ON LOOPS AND ARTICULATORY BIOMECHANICS

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ABSTRACT

This study explores the following hypothesis: forward looping movements of the tongue that are observed in VCV sequences are due partly to the anatomical arrangement of the tongue muscles and how they are used to produce a velar closure. The study uses an anatomically based two-dimensional biomechanical tongue model. Tissue elastic properties are accounted for in finite-element modeling, and movement is controlled by constant-rate control parameter shifts. Tongue raising and lowering movements are produced by the model with the combined actions of the genioglossus, styloglossus and hyoglossus. Simulations of V1CV2 movements were made, where C is a velar consonant and V is [ɑ], [i] or [u]. The resulting trajectories describe movements that begin to loop forward before consonant closure. Examination of subject data show similar looping movements. These observations support the idea that the biomechanical properties of the tongue could be the main factor responsible for the loops.

1. INTRODUCTION

This study is part of a general research project that aims to understand the influence of biomechanics on the movements of speech articulators ([1], [2]). More specifically, this paper investigates the looping movements that are found during velar consonant closures in VCV sequences. Using cineradiographic data, Houde [3] observed in 1967 that in a number of [V1gV2] sequences "*a distinct forward directed gesture takes place during the closure*" of the consonant. More specifically Houde noted, "*When the closure occurs during a forward directed vowel transition (/ugi/, /agi/) … the contact appears to be sustained while sliding along the palate for a distance of up to 6 mm. When the palatal closure occurs during a rearward movement of the tongue …, in some cases (/i'gagi/) its direction is temporarily reversed. It behaves as if forward movement had been superimposed, during contact, on the main rearward movement of the tongue.*" Since such a forward movement also occurs in [V1gV2] sequences where V1=V2, Houde rejected the explanation that this phenomenon would be related to the vowel-to-vowel gesture. Instead, he suggested that it should be the result of a passive effect due to forces generated on the tongue surface by the air pressure behind the contact location.

Since then, many additional observations have been made of such loops (see for instance [4], [5], [6], [7]), and the hypothesized influence of air pressure in back cavity has been further analyzed. Ohala has even suggested in 1983 [8], that this looping movement could be "*a very marked form of active cavity enlargement and could more than compensate for the other factors which disfavor voicing on velars.*" However the hypothesis of active control of the loops has been seriously questioned by data collected on German speakers by Mooshammer *et al*. [7] since these speakers produced articulatory loops during the production of [ɑkɑ], which were even larger than for the voiced [g].

Counter-examples to the passive, aerodynamic explanation have also been found. Indeed some forward movement has been observed during the nasal velar consonant [ŋ] [7], and with consonants produced during ingressive speech [9].

Consequently, it seems that while the potential influence of the air pressure in the back cavity should not be totally disregarded, some other effects may contribute to generating the observed articulatory loops. This study explores the potential contribution of the biomechanical properties of the tongue using a midsagittal, anatomically based, biomechanical model [2].

2. THE TONGUE MODEL

2.1 Description of the model

The biomechanical tongue model developed by Payan and Perrier [2] was used to simulate VCV sequences. The model includes the main muscles responsible for shaping and moving the tongue in the midsagittal plane (posterior and anterior parts of the genioglossus, styloglossus, hyoglossus, inferior and superior longitudinalis and verticalis). Tissue elastic properties are accounted for in finite-element (FE) modeling. Muscles are modeled as general force generators which (1) act on anatomically specified sets of nodes of the FE structure, and (2) modify the stiffness of specific elements of the model to account for muscle insertions into tongue tissues.

In order to model a complete 2D vocal tract, geometrical representations of the mandible and the hyoid bone are added. A single control parameter is used to account for changes in the jaw vertical position. The front and rear parts of the FE tongue model are attached to these geometrical structures. Curves representing the contours of the lips, palate and pharynx in the sagittal plane are also added.

In its original version, this 2D biomechanical model was only able to generate vowel-to-vowel sequences, since contact between the tongue and palate was not taken into account. Therefore, a primary focus of the present work is to implement such contacts, in order to produce stop consonants. To produce more realistic contacts, the number of nodes in the simulation is increased by a factor of four.

2.2 Implementation of tongue/palate contacts

To model the collisions between tongue surface and palatal or velar contours, two algorithms are introduced, that aim (1) at detecting tongue contact and (2) at generating contact forces.

Contact detection

This theoretical problem is considerably simplified here, as the contours in contact (tongue against palate or velum) are both made of points connected by lines. The contact detection problem is thus reduced to the calculation of intersections of segments.

Contact force generation

The method used to calculate the force generated by the contact was originally proposed by Marhefka & Orin [10]. It is a *penalty method*, based on a non-linear relationship between contact force and position/velocity of points located on the tongue surface. Therefore, if the contact detection algorithm observes a node on tongue surface going through the palate or through the velum, a force *F* will be generated in order to act against the intrusion:

$$\vec{F} = (-\alpha \cdot x^n - \mu \cdot \dot{x} \cdot x^n) \cdot \vec{k} \quad if \quad x < 0$$
$$\vec{F} = 0 \quad if \quad x \geq 0$$

where:

x is the inter-penetration distance (a negative value), namely the distance between the node on tongue surface and its orthogonal projection onto palate or velum contours;

$\dot{x}$ is the time-derivative of the inter-penetration distance;

α is a coefficient representing the "stiffness" of the collision;

μ represents the "viscosity" of the collision;

n accounts for the non-linearity;

$\vec{k}$ is a unit vector orthogonal to the palate/velum contours.

The *penalty method* algorithm induces a slight penetration of the tongue into the palate. It is also likely to generate instabilities and oscillations of the movement. The parameters α, μ and n have been fixed at *ad-hoc* values that limit the distance of the penetration and the amplitude of the oscillations: $\alpha = 60$; $\mu = 0.5$; $n = 0.8$.

During contact, the tongue is free to slide along the palate: currently, no specific viscosity coefficient is used in the direction that is parallel to the palatal contour.

2.3. Control of the model

The model is controlled according to Feldman's Equilibrium Point Hypothesis [11]. This theory of motor control, grounded in basic neurophysiological mechanisms of muscle force generation, suggests that the central nervous system controls movements by selecting, for each acting muscle, a threshold muscle length, λ, where the recruitment of α motorneurons (responsible for active forces) starts. If the muscle length is larger than λ, muscle force increases exponentially with the difference between the two lengths. Moreover, Feldman's basic suggestion is that movements are produced from posture to posture, a posture being a stable mechanical equilibrium state of the motor system Hence, in the model, a discrete sequence of control variable values (λs), those specifying the successive postures, would underlie a continuous trajectory. In addition, movements are produced with constant rate shifts of the control variables.

3. SIMULATIONS

3.1 Principles

To evaluate the potential role of the biomechanics in the articulatory trajectories observed during the production of velar consonants, the following simplifying strategies have been adopted for the initial simulation:

- Differences observed in the articulatory patterns between voiced and unvoiced consonants were not accounted for (see [6] for examples of such differences); consequently, the same articulatory targets have been used for voiced and unvoiced velar consonants. We arbitrarily refer to these targets with the phonetic symbol [k].
- Symmetrical patterns of control variable shifts have been chosen for the movements toward and from the consonant.

This approach makes it possible to limit the effects of factors other than biomechanical ones on the shape of the movement patterns. However, since we consider that the target of a phoneme is context-dependent and results from a higher-level planning process (see [12]), two different targets have been used for [k]: a front one with front vowel contexts, and a back one with back vowel contexts. The following principles underlie the design of these consonantal targets:

- The production of consonants consists of movements toward virtual articulatory targets that are located beyond the palate, which therefore cannot be reached. The duration of the contact against the palate depends on the "hold time" of the virtual target and on the distance between the target and the palatal contour. The contact force acting on the tongue depends on the general level of muscular force and on the distance between the virtual target and the palate. We chose articulatory targets for [k] that are located just beyond the surface of the palate.
- The contours of the tongue during the contact have to be similar to the sagittal contours published in the literature for the velar consonants in different contexts. To design the targets for [k] we have taken into account X-ray tracings published for English by Houde [3], and for French by Bothorel *et al.* [13].

The sagittal contours of the vocal tract corresponding to the back and front realizations of [k] used in our simulations are shown respectively in Figs. 1 and 2. Both realizations involve the recruitment of only the posterior Genioglossus (GGp) and the Styloglossus (SG).

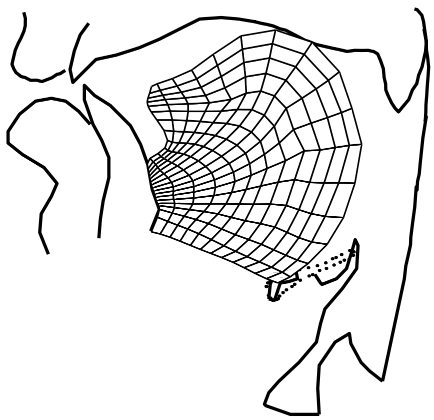

Figure 1: Vocal tract configuration for the back [k]

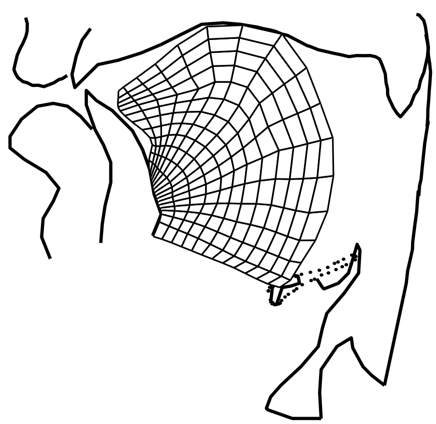

Figure 2: Vocal tract configuration for the front [k]

3.2 Results for [ɑkɑ], [uku] and [iki]

Simulations were generated first in a symmetrical vowel context, for vowels [ɑ], [u], and [i]. The timing of the commands is given in Table 1.

	Duration (ms)
Vowel Hold time	200
Vowel-to-[k] Transition Time	75
[k] Hold Time	150
[k]-to-Vowel Transition Time	75
Vowel Hold Time	200

Table 1: Timing of the commands for the VCV sequences

The trajectories of four nodes located on the upper contour of the tongue in the velar region for the three sequences are depicted on Figures 3, 4 and 5. Most of these trajectories loop upward and forward in a counterclockwise direction.

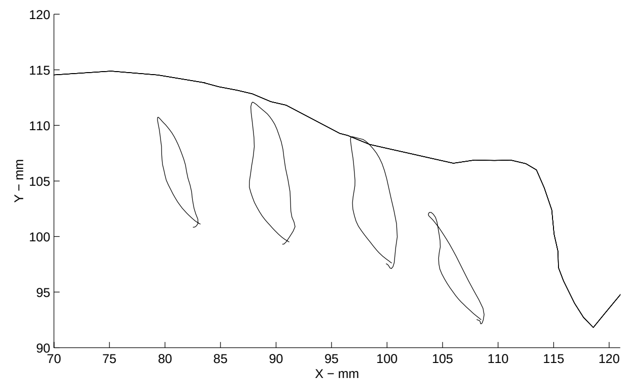

Figure 3 : Trajectories of four nodes on the dorsal contour of the tongue in the simulation of [ɑkɑ]; the solid line above the trajectories depicts the contours of the palate and the front part of the velum. Anterior is to the left. (See Fig. 1.)

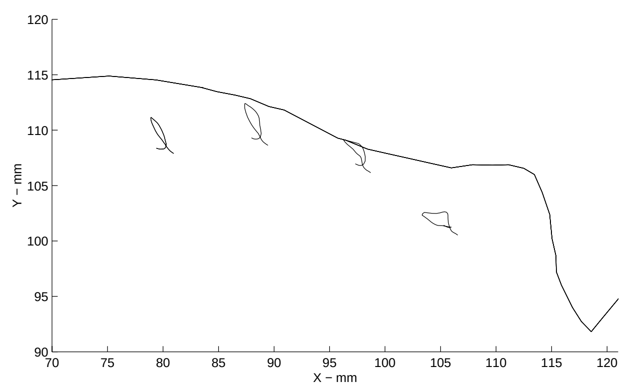

Figure 4 : Trajectories of four nodes on the dorsal contour of the tongue in the simulation of [uku] (see figure 3 for details)

The results of the simulations are in general agreement with the data published in the literature ([3], [4], [6], [7]). Large counterclockwise loops are observed for [ɑkɑ] (Fig. 3). For [uku] (Fig. 4), counterclockwise loops – smaller than for [ɑkɑ] – are observed for the three front nodes; however, the most posterior node describes a clockwise loop. For [iki] in Fig. 5, three of the four trajectories do not describe closed loops, but the downward movement is slightly in front of the upward one. In each case, the tongue slides along the palate during the closure of the consonant –a distance of 2.5 mm for [uku] and [ɑkɑ], and 1.0 mm for [iki]. For [ɑkɑ] the loop becomes even larger during the downward movement, making a maximum width of 4 mm.

Since these simulations did not include aerodynamics, the results indicate that air pressure in the back cavity is probably not the main cause of the loops. This idea is reinforced by the observation that actual [3] and simulated movements curve forward even before contact is made. We hypothesize that the main cause of the loops is the anatomical arrangement of the musculature, whose geometry is very different for the tongue raising and tongue lowering muscles. During contact, the sliding movement may also be influenced by the component of the contact force vector that is parallel to the direction of the palatal curve. The introduction of sliding resistance may reduce but not cancel the sliding movement, especially for [uku] and [ɑkɑ].

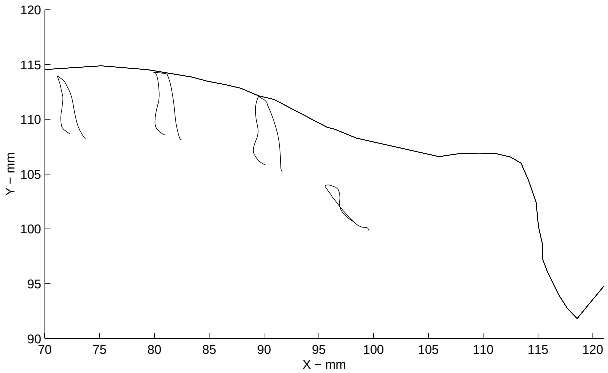

Figure 5 : Trajectories of four nodes on the dorsal contour of the tongue in the simulation of [iki] (see Fig. 3 for details).

3.3 Results for [ikɑ]

Additional simulations have been made for the [ikɑ] sequence. According to data published by Houde [3] and Perkell *et al.* [5], the back realization of [k] was adopted for the velar consonant. The timing of the commands is the same as in the symmetrical VCV simulations.

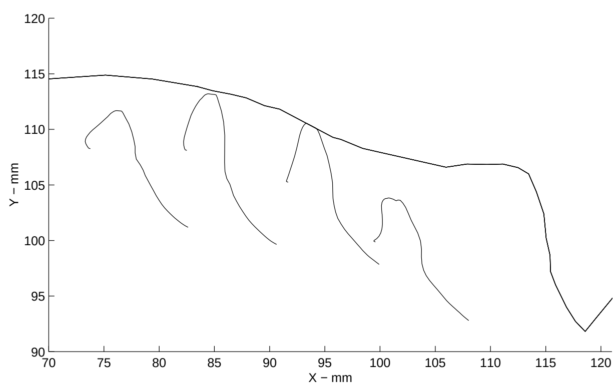

Figure 6 : Trajectories of four nodes on the upper contour of the tongue in the simulation of [ikɑ] (see figure 3 for details)

Figure 6 shows the trajectories of the same four nodes for [ikɑ]. It can be observed that the tongue slides backward along the palate for about 1mm. This is not in complete agreement with the data published in [3] and [5], which depicted, in some cases, very small counterclockwise loops. This difference could be explained by the absence of aerodynamics in the simulation: adding air pressure could affect the course of the movement [9].

4. CONCLUSION

Simulations of VCV sequences (where C is a velar consonant) with a biomechanical model of the tongue, lead to the suggestion that the biomechanical and anatomical properties of the tongue musculature could be the main factor responsible for the loops observed for these movement sequences. However, the results do not preclude the hypothesis of a potential role for air pressure, which would, in addition to the biomechanics, contribute to the observed forward movement of the tongue during consonant closure.

5. REFERENCES

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Acknowledgements

This work was supported by the CNRS, NSF and NIH.