. patient) and palate height/width on % muscle shortening

> H_0: There are no significant differences in % muscle shortening between the 4 subject groups and no significant interaction between palate height/width and effects of glossectomy surgery.
>
> H_1: The muscles will shorten less on the resected side of the patients than the native side or either side of the controls. The % muscle shortening will decrease in the following order: 1) Control larger/smaller side, 2) Patient native side, and 3) Patient resected side, due to scar tissue formation and lack of motor control and innervation on the resected side of the glossectomy patients.

H_2: Subjects with high palate will have greater % muscle shortening of GGp and GH than the subjects with low palate, because GGp and GH contribute to greater elevation of the tongue required in high palate subjects.

H_3: Subjects with wide palate will have greater % muscle shortening of the Ta, Tm, and Tp than the subjects with narrow palate, because Ta, Tm, and Tp contribute to greater constriction of the width of the tongue required in wide palate subjects.

H_4: There is a significant interaction between palatal dimension (height and width) and subject group in their effect on % muscle shortening of Ta and Tm, because both muscles are primarily affected by the resection and the resulting defect will cause them to respond differently to palatal dimension.

Goal 2: Determine the relationship between % muscle shortening in both controls and glossectomy patients

H_0: There is no significant relationship between % muscle shortening in control subjects and glossectomy patient.

H_1: The GGp and GH will be more highly correlated in patients than controls because GH will assist GGp in elevating the tongue for patients.

H_2: All 3 subunits of the T (Ta, Tm, Tp) will be correlated in order to produce a synchronous tongue motion. The extent of correlation will be lesser for the patients in Ta and Tm as they are affected by the glossectomy surgery.

Goal 3: Determine the effects of tumor size (T1 vs. T2) on % muscle shortening on both the native and resected sides of patients

H_0: There is no significant difference in % muscle shortening between the T1 and T2 subgroups on the native and resected sides.

H_1: T2 patients will shorten the Ta and Tm muscles more than T1 patients on the resected side, because T2 patients require greater level of muscle activity in order to compensate for the larger volume of missing tongue tissue.

II. Methods

A. Subject Selection

The participants included 12 control subjects (5 male, 7 female) and 9 glossectomy patients (6 male, 3 female) who are native speakers of American English. They were recruited from the University of Maryland Medical System by advertisement or by recommendation from their surgeons. All subjects demonstrated normal hearing with no history of impaired speech, swallowing, motor disability, or upper respiratory infection. All subjects had a hearing test to confirm normal hearing and speech reception threshold since deficits in these areas can affect speech production. The demographics for the subjects are presented in Table 1. Glossectomy patients were seen at least 8 months after the surgery. Pre-operative MRI were not collected due to some subjects being in pain, most subjects having surgery almost immediately after diagnosis for the best prognosis, and many subjects having already adapted their speech motions to the fairly rigid tumor, so that they cannot necessarily be considered as normal. The analyses of the data were approved by IRB protocol #42060 and the subjects signed IRB approved consent forms prior to participating in the study.

Table 1. Subject Demographics

Controls (n = 12)	Gender	Age (Yr)
C1	M	23
C2	F	31
C3	F	27
C4	F	41
C5	F	45
C6	F	27
C7	F	22
C8	F	26
C9	M	22
C10	M	27
C11	M	52
C12	M	54
Age Mean $\pm$ SD		33.1 ± 11.7
Age Range		22 - 54

Patients (n = 9)	Gender	Age (Yr)	Tumor Size	Closure Method
P1	F	46	T1	PC
P2	M	29	T1	PC
P3	M	44	T1	PC
P4	M	57	T1	PC
P5	F	37	T2	PC
P6	F	40	T2	PC
P7	M	61	T2	RFFF
P8	M	59	T2	PC + Rad
P9	M	45	T2	PC
Age Mean $\pm$ SD		46.4 ± 10.7		
Age Range		29 - 61		

PC – Primary closure
Rad – Radiation therapy
RFFF – Radial forearm free flap

All patients had squamous cell carcinomas (SCC) with no nodal involvement or metastasis and were treated with either partial or hemi-glossectomy by oral and maxillofacial surgeons Drs. Ord and Salama at the University of Maryland Medical System. Patients with larger tumors and those with involvement of the lymph nodes and metastasis to other parts of the body were excluded from the study. Details regarding all aspects of the surgery, such as resection sites, size of the tumor, and types of closure or reconstruction, were obtained from the surgeons to help interpret the patient measurements. The inclusion criteria required all patients to retain one-half of the tongue post-operatively to examine the muscles that are unaffected by glossectomy and common across subject groups. As part of the inclusion criteria, tumor location was limited to the freely movable tongue from the junction of the tongue with the floor of the mouth anteriorly to the circumvallate papilla posteriorly. Tumors located at the base of the tongue were excluded because they have different lymphatic drainage and are treated differently than tumors located elsewhere in the tongue.

Patients were classified into 2 subgroups according to the tumor size using the traditional TNM staging system. 4 patients were in the T1 group (< 2 cm in greatest dimension), and 5 patients were in the T2 group (>2 cm and < 4 cm in greatest dimension). The sizes of surgical ablation ranged from small surface resection to relatively large partial glossectomy. Resection sizes were obtained from the surgical pathology reports available in the patient's charts. The report included the greatest antero-posterior, medio-lateral, and superficial-deep dimensions to the nearest tenth of a centimeter of the specimens that had been submitted for pathological examination. The mean dimension of resection for T1 and T2 tumors were 2.6 x 1.2 x 1.2 cm and 5.1 x 2.2 x 1.9 cm, respectively. Smaller defects were closed using either primary wound healing or local closures and larger defects were closed using free flap. All patients received a partial lateral glossectomy. One patient (P8) received adjuvant radiation therapy post-surgical resection, and one patient (P7) underwent flap reconstruction with a radial forearm free flap (RFFF) for the defect left from glossectomy.

B. Speech Task

The subjects were tested beforehand with a metronome for a high level of repeatability. The subject must repeat the words precisely because multiple repetitions are averaged for good image quality. Control subjects and glossectomy patients were instructed to repeat the word "a souk" (/əsuk/) to a metronome-like stimulus. The word "a souk" was chosen very carefully to meet the following speech and MRI criteria: 1) it begins with a neutral vowel (/ə/ or "uh") to approximate the tongue at rest, 2) it incorporates specific vowel-to-consonant transitions that moves the tongue in an upward and backward direction, 3) its duration is within the MRI collection time of 1 second, which is the time constraint required by the tagged-MRI collection protocol.

In order to properly pronounce a particular word, the tongue must take on and transition through various shapes. The word “a souk” contains consonant-to-vowel and vowel-to-consonant transitions (/s/ → /u/ → /k/), which require large protrusion into the /s/ and then simultaneous retraction and elevation of the tongue into the /uk/, while engaging the jaw very little. Minimal jaw opening means that speech motions are made primarily by tongue deformation, whereas large jaw opening would allow the tongue to be carried along with little deformation. The word initially requires elevation and protrusion of the tongue tip into the /s/ followed by lowering and retraction of the tongue body into the /u/, and then elevation of the tongue body into the /k/. The vowel sound /u/ was chosen because it is a raised back vowel, representing the extreme tongue position for vowel articulation. The defining characteristic of the back vowel is that the tongue is positioned as far posterior and superior as possible in the mouth without creating a constriction[34,53]. The motion into the /uk/ was the focus of this study because it required a large upward and backward motion of the tongue, facilitated by the muscles chosen for measurements.

C. Muscles Chosen for Measurements

In order to study the activity within the hemi-tongue, the patient’s tongue was categorized into the native and the resected sides, while the control’s tongue was categorized into the larger and the smaller sides according to their volumes. The following muscles were chosen for the measurement of muscle length: 1) the genioglossus posterior (GGp), 2) the geniohyoid (GH), 3) the transverse anterior (Ta), 4) the transverse middle (Tm), and 5) the transverse posterior (Tp). These muscles were selected because they are active during elevation and retraction of the tongue, both of which are required for the motion into the /uk/. The GGp is the largest subdivision and its fibers are thicker, stronger, and wider at the base of the tongue than the fibers of the GGa[34], therefore it is more active during the production of raised vowels such as the /u/. The GGp and GH allows elevation of the tongue body by reducing the antero-posterior length of the tongue, whereas the 3 subdivisions of the T (Ta, Tm, Tp) help narrowing of the tongue by decreasing the medio-lateral width.

D. Instrumentation: MRI Protocols

Pre-MRI Recording

Prior to the MRI session, all participants signed an IRB approved consent form and a questionnaire about language background. Dental impressions of upper and lower jaws were taken to make a set of dental casts for every subject. In order to ensure least variability across repetitions, each speaker received a 15-minute training session for speaking in synchrony with the acoustic timing cue (metronome) used in the MRI. This method was developed by Masaki et al[54]. Each subject also received an oral motor function evaluation, intelligibility and articulation tests. Pretesting was performed at the UM Dental School in the Vocal Tract Visualization lab followed by a hearing test at the Department of Otolaryngology-HNS and the MRI scan in the research MRI suite of the UM Medical System.

Dental Cast Measurements

The dental casts for each subject were scanned digitally using Ortho Insight 3D™. MeshLab® software was used to make palate and dental measurements on the digital scans of dental casts, which were saved as x, y, z coordinate points. Pythagorean Theorem in 3-dimensions in Microsoft Excel® was used to obtain dental cast measurements including palate height and width. The palate width was measured across the upper arch from the interface of the gingival margin of the upper left 1st molar at the lingual groove to the interface of the gingival margin of the upper right 1st molar at the lingual groove. Total palate-tooth height was measured from the cusps of the maxillary first molars and to the deepest point in palatal vault. The tooth height of the upper 1st molar was then measured from the gingival margin to the cusp tips and subtracted from the total palate-tooth height in order to obtain the palate height. In one patient, a palatal torus was present and that patient was excluded from the study. The average palate width was 33.71 mm, and subjects were categorized into the narrow palate ($<$ 34 mm) or wide palate ($\geq$ 34 mm) groups. The average palate height was 13.18 mm, and subjects were categorized into the low palate ($<$ 13 mm) or high palate ($\geq$ 13 mm) groups.

MRI Recording

The patients underwent MRI recordings of speech using two types of MRI: tagged-MRI and cine-MRI of speech motion. The two MRI methods provide different information, both useful to the study. Cine MRI allows better determination of tissue edges than tagged-MRI and facilitates determination of muscle endpoints to be tracked in the tagged-MRI data set. The tagged-MRI data tracks the motion of each tissue point inside the tongue, allowing calculation of muscle shortening during speech. The tags are placed just before the subject begins speaking and as the tags move within the tissue, the internal deformation of the tongue can be observed by tracking the tags. For each continuous orthogonal set of slices, tag planes were laid in two directions orthogonal to the imaging plane, resulting in one set of images with vertical tag lines and one with horizontal tag lines. When the images are captured, the tagged tissue planes are visible to the MRI scanner and appear as black lines, which move along with the tissue, allowing the internal deformation of the tongue to be observed and tracked (Figure 9 & 10).

The recording session lasted approximated 90 minutes as it included other recordings not used in this study. The speech task “a souk” took 20 minutes to record as it required multiple repetitions, which were later summed into a single movie in order to image rapid tongue motions with adequate spatial and temporal resolution. Subjects wore headphones in the MRI machine to reduce noise and to hear the experimenter and the metronome cues. The audio system of the MRI console delivered short white-noise pulses through the headphones at predetermined intervals, the metronome beat, and triggered the MRI acquisition synchronously[54,55]. During the MRI scans, the subjects laid in a supine position. Subjects’ heads were in the MRI head and neck coil and were held fairly rigidly. They were also told to hold their head steady since any sort of head movement during the MRI data acquisition is visible as an artifact in the images, making the data unusable.

Cine-MRI was always collected in matching planes to the tagged-MRI datasets. Sagittal, coronal, and axial MRI data stacks were collected from the subjects during multiple productions of the word “a souk”. The tagged slices and the cine slices were made in the same locations, with each slice being 6 mm thick, with an in-plane resolution of 1.87 mm. These were both motion captures and 26 time frames were collected during 1 second of image. A single movie for each orientation was produced by averaging multiple repetitions of the word. The number of slices collected varied depending on the size of the subject's tongue. The sagittal stack consisted of a set of 7-9 contiguous slices, one positioned at the midsagittal plane and the others on each side. This slice orientation provided antero-posterior and superior-inferior information about the position of the tongue within the oral cavity (Figure 6). The coronal stack contained 10-14 slices and provided information of the lateral tongue movement. The axial stack consisted of 10-14 slices and provided lateral and anterior-posterior motion of the tongue.

E. Data Analyses & Muscle Length Measurements

Reconstruction of High-Resolution Tongue Volume

Once the stacks of cine- and tagged-MRI data were collected it was necessary to reconstruct 3D volumes of the tongue to determine the origins and insertions of the muscles of interest, and calculate their changes in length over time during the speech production. The method of reconstructing a super-resolution tongue volume from low-resolution orthogonal MRI was developed by Woo et al. and includes the following steps: 1) preprocessing to address different orientation, size, and resolution, 2) registration to correct subject motion between acquisitions, 3) intensity normalization between volumes, and 4) region-based maximum a posteriori Markov random field (MAP-MRF) reconstruction[51]. The goal was to reconstruct a single high-resolution volume with better muscle and fine anatomical detail from 3 orthogonal scans that approximates the original in-plane resolution in all three directions. The axial orientation was chosen as the target because it allows visualization of the lateral shape of the tongue tip.

Image Segmentation & 3D Reconstruction of Tongue

Segmentation of the tongue was performed semi-automatically using RWSegmentation program in MATLAB® (MathWorks) and the tongue volume was calculated from the number of voxels. The “seeds” were selected manually in the region of interest in sagittal, coronal, and axial slices of cine-MRI and the region was grown along the tissue fibers that originate from the seed point (Figure 12). Using identical parameters allows superimposition of MRI data and reconstruction of three-dimensional volumes for each time frame. The 3D tongue surface segmented from each cine-MRI was used as a ‘mask’ in the tagged-MRI volume. After image segmentation, subsequent 3D reconstruction was completed by combination of orthogonal (sagittal, coronal, axial) stacks. The contours of the reconstructed 3D tongue surface was manually extracted from each image using interpolation and the whole tongue was segmented as one unit without including the epiglottis.

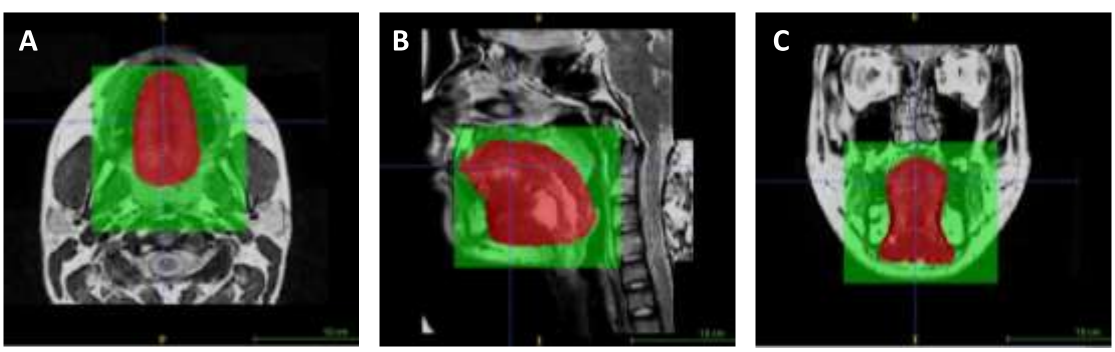

Figure 12. Segmentation of the tongue: Axial (A), Sagittal (B), Coronal (C)

Selection of Tissue Points

Using the cine-MRI super-resolution volumes, tissue points were selected in close proximity to the origin and insertion of the muscles of interest in order to observe the change in muscle length. In the HARP-IDEA program, a cursor was used to move the axial, coronal, and sagittal planes independently and to indicate their three-dimensional spatial relationship. Using the parallel displays of all 3 planes, the mid-sagittal plane indicated by the nasal septum and bilateral facial structures was identified in the coronal view. All tissue points were chosen in either the sagittal or coronal planes depending on the direction of muscle fibers, although the muscles are considered lengthwise (GGp, GH) or crosswise (Ta, Tm, Tp) and they may be slightly oblique. The following number of equidistant tissue points were selected for each muscle in both hemi-tongues: 1) GGp (4 points), 2) GH (3 points), 3) Ta (3 points), 4) Tm (3 points), 5) Tp (3 points) (Figure 13). The lengths of GGp and GH were measured in the para-sagittal left, and right images because the muscle fibers run sagittally. The GGm-GGp boundary is the line of connective tissue that extends along the orientation of the short tendon of the GG, which is seen as a bright line arising from the mental spine of the mandibular symphysis (Figure 6B). The lengths of 3 subdivisions of the transverse muscle were measured in the coronal images because the fibers run horizontally and are visible in the coronal plane. The additional tissue points in the middle were selected to be used if tracking error occurs at the points near muscle origin and insertion. In order to allow smooth tracking with no abrupt changes in displacement, the innermost and outermost tissue points were chosen to be slightly interior to the tongue surface to minimize tracking errors, because tissue points located too close to the surface of the tongue track poorly due to the need to extrapolate motion points beyond the last tags in the tongue.

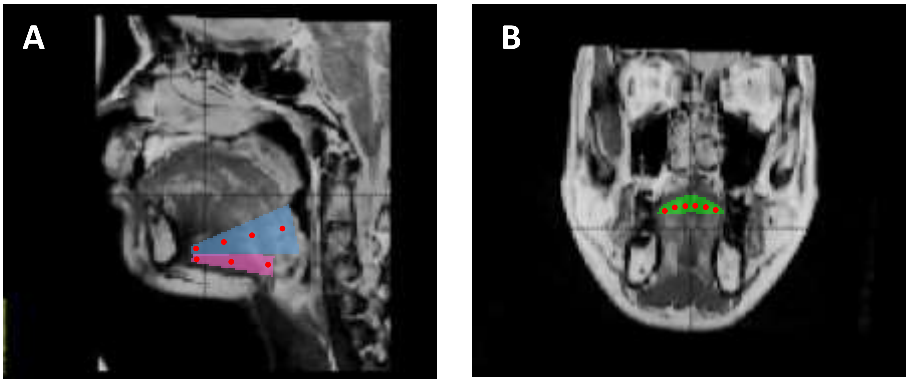

Figure 13. A. Tissue points selected for GGp (Blue) and GH (Pink)
B. Tissue points selected for Tm (Green)

3D Tracking of Tissue Points & Calculation of Muscle Lengths

The 3D displacement fields of all the tissue points in the tagged super-resolution MRI volumes were calculated using HARP (Harmonic Phase Imaging), a custom program developed to track tag motion in MRI[40]. HARP was improved to track motion in 3D using IDEA (Incompressible Deformation Estimation Algorithm), which interpolates the 2D motion of 3 orthogonal data stacks into 3D motion[52]. This program allowed us to track the motion of each tissue point inside the tongue during speech for the controls and glossectomy patients (Figures 14). The 3D tracking starts with the user selecting points in a single plane, which are then tracked in 3D during “a souk” for 1 second over 26 time frames.

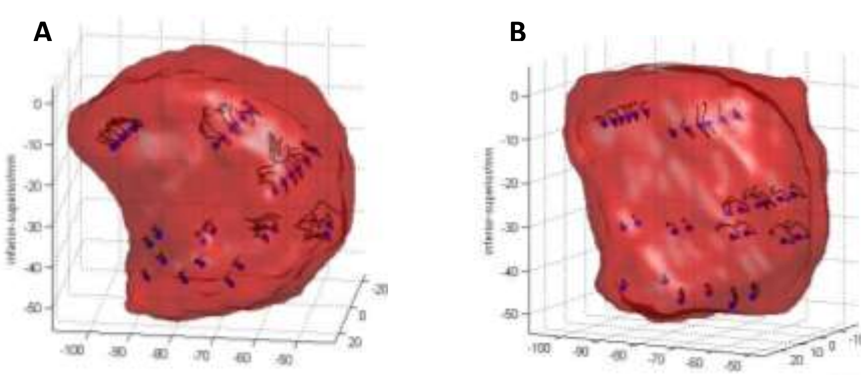

Figure 14. 3D Tissue point tracking using HARP-IDEA during /əsuk/:
Normal Control C1 (A) and Glossectomy Patient P6 (B)

The muscle activity was examined by using the tissue point coordinates at two different time points, 1) the baseline length at the /ə/ and 2) the shortest length between the /s/ and the /uk/, and calculating the % muscle shortening in order to account for the difference in initial lengths of the muscle among subjects. These data were used to determine subject-specific relationship between the tongue motion patterns and to characterize and distinguish the muscle activity in each subject group. The x, y, z coordinates of the tissue points for each muscle were tracked using HARP-IDEA throuhout 26 time frames. The coordinate data were then transferred into a Microsoft Excel® worksheet where all of the muscle length calculations were performed. The displacement of each tissue point was determined relative to the neutral position at the onset of /ə/ (occurring at different time frames across subjects) using the following formula derived from the Pythagorean Theorem:

$$\text{Displacement (mm)} = \sqrt{(Z2 - Z1)^2 + (Y2 - Y1)^2 + (X2 - X1)^2}$$

The initial muscle length was calculated as the difference between the tissue point closest to the origin and the insertion of each muscle at the onset of the /ə/. The change in muscle length was calculated as the percentage of difference between the initial muscle length and the shortest muscle length between the /s/ and /uk/, using the following formula:

$$\text{\% Muscle Shortening} = \frac{L\text{ə} - Lmin}{L\text{ə}} \text{ x } (-100)$$

Where $L_{ə}$ is the length of the muscle at the time frame for /ə/; L_{min} is the shortest length occurring between /s/ and /uk/. The % muscle shortening was plotted over time in Figure 15. Note that positive values indicate shorter muscle lengths and negative values indicate longer muscle lengths. The shortest muscle length between /s/ and /uk/ was chosen because during the /uk/, the tongue body undergoes the greatest amount of retraction and elevation in the phrase in order to contact with the palate for the /k/. The shortening of these 5 chosen muscles should be important to executing this gesture.

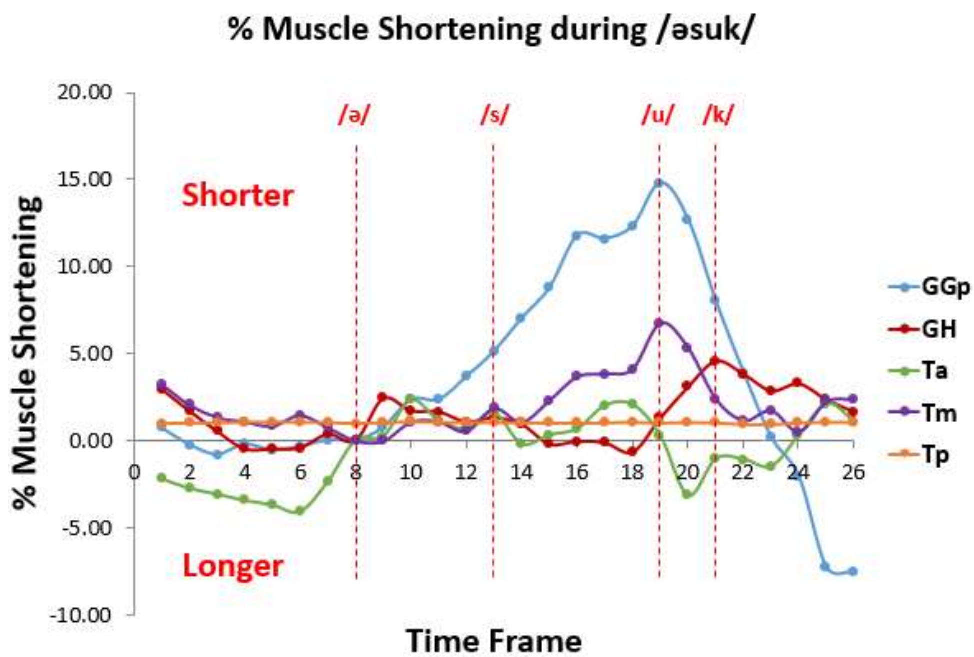

Figure 15. The % muscle shortening during /əsuk/ on control's (C1) smaller side hemi-tongue

F. Statistical Analysis

Table 2. Summary of the experimental variables for each goal

Goal	**Independent Variable (Categorical Data)**	**Dependent Variable (Measured Data)**	**Statistical Test**
1	Subject group (Hemi-tongue) 1) Control: Larger side 2) Control: Smaller side 3) Patient: Native side 4) Patient: Resected side	% Muscle Shortening 1) Posterior Genioglossus 2) Geniohyoid 3) Transverse Anterior 4) Transverse Middle 5) Transverse Posterior	1-way ANOVA (Difference)
	Palatal Height 1) Low palate (< 13 mm) 2) High palate (≥ 13 mm)		2-way ANOVA (Difference + Interaction)

Table 2 (Cont'd). Summary of the experimental variables for each goal

Goal	Independent Variable (Categorical Data)	Dependent Variable (Measured Data)	Statistical Test
1	Palatal Width 1) Narrow palate (< 34 mm) 2) Wide palate ($\geq$ 34 mm)	% Muscle Shortening 1) Posterior Genioglossus 2) Geniohyoid 3) Transverse Anterior 4) Transverse Middle 5) Transverse Posterior	2-way ANOVA (Difference + Interaction)
2	**Variable 1 (Measured Data)**	**Variable 2 (Measured Data)**	**Statistical Test**
	% Muscle Shortening 1) Posterior Genioglossus 2) Geniohyoid 3) Transverse Anterior 4) Transverse Middle 5) Transverse Posterior	% Muscle Shortening 1) Posterior Genioglossus 2) Geniohyoid 3) Transverse Anterior 4) Transverse Middle 5) Transverse Posterior	Pearson's R (Relationship)
3	**Independent Variable (Categorical Data)**	**Dependent Variable (Measured Data)**	**Statistical Test**
	Tumor size (Patients) 1) T1 tumor 2) T2 tumor	% Muscle Shortening 1) Posterior Genioglossus 2) Geniohyoid 3) Transverse Anterior 4) Transverse Middle 5) Transverse Posterior	1-way ANOVA (Difference)

A power analysis was not performed since the sample size was limited and all glossectomy patients who met the selection criteria were included in the study. Statistical analyses were performed using SPSS Statistics 23® (IBM) and MYSTAT 12® (Hewlett-Packard) software with a significance level set at $p \leq 0.05$. A p value ≤ 0.05 signified that there was a 5% probability that the results found were due to chance and not due to manipulation of independent variables. An Analysis of Variance (ANOVA) test was used to determine if the mean differences were statistically significant. ANOVA is a parametric test, which requires the following assumptions: 1) the values on the dependent variable are normally distributed around the mean in the population (normality), and 2) population variances in each group are equal (homogeneity of variance). In addition to the above assumptions, the dependent variable should be measured on a continuous scale and the independent variables should be measured on a categorical scale. The data used in this study includes 21 controls and 9 patients, which is small and non-matching in group size, and probably violate the requirements for use of parametric statistics, including ANOVA. However, we consider this study to be preliminary, and wish to consider the relationships between multiple variables. Therefore, we used ANOVA test to uncover any differences that might be worthy of future exploration.

One-way ANOVA tests were used to study the effects of subject group, palate height/width, and tumor size on % shortening for the selected tongue muscles. A factorial ANOVA (2-way ANOVA) test was utilized to analyze the main effects of subject group and palate dimension (height and width), as well as the interaction in their effects on the muscle shortening in each subject group. When the independent variable has more than 2 levels, the significant p value for ANOVA can tell us that there is a significant difference between some of the conditions, however, does not tell us which group means are different. Therefore, a post hoc test, i.e. Tukey HSD (Honest Significant Difference), was performed when a statistical significance was found between more than 2 groups in order to conduct pairwise multiple comparisons to identify which mean differences are significant. A Pearson's r test was used to analyze the correlations between % shortening of different tongue muscles. The correlation coefficients and their associated confidence intervals and p-values were calculated. Due to the small sample size ($n = 21$), any results with a trend approaching significance ($0.05 < p < 0.10$) were also reported.

III. Results

Goal 1: Determine the effect of subject group (control vs. patient) and palate height/width on % muscle shortening

Figure 16 and Table 3 summarize the % muscle shortening of each hemi-tongue in controls and patients, categorized into 4 subject groups. When moving into the /uk/, controls had greater shortening of all muscles on the larger side than the smaller side of the tongue (Figure 16). Patients showed this asymmetrical pattern with the same magnitude only for Tm, while showing more symmetrical muscle shortening for all the other muscles. The means in Table 3 show that the muscle with the most shortening was Ta, for all subject groups except the controls' smaller side. The GGp showed the second most shortening for all subjects. The Tm and Tp shortened less than the GGp and GH for controls, but not for patients. For patients, the Tm on the native side shortened considerably during the /uk/. Overall, the controls demonstrated a greater difference between the two hemi-tongues compared to the patients, who showed relatively similar muscle shortening on the native and resected sides.

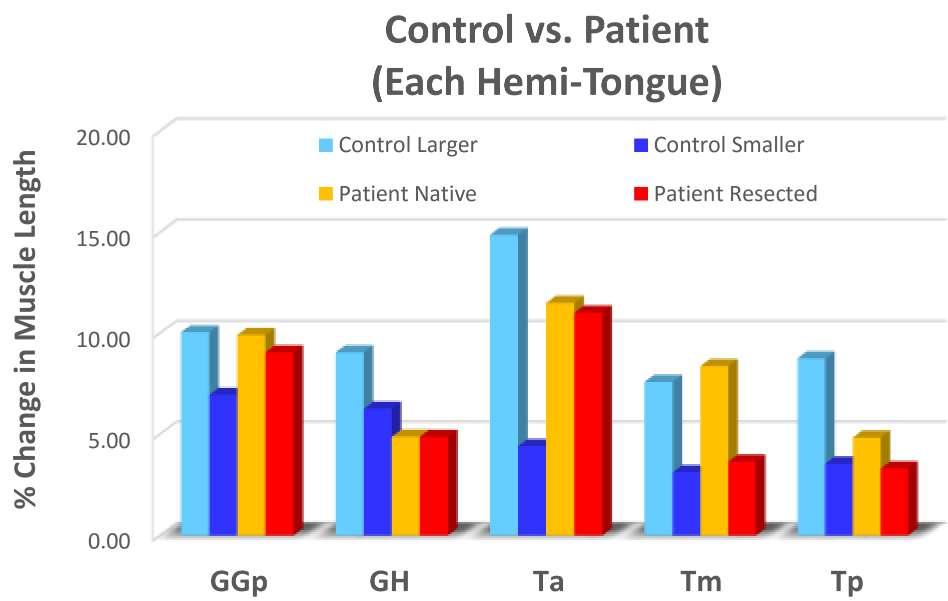

Figure 16. The % muscle shortening of each hemi-tongue in controls and patients

Table 3. The % muscle shortening of each hemi-tongue in controls and patients

Subject Group	Subjects	% Muscle Shortening				
		GGp	**GH**	**Ta**	**Tm**	**Tp**
Control Larger Side (n = 12)	C1	16.3307	5.1042	10.1903	8.3521	14.2815
	C2	1.9878	13.0589	14.8986	7.4530	2.4133
	C3	16.0715	31.5637	41.9157	18.8229	23.9681
	C4	9.2010	19.0829	12.9428	4.5205	11.5818
	C5	3.3208	-0.0460	4.8192	3.7341	6.0347
	C6	4.8317	4.3224	13.3521	4.1248	8.7649
	C7	2.5444	3.1451	15.7427	4.5409	4.9622
	C8	13.4083	21.9085	4.1055	4.2678	10.4332
	C9	18.1000	4.2796	20.2491	1.9048	10.9804
	C10	11.3557	1.8185	22.7460	5.3535	2.3190
	C11	13.2035	2.2295	15.3536	23.2031	8.1661
	C12	10.1007	1.9288	2.0992	4.6664	0.9254
	Mean + SD	**10.0380 ± 5.7049**	**9.0330 ± 10.0758**	**14.8679 ± 10.5802**	**7.5787 ± 6.5578**	**8.7359 ± 6.3447**
Control Smaller Side (n = 12)	C1	0.8520	0.9542	0.9767	0.9328	1.0099
	C2	14.7992	4.5828	2.3323	6.7240	-0.9901
	C3	-0.4816	8.3914	1.3207	3.2981	2.1405
	C4	9.8975	24.8818	28.8361	6.4745	15.4960
	C5	7.7595	13.2071	12.8733	2.6701	2.1619

Table 3 (Cont'd). The % muscle shortening of each hemi-tongue in controls and patients

		C6	2.4327	-2.5754	0.1204	-0.3281	0.2534
		C7	1.9993	3.5846	2.7199	1.9934	0.2131
		C8	1.6736	1.1671	6.9572	-0.5731	0.5094
		C9	12.5595	14.4360	2.7592	2.9064	8.9531
		C10	11.4085	3.7819	-8.4896	-4.3482	8.4952
		C11	11.1091	0.3659	-6.1580	0.8975	0.3188
		C12	2.3814	1.4806	8.8249	14.9997	4.6309
	Mean + SD		**6.9339 + 5.1254**	**6.2538 + 7.7725**	**4.4034 + 9.6465**	**3.1174 + 4.7991**	**3.5416 + 4.9927**
Patient Native Side (n = 9)	T1	P1	17.0096	11.0522	22.4997	27.4789	-0.9305
	T1	P2	10.5764	1.0526	26.3383	26.7452	15.5269
	T1	P3	9.3855	5.1121	11.4860	9.1845	3.7753
	T1	P4	10.7573	5.2031	9.4459	5.3728	9.0888
	T2	P5	8.6666	2.4761	0.7053	1.1287	0.6671
	T2	P6	12.0237	-0.9503	4.0553	4.2439	5.0979
	T2	P7	12.6771	10.7410	0.6784	-3.7856	3.2283
	T2	P8	6.6225	0.8579	10.8654	1.3388	5.2705
	T2	P9	1.3042	8.2833	17.4338	3.5083	1.7456
	Mean + SD		**9.8914 + 4.3355**	**4.8698 + 4.3986**	**11.5009 + 9.1519**	**8.3573 + 11.1956**	**4.8300 + 4.9564**
Patient Resected Side (n = 9)	T1	P1	11.1286	12.6918	20.4908	6.9755	3.1654
	T1	P2	10.2761	-1.3911	10.1837	16.8751	9.9633
	T1	P3	9.3433	11.1579	8.8277	2.1512	0.6931
	T1	P4	7.7498	3.2788	7.8280	6.3378	8.0580
	T2	P5	8.4000	2.7163	13.1875	3.4138	3.0154
	T2	P6	9.6874	1.2335	2.7686	4.2047	-0.4354
	T2	P7	10.6978	8.7109	26.6713	-6.7495	4.3776
	T2	P8	9.2202	2.5991	-8.6819	0.9725	0.0589
	T2	P9	4.8317	2.7955	17.8757	-1.4708	0.8519
	Mean + SD		**9.0372 + 1.9028**	**4.8659 + 4.8027**	**11.0168 + 10.3580**	**3.6345 + 6.4936**	**3.3054 + 3.6322**

The effect of subject group on shortening of the muscles during elevation and retraction of the tongue into /uk/ was determined using 1-way ANOVA (Table 4). The Tp ($p = 0.06$) and Ta ($p = 0.093$) did not quite achieve the conventional levels of statistical significance ($p \leq 0.05$), but showed a trend approaching significance. Since the independent variable (subject group) had 4 levels, a multiple comparison was completed using Tukey HSD test to determine which subgroups were significantly different (Table 5). The Ta (p = 0.065) and Tp (p = 0.083) showed a trend toward significance on the larger and smaller sides of the control only.

Table 4. 1-Way ANOVA: Effect of subject group on muscle length

		Sum of Squares	**df**	**Mean Square**	**F**	**Sig.**
GGp	Between Groups	0.007	3	0.002	1.087	0.366
	Within Groups	0.083	38	0.002		
	Total	0.090	41			
GH	Between Groups	0.013	3	0.004	0.750	0.529
	Within Groups	0.212	38	0.006		
	Total	0.225	41			
Ta	Between Groups	0.069	3	0.023	2.294	**0.093***
	Within Groups	0.378	38	0.010		
	Total	0.447	41			
Tm	Between Groups	0.022	3	0.007	1.374	0.265
	Within Groups	0.207	38	0.005		
	Total	0.229	41			
Tp	Between Groups	0.022	3	0.007	2.691	**0.060***
	Within Groups	0.102	38	0.003		
	Total	0.124	41			

* Approaching significance (0.05 < p < 0.10)

Table 5. Turkey HSD Test for Multiple Comparisons: Effect of subject group on muscle length

Dependent Variable	(I) Subject Group	(J) Subject Group	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Ta	1.0	2.0	-0.1046	0.0407	**0.065***	-0.2141	0.0048
		3.0	-0.0337	0.0440	0.870	-0.1519	0.0845
		4.0	-0.0385	0.0440	0.818	-0.1567	0.0797
	2.0	3.0	0.0710	0.0440	0.384	-0.0472	0.1892
		4.0	0.0661	0.0440	0.446	-0.0521	0.1843
	3.0	4.0	-0.0048	0.0470	1.000	-0.1312	0.1215
Tp	1.0	2.0	-0.0519	0.0211	**0.083***	-0.1087	0.0049
		3.0	-0.0391	0.0228	0.332	-0.1004	0.0223
		4.0	-0.0543	0.0228	0.099*	-0.1157	0.0070
	2.0	3.0	0.0129	0.0228	0.942	-0.0485	0.0742
		4.0	-0.0024	0.0228	1.000	-0.0637	0.0590
	3.0	4.0	-0.0152	0.0244	0.924	-0.0808	0.0503

* Approaching significance (0.05 < p < 0.10)

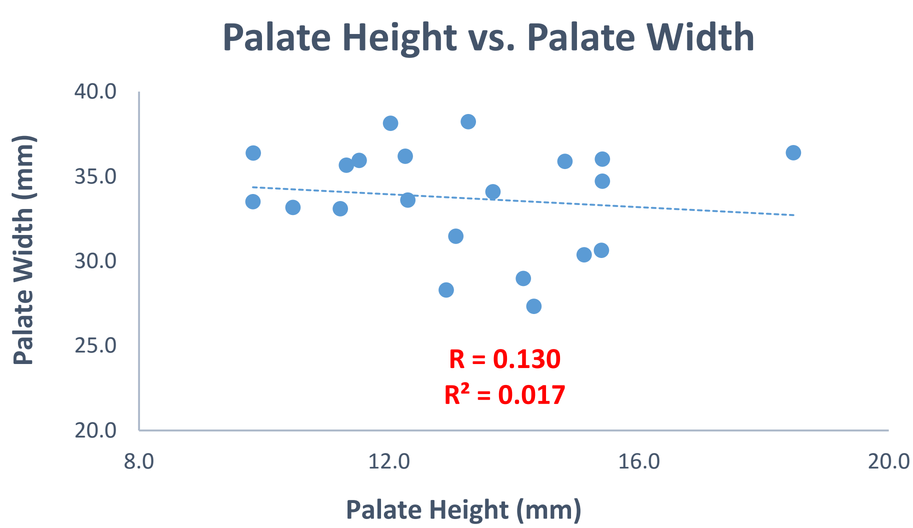

Figure 17. Correlation between palate height and width

Figure 17 confirms that there is no significant correlation (R = -0.131, R^2 = 0.017) between the palate height and the palate width. A borderline trend was found in the effect of subject group on the Tp (p = 0.095) muscle shortening. There was a strong tendency toward significance in the effect of palate height on the GH (p = 0.052) muscle shortening in controls (Table 6). Table 7 summarizes the mean % muscle shortening for the high and low palate groups. Greater mean % shortening of GH occurred in high palate subjects (Figure 18). The % muscle shortening for individual subjects in low and high palate groups can be found in Table I (See Appendix). No other muscles showed statistically significant difference between subject group and high vs. low palate. No significant interactions were found between subject group and palate height in their effect on % shortening for any of the muscles (Table 6).

Table 6. 2-Way ANOVA: Effect of subject group and palate height on muscle length

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.
Subject Group	GGp	0.008	3	0.003	1.179	0.332
	GH	0.009	3	0.003	0.520	0.672
	Ta	0.065	3	0.022	2.224	0.103
	Tm	0.022	3	0.007	1.213	0.320
	Tp	0.02	3	0.007	2.298	**0.095***
Palate Height	GGp	0.001	1	0.001	0.656	0.424
	GH	0.022	1	0.022	4.042	**0.052***
	Ta	0.013	1	0.013	1.334	0.256
	Tm	0.001	1	0.001	0.135	0.716
	Tp	0	1	0	0.075	0.785
Subject Group x Palate Height	GGp	0.004	3	0.001	0.575	0.635
	GH	0.001	3	0	0.050	0.985
	Ta	0.034	3	0.011	1.149	0.343
	Tm	0.001	3	0	0.043	0.988
	Tp	0.005	3	0.002	0.548	0.653

* Approaching significance (0.05 < p < 0.10)

Table 7. The mean % muscle shortening for low and high palate groups

Palate Height		GGp	GH	Ta	Tm	Tp
Low Palate	Mean	8.4424	3.7931	8.5345	6.0735	4.8047
	± SD	± 4.1046	± 5.3510	± 9.0283	± 8.1459	± 4.6353
High Palate	Mean	9.3261	8.8728	11.9648	5.2186	5.6570
	± SD	± 5.2051	± 8.2573	± 11.5398	± 6.9766	± 6.2477

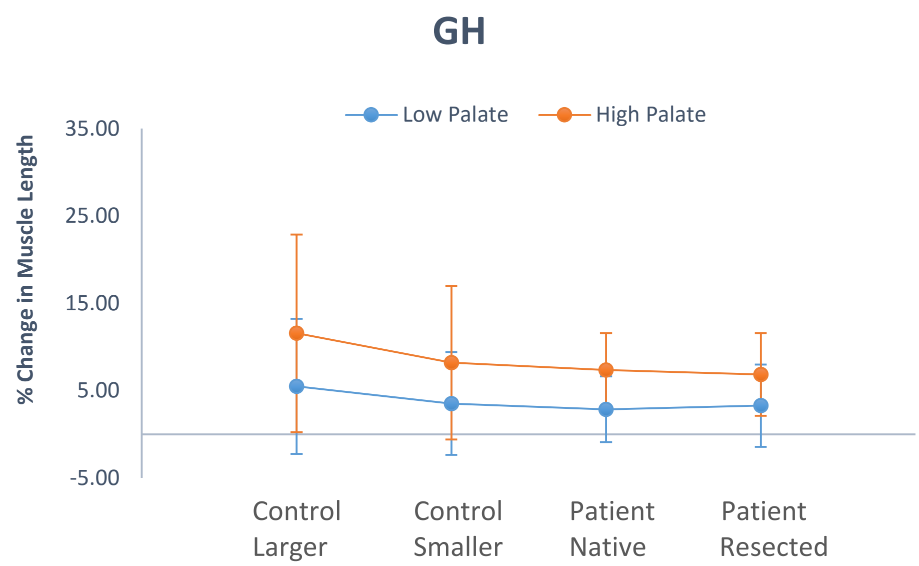

Figure 18. The effect of palate height on % muscle shortening of GH

There were statistically significant differences in the effect of subject group on the Ta (p = 0.047) and Tp (p = 0.029) muscle shortening (Table 8). Table 9 summarizes the mean % muscle shortening for the narrow and wide palate groups. Significant main effect of palate width on muscle shortening was found in the GH (p = 0.018) and Ta (p = 0.001) (Figures 19-20). There was no significant interaction between subject group and palate height in their effect on muscle shortening for all measured muscles (Table 8). The % muscle shortening for individual subjects in narrow and wide palate groups can be found in Table II (See Appendix).

Table 8. 2-Way ANOVA: Effect of subject group and palate width on muscle length

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.
Subject Group	GGp	64.441	3	21.480	0.901	0.451
	GH	253.612	3	84.537	1.647	0.197
	Ta	696.149	3	232.050	2.936	**0.047****
	Tm	180.407	3	60.136	1.053	0.382
	Tp	251.371	3	83.790	3.379	**0.029****
Palate Width	GGp	7.615	1	7.615	0.320	0.576
	GH	314.985	1	314.985	6.137	**0.018****
	Ta	954.222	1	954.222	12.074	**0.001****
	Tm	6.853	1	6.853	0.120	0.731
	Tp	51.850	1	51.850	2.091	0.157
Subject Group x Palate Width	GGp	6.329	3	2.110	0.089	0.966
	GH	27.982	3	9.327	0.182	0.908
	Ta	124.912	3	41.637	0.527	0.667
	Tm	123.028	3	41.009	0.718	0.548
	Tp	101.912	3	33.971	1.370	0.268

** Statistically significant ($p \leq 0.05$)

Table 9. The mean % muscle shortening for narrow and wide palate groups

Palate Width		GGp	GH	Ta	Tm	Tp
Narrow Palate	Mean ± SD	9.5476 ± 4.5705	8.8254 ± 8.4548	15.3703 ± 11.2815	5.9734 ± 9.5524	6.2117 ± 6.5220
Wide Palate	Mean ± SD	8.3213 ± 4.8038	4.2979 ± 5.6622	5.7504 ± 7.1741	5.3096 ± 5.1280	4.3779 ± 4.3212

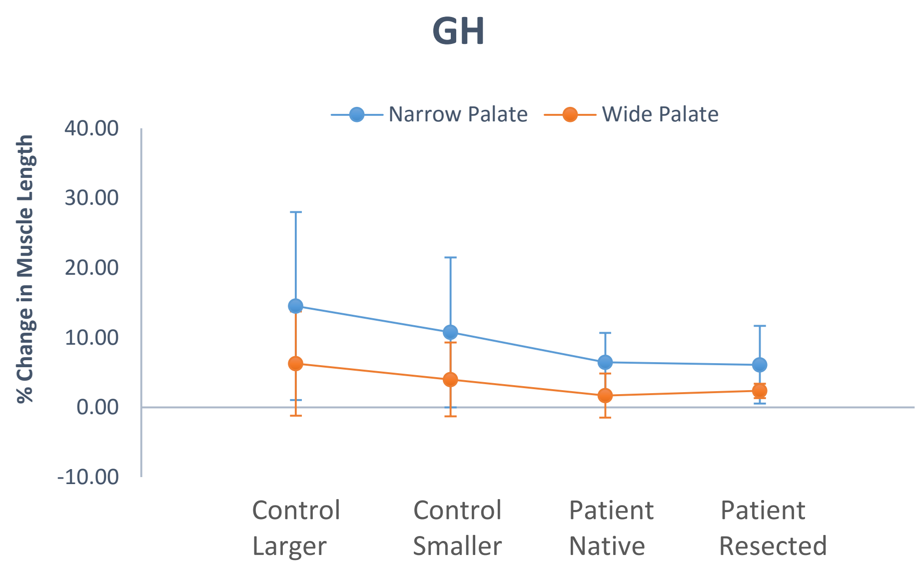

Figure 19. The effect of palate width on % muscle shortening of GH

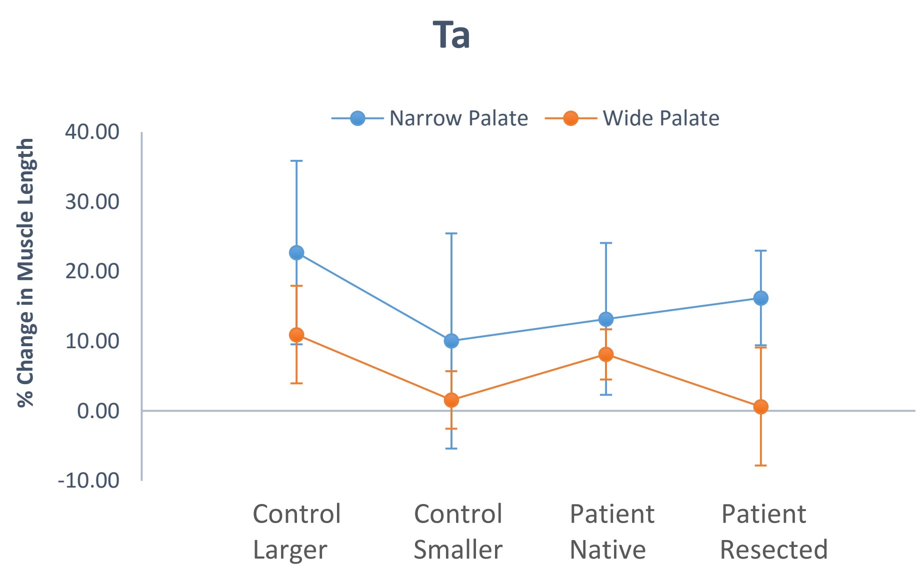

Figure 20. The effect of palate width on % muscle shortening of Ta

Goal 2: Determine the relationship between % muscle shortening in both controls and glossectomy patients

Pearson's R tests were used to examine correlated shortening between the muscles in each hemi-tongue separately. Table 10 shows a larger number of significant correlations for the controls (5) than the patients (1). On the controls' larger side, the Tp showed significant correlations with three other muscles, the GGp (R = 0.589, R^2 = 0.3473), GH (R = 0.694, R^2 = 0.4816), and Ta (R = 0.605, R^2 = 0.3663). Figures 21-23 reflect these weak positive correlations. On the controls' smaller side, the GH demonstrated significant associations with the Ta (R = 0.747, R^2 = 0.5582) and the Tp (R = 0.776, R^2 = 0.6026) as shown in Figures 24-25. The glossectomy patients showed a significant correlation between the Ta and Tm (R = 0.806, R^2 = 0.7398) on the native side (Figure 26), but no correlations on the resected side.

Table 10. Pearson's R Test: Correlation between the muscle shortening

		GGp	GH	Ta	Tm	Tp
Control Larger (n = 12)	**GGp**					
	GH	0.275 0.0756				
	Ta	0.335 0.112	0.485 0.235			
	Tm	0.321 0.103	0.279 0.0778	0.498 0.248		
	Tp	**0.589*** **0.347**	**0.694*** **0.482**	**0.605*** **0.366**	0.435 0.189	
Control Smaller (n = 12)	**GGp**					
	GH	0.320 0.102				
	Ta	-0.062 0.00384	**0.747*** **0.558**			
	Tm	-0.078 0.00608	0.197 0.0388	0.494 0.244		
	Tp	0.313 0.0980	**0.776*** **0.602**	0.536 0.287	0.128 0.0164	

Table 10 (Cont'd). Pearson's R Test: Correlation between the muscle shortening

Patient Native (n = 9)	**GGp**					
	GH	0.211 0.0445				
	Ta	0.016 0.000256	0.121 0.0146			
	Tm	0.455 0.207	0.073 0.00533	**0.860*** **0.740**		
	Tp	-0.019 0.000361	-0.508 0.258	0.354 0.125	0.300 0.090	
Patient Resected (n = 9)	**GGp**					
	GH	0.359 0.129				
	Ta	0.057 0.00325	0.469 0.220			
	Tm	0.240 0.0576	-0.382 0.146	-0.251 0.0630		
	Tp	0.186 0.0346	-0.258 0.0666	0.259 0.0671	0.596 0.355	

R (top), R^2 (bottom)
* Correlation is significant at the 0.05 level (2-tailed)

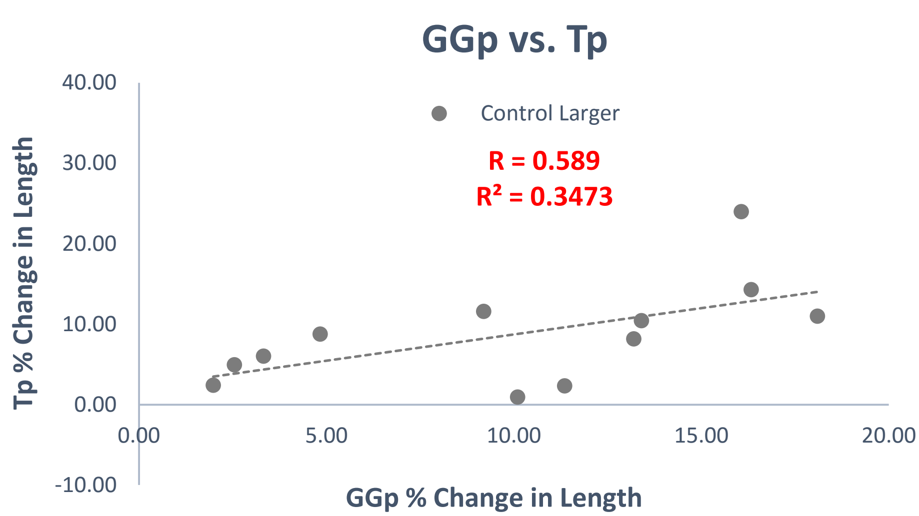

Figure 21. The relationship between the GGp and the Tp on the control's larger side

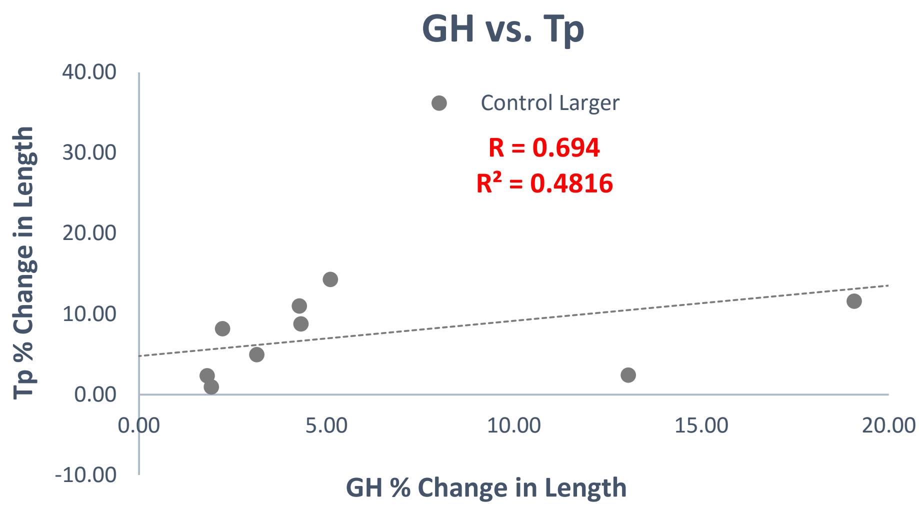

Figure 22. The relationship between the GH and the Tp on the control's larger side

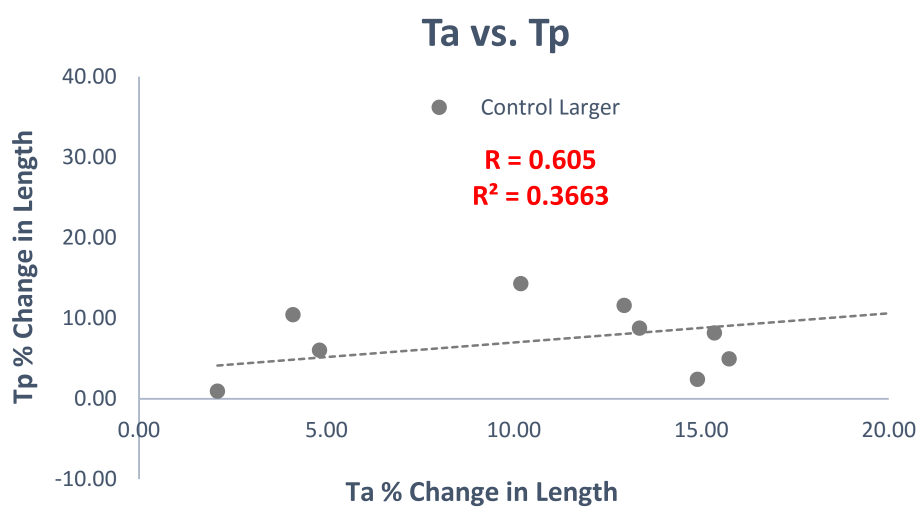

Figure 23. The relationship between the Ta and the Tp on the control's larger side

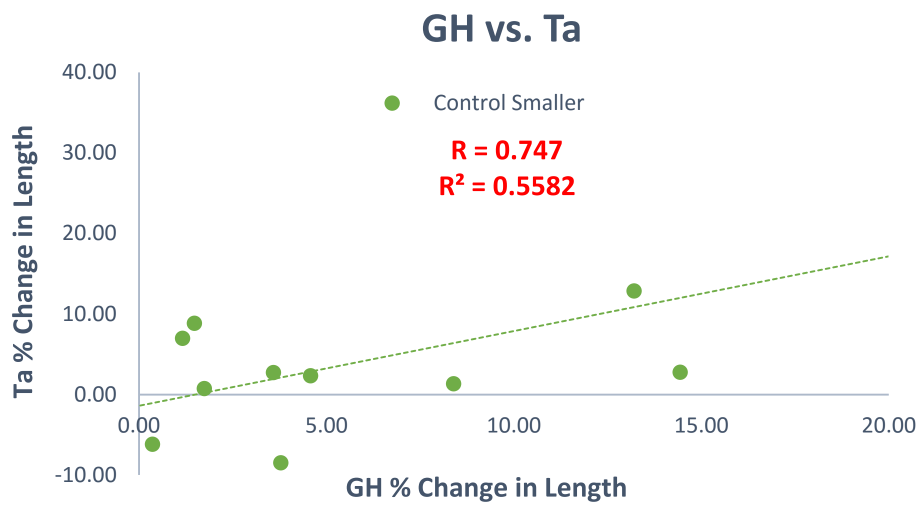

Figure 24. The relationship between the GH and the Ta on the control's smaller side

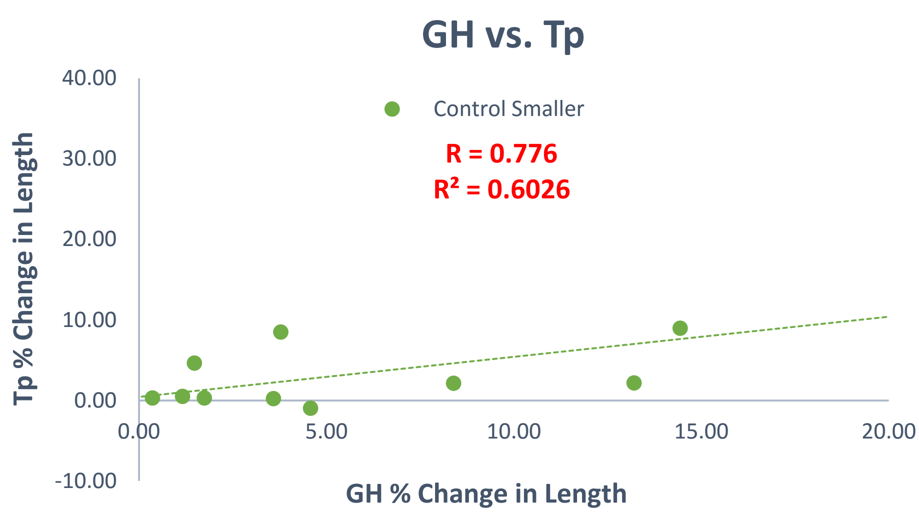

Figure 25. The relationship between the GH and the Tp on the control's smaller side

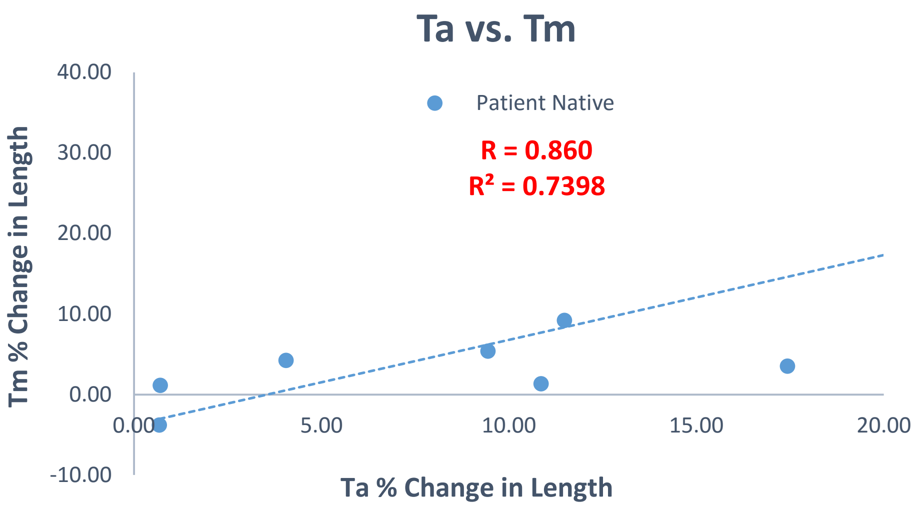

Figure 26. The relationship between the Ta and the Tm on the patient's native side

Goal 3: Determine the effects of tumor size (T1 vs. T2) on % muscle shortening on both the native and resected sides of patients

Table 11 summarizes the % muscle shortening from /s/ to /uk/ relative to /ə/. The T1 subgroup included 4 patients (P1 - P4) and the T2 subgroup included 5 patients (P5 - P9). Figures 27-31 show the mean % muscle shortening on the native and resected sides for the T1 and T2 patients, as well as those for the control to allow easy comparison. Two patterns of interest emerge. First, T1 patients showed more muscle shortening than T2 patients, for all measured muscles on both the native and resected sides. Second, T1 patients had greater muscle shortening on the native side, except for GH, which had the reverse pattern. For T2 patients only, the Ta had greater muscle shortening on the resected side.

Table 11. The mean % muscle shortening in T1 and T2 patient subgroups

Patient Group		% Muscle Shortening				
		GGp	GH	Ta	Tm	Tp
		Native side				
T1 Tumor (n = 4)	Mean ± SD	11.9322 ± 3.4392	5.6050 ± 4.1150	17.4425 ± 8.2490	17.1954 ± 11.5600	6.8651 ± 7.0779
		Resected side				
T1 Tumor (n = 4)	Mean ± SD	10.4692 ± 0.8514	8.7876 ± 6.8242	14.9983 ± 6.3664	8.2443 ± 6.1870	4.2468 ± 3.9852
		Both sides				
T1 Tumor (n = 4)	Mean ± SD	11.2007 ± 2.4477	7.1963 ± 5.4872	16.2204 ± 6.9455	12.7198 ± 9.8269	5.5560 ± 5.4987
		Native side				
T2 Tumor (n = 5)	Mean ± SD	8.2588 ± 4.6072	4.2816 ± 5.0023	6.7476 ± 7.2757	1.2868 ± 3.1399	3.2019 ± 2.0261
		Resected side				
T2 Tumor (n = 5)	Mean ± SD	8.5674 ± 2.2474	3.6111 ± 2.9219	10.3642 ± 13.7000	0.0741 ± 4.4151	1.5737 ± 2.0489
		Both sides				
T2 Tumor (n = 5)	Mean ± SD	8.4131 ± 3.4213	3.9463 ± 3.8782	8.5559 ± 10.5156	0.6805 ± 3.6679	2.3878 ± 2.1040

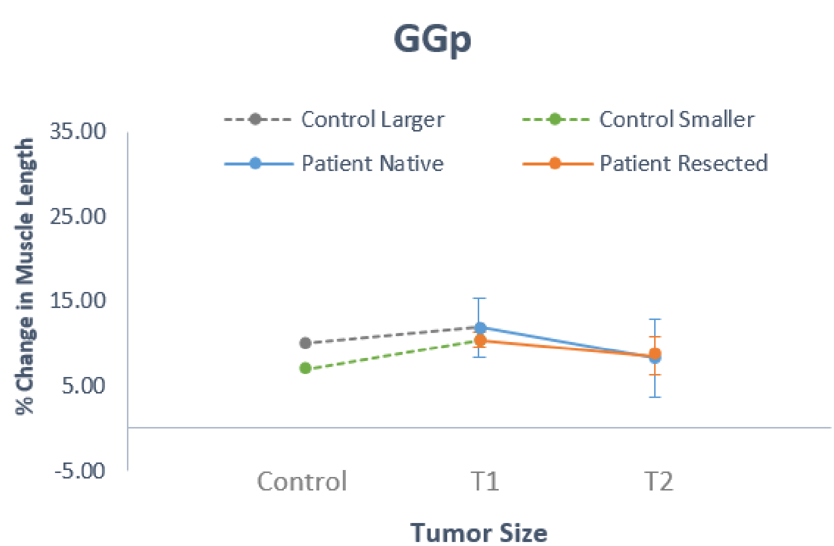

Figure 27. The mean % muscle shortening of GGp in T1 and T2 patients

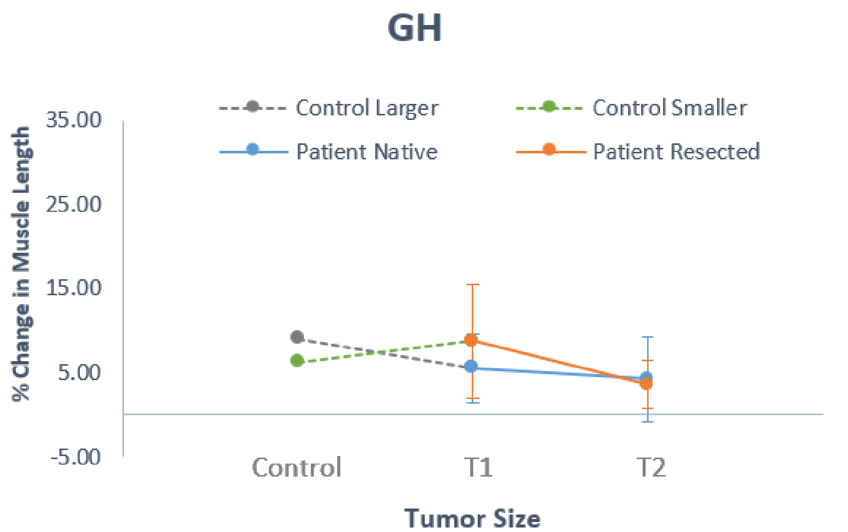

Figure 28. The mean % muscle shortening of GH in T1 and T2 patients

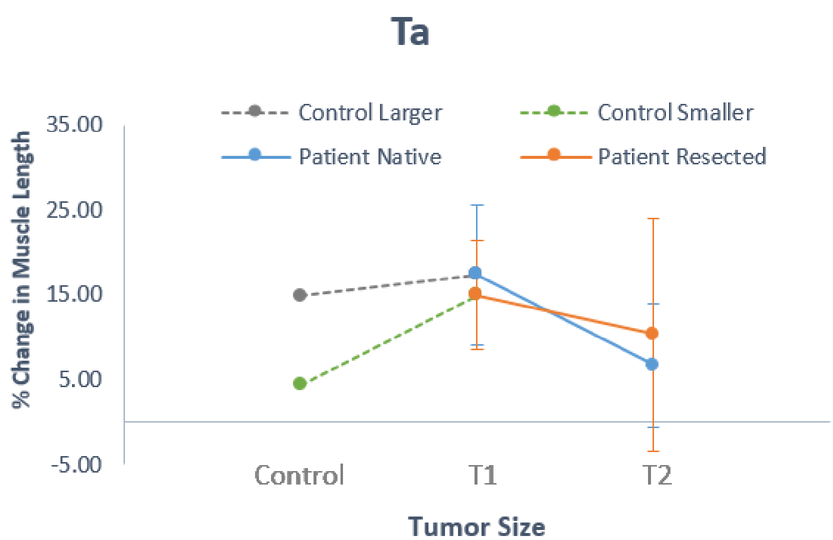

Figure 29. The mean % muscle shortening of Ta in T1 and T2 patients

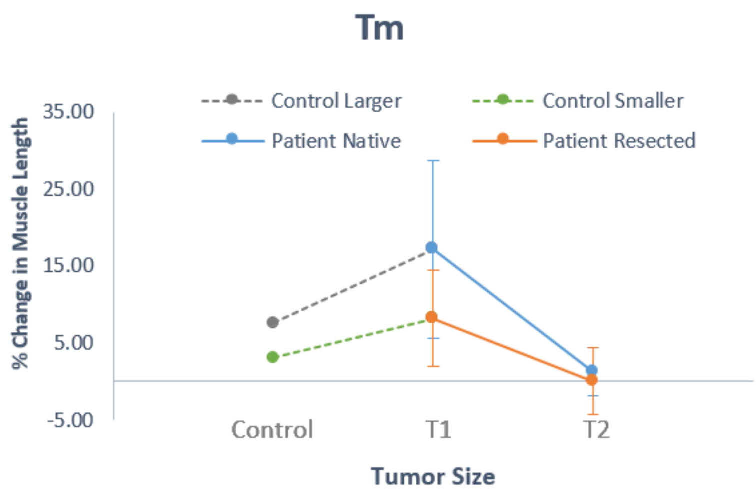

Figure 30. The mean % muscle shortening of Tm in T1 and T2 patients

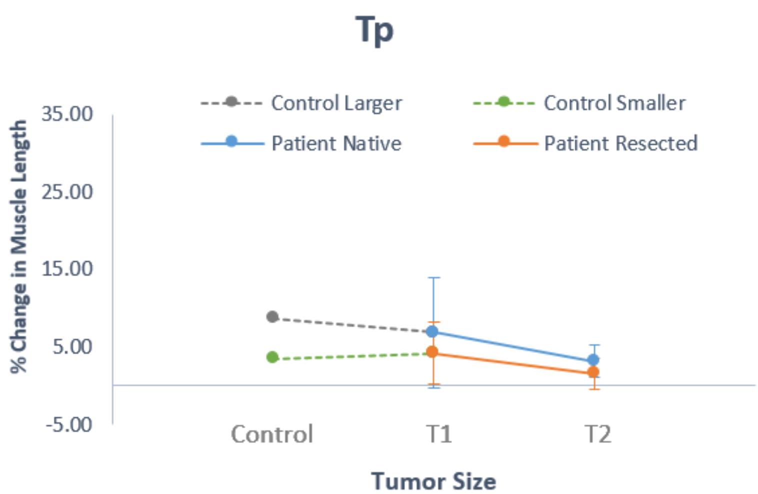

Figure 31. The mean % muscle shortening of Tp in T1 and T2 patients

Results of the ANOVA tests (Tables 12) showed that on the native side, T1 patients had significantly greater Tm ($p = 0.020$) muscle shortening than T2 patients (Figure 30). The Ta showed a trend toward more shortening in T1 patients ($p = 0.077$), and there was no significant difference between T1 and T2 patients for GGp, GH, and Tp. On the resected side (Table 13), T1 patients showed more Tm ($p = 0.058$) muscle shortening than T2 patients. There was no significant difference in the % shortening of GGp, GH, Ta, and Tp between T1 and T2 subgroups during elevation and retraction of the tongue from the /s/ to /uk/.

Table 12. 1-Way ANOVA: Effect of tumor size on muscle length of the patient's native side

		Sum of Squares	df	Mean Square	F	Sig.
GGp	Between Groups	29.985	1	29.985	1.743	0.228
	Within Groups	120.390	7	17.199		
	Total	150.376	8			
GH	Between Groups	3.892	1	3.892	0.181	0.684
	Within Groups	150.891	7	21.556		
	Total	154.784	8			
Ta	Between Groups	254.176	1	254.176	4.278	**0.077***
	Within Groups	415.880	7	59.411		
	Total	670.055	8			
Tm	Between Groups	562.403	1	562.403	8.941	**0.020***
	Within Groups	440.335	7	62.905		
	Total	1002.738	8			
Tp	Between Groups	29.821	1	29.821	1.252	0.300
	Within Groups	166.711	7	23.816		
	Total	196.532	8			

** Statistically significant ($p \leq 0.05$)
* Approaching significance ($0.05 < p < 0.10$)

Table 13. 1-Way ANOVA: Effect of tumor size on muscle length of the patient's resected side

		Sum of Squares	df	Mean Square	F	Sig.
GGp	Between Groups	2.483	1	2.483	0.656	0.445
	Within Groups	26.483	7	3.783		
	Total	28.966	8			
GH	Between Groups	17.713	1	17.713	0.743	0.417
	Within Groups	166.815	7	23.831		
	Total	184.528	8			
Ta	Between Groups	4.791	1	4.791	0.039	0.849
	Within Groups	853.514	7	121.931		
	Total	858.305	8			
Tm	Between Groups	142.604	1	142.604	5.126	**0.058***
	Within Groups	194.731	7	27.819		
	Total	337.335	8			
Tp	Between Groups	33.735	1	33.735	3.288	0.113
	Within Groups	71.810	7	10.259		
	Total	105.544	8			

* Approaching significance ($0.05 < p < 0.10$)

IV. Discussion

This study employed cine-MRI and tagged-MRI techniques to explore the compression and extension patterns of the tongue muscles. The goal was to determine whether shortening of key muscles was linked to the surface deformation necessary to elevate and retract the tongue in order to produce the /k/. The analyses for muscle shortening were carried out on the basis of the following assumptions: 1) the activity of an individual muscle can be inferred by measuring the change in muscle length, and 2) the internal deformation of the tongue tissue helps interpret the contraction pattern of deep tongue muscles. We are aware that muscle shortening is not always due to muscle contraction, but we use this interpretation because this is preliminary work and will provide insight for future research.

A. Effects of Glossectomy and Palate Height/Width

The results showed that, in controls, the muscles on the larger side shortened more than the smaller side for all measured muscles. A 1-way ANOVA test revealed that, Ta shortened 10.5% ($p = 0.065$) more and Tp shortened 5.2% ($p = 0.083$) more on the controls' larger side than the smaller side. Overall, the controls demonstrated a marked asymmetry between the two hemi-tongues compared to the patients, suggesting that the controls underused one side of the tongue. We could speculate that the controls used one side primarily because it was sufficient to achieve the tongue elevation and surface deformation required to produce the /k/. Asymmetry like this is consistent with a rotational motion, which may result from the MRI acquisition method, as it requires many sequential repetitions of the speech task. It is not uncommon for speakers to minimize their motion in this situation. This minimization might utilize different amounts of shortening on each side and include left-to-right rotation, which reduces the amount of tongue tissue to be moved[46].

We hypothesized that, for patients, the muscles would shorten less on the resected side than on the patients' native side or either side of the controls, due to scar tissue formation, loss of tissue, and reduced motor control and innervation on the resected side of the glossectomy patients. However, the findings of this study did not support our hypothesis. Both the native and resected sides in patients showed similar muscle shortening for all muscles except Tm, which followed the asymmetrical shortening pattern as in controls. It is interesting that glossectomy patients in general demonstrated less asymmetry, because the asymmetric tongue anatomy caused by glossectomy surgery was expected to result in more asymmetric muscle shortening compared to controls. In glossectomy patients, the resected side still moved in synchrony with the rest or the tongue despite the lack of tissue mass, suggesting that patients need to use both sides of the tongue to accomplish the tongue elevation. Approximately symmetric muscle shortening of the 4 muscles (GGp, GH, Ta, and Tp) in patients may be explained by the functional adaptation of the residual muscles on the resected side and the compensatory mechanism provided by the native side of the tongue. The fact that the patients did not use the same strategy as the controls to minimize tongue motion during repetitive speech task, implies that they either were unable to rotate the tongue, or that they needed effort from both sides to create the gesture.

A previous study by Stone et al.[56] found that the motion patterns of glossectomy patients with small (T1 and T2) tumors were essentially similar to normal controls during the transition from /u/ to /k/. In accordance with this evidence, the present study revealed no statistically significant differences between the controls and the patients in the mean % shortening of any of the measured tongue muscles. However, several interesting findings were observed when looking at the shortening patterns of each muscle. For GGp and Ta, both the native and resected sides of the patients showed % muscle shortening similar to the controls' larger side, suggesting greater overall engagement of the patients' resected side for these muscles (Figure 16). For Tm, the patients showed the same asymmetrical muscle shortening pattern as the controls, where the larger side shortened more than the smaller side, consistent with one side of the tongue working harder than the other. This similar pattern of muscle shortening in controls and patients suggests that the effect of surgery on Tm was not severe enough to induce symmetrical shortening. For GH and Tp, both sides of the patients shortened to the same extent or less compared to the controls' smaller side, suggesting very little engagement of these muscles in patients during motion into the /k/.

Figure 16 and Table 3 show that, for both controls and patients, the Ta and GGp were the most active muscles. In all subject groups except the control's smaller side, Ta showed the greatest % muscle shortening. However, the Ta also showed the greatest standard deviation in all subject groups except the control's smaller side, indicating a substantial variability in the Ta muscle activity among the subjects. The Ta is a small muscle and its shortening suggests that it is working hard to narrow the tongue which would elongate the tongue tip and actively involved in elevation and retraction of the tongue into the /uk/. The GGp showed the second most shortening. This is unsurprising since the GG is the largest muscle that makes up most of the tongue's bulk, therefore, it is expected to have a major role in tongue movement. The GGp is a large subsection of that muscle, which elevates the tongue body by pulling the posterior region forward.

Since the tongue is a muscular hydrostat, the overall volume of the tongue remains constant as the tongue is deformed into different shapes to make the appropriate speech sounds. As the tongue body is elevated toward the palate to produce the /k/, the width and length of the tongue must be decreased to accommodate this vertical expansion. It is known that glossectomy patients have more complex anatomy than controls because of the deformed, asymmetric tongue surface and scar tissue formation. Moreover, reduced tongue volume in glossectomy patients may require tongue length and width to decrease more than that of the control subjects in order to achieve palatal contact during the /k/. Although the internal tongue motion might be altered in glossectomy patients due to partial removal of one side of the tongue, the muscles on both sides were able to compensate independently for the missing tissue in order to achieve the displacement required for elevation and retraction of the tongue to produce palatal contact.

Palate height and width were expected to influence muscle shortening because the tongue interacts precisely with various intra-oral structures to perform articulatory functions. We hypothesized that the subjects with a high palate would have greater muscle shortening of GGp and GH, because these muscles might contribute to greater elevation of the tongue. The present study revealed that GH ($p = 0.052$) was the only muscle affected by palate height, with 5.1% more shortening in high palate subjects (Table 7). No significant differences were found in % shortening between the high and low palate subjects for any of the other measured muscles. It appears that GH was more actively engaged to elevate the tongue body when the tongue needed to move farther, as in high palate subjects. However, the patients did not use greater GH shortening than the controls (Table 3), so surgery did not cause them to use GH as a supplement to GGp as we expected. Instead, the GGp was able to sufficiently compensate for any additional effort required after the surgery.

For palate width, we expected to see greater muscle shortening of Ta, Tm, and Tp in wide palate subjects, because these muscles contribute to greater constriction of the width of the tongue. In contrast to our hypothesis, the results showed that only Ta ($p = 0.001$) and GH ($p = 0.018$) shortened more in narrow palate subjects. Narrow palate subjects showed 9.6 % greater Ta and 4.5% greater GH muscle shortening than those with wide palate (Table 9). This is not surprising as we would expect the transverse muscle to shorten more in order to cause more narrowing in narrow palate subjects. However, there is no clear explanation for why GH would shorten more in narrow palate subjects. Thus, we believe that there are other mitigating factors, which contribute to muscle shortening in wide vs. narrow palate, which we have not measured.

It is interesting that the GH was the only muscle affected by both palate height and palate width, where high and narrow palate was associated with greater GH muscle shortening. The GH muscle shortening was found to be independent of the subject groups (controls vs. patients), therefore we can infer that the increased muscle shortening of the GH is not a compensatory behavior but truly due to the palate dimension. A greater GH activity may be part of the gesture needed for the very large elevation to produce the /k/, which in turn requires a large tongue deformation. There are two plausible explanations for this finding. First, the anatomic location of the GH below the tongue puts it in the right place to aid elevation of the tongue effectively and achieve contact with the palate. Second, the GH is a suprahyoid muscle, therefore supplements the actions of elevators of the tongue (GGp, Ta, Tm, Tp) during the upward and backward motion into the /k/.

We conjectured a significant interaction between palatal dimension (height and width) and subject group in their effect on % muscle shortening of Ta and Tm, because both muscles are primarily affected by the resection and the resulting defect will cause them to respond differently to palatal dimension. However, 2-way ANOVA tests (Tables 6 & 8) revealed no statistically significant interaction between the effects of palate height or width and glossectomy on muscle shortening. This suggests that the effect of glossectomy on muscle activity is independent of the palate dimension. Figure 17 also confirms that no significant relationship existed between the palate height and the palate width, validating independent ANOVA tests for the height and width.

B. Relationship between shortening of tongue muscles

We hypothesized that GGp and GH would be more highly correlated in patients than controls because GH might assist GGp in elevating the tongue for patients. Interestingly, results showed no correlation between GGp and GH. Although both GGp and GH play role in elevating the tongue, their functions are quite different. They are adjacent to each other and their fibers are oriented in the same direction, however GH inserts on the hyoid bone, whereas GGp inserts on the soft tissue of the posterior tongue. GH is especially important in swallowing, during which it elevates the hyoid bone and tongue during swallowing to protect the airway. On the other hand, GGp pulls the base of the tongue forward and assist elevating the tongue body.

Nevertheless, the results did show some other interesting correlations. We expected all 3 segments of the T (Ta, Tm, Tp) would be correlated in order to produce a synchronous motion, although the patients might show a weaker correlation between Ta and Tm as they are likely to be affected by the surgery. Pearson's R test (Table 10) revealed that more correlations were found in the controls than the patients. The controls showed a positive correlation between 5 pairs of muscles, whereas the patients showed a positive correlation between only 1 pair of muscles. Contrary to our hypothesis, different muscles were correlated for the controls and patients, suggesting the relationships between the muscles were affected by the surgery.

The R^2 value is the percentage of variation in one variable that is explained by another variable. The higher the R^2 value, the better you can predict the value of one variable by the other variable. On the controls' larger side (Figures 21-23), Tp showed a positive correlation with the following muscles: GGp ($R = 0.589$, $R^2 = 0.347$), Ta ($R = 0.605$, $R^2 = 0.366$), and GH ($R = 0.694$, $R^2 = 0.482$). On the controls' smaller side (Figures 24-25), GH showed a significant positive correlation with Ta ($R = 0.747$, $R^2 = 0.558$) and Ta ($R = 0.776$, $R^2 = 0.602$). These results demonstrate that, in normal controls, the muscles that decrease the length (GGp, GH) and the width (Ta, Tp) of the tongue function synergistically to elevate and retract the tongue during the motion from the /s/ to /uk/.

Unlike the normal controls, the patients exhibited lack of coordinated muscle activity between the above mentioned muscles. However, on the patients' native side (Figure 26), Ta showed a very strong positive correlation with Tm ($R = 0.860$, $R^2 = 0.740$), indicating that muscle shortening of the Ta and Tm were highly coordinated on patients' native side and this relationship was stronger than any relationships found in controls. The relationship between the Ta and Tm muscle shortening on the native side appears to be an adaptive behavior because their activities are not tightly linked on the resected side or on either side of the controls. This remarkably strong relationship between the Ta and Tm further supports that both muscles, which are located close to the site of the resection, are actively involved in compensatory behavior in glossectomy patients. On the patients' resected side (Table 10), no significant correlations were found, suggesting that none of the muscles shortened in a coordinated manner and the patients did not use similar muscle shortening patterns on the resected side during the motion into the /uk/.

C. Effects of Tumor Size

We predicted that T2 patients would show Ta and Tm shortening more than T1 patients on the resected side, because T2 patients might require greater muscle shortening in order to compensate for the larger volume of missing tongue tissue. We also expected the function of the native side to be undisturbed by resection in both T1 and T2 patients. The results showed that T1 patients exhibited greater Ta and Tm muscle shortening than T2 patients, suggesting that the size of the tumor and resection affected the Ta and Tm muscle activity. On the native side (Table 12), T1 patients had 15.9% greater Tm ($p = 0.020$) and 10.7% greater Ta ($p = 0.077$) muscle shortening than the T2 patients. It is possible that for T2 patients, not shortening the Ta and Tm as much allows them to avoid excessively narrowing the tongue and produce an inadequate /uk/ gesture.

On the resected side (Table 13), T1 patients showed 8.2% greater Tm ($p = 0.058$) muscle shortening than T2 patients, while T2 patients had almost no Tm muscle shortening. This significant lack of Ta and Tm muscle activity in T2 patients, especially on the resected side, is consistent with loss of function of these muscles, which are most likely affected by the surgery. Since T1 patients have a larger volume of residual tissue on the resected side than T2 patients, the T1 patients may be capable of producing greater muscle shortening to accommodate the elevation of the tongue. In addition, the muscles on the resected side of T1 patients may be stronger due to better preserved muscle mass and innervation, allowing greater muscle shortening. The following are a few plausible explanations for the lack of significant disruption in the Ta muscle shortening on the resected side of patients with larger resections. The presence of a large number of motor and sensory neurons in the tongue and complex motor control may contribute to its adaptive and compensatory capacity of the tongue after partial glossectomy. Another factor influencing the compensatory mechanism is the condition of hypoglossal nerve (CN XII), which is almost never cut during surgery and its removal is rare unless a very large tumor is resected.

The other 3 muscles (GGp, GH, Tp) showed no significant difference in muscle shortening between T1 and T2 patients during elevation and retraction of the tongue. Although the tongue tip might have been affected by the surgical resection, the musculature and innervation of the tongue body and posterior tongue were left relatively unaltered, therefore the Tp and often the GGp were not expected to behave differently between T1 and T2 patients. However, it is interesting to note that the T1 patients had greater muscle shortening on the native side for all muscles, except for GH, which had a reverse pattern. The greater GH muscle shortening on the resected side of T1 patients may be attributed to the patient with radiation therapy (P7), who showed a very large GH shortening (26.6%) on the resected side.

In order to properly form the /k/, the body of the tongue must be brought upward and backward in the mouth to achieve palatal contact at its posterior surface. It is, therefore, reasonable to expect that there may not be a significant difference in tongue displacement between patients with different resection sizes since they have intact posterior tongues. In agreement with this hypothesis, T1 and T2 patients did not show significantly different muscle shortening for GGp and Tp, which are located posterior to the resection site. However, Ta and Tm, both of which are close to the resection site, showed reduce muscle shortening in patients with larger resections. This may be an indication of greater speech impairment, which is consistent with previous studies[18,19], which found the post-operative speech assessment to be positively correlated with the amount of remaining tongue tissue. Because a larger section of the tongue had been removed for T2 tumors, the surgery in T2 patients might have caused more damage to the musculature and corresponding innervation on the resected side. On the native side of T2 patients, the decreased Tm muscle activity might be responsible for balancing the tongue width reduction in order to maximize elevation and minimize excessive narrowing, which may distort speech.

D. Effects of Flap Reconstruction and Radiation

Previous studies have shown conflicting evidence for the effect of closure procedure on the post-operative function of the tongue during speech. Some studies[27,57] have found post-operative speech to be more lucid with primary closure, whereas other studies[47,57,58] have found this to be true with flap reconstruction or have shown no significant difference in post-operative speech between the two closure methods. Several interesting observations were made for the patients in the present study who received flap reconstruction or radiation therapy in addition to tumor resection. The patient with flap reconstruction (P7) presented a significantly greater Ta muscle shortening on the resected side (26.7%) than the native side (0.68%), compared to other patients who only had primary closure (Table 3). This finding suggests that the resected side with flap reconstruction need to shorten significantly more in order to elevate the tongue to produce the /uk/. The flap reconstructed patient has non-muscular, high fat, skin tissue attached onto the surgical site, which may have caused physical constraints at the boundary. The increased muscle shortening on the resected side of the flap patient seems counterintuitive, as one might expect the flap reconstruction to provide added bulk and weight resulting in decreased muscle activity. There is a plausible theory that can explain the greater Ta activity on the resected side. In the flap patient, the additional bulk and weight of the flap must be moved using the remaining reduced musculature, therefore the muscle needs to shorten more in order to overcome the rigidity of scar tissue and the larger force required to move the weight of the flap.

In contrast, Ta in the patient with radiation therapy (P8) showed a lengthening (-8.7%) on the resected side, while showing a normal shortening (10.9%) on the native side (Table 3). This finding is consistent with a previous study[32], in which impaired functional speech outcome was attributed to the late complications of radiotherapy including subcutaneous fibrosis, mucosal edema, trismus, and salivary gland atrophy. Radiation therapy may cause permanent tissue scarring, resulting in the reduced activity of the tongue muscles on the resected side.

In general, the results of the present study revealed that post-operative muscle shortening varied widely among patients who have undergone the same type and size of the resection. This is attributed to significant subject variability in patients' natural wound healing process, which causes wound contraction and scar tissue formation that may affect post-surgical mobility of the tongue. Other factors contributing to the tongue motion patterns in glossectomy patients may include the scar immobility, flap bulk, and associated tongue fatigue. In addition, the surgical intervention, such as the location of resection and suturing technique used, also may have influenced the level of subject variability.

E. Study Limitations

The most critical weakness in the present study is the small number of subjects, therefore, this study should be considered preliminary. The observations may help explain the changes in post-operative tongue muscle activity in glossectomy patients, however should be examined with caution and cannot be considered conclusive. The limited number of glossectomy patients included in the study is partly due to the inclusion criteria for small tumors (T1 or T2) only. The absence of significant difference in muscle shortening between controls and patients can be due to a small sample size, and the difference may become more apparent with sufficient number of subjects in each group. Another limitation of the present study is not having matched control and patient groups for statistical analyses. In spite of the inclusion and exclusion criteria that were used to recruit study subjects, the age, gender, and race were not matched between the controls and glossectomy patients. Other confounding factors that may have influenced the patient's post-surgical outcome, include the variability in surgical techniques, the extent of wound healing, and the amount and characteristics of scarring.

One limitation in the evaluation of the interaction between muscle activity and palate dimension is the failure to detect correlation that may exist between palate height and palate width. Although the present study found no correlation between palate height and palate width, the small sample size makes it difficult to identify potential positive or negative correlation between the height and width of the palate. Furthermore, there was an absence of significant interaction effect on muscle shortening by subject group and palatal dimension, despite the expectation that patients with a high palate would shorten tongue elevators (i.e. GGp and GH) to a greater extent than controls. This result may be due to factors influencing the palatal width and height measurements, such as the shape of the dental arch and the bucco-lingual inclination of the teeth. Despite these limitations, the findings of the present study may guide future research by highlighting areas for further investigation and providing basic knowledge about the muscle activity of the tongue in post-glossectomy patients.

F. Future Research

One of the goals for future research is to recruit a greater number of controls and patients that are matched in terms of demographic features (age, gender, and race) in order to satisfy the minimum sample size requirements for statistical power. Larger sample size will help elucidate the motor control strategies used by glossectomy patients, as well as allow more statistically significant, evidence-based conclusions to be made beyond simple observation of differences. Since it is possible that patients with a larger resection would need greater shortening to reach the palate, studying the interaction of palatal dimension and tumor size in their effect on muscle shortening may provide valuable insight into the role of palatal dimension. Comparison of pre- and post-operative tongue movement in glossectomy patients may allow us to conduct a longitudinal study the movement of the tongue and muscle activity before and after the glossectomy surgery and reduce the effect of individual variability. In addition, studying the activity of other intrinsic and extrinsic tongue muscles involved in other types of movements (i.e. depression and protrusion) will allow us to better understand the agonistic and/or antagonistic interactions between them. Future studies may also include obtaining experimental insights about the stiffness of tumor tissue and changes in configuration and mechanical properties of the soft tissue due to the scar in post-surgical tongue of glossectomy patients.

V. Conclusion

The aim of this study was to compare the change in tongue muscle length of the controls and the glossectomy patients using cine- and tagged-MRI, and to determine the relationship between palatal dimension and muscle activity during speech. Despite the limited number of subjects included in the study, several interesting findings were observed that warrant further investigation. The average muscle shortening of both hemi-tongues showed no significant difference between the controls and patients, suggesting that the tongue muscle activity was mostly maintained in post-glossectomy patients with small (T1 and T2) tumors. During repetitive speech task, the controls demonstrated asymmetric muscle activity with the larger side showing a greater muscle shortening than the smaller side. However, in the glossectomy patients, the lack of tongue tissue induced relatively symmetric muscle shortening on the native and resected sides during elevation and retraction of the tongue from /s/ into /uk/. This suggests that the patients require efforts on both sides of the tongue in order to compensate for the missing tongue tissue. High palate subjects showed greater GH shortening, while wide palate subjects showed greater GH and Ta shortening, suggesting that GH and Ta are integral to elevation and narrowing of the tongue. The results also showed that the palate effects were independent of the surgical effects for all measured muscles. The controls demonstrated a significant positive correlation between shortening of five pairs of muscles on both sides, suggesting that the muscles that decrease the length and the width of the tongue function synergistically to elevate and retract the tongue from the /s/ to /uk/. The patients showed a strongly positive correlation between the Ta and the Tm on the native side, indicating that these two muscles located near resection site work in concert to create a compensatory behavior in glossectomy patients. The resection size seemed to significantly affect the mean % muscle shortening in the patients. The T2 patients showed less shortening than T1 patients on both the native and the resected sides, suggesting greater impairment in T2 patients. Nevertheless, these results should to be interpreted with caution due to a small sample size (n = 21). For future studies, a larger number of patients and controls can help us elucidate the complex muscle activity of the tongue and the compensatory behaviors in the post-glossectomy patients. The present study demonstrates that the quantitative MRI analysis and 3-dimensional muscle tracking can be used to predict the potential effects of the glossectomy on the tongue muscle activity and may serve as valuable tools for pre-operative planning as well as post-operative speech therapy for glossectomy patients.

APPENDIX

The % Muscle Shortening of Individual Subjects in Low and High Palate Groups

Table I. The % muscle shortening in low vs. high palate subjects

Larger / Native Side		GGp	GH	Ta	Tm	Tp
Low Palate (n = 10)	C4	9.2010	19.0829	12.9428	4.5205	11.5818
	C5	3.3208	-0.0460	4.8192	3.7341	6.0347
	C9	18.1000	4.2796	20.2491	1.9048	10.9804
	C11	13.2035	2.2295	15.3536	23.2031	8.1661
	C12	10.1007	1.9288	2.0992	4.6664	0.9254
	P2	10.5764	1.0526	26.3383	26.7452	15.5269
	P3	9.3855	5.1121	11.4860	9.1845	3.7753
	P6	12.0237	-0.9503	4.0553	4.2439	5.0979
	P8	6.6225	0.8579	10.8654	1.3388	5.2705
	P9	1.3042	8.2833	17.4338	3.5083	1.7456
High Palate (n = 11)	C1	16.3307	5.1042	10.1903	8.3521	14.2815
	C2	1.9878	13.0589	14.8986	7.4530	2.4133
	C3	16.0715	31.5637	41.9157	18.8229	23.9681
	C6	4.8317	4.3224	13.3521	4.1248	8.7649
	C7	2.5444	3.1451	15.7427	4.5409	4.9622
	C8	13.4083	21.9085	4.1055	4.2678	10.4332
	C10	11.3557	1.8185	22.7460	5.3535	2.3190
	P1	17.0096	11.0522	22.4997	27.4789	-0.9305
	P7	12.6771	10.7410	0.6784	-3.7856	3.2283
	P5	8.6666	2.4761	0.7053	1.1287	0.6671
	P4	10.7573	5.2031	9.4459	5.3728	9.0888
Smaller / Resected Side		**GGp**	**GH**	**Ta**	**Tm**	**Tp**
Low Palate (n = 10)	C4	7.7595	13.2071	12.8733	2.6701	2.1619
	C5	2.4327	-2.5754	0.1204	-0.3281	0.2534
	C9	11.4085	3.7819	-8.4896	-4.3482	8.4952
	C11	2.3814	1.4806	8.8249	14.9997	4.6309
	C12	7.6685	1.7420	0.7441	2.6947	0.3166
	P2	10.2761	-1.3911	10.1837	16.8751	9.9633
	P3	9.3433	11.1579	8.8277	2.1512	0.6931
	P6	9.6874	1.2335	2.7686	4.2047	-0.4354
	P8	9.2202	2.5991	-8.6819	0.9725	0.0589
	P9	4.8317	2.7955	17.8757	-1.4708	0.8519
High Palate (n = 11)	C1	14.7992	4.5828	2.3323	6.7240	-0.9901
	C2	-0.4816	8.3914	1.3207	3.2981	2.1405
	C3	9.8975	24.8818	28.8361	6.4745	15.4960
	C6	1.9993	3.5846	2.7199	1.9934	0.2131
	C7	1.6736	1.1671	6.9572	-0.5731	0.5094
	C8	12.5595	14.4360	2.7592	2.9064	8.9531
	C10	11.1091	0.3659	-6.1580	0.8975	0.3188
	P1	11.1286	12.6918	20.4908	6.9755	3.1654
	P7	10.6978	8.7109	26.6713	-6.7495	4.3776
	P5	8.4000	2.7163	13.1875	3.4138	3.0154
	P4	7.7498	3.2788	7.8280	6.3378	8.0580

Table II. The % muscle shortening in narrow vs. wide palate subjects

Larger / Native Side		**GGp**	**GH**	**Ta**	**Tm**	**Tp**
Narrow Palate (n = 10)	C3	16.0715	31.5637	41.9157	18.8229	23.9681
	C4	9.2010	19.0829	12.9428	4.5205	11.5818
	C7	2.5444	3.1451	15.7427	4.5409	4.9622
	C9	18.1000	4.2796	20.2491	1.9048	10.9804
	P1	17.0096	11.0522	22.4997	27.4789	-0.9305
	P2	10.5764	1.0526	26.3383	26.7452	15.5269
	P3	9.3855	5.1121	11.4860	9.1845	3.7753
	P7	12.6771	10.7410	0.6784	-3.7856	3.2283
	P5	8.6666	2.4761	0.7053	1.1287	0.6671
	P9	1.3042	8.2833	17.4338	3.5083	1.7456
Wide Palate (n = 11)	C1	16.3307	5.1042	10.1903	8.3521	14.2815
	C2	1.9878	13.0589	14.8986	7.4530	2.4133
	C5	3.3208	-0.0460	4.8192	3.7341	6.0347
	C6	4.8317	4.3224	13.3521	4.1248	8.7649
	C8	13.4083	21.9085	4.1055	4.2678	10.4332
	C10	11.3557	1.8185	22.7460	5.3535	2.3190
	C11	13.2035	2.2295	15.3536	23.2031	8.1661
	C12	10.1007	1.9288	2.0992	4.6664	0.9254
	P6	12.0237	-0.9503	4.0553	4.2439	5.0979
	P4	10.7573	5.2031	9.4459	5.3728	9.0888
	P8	6.6225	0.8579	10.8654	1.3388	5.2705
Smaller / Resected Side		**GGp**	**GH**	**Ta**	**Tm**	**Tp**
Narrow Palate (n = 10)	C3	9.8975	24.8818	28.8361	6.4745	15.4960
	C4	7.7595	13.2071	12.8733	2.6701	2.1619
	C7	1.6736	1.1671	6.9572	-0.5731	0.5094
	C9	11.4085	3.7819	-8.4896	-4.3482	8.4952
	P1	11.1286	12.6918	20.4908	6.9755	3.1654
	P2	10.2761	-1.3911	10.1837	16.8751	9.9633
	P3	9.3433	11.1579	8.8277	2.1512	0.6931
	P7	10.6978	8.7109	26.6713	-6.7495	4.3776
	P5	8.4000	2.7163	13.1875	3.4138	3.0154
	P9	4.8317	2.7955	17.8757	-1.4708	0.8519
Wide Palate (n = 11)	C1	14.7992	4.5828	2.3323	6.7240	-0.9901
	C2	-0.4816	8.3914	1.3207	3.2981	2.1405
	C5	2.4327	-2.5754	0.1204	-0.3281	0.2534
	C6	1.9993	3.5846	2.7199	1.9934	0.2131
	C8	12.5595	14.4360	2.7592	2.9064	8.9531
	C10	11.1091	0.3659	-6.1580	0.8975	0.3188
	C11	2.3814	1.4806	8.8249	14.9997	4.6309
	C12	7.6685	1.7420	0.7441	2.6947	0.3166
	P6	9.6874	1.2335	2.7686	4.2047	-0.4354
	P4	7.7498	3.2788	7.8280	6.3378	8.0580
	P8	9.2202	2.5991	-8.6819	0.9725	0.0589

Glossary

GG	Genioglossus (GGa: anterior, GGm: middle, GGp: posterior)
GH	Geniohyoid
T	Transverse (Ta: anterior, Tm: middle, Tp: posterior)
MRI	Magnetic resonance imaging
Raised vowel	A vowel sound where the body of the tongue is raised toward the soft palate (i.e. /i/, /u/)
Back vowel	A vowel sound where the tongue to be positioned as far back as possible in the mouth (i.e. /u/, /o/)
/ə/	Schwa. The lax, neutral sound in American English as in "**a**fraid"
/u/	The vowel in "g**oo**se" in American English
/k/	The consonant in "**c**at" or "ba**ck**" in American English
/s/	The consonant in "**s**un" or "mi**ss**" in American English

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