MODELLING THE INTERNAL TONGUE USING PRINCIPAL STRAINS

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ABSTRACT

This paper used a newly developed technique, tagged Cine-Magnetic Resonance Imaging (tMRI), to examine the internal deformation of the tongue during speech. Two studies examined local internal tongue motion in 2D and 3D. The first study examined the motion of approximately 40 points within the tongue, in each of three sagittal slices (L, M, R), tracked during the movement from /k/ to /ʌ/. Measurements of tag positions were made at 7 consecutive time-phases (frames). A mechanical model of tongue deformation, similar to a finite element analysis, calculated local homogeneous stretch based on the deformations of the tag points between the consonant and vowel. 110 internal tongue locations were probed and principal strains were calculated for them using this model. The principal strains revealed local compression and extension patterns from which inferences can be drawn about the activities of Verticalis, Hyoglossus and Superior Longitudinal muscles. The second study tracked 3D motion and calculated 3D strains from multiplanar tMRI images, for the syllable /kʌ/. Three orthogonal tag planes (*x*, *y*, *z*) were collected for 24 consecutive time-phases in sagittal and axial slices. A B-spline model tracked tag deformation in each plane and reconstructed 3D deformation. This model is being adapted from cardiac tagging methods and preliminary data are presented.

INTRODUCTION

It is difficult to measure the movements of local regions within the human tongue and determine their effect on the tongue surface. It is useful to do so, however, because the human tongue has a complicated musculature that is not easily reconciled with the deformation patterns seen on the tongue surface during speech. The relationship between muscle activity and surface activity is a key component to understanding how speech is controlled and how it breaks down in various disorders.

The data and models presented here are intended to add details about the kinematics of the tongue during speech by examining the detailed motion of the internal tongue during speech. Some anatomical information on tongue muscles is available from dissections and histological studies (cf. Abd El Malek, 1939, Carpentier, and Pajoni, 1989, Miyawaki, 1974). EMG data are another source of muscle information (Miyawaki, 1975, Honda and Kusakawa, 1997, MacNeilage and Sholes, 1964, Maeda and Honda, 1994, Niimi et al., 1994). Nonetheless, EMG is not a commonly used instrument, because it is invasive, unpleasant and difficult to interpret. There is a small body of material detailing the activity of the internal tongue using tagged MRI. These tagged MRI images have been used to predict tongue muscle activity in vowel production (Niitsu et al., 1992, Kumada et al., 1992, Dang and Honda, 1997) and non-speech movements (Napadow et al., 1999). In the above studies tag positions were measured in two positions: rest and sustained vowel or non-speech gesture.

The present studies used tagged Cine-MRI (tMRI) and simple kinematic representational models to track tags through a complete CV motion and to represent the internal deformations. Kinematic representations like these are physiologically accurate and simple to understand making them appealing descriptors of tongue motion. The studies examined reference (consonant) and deformed (vowel) tongue deformation, similar to the above studies, but the data come from *Cine*-MRI images collected at multiple frames per second, not static sounds. Local tissue stretch and in-plane shear are modeled; from these, principal strains (direction and extent of stretch at local tissue points) are calculated and underlying muscle contraction patterns inferred. Because of the experimental nature of this method the models have been applied only to limited, preliminary data sets.

Two studies are presented. The first develops a 2D local kinematic model of tongue motion based on mechanical deformations. The second uses B-splines to track and combine tag planes into local 3D motion over time. Both studies used a single (but different) male English speaker who had no dental fillings and was pre-tested for good rhythmic skills, because the syllables had to be repeated multiple times. Tags decayed in about 500-600 ms allowing enough time for CV motion to be measured.

STUDY 1: 2D LOCAL KINEMATIC MODEL

A 19 year old speaker said the syllable /kʌ/ 32 times each while left, mid, and right sagittal images (with an overlaid grid of tags) were made. Seven time-phases (frames) were recorded. Image planes were 7 mm thick and spatial resolution was 2.4mm x 2.4mm. Movement of forty internal points in each slice was tracked across the image sequence. Principal strains were calculated on the extreme consonant and vowel frames, because the intervening movements were too small to rule out measurement error. Full details of this procedure appear in Davis, 1999.

A simple model was developed for each sagittal plane based on a finite-element type mesh derived from the movement of the tag points. The modeled planes could be probed at regions of any size and principal strains calculated for that region. In the reference state the nodes had coordinates (X_j, Y_j). In the deformed state the nodes had coordinates (x_j, y_j). The two in-plane displacement components, $u_j = u(X_j, Y_j) = x_j - X_j$ and $v_j = v(X_j, Y_j) = y_j - Y_j$, were calculated at each node.

A finite element type mesh, made up of triangular and quadrilateral elements, was created from these nodes. The details of the node point identification algorithms and point-tracking procedures can be found in Davis, 1999. Displacements of any arbitrary point within the tongue were calculated from the finite element type basis functions, $F_j(X,Y)$ and the displacements measured (u_j, v_j) at each associated node. These basis functions have the characteristic that $F_j \; (X_j,Y_j)=d_{ij}$, where d_{ij} is the Kronecker delta defined by $d_{ij} = 1$ if $i = j$ and $d_{ij} = 0$ if $i \neq j$.

First the number of closest nodes, *N*, was found which defined the quadrilateral (N = 4) or triangular (N = 3) element in which any generic point was located. Second, the N closest nodes, (X_j,Y_j), j=1,…,N, were used to define the basis functions, $F_j\,(X,Y)$ in that element (Cook, et al., 1989). The displacement of any point in an element could then be found using the known displacements, u_j and v_j, and the basis functions $F_j\,(X,Y)$ from

$$u(X,Y) = \sum_{j=1}^{N} u_j\, f_j(X,Y) \quad \text{and.}$$

$$v(X,Y) = \sum_{j=1}^{N} v_j\, f_j(X,Y) \qquad (1)$$

Once the displacements had been determined for a selected number of points in a tongue plane, we could determine the in plane Lagrangian strain tensors and hence the principal strains and their directions. The tag intersection points were independent across planes. Therefore, local models were calculated for each sagittal image plane individually.

Results

These representational models allowed for local homogeneous deformations in 2D and 3D. These models gave the simplest possible kinematic interpretation of the internal tongue deformations. A natural use of the models was to infer muscle action from the local contractions. Figure 1A shows the right-sagittal surface and internal points tracked over four successive frames. The time-motion progression is from black to gray, color-coding the direction and extent of motion. The downward motion of the upper tags occurred early in the sequence (black), whereas the backward motion occurred later (gray). Tag motion is tissue motion. Figure 1B shows two grids that connect the tag points for /k/ (gray) and /ʌ/ (dark gray). The internal deformations are seen by comparing the squares in /k/ with the deformed quadrilaterals in /ʌ/. Figure 1C depicts the principal strain model developed for /kʌ/. The principal strain lines indicate the extent and direction of local 2D compression or expansion within the tongue. This method could complement EMG for assessing muscle activity within the tongue. The strain lines of Figure 1C suggest activity of several muscles: Verticalis (V), Hyoglossus (HG) and Superior Longitudinal (SL).

Discussion

Principal strains reflect muscle shortening (active contraction or passive compression) and muscle lenghtening (passive extension). In addition, tongue muscle is locally volume preserving. So if two strain lines at a single point indicate compression, extension must occur in the cross-sectional, or lateral plane. The surface and internal tag movements seen for /kʌ/, as in Figure 1A, were compared. The upper surface of the tongue moved downward as did the tags of the upper third of the tongue. The posterior surface moved backward as did the tag movements of the middle third. Careful examination of the middle third of the tongue, however (Fig 1B,C), revealed that the posterior region was compressed horizontally and the surface backing was due primarily to expansion in the middle of the tongue (i.e., Verticalis). To get a complete picture of the internal-to-surface relationships true 3D data are needed.

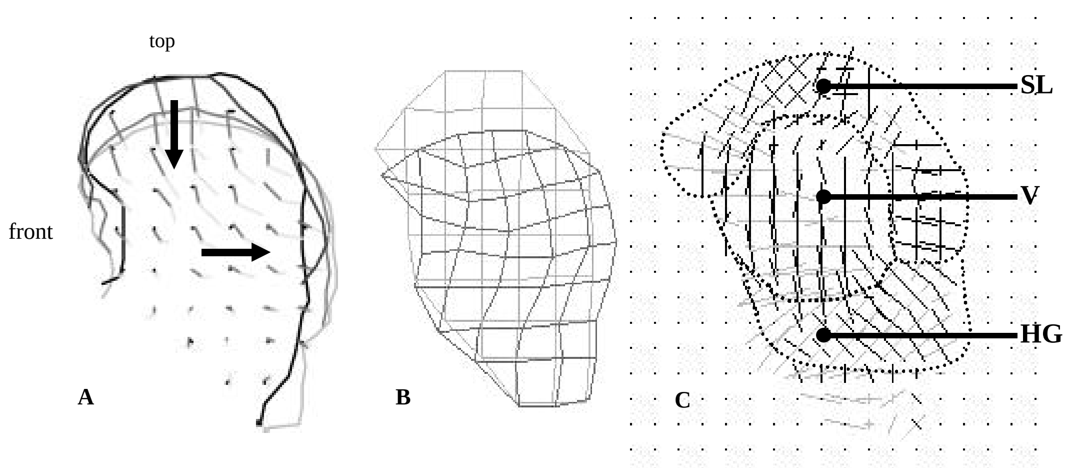

Figure 1. Right-sagittal (11 mm from midline) tongue contours showing tongue movement for the CV /kʌ/. Orientation is the same for A, B, C. **(A)** shows the tongue edges and tag points as they move from /k/ (black) to /ʌ/ (gray). Data were collected at 7 fps. The motion shows the downward and backward direction of movement in the first 4 frames (@ 56 ms/frame for a total of 224 ms). **(B)** shows 2 grids made by connecting tag points (as seen in A) for /k/ (gray, frame 1) and /ʌ/ (black, frame 4). The tongue compresses vertically and expands horizontally. **(C)** shows principal strains, which are the two largest deformations (expansion or compression) and their respective direction, for each local region probed. Black lines indicate compression and gray lines indicate expansion. The principal strains are computed from the elements (squares) in B. Three muscles are inferred from the strains: superior longitudinal (SL)contracts circumferentially, verticalis (V) contracts vertically, and hyoglossus (HG) contracts downward and backward.

STUDY 2: 3D LOCAL KINEMATIC MODEL

This study is the preliminary trial for applying a 3D tagged Cardiac MRI method to the tongue. The method is not dependent on cardiac geometry and so is adaptable to other structures such as the tongue.

A 23 year old speaker said the syllable /KA/ 18 times for each slice recorded. Repetitions were repeated at 1 sec intervals and 24 time-phases (frames) per second were collected. Image planes were 7 mm thick with a spatial resolution of 1.2 mm x 2.4 mm. Five contiguous sagittal slices were recorded twice, once each with horizontal and vertical tag planes. Ten axial slices were recorded one time with lengthwise (anterior-to-posterior) tag planes. These tag planes reflected deformations in the *y*, *z* and *x* directions respectively. These three orthogonal sets of tag planes were tracked through time. First, in each of the 24 time phases tongue boundaries were contoured interactively (Shechter, et al., 1999) and tags were detected automatically (Guttman, et al., 1997). Next, the tagged tissue was tracked with a 4D B-spline method (Ozturk, et al., 1999) that combined the sparse 1D displacement of each set of images over time. The motion tracking of the three parallel tag stacks provided 3D deformation and strain tensor components throughout the defined volume.

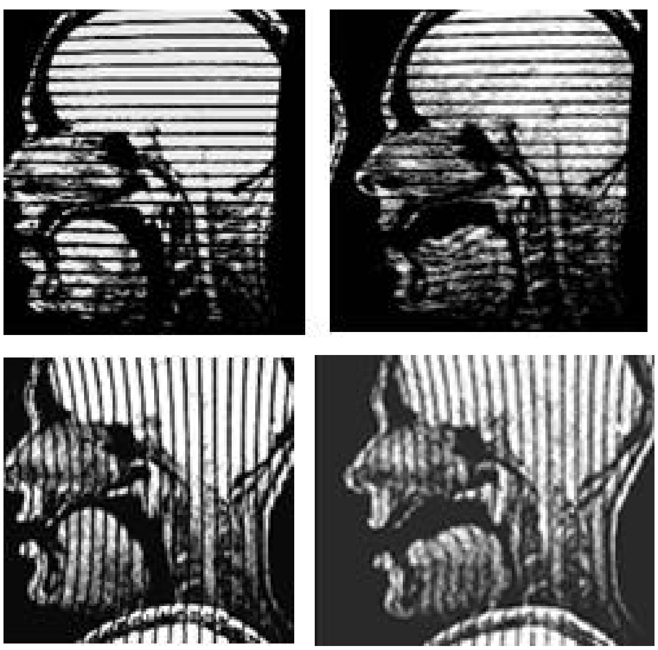

Figure 2. Midsagittal images from the 3D study for the CV /KA/. The black lines are tag planes in the horizontal (top) and vertical (bottom) direction for /K/ (left) and /A/ (right). A local depression on the upper tongue surface is visible just behind the blade (top). Backward motion is apparent in the vertical tags.

The 3D study is in progress. Contours and tags have been extracted and 3D deformation from /K/ to /A/ is being computed. Local deformations appear on visual inspection to be consistent with the earlier data and the additional dimension should allow for improved discrimination concerning the effects of lateral and medial muscles. The different effects of local translation and stretch will also be examined.

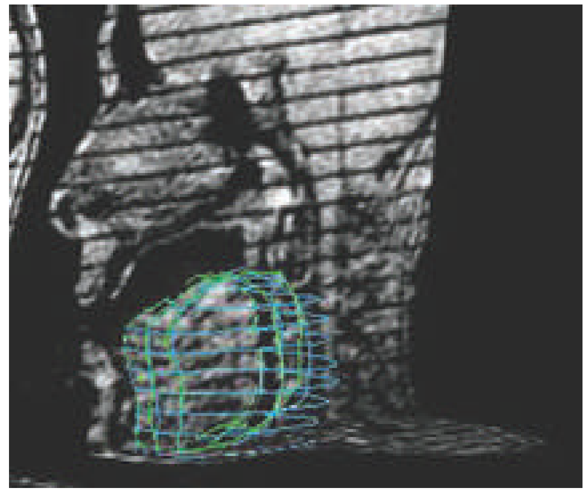

Figure 3. Midsagittal MRI slice (rotated 45^{o}) with 8 axial and 2 left sagittal contours superimposed.

CONCLUSIONS

In the 2D study principal strains detailed regions of compression and extension in the tongue and showed links between internal tissue strain and surface deformation. The strains were interpreted with respect to internal muscle activity. Superior Longitudinal, Hyoglossus, and Verticalis (the last of which is inaccessible to EMG) appeared to contribute in /k/-to-/A/ tongue lowering. The 3D data are consistent visually with the 2D data. The mechanical model is being expanded to 3D to extract the effects of lateral and medial muscle activity more accurately. Models for deriving local principal strains from tMRI tongue images appears very promising for future representation of the tongue musculature. The measures may also detail the relationship between internal and surface movement and examine independently the effects of local stretch and translation.

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