CONSIDERATION OF MUSCLE CO-CONTRACTION IN A PHYSIOLOGICAL ARTICULATORY MODEL

Jianwu DANG[1,2,3] and Kiyoshi HONDA[2]

[1]Japan Advanced Institute of Science and Technology, Ishikawa, Japan
[2]ATR Human Information Science, Kyoto, Japan, and [3]ICP, Grenoble, France
jdang@jaist.ac.jp and honda@atr.co.jp

Abstract

Physiological models of the speech organs must consider co-contraction of the muscles, a common phenomenon taking place during articulation. This study investigated co-contraction of the tongue muscles using the physiological articulatory model that replicates midsagittal regions of the speech organs to simulate articulatory movements during speech [1,2]. The relation between the muscle force and tongue movement obtained by the model simulation indicated that each muscle drives the tongue towards an equilibrium position (EP) corresponding to the magnitude of the activation forces. Contributions of the muscles to the tongue movement were evaluated by the distance between the equilibrium positions. Based on the EPs and the muscle contributions, an invariant mapping (the EP map) was established to function the connection of a spatial location to a muscle force. Co-contractions between agonist and antagonist muscles were simulated using the EP maps. The simulations demonstrated that coarticulation with multiple targets could be compatibly realized using the co-contraction mechanism. The implementation of the co-contraction mechanism enables relatively independent control over the tongue tip and body.

1. Introduction

During speech production, skilled articulatory movements are realized by well-practiced muscular movements. A number of researchers have endeavored to discover the relation between tongue movement and muscle activation using experimental approaches such as EMG experiments [3,4]. However, such observations succeeded for only a few large muscles, such as the extrinsic tongue muscles. Functions of the intrinsic muscles of the tongue have been investigated using the tagging MRI [5, 6], but the accuracy of such investigations is questioned, since a number of muscles are co-activated even in executing a simple movement. Further, it is often difficult to determine accurately the mechanical load of a muscle because the load depends on the situations of many other muscles. However, a physiological model of the human speech organs can provide an alternative means to understand certain characteristics of speech production. This study investigates muscle coordination of the articulatory muscles using our physiological articulatory model.

2. Configuration and Muscular Structure of the Model

2.1. Configuration of the model

A partially 3D physiological articulatory model has been constructed based on volumetric magnetic resonance imaging (MRI) data obtained from a male Japanese speaker, which consisted of the tongue, jaw, hyoid bone, and vocal tract wall. The articulatory model used in this study is derived from the previous version [1,2]. In the new version, the model employed a truss structure consisting of viscoelastic cylinders in place of the volumeless spring network and achieved a "semi-continuum" model of the tongue tissue. The initial shape of the model adopts the tongue shape of a Japanese vowel [e]. The outlines of the tongue body were extracted from the sagittal slices with a 1.0-cm interval. Mesh segmentation of the tongue tissue roughly replicates the fiber orientation of the genioglossus muscle. The outline of the tongue body in each plane was divided into ten radial sections that fan out from the genioglossus' attachment on the jaw to the tongue surface. In the perpendicular direction, the tongue tissue was divided into six sections concentrically. A 3D mesh model was constructed by connecting the section nodes in the midsagittal plane to the corresponding nodes in the left and right planes. Thus, the model represents the principal region of the tongue by a 2-cm-thick layer bounded with three sagittal planes. Based on the same MRI data set, the vocal tract wall and the jaw were constructed in 3D with a width of 2.8 cm in the left-right dimension (see [1,2] for details).

2.2. Muscular Structure of the Model

Figure 1 shows the muscular structure of the model, where the larger muscles were examined based on a set of MR images obtained from the target speaker [1, 2]. The orientation of the tongue muscles was also examined with reference to the literature [7, 8]. Figure 1(a) shows the genioglossus (GG), which runs midsagittally in the central part of the tongue. Since the GG is a triangular muscle and different parts of the muscle exert different effects on tongue deformation, it can be functionally separated into three segments: the anterior portion (GGa) indicated by the dashed lines, the middle portion (GGm) shown by the gray lines, and the posterior portion (GGp) denoted by the dark lines. The thickness of the lines represents an approximate size of the muscle units, and the thicker the line, the larger the maximum force generated. Figure 1(b) and 1(c) show the arrangement of the hyoglossus (HG) and styloglossus (SG) in the parasagittal plane, where the thickest line represents the hyoid bone. In addition, two tongue-floor muscles, the geniohyoid and mylohyoid, are also shown in the parasagittal planes. The top points of the mylohyoid bundles are attached to the medial surface of the mandibular body. All the muscles are designed symmetrically on the left and right sides. Figure 1(d) shows the structure of the verticalis in a cross-sectional view sliced at the 5th section from the tongue floor, denoted in Fig. 1(e). Fig 1 (e) shows three intrinsic muscles of the superior longitudinalis (SL), inferior longitudinalis (IL) and transversus. The transversus runs in the left-right direction, and its distribution is plotted in star markers. Altogether, eleven muscles are included in the tongue model.

Figure 1 (f) shows the model of the jaw-hyoid bone complex. The jaw model consists of four nodes on each side, which are connected by five rigid beams (thick lines) to form two triangles with a shearing-beam. The tongue is combined with the jaw at the mandibular symphysis. The model of the hyoid bone has three segments corresponding to the body and bilateral greater horns. The small circles indicate the fixed attachment points of the muscles. All of these muscles are modeled symmetrically on the left and right sides. Jaw movements in the sagittal plane are composed of rotation (change in orientation) and translation (change in position). The muscles involved in the jaw movements were roughly separated into two groups: the jaw closer group and opener group.

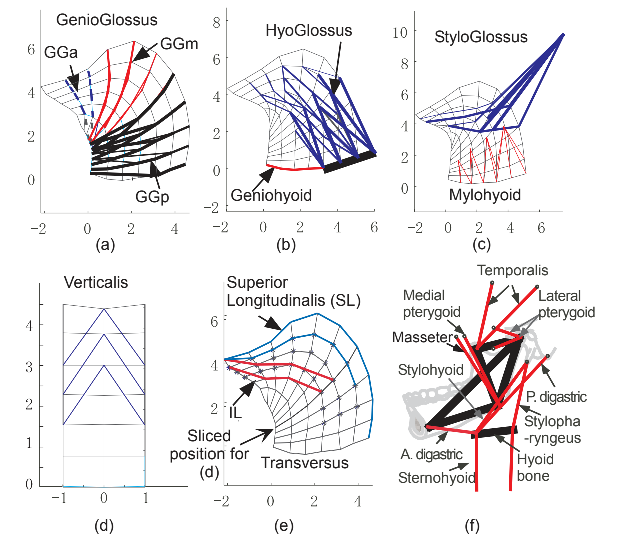

Figure 1: Muscular structure of the model. (a)-(e): the tongue muscles in the midsagittal and/or parasagittal planes (in cm), (f) the complex of the mandible and hyoid bone.

3. Construction of the EP map

Activating a muscle by a certain force, the tongue moves to an equilibrium position. The equilibrium position depends on both the muscles and force levels, but is independent of starting points. Therefore, the equilibrium position provides an invariant mapping function between a muscle force and a spatial point. Based on the equilibrium position (EP), a stationary coordinate can be constructed in the articulatory space. To build up such a coordinate, each muscle was activated by an altering force with a duration of 300 ms, where the force was designed to be six levels: 0.0, 0.1, 0.2, 0.4, 1.0, 2.5, 4.0, and 6.0 N.

3.1. Muscle Force and Equilibrium Position

In this study, we used two control points, the tongue tip (the tongue tip) and tongue dorsum, to describe tongue movements. Therefore, the coordinates were established for these two points, respectively, based on the EPs obtained by exciting each muscle. Figure 2 shows the coordinates for the tongue tip and dorsum while the jaw was in the rest position. It is interesting to find that for each muscle its EPs shift monotonically as the force level increases. The line built on the EPs can be considered as a "vector" that spreads out from the rest position. The HG moves the tongue tip backward and slightly upward as the activation level increases. The SG almost drives the tongue tip backward horizontally while the GGa draws the tongue tip downward. The tongue tip is driven forward-upward by the GGp and forward-downward by the GGm. The intrinsic muscles SL and IL move the tongue tip largely upward-backward and downward-backward, respectively.

One can see that there is a large blank space between the vectors of SL and GGp in the tongue tip coordinate if considering the signal muscles only. This means that no muscle can move the tongue tip in this direction. Since this region is important for constructing the alveolar consonants, we proposed a muscle group consisting of the transversus (T) and the SL to fill this blank space with a new EP vector (T-SL). After adding the muscle group, the EP vectors distribute almost uniformly in the coordinate for the tongue tip. Such a structure provides a capability for moving the tongue tip toward any direction.

The right panel shows a number of larger EP vectors for the dorsum. Differing from the tongue tip, the dorsal coordinate has much larger scale in the horizontal direction than that in the vertical direction. The extrinsic muscles (except the GGa) have definitely larger EP vectors than the others. The EP vectors of the GGp and HG show completely opposite directions. This indicates that the GGp and HG work antagonistically in governing the tongue dorsum. Similarly, the GGm and SG is another antagonist muscle pair. Therefore, there are obviously two larger antagonist muscle pairs for controlling the dorsum. As the SG moves the dorsum upward and backward, the dorsum begins to cross through the hard palate when the force reaches one Newton. The GGp moves the dorsum forward and upward to contact with the hard palate. The EP vector of the GGp did not reach the hard palate because the control point was not the highest point of the dorsum during such a deformation.

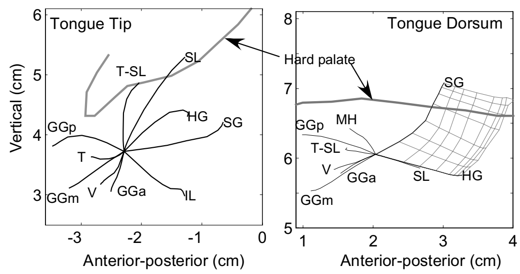

Figure 2: Coordinates consisting of the equilibrium positions of each muscle, where the activation force varied from 0 to six Newton. The network shows the contour for the force levels.

3.2. Construction of the EP map

In the proposed model, there are eleven muscles involved in the tongue body. To simplify the problem this study focuses on the major muscles only. Muscles' contribution is evaluated using the amplitude of the EP vector.

Among the EP vectors, the SL has the largest amplitude in the tongue tip coordinate while the SG generated the largest vector for the tongue dorsum. The vector amplitudes are normalized by the maximum values for the tongue tip and dorsum, respectively. The normalized amplitudes reflect a relative contribution of the muscles, and they are referred to as the *contribution rate*. Table 1 shows the contribution rate of the muscles. A muscle is considered to have a contribution to the tongue movement if its contribution rate is larger than 0.3. The superscripted * denotes the muscles with a contribution rate larger than 0.5. As a result, the most extrinsic muscles (except the GGa) have larger power to control both the tongue tip and tongue dorsum. Among the intrinsic muscles, the SL and IL showed definite contributions for the tongue tip. The transversus demonstrated a certain contribution when it is grouped with the SL, which plays an important role in increasing the control freedom. The geniohyoid showed no significant contributions to any control point. Note that this study only used two specific points to evaluate contribution of the muscles. If different observation points are adopted, a dissimilar contribution rate may be obtained for some muscles, *e.g.* the geniohyoid.

Table 1: Contribution rate of the tongue muscles.

Muscle names	the apex	the dorsum	Contribution to
Genioglossus A.	0.37	0.39	Both
Genioglossus M.	0.58	0.72	Both*
Genioglossus P.	0.68	0.74	Both*
Hyoglossus	0.74	0.86	Both*
Styloglossus	0.94	1	Both*
Longitudinalis	1	0.45	Tip*
Inferio Longitudinalis	0.69	0.13	Tip*
Verticalis	0.36	0.43	Both
Transversus	0.31	0.22	Tip
T-SL	0.65	0.17	Tip*
Myohyoid	0.21	0.36	Dorsum
Geniohyoid	0.23	0.13	None

To develop a control method, it is needed to re-inspect the EP vectors based on the contribution and the freedom of model control. All the EP vectors shown in Fig. 2 have a contribution rate larger than 0.3. In the coordinate of the tongue tip, the GGa and verticalis (V) have relative small vectors with a similar direction. These two vectors are taken into account because they increase the degree of the freedom. The transversus (T) is also taken into account because it increases the degree of freedom in 3D although it shows no importance in 2D.

In the dorsal coordinate, the EP vector of the MH is located in the space between GGp and SG, and contributes to widening the contact area of the dorsum and the hard palate. For this reason, the MH is included in the dorsal coordinate for the control, although its vector is smaller than that of the extrinsic muscles. The GGa and V have a similar EP vector to that of the GGm, but their amplitude is about a half of that of the GGm. These muscles are not considered as an independent factor in the control method since they do neither contribute significantly nor increase the degree of the freedom. For the same reason, the SL and T-SL are not treated as an independent factor. However, these muscles are taken into account in muscle co-contraction, described in the latter part.

Based on the above consideration, five major muscles are taken into account in controlling the tongue dorsum, and nine muscles and one muscle group are used for the tongue tip. Thus, a mapping between the spatial point and the muscle forces can be obtained based on the selected EP vectors. An example is shown in the right panel of Fig. 2 by the network, which consists of the SG and HG. The contour lines correspond to the six force levels. Such a network of the contour lines is named the *equilibrium position map* (EP map). With the EP map, any arbitrary point inside the region of the map can be reached using the forces interpolated from the contour lines.

4. Co-contraction of the Muscles

To form a tongue shape by muscle contraction, the most effective way in view of the minimal energy principle is that two agonist muscles work together so that the muscle forces can be easily estimated via the EP map shown in Fig. 2. During speech, however, the situation is much more complicated because to reach a target more than two agonist muscles possibly work together, or some agonist-antagonist muscles co-contract at the same time. For these reasons, co-contractions among the muscles must be taken into account. In this study, the co-contractions between the agonist and antagonist muscles were simulated using muscle groups with three muscles.

4.1. Co-contraction between Agonist and Antagonist

We designed five muscle groups to generate some potential co-contractions during speech. Figure 3 shows the co-contractions for four muscle groups and Figure 4 shows another one with an example of its application. The thick dark lines show a part of the EP vectors of coordinates, which were generated by activating each single muscle. The thin dark lines and pale lines denote the equilibrium trajectories for two synergistic muscles in the group, respectively. The attachment of the thin dark and pale lines corresponds to activation levels of another extrinsic muscle in the same muscle group.

The combination of the SG and the muscle group of the GGp and SL, shown in Fig. 3 (a), can move the tongue tip to an apical target by the muscle group and control the palatal target by the SG. This mechanism is able to realize a compatible target set for both the tongue tip and the dorsum. It is interesting to find that the muscle group is working as synergists for the tongue tip while they are functioning as an antagonist pair for the tongue dorsum. If a proper force ratio is chosen for the GGp and SL, the tongue tip position can be manipulated without interfering the tongue dorsum. Figure 3 (b) shows a co-contraction between the GGp and the muscle pair of the GGa and IL. Using this combination, the tongue tip can be withdrawn with no interference in the dorsum because the GGa and IL work as antagonists for the dorsum. The co-contraction shown in Fig. 3 (c) can make a posture with a lower dorsum and a higher tongue tip. An optimal dorsum position can be realized using a proper force ratio for the muscle pair of the GGp and SL. Figure 3 (d) shows another way to realize the same function as shown in Fig. 3 (c). In this case, the muscle pair consists of two intrinsic muscles. These two muscles demonstrated similar functions for the tongue tip, while they work antagonistically for the dorsum. The benefit of using this muscle pair is that the dorsum position can be adjusted by a balance of the two muscles. In these examples, one can find that the co-contraction can also be used to maintain a kinematic system stable.

4.2. Application of the Co-contraction

Figure 4 shows an application of the co-contraction, where the GGp and HG are antagonist muscles, especially for the dorsum.

In this example, we estimate muscle forces according to a consonantal target with two features. The crucial feature on the tongue tip is shown by the filled circle, and an indecisive feature for the dorsum is indicated by the open circle.

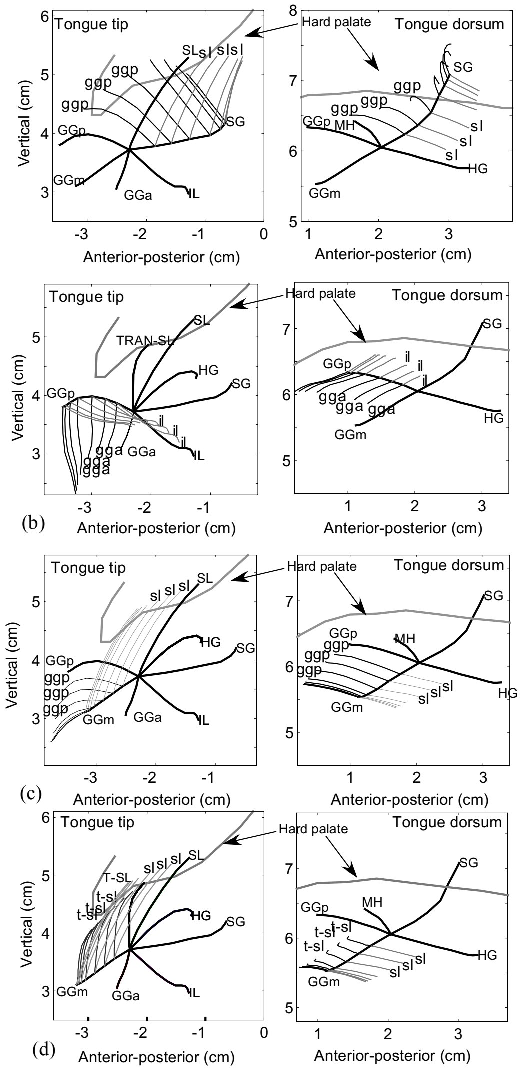

Figure 3: Co-contractions within muscle groups (a) SG and a muscle pair of the GGp and SL; (b) GGp and a muscle pair of the GGa and IL; (c) GGm and a muscle pair of the GGp and SL; (d) GGm and a muscle pair of the T-SL and SL.

In Fig. 4, one can see that the HG is the major muscle to drive the tongue dorsum toward the dorsal target while the muscle pair of the GGp and SL is one of the muscle groups to realize the apical target. Among the force combinations, for example, three combinations of the ggp_1-sl_1, ggp_2-sl_2 and ggp_3-sl_3 are capable of moving the tongue tip to reach the apical target. The difference between them is that they have different co-contraction levels with HG, whose force was 0.0, 0.1, and 0.2 N, respectively. Since all three combinations can guarantee the crucial feature, the decision finally depends on their behaviors of the force sets on the indecisive feature. The circled numbers in the dorsal coordinate are the predicted locations for these three force sets. The location of the circled 3 is the best one in the three sets for the given dorsal target. Therefore, the force set of the ggp_3-sl_3 and HG with 0.2 N is the optimal one for the given target.

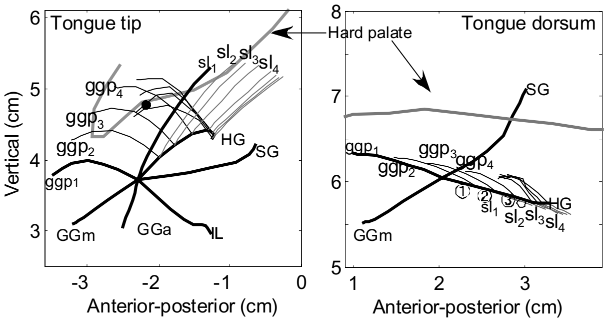

Figure 4: An example to realize coarticulation by muscle cocontraction.

Generally, to estimate an activation pattern for a given target, all possible force combinations are searched out in the EP maps. The square summation of the muscle forces is calculated for each combination. According to the minimal energy principle, the muscle group with the smallest force summation is the optimal one to form the target.

5. Conclusions

This study first examined the relation between the muscle force and tongue movement using our physiological articulatory model. The results indicated that each muscle drives the tongue towards an equilibrium position (EP) corresponding to the magnitude of the activation forces. Accordingly, an invariant mapping, the EP map, was established to function the connection of a spatial location and a muscle force. Simulation using the EP maps showed that the multiple targets could be compatibly realized by using the co-contraction mechanism. In the tongue muscles, there are several muscle groups working as synergists for one control point but as an antagonist pair for the others. This property allows us to manipulate a part of the tongue but not interfere the other parts significantly.

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6. References

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