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A COMPUTATIONAL MODEL OF THE TONGUE*

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Purpose

In the spring meeting of 1974, Joe Perkell reported on a computational simulation of the tongue which is approximated as a two-dimensional lumped-constant elastic system.[1] We have been interested in this type of work especially in relation to our new x-ray measurements of tongue movements during speech utterances and also considering the recent anatomical data of the tongue obtained by one of the present coauthors.[2] This paper is a preliminary report on our version of modelling the tongue. It is designed for studies of the static characteristics of the tongue as a three-dimensional linear system under simplified geometric boundary constraints. A computer program has been written and a first version of the model is now in operation for accumulating experience with its use, in order to arrive at a simple and efficient representation of the speech organ as a descriptive framework of speech events.

Computation Procedure

The complex continuum of the tongue body is functionally divided into 14 constituent units with elementary shapes (Figure 1). In this figure, to the left is the tip of the tongue. Only one half of the tongue body cut along the midsagittal plane, i.e. the y-z plane, is considered, assuming symmetry of the tongue in respect to this plane. The set of constituent units or blocks as shown here are selected so that within each unit, the muscular property can be approximated by uniformly distributed elastic characteristics. Two or more muscles may cause contraction of the same unit in different directions. For the computational purpose, each of the units is further divided into a few tetrahedral elements.

It is assumed that the reactive strain within each tetrahedral element is uniform and is uniquely related to the (relative) displacements of its four vertexes. Also, the tissue (or muscle) of the tongue body is presently assumed to have linear isotropic elastic properties, the volume of the substance being essentially incompressible. Then, following the standard procedures in the finite element method,[3] a set of forces at all the vertexes of each tetrahedron is calculated to represent the effects of the elastic stresses that exist within the element. The elastic stresses may be caused either by the passive elastic reaction to the outside forces, or by active contraction of the "internal muscles" that exist within the pertinent unit. By considering all such forces contributed from all tetrahedra that are related to each nodal point, we can set up a set of linear

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equations to represent equilibrium at every nodal point in terms of the coordinate values of all 24 nodal points. External forces may be applied in a form of direct force applied at a nodal point representing contraction of an external muscle that exists outside this system. The nodal point displacements are calculated as the response to a pattern of input specifications, i. e. all the muscular contractions.

Modelling the Structure of the Tongue Body

In the present program, the computation is performed in the mandible-fixed coordinate system. The maxilla moves relative to this system as a variable boundary condition. The two nodal points at the frontal edge of the basal plane (which are considered to be directly fixed to the mandible) are spatially fixed. Two nodal points at the back end on the basal plane are presently constrained so that only displacements in the horizontal plane are allowed.

The tongue body is surrounded by a hardwall of an ellipsoidal vertical cylinder continued into an ellipsoidal shell simulating the roof of the mouth cavity (Figure 2). The nodal points on the upper and the lateral surfaces of the tongue body are constrained not to go beyond these hard-walls when deformed.

Computation first gives the displacements of all nodal points without considering the boundary walls. Then, by using the method of Lagrangian multiplicatory coefficients, the hardwall constraints are imposed as boundary conditions, and the calculation is iterated. Figure 3 shows an output display of calculated coordinate values and the forces pushing those nodal points back against the boundary walls. The consistency of the boundary conditions in terms of the resulting binding forces is examined by the experimenter, and the computation is iterated a few times until convergent results are obtained. The total computation typically takes a few minutes using our DDP-224.

In the present program as the input, we specify the unit numbers, directions and magnitudes of contractions for the internal muscles, and the node point numbers, directions and magnitudes of the external forces for external muscles. Jaw position is presently entered as a parameter.

Output Displays and Some Examples

Figure 4 shows lateral views of three different configurations. At the top we see a lateral view of the neutral tongue shape, i. e. without any internal or external forces applied. At the bottom to the right is the deformed tongue when we contract two units, 9 and 10, simulating the posterior and central parts of the genioglossus muscles, before we impose the boundary conditions. To the left is the result of calculation after imposing the boundary conditions of the hard walls. The effects of hard wall constraints are complex; for example, as the result of constraining deformation in the upper portions of the tongue, the shortening of the bottom side is much more moderate than that under no such constraints in spite of the fact that the same forces of contraction for this unit are used. The configuration represents a front vowel articulation.

Figure 5 shows the result of exerting an external force. The node #3 is pulled upward and backward on the side, and the result is a retraction of the tongue body with slightly raised posterior parts of the tongue surface. This simulates the effect of the styloglossus muscle which is assumed to be responsible for the vowel [a], for example.

Figure 6 shows some front views of the tongue. Notice that only the left half of the tongue is shown. Figure 6 (a) is the neutral shape. Figure 6 (b) is the result of contracting the genioglossus for a front vowel. Even though the forces are only within the direction parallel to the midsagittal plane, we see that the side of the lower part of the tongue body is inflated as the result of contraction of the muscles inside near the bottom.

Figure 6 (c) is the result of introducing contracting forces in the anterior upper units in the horizontal, i.e. left to right direction (unit 12). This simulates the contraction of the anterior part of the transverse muscles, one of the intrinsic muscles, which is used for bulging and protruding the tongue tip forward. It also results in raising the anterior surface of the tongue blade, which is shown to be in contact with the palate on its sides, leaving a narrow groove of the vocal tract along the midsagittal line.

Figure 6 (d) is a combination of the two configurations in (b) and (c). The sides of the blade are in contact with the palate, and this may be similar to a palatized front vowel.

Effects of contraction of different muscular units on the tongue shape are being studied using this model.

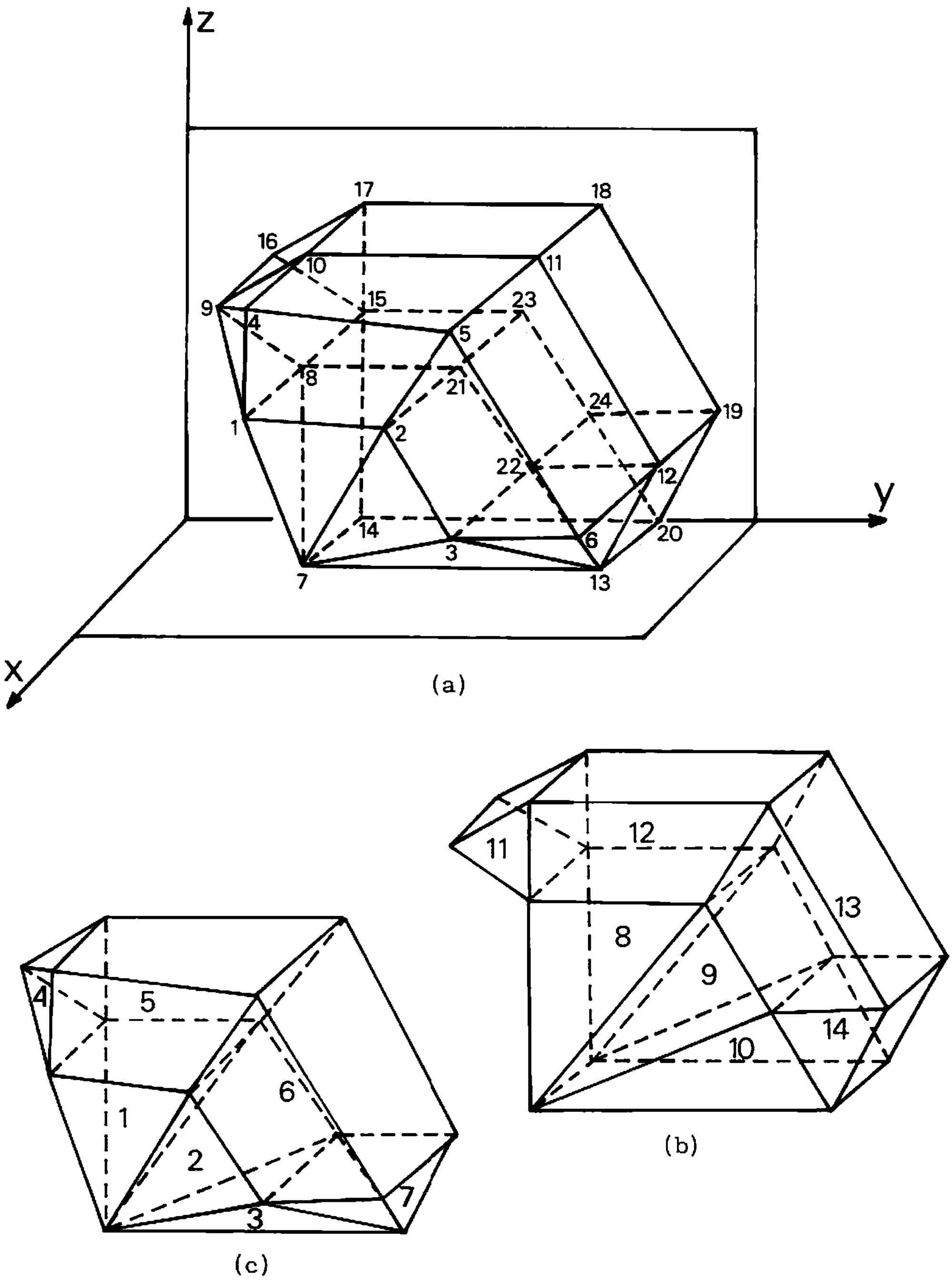

Fig. 1. Division of the tongue model into 14 units. The entire shape (a) is shown in two parts: (b) medial part and (c) lateral part. Numerals in (a) identify the nodal points, numerals in (b) units. The y-z plane represents the midsagittal plane, on which the nodal points 14-20 and 23-24 are bound. Nodes 7-14 are fixed, and nodes 13 and 20 are bound on x-y plane.

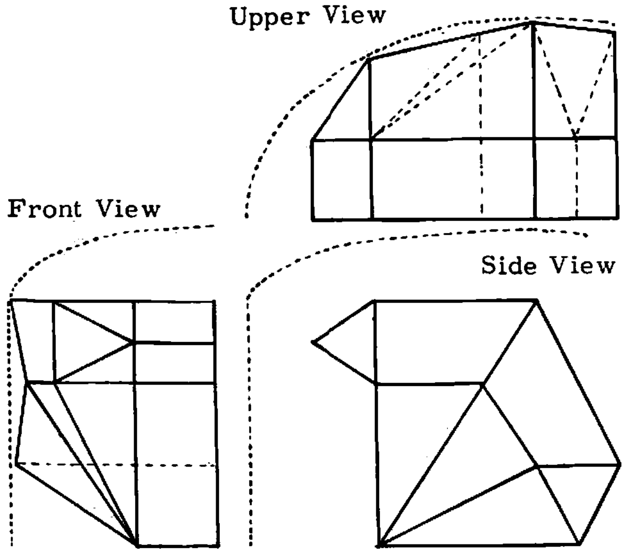

Fig. 2. Projections of the neutral tongue shape in x- (side view), y- (front view), and z- (top view) directions. The walls are (1) the side wall in a form of elliptic cylinder with a vertical (z-direction) axis and (2) an ellipsoid cut into halves, the top half forming a palatal roof and the lower edge continuing to the side wall.

coordinates of 24 nodal points

x	y	z
-10	108	61
-44	170	106
-115	313	300
-28	68	38
-164	191	127
-240	332	253
0	0	0
-5	33	24
17	-7	-4
-22	-23	27
-63	66	42
-221	206	13
0	123	0
0	0	0
0	35	37
0	0	-32
0	-52	26
0	44	77
0	326	63
0	5	0
-30	32	0
-44	127	16
0	43	34
0	35	-22

14353. 6707. 8307. -262. ← binding forces

0 0 1 0 1 1 1 0 0 0 0 0 ← contact (1) noncontact (0) of external nodes

-90611. ← basal fixation force

Fig. 3. Output display of calculated coordinate values and the binding forces.

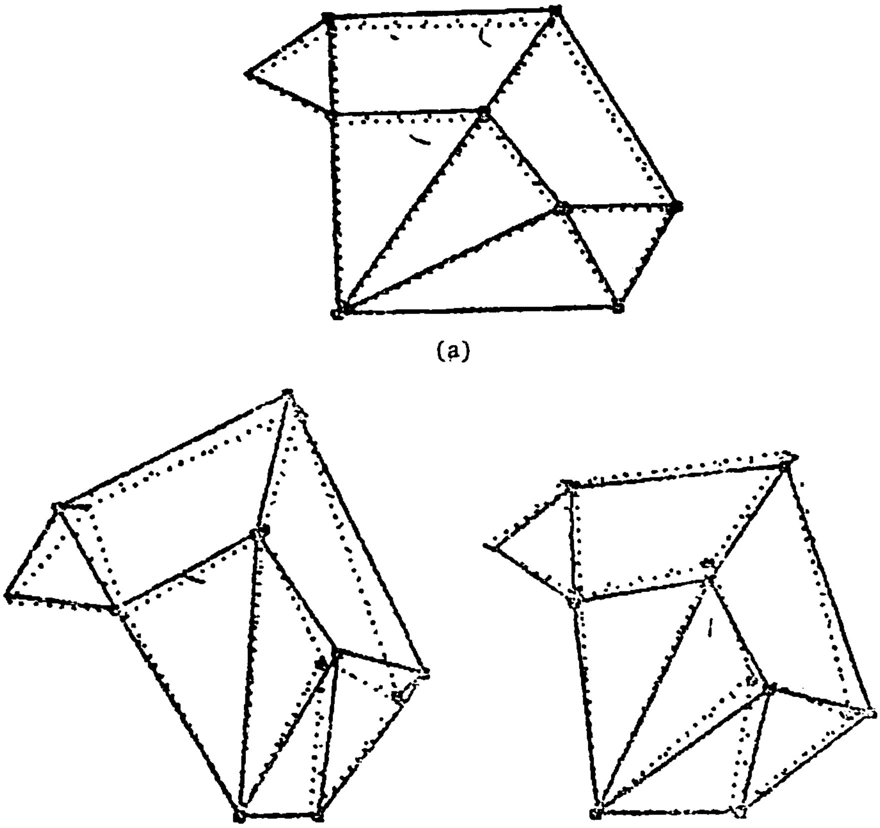

Fig. 4. The effect of contracting the posterior and central part of the genioglossus muscles (output display on a storage type oscilloscope), (a) neutral shape, (b) result of the muscular contractions without the boundary conditions, (c) same with the boundary conditions.

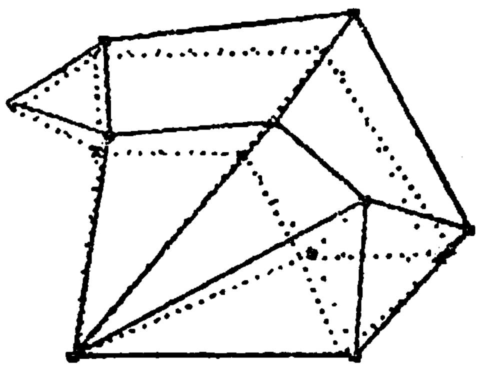

Fig. 5. The effect of pulling the node No. 3 in the y-z direction.

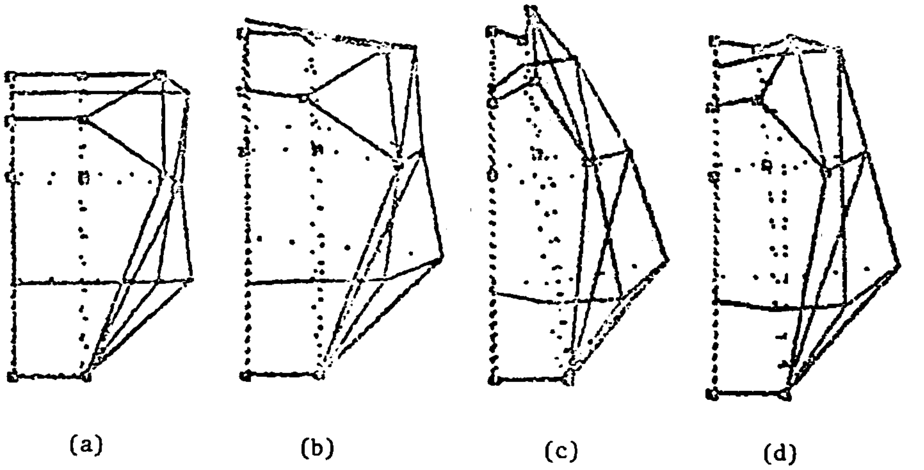

Fig. 6. Front views of (a) neutral position, and the results of contraction of (b) posterior and central part of the genioglossus muscles, (c) anterior part of the transverse muscles, (d) combination of the two configurations (b) and (c).

TABLE I

Division of the Model into 14 Units
and the Related Internal Muscles

Unit	Postulated Muscles	Direction of Tension
I	inferior longitudinal	y.z*
II	inferior longitudinal	-y.z*
III	none	
IV	superior longitudinal	y.z
	inferior longitudinal	-y.z
	transverse	x
	vertical	z
V	superior longitudinal	y
	inferior longitudinal	-y.z
	transverse	x
	vertical	-x.z
VI	superior longitudinal	-y.z
	transverse	x
	vertical	-x.z
VII	none	
VIII	genioglossus	y.z
IX	genioglossus	y.z
X	genioglossus	y.z
XI	superior longitudinal	y.z
	transverse	x
	vertical	z
XII	genioglossus	y.z
	superior longitudinal	y
	transverse	x
	vertical	-x.z
XIII	genioglossus	y.z
	superior longitudinal	-y.z
	transverse	x
	vertical	-x.z
XIV	genioglossus	y.z
	transverse	x

* y.z and -y.z mean that the direction of tension is along the lines y=z and y=-z, respectively.

TABLE II

External Muscles and their Attachments on Nodal Points

Muscle	Nodal Points	Direction of Force
Styloglossus	2, (21)	y.z
Pharyngeal constrictor	6, (12)	y
Hyoglossus	2, 21	-y.z

References

1) Perkell, J. S. (1974), "A Physiologically-Oriented Model of Tongue Activity in Speech Production," PhD Dissertation, MIT, September 1974.
2) Miyawaki, K. (1974), "A Study of the Musculature of the Human Tongue: Observations on Transparent Preparations of Serial Sections," Ann. Bull., RILP, No. 8, 23-50.
3) Zienkiewicz, O. C. (1971), The Finite Element Method in Engineering Science, McGraw-Hill, London.