A Design of Laryngeal Structures for a Physiological Articulatory Model

Chao-Min WU[1], Jianwu DANG[1,2], and Kiyoshi HONDA[1]

[1]*ATR Human Information Processing Res. Labs.,*
2-2 Hikaridai, Seika-cho, Soraku-gun, Kyoto, 619-02, Japan
[2]*Dept. of Electrical and Comuter Eng. Univ. Waterloo,*
Waterloo, Ontario, Canada, N2L 3G1

Summary: A model of the hyoid-larynx complex is designed to be incorporated into a physiological articulatory model. The previously reported articulatory model consists of the tongue, mandible, hyoid bone, and vocal tract wall. The aim of this work is to include the laryngeal structures to simulate the tongue-larynx interaction which is observed in natural speech. The framework of laryngeal structures is composed of the thyroid, cricoid, and arytenoid cartilages, which are connected by muscles, ligaments and joints. The form and geometry of the cartilages are extracted from volumetric MR images of a male speaker and represented in a quasi-3D shape. They are modeled to yield joint rotation and translation as well as vertical movements. The ligaments and muscles are represented by mass-points with viscoelastic springs, and the cartilages are composed by springs with an extremely large stiffness. Laryngeal factors of F0 control such as cricothyroid rotation and laryngeal vertical movement are demonstrated in the simulation, and plausible dynamic behaviors of the tongue-larynx interaction are observed.

INTRODUCTION

It is generally accepted that laryngeal control for fundamental frequency (F0) change often involves the interaction between laryngeal and supralaryngeal articulators. This interaction results in the action of the cricothyroid joint and changes in vocal fold length. For example, the interaction between the tongue and larynx is mediated by the hyoid bone via muscles and connective tissues. The hyoid bone moves forward due to the contraction of the geniohyoid or the posterior genioglossus muscle. This action rotates the thyroid cartilage forward around the cricothyroid joint and stretches the vocal folds to raise F0 [1]. In addition, Hirai et al. [2] showed a physiological mechanism of F0 control by vertical laryngeal movement based on the measurement of magnetic resonance images (MRI). Vertical movement of hyoid-larynx complex rotates the cricohyoid cartilage along the anterior convexity (lordosis) of the cervical spine and vocal fold tension changes. In our earlier study [3], a two-dimensional articulatory model was designed to explore these F0 control mechanisms. This study is aimed to extend our 3D physiological articulatory model [4] to include laryngeal structures and to explore such tongue-larynx interactions which are observed in natural speech.

The previously reported articulatory model consists of the tongue, mandible, hyoid bone, and vocal tract wall. The geometry of these organs was extracted from volumetric MRI of a male Japanese speaker. These organs were represented in a quasi-3D shape to replicate a 2-cm thick midsagittal slice formed by three parasagittal planes for tongue
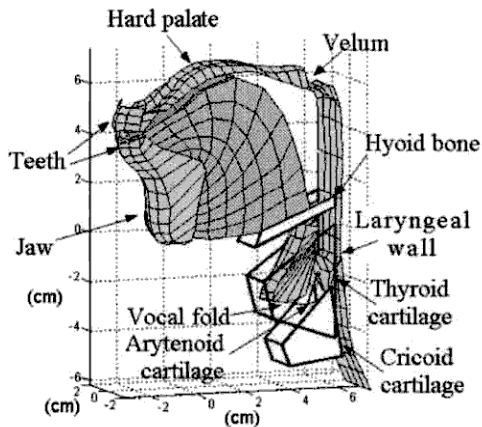
FIGURE 1: Configuration of the physiological articulatory model of speech organs.
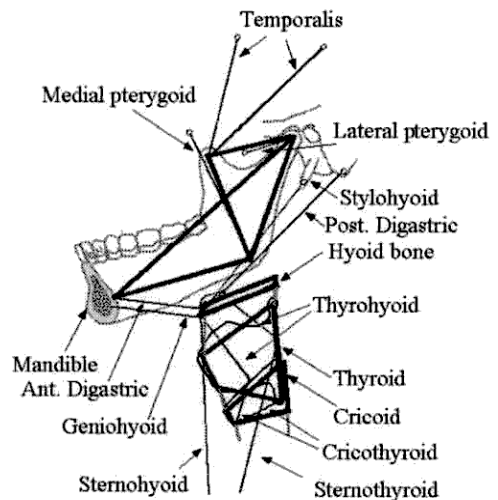
FIGURE 2: Framework of the jaw and the hyoid-larynx complex with related muscles and ligaments.

body and a 3-cm thick vocal tract wall. It is modeled as a mass-spring network for both soft tissue and rigid organs. The present study adds the laryngeal structures (also 2-cm wide) to the exisiting articulatory model. The framework of laryngeal structures is composed of the thyroid, cricoid, and arytenoid cartilages, which are connected by muscles, ligaments and joints. The form and geometry of the cartilages were extracted from the same MRI data and also represented in a quasi-3D shape. The cricothyroid and cricoarytenoid joints are modeled to produce joint rotation and translation. The ligaments and muscles are represented by viscoelastic springs, and the cartilages are composed by mass-points with springs with an extremely large stiffness. As a result, laryngeal factors of F0 control such as cricothyroid rotation and laryngeal vertical movement are demonstrated in the simulation, and plausible dynamic behaviors of the tongue-larynx interaction are discussed.

MODEL OF LARYNGEAL STRUCTURES

The model configuration is shown in Fig. 1. In the model, the hyoid-larynx complex is connected by muscles and ligaments and implemented as a moveable object. Their positions and outlines were traced from MRI pictures with reference to anatomical descriptions. The hyoid bone is modeled by four mass-points on each side, which form three segments with thickness to represent body and two greater horns. Each segment is formed by four mass-points and connected by parallel rigid beams. Additional mass-point is placed on each side-segment at the mid point of the bottom rigid beam for the thyrohyoid muscle attachment. The thyroid cartilage is modeled by ten rigid beams to form one middle rectangular plane that joins two trapezoidal planes on each side. Two additional mass-points are added to each trapezoidal plane to represent the oblique line

TABLE 1: Organs and muscles in the model

Organs	Mandible, Hyoid bone, Thyroid cartilage, Cricoid cartilage, Arytenoid cartilage
Laryngeal muscles	Cricothyroid, Vocalis
Supralaryngeal muscles	Digastric, Stylohyoid, Geniohyoid
Infralaryngeal muscles	Sternohyoid, Sternothyroid, Thyrohyoid
Jaw muscles	Temporalis, Lateral pterygoid, Medial pterygoid, Mylohyoid
Others	Cricothyroid joint, Cricoarytenoid joint, ligaments

on the thyroid lamina to provide attacments for the thyrohyoid and sternothyroid muscles. In a similar way, the cricoid cartilage is modeled by eight mass-points and connected by 12 rigid beams to establish two rectangular planes (front arch and posterior plate) to join the bilateral quadrilateral planes in the middle. Unlike the other laryngeal cartilages, the arytenoid cartilage is modeled by two triangular planes which are formed by three mass-points and three rigid-beams on each side. The cricothyroid and cricoarytenoid joints have elastic elements to constrain translation and excess rotation.

Once the positions and outlines of rigid structures were determined, muscles and ligaments were added to connect all the structures on the action points based on the anatomical description. Fig. 2 shows the model framework of the mandible and laryngeal structures with related muscles and ligaments. Table 1 summarizes all the components implemented in the laryngeal structural model. A rheological model of isolated muscle similar to [5] was adopted to approximate properties of soft tissues. which includes viscoelastic and contractile elements in parallel. The force generated by the muscle is determined by the sum of passive component and active force which depends on thickness of muscle and its activation level. The ligament is modeled as a spring without contractile elements. The cartilages are composed by springs with extremely large stiffness. To successfully replicate the vertical laryngeal movement, the original vocal tract wall was extended to the level of lower cervical spine (C7). The curvature of the cervical spine provides a fixed wall for the cricoid cartilage to move vertically. The interaction between the cricoid cartilage and the cervical spine is critical to assure a natural simulation. In the present model, elastic springs were added between two structures to maintain appropriate distance when the cricoid cartilage slides vertically along the cervical spine.

SIMULATION RESULT

To examine overall performance of the model for the interaction between laryngeal and supralaryngeal speech organs, two simulation experiments were performed. Experiment 1 was to see the effect of horizontal movements of the hyoid bone on the vocal fold length. Experiment 2 was to simulate the effect of the vertical laryngeal movement on the vocal fold length.

Experiment 1 was performed by providing a force to activate the geniohyoid muscle. Contraction of the geniohyoid muscle applied a horizontal force on the hyoid bone and caused the hyoid bone to move forward. This action rotated the thyroid cartilage forward
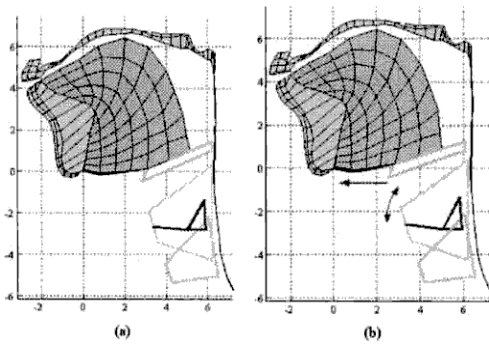
FIGURE 3: Simulation results of horizontal movement of the hyoid bone: (a) before and (b) after the geniohyoid muscle contraction.
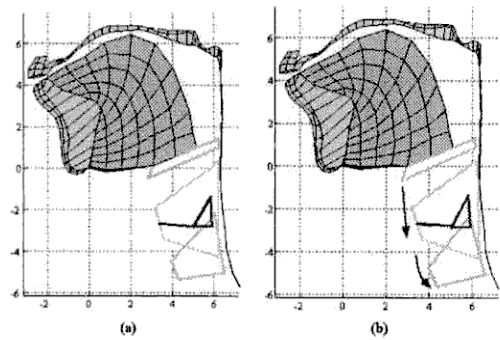
FIGURE 4: Simulation results of vertical movement of the larynx: (a) before and (b) after strap muscles contraction.

and downward to change the vocal fold length. Fig. 3 (a) and (b) illustrates the results of experiment 1 before and after the geniohyoid muscle contraction.

Experiment 2 was conducted to apply a force to the strap muscles such as the sternothyroid and sternohyoid muscle. Contraction of the strap muscles pulled the laryngeal structures downward along the wall of the cervical spine. The cricoid cartilage moved downward along the anterior convexity of the cervical spine wall and rotated to the direction to shorten the vocal folds. Fig. 4 (a) and (b) shows the results of experiment 2 before and after the strap muscle contraction.

CONCLUSIONS

This report describes details of our model of laryngeal structures. This model is designed to simulate the laryngeal and extralaryngeal articulator interaction using muscle contraction. The results of simulation replicate the movement patterns of the laryngeal structures observed in natural speech. Performance of the model indicates the mass-spring network of speech organs can represent the interaction between the laryngeal and extralaryngeal articulators.

REFERENCES

[1] Honda, K., "Relationship between pitch control and vowel articulation," in D.M. Bless and J.H. Abbs (eds.) *Vocal Fold Physiology*, San Diego, College-Hill Press, 1983, pp. 286–297.

[2] Hirai, H., J. Dang, and K. Honda, "Analysis of magnetic resonance images on the physiological mechanisms of fundamental frequency control," J. Acoust. Soc. Jpn. **50**, pp. 296–304 (1994), in Japanese.

[3] Honda, K., H. Hirai, and J. Dang, "A physiological model of speech production and the inplication of tongue-larynx interaction," in *Proc. of ICSLP94*, Yokohama, Japan, pp. 175–178, 1994.

[4] Dang, J. and K. Honda, "Speech production of vowel sequences using a physiological articulatory model," *in Proc. of ICSLP98*, Sydney, Australia, pp. 639–642, 1998.

[5] Morecki, A., "Modeling, mechanical description, measurements and control of the selected animal and human body manipulation and locomotion movements," in A. Morecki (ed.) *Biomechanics of Engineering - modeling, simulation, control*, New York, Springer-Verlag, 1987, pp. 1–87.