Modeling Asymmetrical Movements of Normal and Pathological Tongue

Satoru Fujita[1*], Jianwu Dang[1*], Noriko Suzuki[2#], Kiyoshi Honda[3†]

[1]School of Information Science, Japan Advansed Institute of Science and Technology
1-1 Asahidai, Nomi-city, Ishikawa 923-1292, Japan

[2]School of Dentistry, Showa University
2-1-1 Kitasenzoku, Ohtaku, Tokyo 145-8515, Japan

[3]Laboratoire de Phonetique et de Phonologie, CNRS-Paris Univ.3
19, rue des Bernardins, 75005 Paris, France

*{sfujita, jdang}@jaist.ac.jp, #norikos@senzoku.showa-u.ac.jp,
†honda@atr.jp

Abstract. *Simulation techniques using 2D or 3D tongue models have been adopted in investigating mechanisms of speech production. However, large asymmetric deformations of the tongue have not been challenged yet for both normal and pathologic cases. In this study, a full 3D tongue model was constructed by extending an existing partial 3D model, and it is used to perform large asymmetric 3D deformations to generate tongue gestures with bending and torsion. Furthermore, simulations of a hemi-laterally reconstructed tongue demonstrated tongue protrusion with a bending motion, as often observed in real pathological cases. These results confirmed that the proposed tongue model performed behaviors of normal and pathological tongues and that this model can be a useful tool for the study of speech disorders with pathology of the tongue.*

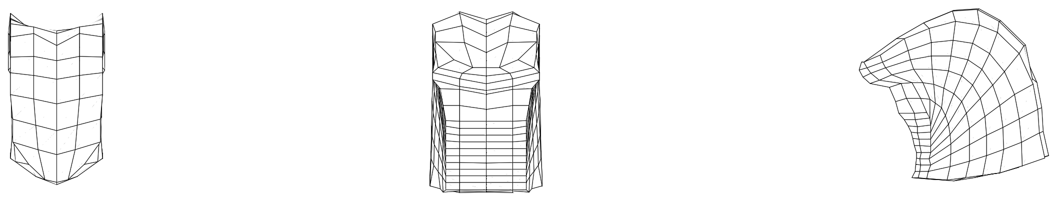
1. Introduction

This study employs a physiological tongue model to investigate motor patterns of normal and pathological tongues in large asymmetric movements. To do so, a full 3D physiological tongue model was constructed based on the existing partial 3D model, and the muscular structure was rearranged to replicate realistic anatomical structures. Then, capabilities of generating large asymmetric tongue motions were evaluated by testing bending and torsional deformation. Furthermore, movements of the hemi-laterally reconstructed tongue were simulated under the conditions, where all the muscles were removed in the reconstructed portion to model a flap. The stiffness and viscosity of the flap were changed to estimate the proper material for the reconstruction.

One purpose of this study is to develop a physiological simulator to estimate the extent of disorders after hemi-lateral glossectomy. To this end, a physiological articulatory model was used to simulate tongue movements under a variety of conditions. In the preceding study, Dang and Honda constructed a partial 3D (2.5D) physiological articulatory model for speech production under the normal condition [Dang and Honda, 2004]. Their model consisted of a tongue with 2-cm width in the midsagittal portion along with the jaw, hyoid bone, and vocal-tract wall. By employing the displacement-based finite element method (X-FEM), the model was capable of producing fast and large deformations during tongue movements

2. Construction of 3D physiological tongue model

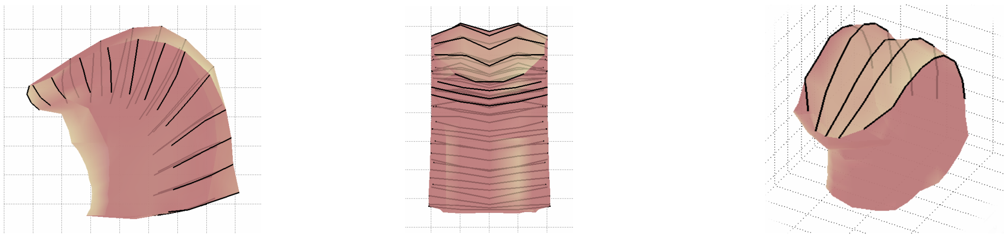
The partial 3D (2.5D) model has been successful to realize the process of speech production from articulatory targets to sound generation. It can also perform large deformations with symmetric movement of the tongue. However, it is natural to consider that asymmetric movements take place in the disorders of speech and mastication. To simulate those movements using a computational model, the 2.5D model was modified to have bilateral portions. Following the method proposed by Dang and Honda, the mesh structure of the model was based on the arrangement of the genioglossus muscle that fans out from the attachment of the muscle on the mandible, while the tongue was extended to five layers in the left-right dimension and adjusted to the realistic shape. The new tongue model consisted of 11 layers with nearly equal intervals in the longitudinal direction, seven layers in the perpendicular direction, and five layers in the left-right dimension, while the maximum width of this model was extended to 5.5 cm. Figure 1 shows the mesh structure of the proposed 3D tongue model.



(a) Top view (b) Front view (c) Left view

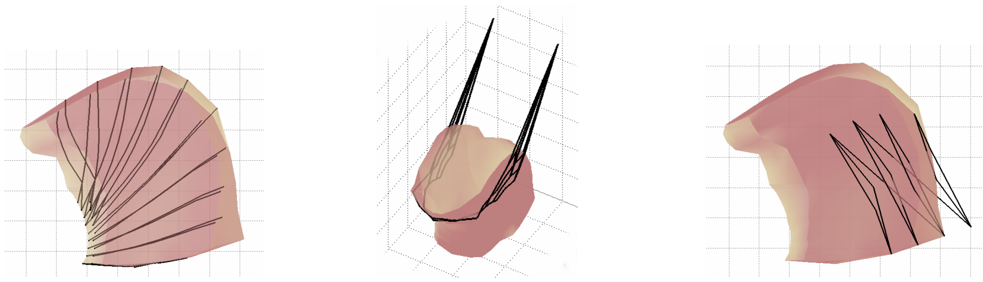
Figure 1. Structure of the proposed 3D tongue model.

The extrinsic tongue muscles, the genioglossus (GG), styloglossus (SG), and hyoglossus (HG), were arranged mainly based on MRI analysis, while the intrinsic muscles such as the superior longitudinal (SL), inferior longitudinal (IL), transverse (T), mylohyoid (MH), and vertical (V) were mainly based on anatomical data [Takemoto, 2001]. All the muscles were arranged in bilateral symmetry. The bilateral muscles were configured to be controlled independently and major muscles were divided into three parts: anterior, middle and posterior. Altogether, 37 muscle units can be controlled independently in this model. Figure 2 and Figure 3 show the major intrinsic and extrinsic muscles used in this study.



(a) Vertical (V) (b) Transverse (T) (c) Superior Longitudinal (SL)

Figure 2. Intrinsic muscles.



(a) Genioglossus (GG) (b) Styloglossus (SG) (c) Hyoglossus (HG)

Figure 3. Extrinsic muscles.

The physical and physiological parameters of the model are the same as those of the existing model [Dang and Honda, 2004]. The major parameters used in this model are shown in Table 1.

Table 1. Parameters of the proposed model.

Parameter	**Value**
Density of soft tissues	1.0 g/cm^3
Young's modulus	300kPa
Viscosity	30 kPa
Poisson ratio	0.49
Gravity	0 cm/s^2

Time step for calculation	0.005 sec

To observe basic movements of the tongue, the gravity was not considered in this study, and a minimum-volume-change constraint was applied to the whole tongue body and to individual mesh elements to realize the incompressibility of the soft tissues.

3. Simulation of pathological tongue motion

3.1 Evaluation of the proposed model

Although large asymmetric movements are not observed in normal speech, they take place during human vital activities such as ingestion and swallowing. This study attempts to construct a physiological tongue model to simulate large asymmetric movements. To do so, bending and torsional tasks were used for qualitative evaluation. An assumption in this simulation is that the bilateral bundles of the muscles can be controlled separately. Muscle activation patterns for motions were obtained from simulations after many trials.

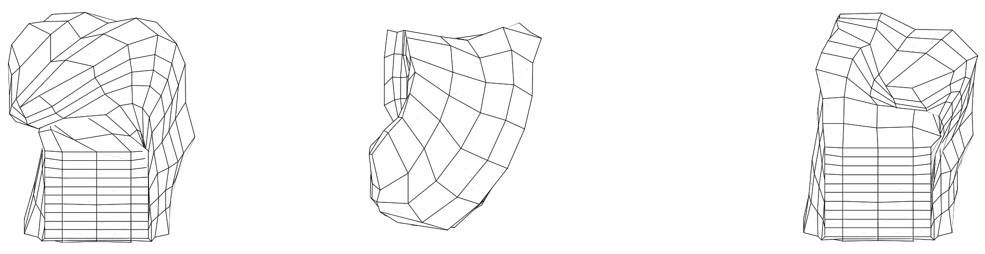
Figure 4-(a) and (b) show the results of right bending motion of the anterior tongue. The muscle force pattern was:

Right: SG(2N), SLa-m(3N), Va-m(0N), Ta-m(0N)

Left: SG(0N), SLa-m(0N), Va-m(3N), Ta-m(3N)

Here, 'a' and 'm' mean anterior and middle respectively, and 'N' is force unit, Newton. The muscles not mentioned above were not activated. The duration of muscle activation was set to 200 msec for all simulations.

The left side was elongated by co-contraction of Va-m and Ta-m, while the right side was retracted by co-contraction of SG and SLa-m. These asymmetric co-contractions generated a torque to the right direction.



(a) right bend (front view) (b) right bend (top view) (c) sinistrorse torsion

Figure 4. Results of simulation for large asymmetric motion of anterior tongue.

Figure 4-(c) shows the results of sinistrorse motion. The muscle force pattern was:

Right: HG(0N), SGp(1N), SLa-m(3N), IL(0N), Va-m(0N), Ta-m(0N)

Left: HG(3N), SGa-m(1N), SLa-m(0N), IL(1N), Va-m(1N), Ta-m(1N)

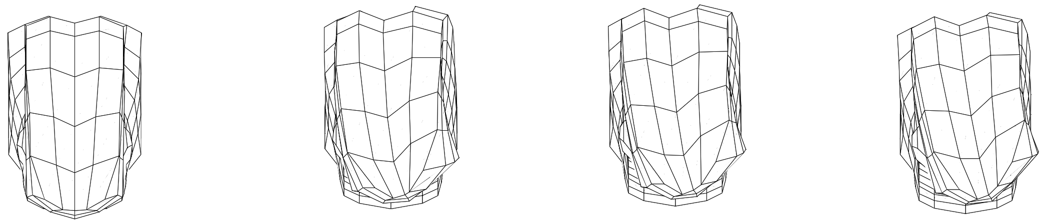
The contraction of the right side of SGp and SLa-m raised the right side of the tongue, while the contraction of HG, SGa-m and IL in the left side lowered the left side. The contraction of Ta-m and Va-m in the left side made the left side tongue stiffened along with SGa-m and IL, as they made forces with three orthogonal directions [Smith and Kier, 1989]. In this simulation, an assumption that SGp and SGa-m can be controlled independently was introduced to emphasize the asymmetry.

3.2 Simulation of a reconstructed tongue

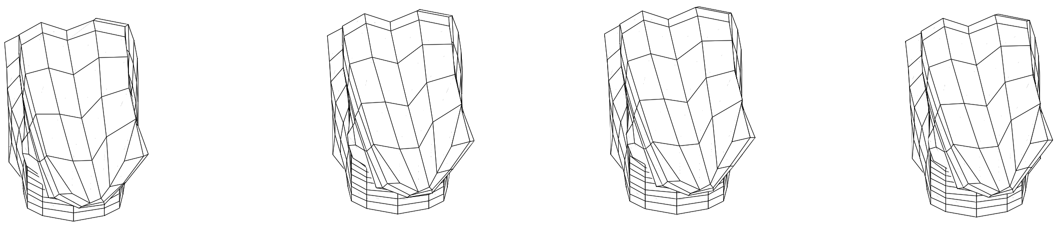
Reconstruction surgery recovers the physical defect caused by glossectomy using alternative material such as soft tissue transplanted from other sites (called a flap). In the case that the tongue was hemi-laterally reconstructed, patients suffer from difficulty in making protrusion motion [Matsunaga et al., 2002]. The difficulty may partly be caused by the property of the flap differing from the tongue tissue. In this study, we designed numerical experiments to investigate the effects of the flap on protrusion movements of a reconstructed tongue using the physiological tongue model.

To simulate a reconstructed tongue, an interface was employed to replicate a surgery in the model [Chihara et al., 2006], where the muscles in the reconstructed portion were removed. The influence of the physical property of the flap on the basic tongue motion was examined by altering the stiffness and viscosity of the flap from 0.25 times to 8.0 times of the value for the normal soft tissue. The muscle force pattern for protrusion was set to: Va-m(3N), Ta-m(3N) symmetrically.

Figure 5 shows the simulation results. As seen in Figure 5(a), the normal model produced forward protrusion with no deviation, while the tongue model with left-side reconstruction showed protrusion along with bending movement to the left side, which is slightly less than in the normal case, as seen in Figure 5(b - h). As the stiffness and viscosity increases, the bending becomes more extreme. Figure 6 shows the relationship between physical properties (the stiffness and viscosity of the flap with multiplying factor 0.25 to 8.0) and the displacement of the apical tongue node caused by the flap. This plot shows a logarithmic relation between them: as the rigidity of the flap increases the degree of lateral deviation becomes more extreme. This result is compatible with the observation of the patients with reconstruction [Matsunaga et al., 2002]. It is also true in the case of hemi-lateral paresis that the tongue bends to the paralyzed side [Keduka 2002]. The simulation reveals that the behavior of the reconstructed tongue is dependent on the physical properties of the flap tissue used in the reconstruction. As seen in the simulation, in all the reconstructed cases, the model demonstrated bending to the left to some extent. This phenomenon appears to be caused by asymmetric muscle structure due to surgical removal of the muscles.



(a) Normal model　(b) Flap in left (x 0.25)　(c) Flap (x 0.5)　(d) Flap in left (x 1.0)



(e) Flap in left (x 2.0)　(f) Flap (x 4.0)　(g) Flap (x 6.0)　(h) Flap in left (x 8.0)

Figure 5. Protrusion of the normal model (a), and left-side reconstructed models (b) – (h), in downward view. The stiffness and viscosity of the reconstructed portion (flap) were 0.25 – 8.0 times of those of the normal portion. The larger bending to the reconstructed side is seen as the stiffness and viscosity of the flap increased.

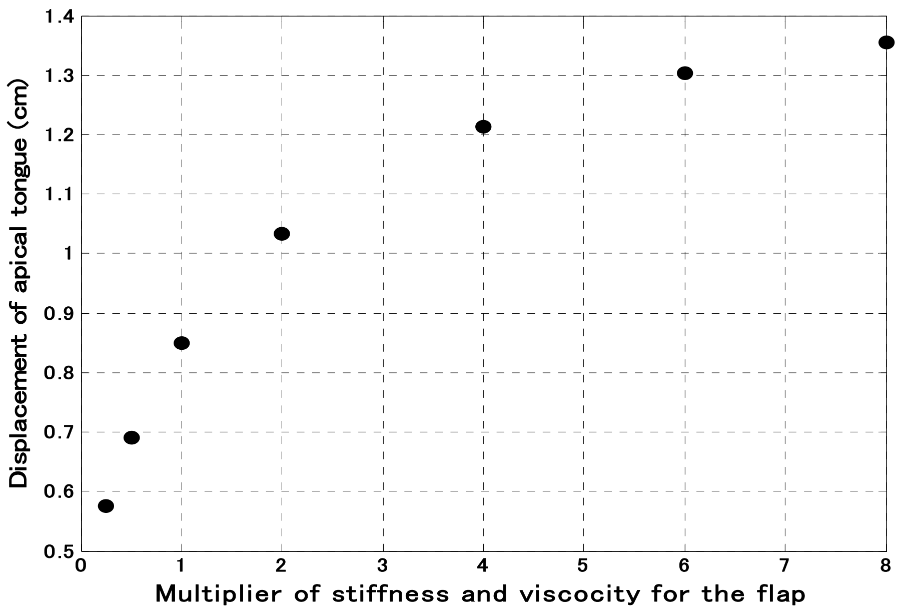


Figure 6. Relation between the multiplying factor of the stiffness and viscosity for the flap, and the displacement of the apical tongue node in protrusion, in comparison with the cases for the normal model.

4. Discussion

Due to the incompressibility of the soft tissue, a contraction in one direction causes extension to the direction perpendicular to the contraction. In the present simulation of a normal tongue, co-contraction of two orthogonal muscles Va-m and Ta-m was employed to produce tongue elongation in the longitudinal direction. To generate a lateral bending motion of the anterior tongue, co-contraction of left-side Va-m and Ta-m was used to elongate the left side, while the right side was retracted by SG and SLa-m. Although, deformation in one side could make a bending motion, muscle activation on the both sides successfully generate a larger bending.

In the case of torsional task, the human tongue can make a large rotation of the apex at nearly 90 degree. However, the simulation demonstrated only a limited rotation. Although we have not tested muscle force patterns exhaustively, this result suggests that the human tongue has a larger degree of freedom and that the model needs refinement of the musculature to generate larger torsional movements.

A co-contraction of Va-m and Ta-m was used to generate a protrusion of the tongue, and then the anterior tongue retracted in vertical and lateral direction simultaneously. Since these effects are also observed on human tongue protrusion, the tested force pattern may be consistent with that for the human's. However, in the simulation, a downward movement was observed during the protrusion, and activation of SL decreased the downward movement. So, SL may be also used in horizontal protrusion. Though, simulations of protrusion with SL activation presented the similar bending property on the reconstructed tongue model.

The simulations on hemi-laterally reconstructed tongue demonstrated that the softer flap made fewer disturbances to movements in the normal portion. From this point of view, to make a flap as soft as possible may help the tongue motion in speaking. However, in ingestion, the tongue interacts with foods, and it needs stiffness of the tongue to some extent. To find the proper property of the flap from various viewpoints is a remaining study.

5. Conclusion

A full 3D physiological tongue model was constructed to simulate large asymmetric movements under the normal and pathological conditions. It was confirmed that the proposed model was capable of realizing large asymmetric movements under the normal condition. In the normal case, the tongue model generates protrusion with no deviation, while in reconstructed cases, the tongue bended to the reconstructed side. This phenomenon of the reconstructed tongue model resembles the observations in the real pathological case. Moreover, the nonlinear relation between physical properties of the flap and the extent of the bending was obtained from simulations.

The simulations showed that this model can be a useful tool for the study of speech disorders with pathology of the tongue. For further improvements, it is necessary to collect data from the real cases and quantitatively evaluate the behaviors of the model. Development of an efficient control method is another issue remaining in the future work.

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