Biomechanics and vocal tract morphology

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Outline

- Introduction
- Some basics about biomechanics and orofacial biomechanics
- 2D and 3D models of the tongue and the face
- Biomechanics and control
- Influence of tissues stiffening on speech articulation (Pathology)
- Muscle direction variability, Palate morphology and articulatory control accuracy
- Variations in Orbicularis Oris implementation and lip protrusion.
Collaborators

- Project SPRECHArt (DFG - PI Susanne Fuchs)
  - Ralf Winkler & Susanne Fuchs
- Project SkullSpeech (ANR)
  - Mohammad Nazari, Guillaume Barbier, Yohan Payan
- Collaboration Gipsa-lab – ArtiSynth (UBC Vancouver)
  - Ian Stavness, Sydney Fels
Introduction

- Little studies about speaker-specific biomechanics and motor control
- Biomechanics: a constraint not a determining factor
- Models: provide information about the constraint
- Evaluation with experimental data requires models of motor control
  - Comparison with data validates, contradicts hypotheses about motor control strategies
  - Biomechanical models can suggest hypotheses about motor control
Biomechanics?

- **Muscles anatomy:**
  - Which muscles?
  - Which direction?
  - On which part of body?

- **Muscles mechanics**
  - Which maximum level of force?
  - Central and feedback contribution to muscle activation

- **Articulatory Dynamics (=Force representation)**
  - Which inertia (mass)?
  - Which elasticity (Stiffness, Young and Shear Modulus)?
  - Which damping?
  - **Which interaction with external structures?**
Specificity of oro-facial biomechanics: articulators are mainly soft bodies

- Force do not only generate displacement but also (and mainly) deformation (strain)
  - Strain occurs in three directions and not only in the direction of the force

Specificity of oro-facial biomechanics: articulators are mainly soft bodies

- Force $\rightarrow$ Stress
- Displacement $\rightarrow$ Strain
- Non-linear stress–strain relation:

- Non constant stiffness: $\frac{d(\text{Stress})}{d(\text{Strain})}$ (Young Modulus)

Tongue anatomy

- Anatomical data

Netter, 2004

2D Tongue Model
Payan & Perrier, Speech Comm 1997
Perrier et al., JASA 2003

Posterior genioglossus
Anterior Genioglossus
Hyoglossus
Styloglossus
Verticalis
Inferior Longitudinalis
3D Tongue Model
Gerard et al, 2006; Buchaillard et al., JASA 2009

Posterior Genioglossus
3D Tongue Model
Gerard et al, 2006; Buchaillard et al., JASA 2009
- Medium Genioglossus
3D Tongue Model
Gerard et al, 2006; Buchaillard et al., JASA 2009

- Anterior genioglossus
3D Tongue Model
Gerard et al, 2006; Buchaillard et al., JASA 2009

- Styloglossus
3D Tongue Model
Gerard et al, 2006; Buchaillard et al., JASA 2009

- Hyoglossus
3D Tongue Model
Gerard et al, 2006; Buchaillard et al., JASA 2009

- Verticalis
3D Tongue Model
Gerard et al, 2006; Buchaillard et al., JASA 2009

Transversalis
3D Tongue Model
Gerard et al, 2006; Buchaillard et al., JASA 2009

Geniohyoid
3D Tongue Model
Gerard et al, 2006; Buchaillard et al., JASA 2009

- Mylohyoid
3D Tongue Model
Gerard et al, 2006; Buchaillard et al., JASA 2009
Face anatomy

http://www.anatomy.tv
3D Face model
Nazari et al., CMBBE 2010

- Implementation of macrofibers in reference to the skull
3D Face model
Nazari et al., CMBBE 2010
Lip protrusion/rounding: Shaping by stiffening
Nazari et al., Motor Control, 2011

Results
Lip protrusion/rounding: Shaping by stiffening
Nazari et al., Motor Control, 2011

- Lip Parameters for Studying Speech Production

Abry & Boë, 1986
Lip protrusion/rounding: Shaping by stiffening
Nazari et al., Motor Control, 2011

No stress-stiffening

With stress-stiffening
Impact of tissue stiffening (Pathology)

Normal stiffness
Impact of tissue stiffening (Pathology)

Normal stiffness x 3
Impact of tissue stiffening (Pathology)

Normal stiffness x 6
Impact of tissue stiffening (Pathology)

Normal stiffness x 10
Variability in muscle orientation - YPM
Variability in muscle orientation - AV
Variability in muscle orientation - CS
Variability in muscle orientation – [i] YPM

Muscle activations

<table>
<thead>
<tr>
<th>Muscle</th>
<th>GGP</th>
<th>GGA</th>
<th>HYO</th>
<th>STY</th>
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</thead>
<tbody>
<tr>
<td>Value</td>
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<td>0</td>
<td>0</td>
<td>4.4</td>
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</tbody>
</table>

Ratio GGP/STY = 0.75
Variability in muscle orientation – [i] AV

Muscle activations

<table>
<thead>
<tr>
<th></th>
<th>GGP</th>
<th>GGA</th>
<th>HYO</th>
<th>STY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4.9</td>
<td>0</td>
<td>0</td>
<td>6.6</td>
</tr>
</tbody>
</table>

Ratio $\text{GGP/STY} = 0.75$
Variability in muscle orientation – [i] CS

Muscle activations

<table>
<thead>
<tr>
<th>GGP</th>
<th>GGA</th>
<th>HYO</th>
<th>STY</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.8</td>
<td>0</td>
<td>0</td>
<td>1.5</td>
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</tbody>
</table>

Ratio GGP/STY = 1.9
Variability in muscle orientation – [i] YPM

Subject: ypm - F1-F2 plan (poles)

Subject: ypm - F2-F3 plan (poles)
Variability in muscle orientation – [i] AV

Subject: av - F1-F2 plan (poles)

Subject: av - F2-F3 plan (poles)
Variability in muscle orientation – [i] CS

Subject: cs - F1-F2 plan (poles)

Subject: cs - F2-F3 plan (poles)
Variability in muscle orientation – [i]

Summary: AV has - the largest ratio VarF2/VarF1
- the smallest VarF1
- the largest VarF3

AV's tongue remains very close to the palate while moving backward.
Variability in muscle orientation – [i] YPM

Constriction becomes more open but remains at the same location
Variability in muscle orientation – [i] AV

Constriction opens slightly and moves backward
Variability in muscle orientation – [i] CS

Constriction becomes more open but remains at the same location.
Variability in muscle orientation – YPM

GGP

STY

GGA

HYO
Variability in muscle orientation – AV

GGP  STY

GGA  HYO
Variability in muscle orientation – CS

![Diagram showing muscle orientation variability with labels GGP, STY, GGA, and HYO.](image-url)
YPM – EFFECT of STYLOGLOSSUS

Initial constriction region

[i] at target

Same final constriction region

Main direction of displacement associated with STY activation
AV – EFFECT of STYLOGLOSSUS

[i] at target  
Main direction of displacement associated with STY activation

Initial constriction region

New constriction region

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CS – EFFECT of STYLOGLOSSUS

Initial constriction region

Same final constriction region

[i] at target

Main direction of displacement associated with STY activation
First conclusion

- Muscle orientation influences the relation between motor commands and spectral patterns

- Does it influence the acoustic speaker-specific variability.
- Does it influence motor control strategy/accuracy?
Basic idea:
For a flat palate of local variation of the tongue position will induce more change in the cross-sectional area → More change in the acoustical domain.
Palate shape and articulatory variability

Brunner, Fuchs and Perrier, JASA 2009

Measure of palate curvature in the coronal plane: \( \alpha \)

- A high value corresponds to a flat palate
- A low value corresponds to a domeshaped palate.

Measure of articulatory variability with EPG:

- COG
- Number of contacts.
Palate shape and articulatory variability
Brunner, Fuchs and Perrier, JASA 2009

Articulatory variability (32 speakers)
Palate shape and articulatory variability
Brunner, Fuchs and Perrier, JASA 2009

Acoustical variability (32 speakers)
Conclusion

- Speakers tend to adapt their articulatory variability to the coronal shape of the palate in order to preserve the acoustic correlates of a good perception of the phoneme.
Variability in muscle orientation and palate shape

- Consequences for speech production and speech perception
  - **Obviously**: inter-speaker differences in the required accuracy in motor control
  - **Probably**: inter-speaker differences in co-articulation patterns and in the influence of speaking rate variation
  - **Possibly**: inter-speaker differences in perceptual sensitivity to local acoustical variations (Shiller et al., JASA, 2009)
Shiller, Sato, Gracco, Baum (2009)

Perceptual recalibration of speech sounds following speech motor learning.

Perturbation of the auditory feedback

/s/ versus /ʃ/

FIG. 2. Schematic depicting the sequence of procedures for each of the three groups of subjects: (1) speech production with altered auditory feedback (AF, top), (2) speech production with unaltered auditory feedback (UF, middle), and (3) passive listening (PL, bottom). The numbers underneath the horizontal lines indicate the number of words spoken. See text (Secs. II D and II E) for details.
Shiller, Sato, Gracco, Baum (2009)

Shift of the perceptual /s/-/ʃ/ boundary

Group 1
Perceptuomotor adaptation

Group 2
Selective adaptation

Group 3
No effect
Variability in muscle orientation and palate shape

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A high sensitivity of speech spectral patterns to motor variability increases the intolerance to motor variability and in turn could increase the acuity of speech perception in this region.
Variation in orbicularis oris implementation and lip protrusion
Stavness, Nazari, Perrier, Demolin, Payan, JSLHR, 2013

Karitiana speaker: vowel [o] [koβot], “sweet.
(Courtesy of Didier Demolin)

French: vowel [u]
(Courtesy of Pierre Badin)
Variation in orbicularis oris implementation and lip protrusion
Stavness, Nazari, Perrier, Demolin, Payan, JSLHR, 2013

Modeling variation in OO Implementation

1,2,3,4: marginal to peripheral
S,M,D: Superficial to depth
Variation in orbicularis oris implementation and lip protrusion
Stavness, Nazari, Perrier, Demolin, Payan, JSLHR, 2013

Example of OO Implementation
M3
Variation in orbicularis oris implementation and lip protrusion

Middle and peripheral implementation generates protrusion and rounding
Variation in orbicularis oris implementation and lip protrusion
Stavness, Nazari, Perrier, Demolin, Payan, JSLHR, 2013

Differences in peripheralness between upper and lower lips
Conclusion

- Variations across populations in the world on the Orbicularis Oris implementation could contribute to explain some aspects of the phoneme distributions in the world languages as well as the variation of the phonemic characteristics across languages and their diachronic evolution.

- Inter-individual variations with a population in the OOS and OOI implementation could determine variation in the protrusion and rounding gestures → Coarticulation
To know more

A biomechanical model of cardinal vowel production: Muscle activations and the impact of gravity on tongue positioning

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(Received 18 March 2009; revised 31 July 2009; accepted 23 July 2009)

A three-dimensional (3D) biomechanical model of the tongue and the oral cavity, controlled by a functional model of muscle force generation (a model of the empirical point hypothesis) and coupled with an acoustic model, was exploited to study the activation of the tongue and mouth floor muscles during the production of French cardinal vowels. The selection of the motor commands to control the tongue and the mouth floor muscles was based on literature data, such as electromyographic, electrophysiological, and kinematic data. The tongue shapes were also compared to data obtained from the speaker used to build the model. 3D modeling offered the opportunity to investigate the role of the transversals, in particular, its involvement in the production of high front vowels. It was found, with this model, to be indirect via reflex mechanisms due to the activation of surrounding muscles, not voluntary. For vowel /i/, local mean command variations for the main tongue muscles revealed a non-negligible modification of the acoustic space in contradiction to the saturation effect hypothesis, due to the role of the anterior glosaeae. Finally, the impact of subject position (supine or supine) on the production of French cardinal vowels was explored and found to be negligible.

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I. INTRODUCTION

Speech movements and acoustic speech signals are the results of the combined influences of communicative linguis-
tic goals, perceptual constraints, and physical properties of the speech production apparatus. To understand how these different factors combine and interact with each other requires an efficient approach that develops realistic physical models of the speech production apparatus and/or speech perception systems. The predictions of these models can then be com-
pared with experimental data, and used to infer information about parameters or control signals that are not directly meas-
surable or the recognition of which is difficult and not completely reliable. Such a methodological approach under-
lies the present work, in which a biomechanical model of the vocal tract has been used to study muscle control in vowel production, its impact on vocal-tract variability, and its influence on vowel production in supine-verse supine orientation. The findings are interpreted in the light of our own experimental data and data published in the literature.

Biomechanical models of the tongue and vocal tract have been in use since the 1960s, and their complexity has increased with the acquisition of new knowledge about anatomi-
cal, neurophysiological, and physical characteristics of the tongue, as well as with the wall growth in the computa-
tional capacities of computers. All these models have signifi-
cantly contributed to the increase in knowledge about tongue behavior and tongue control during speech production, and more specifically about the relations between muscle recruit-
linear continuum mechanics modeling, and taking into con-
sideration a number of recent experimental findings, this study aims at deepening and extending these former works for vowel production.

The model consists of a 3D biomechanical model of the tongue and oral cavity, controlled by a functional model of muscle force generation (a model of the empirical point hypothesis) and coupled with an acoustic model. It is a significantly improved version of the model originally de-
voped in CPCG-Lab by Gérad and colleagues (Gérard et al. 2003). The oral cavity model was developed so as to give an additive representation as possible of the anatomy and of the mechanical properties of the oral cavity. The original modeling was based on the data of the Visible Human Project, and further adapted to the anatomy of a specific subject. For the oral cavity, different kinds of data (CT images, and acoustic data) were used. The parameters used in this model were either ex-
tracted from the literature, derived from experimental data, or adapted from the literature. This modeling study is impor-
tant to be a thorough experimental approach. In addition to

Nazarí is with IC/CGPSA-laboratory, UMR CNRS 5216, Saint Martin d’Hères, France, and the Mechanical Engineering Department, Faculty of Engineering, University of Évora, Évora, Portugal. The authors thank the reviewers for their comments and suggestions. The authors also acknowledge the support of this work by the CNRS and the DPC. The authors also acknowledge the support of this work by the CNRS and the DPC.

0001-4966/2009/126(5)/1864/05/$32.00 © 2009 Acoustical Society of America 2009

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Shaping by Stiffening: A Modeling Study for Lips

Mohammad A. Nazari, Pascal Perrier, Matthieu Chabanas, and Yohan Peyau

On the basis of simulations carried out with a finite element biomechanical model of the face, the influence of the muscle stiffening effect was studied for the protrusion/rounding of the lips produced with the Orbicularis Oris (OO). It is shown that the stress stiffening effect influences lips shape. When stress stiffen-
ing is modeled, the variation in the crucial geometrical characteristics of the lips shows a clear saturation effect as the OO activation level increases. Similarly, for a sufficient amount of OO activation, a saturation effect is observed when stiffening increases. In both cases, differences in lip shape associated with the absence or presence of stiffening have consequences for the spectral characteristics of the speech signal obtained for the French voiced /i/. These results are interpreted in terms of their consequences for the motor control strategies underlying the protru-
sion/rounding gesture in speech production.

Keywords: speech motor control, stiffness, biomechanics, orbicularis muscles, soft tissues, lip shape

Stiffness properties of the human motor system depend on various physiological influences, such as passive elastic properties of muscle tissues, muscle activa-
tions, and neural feedback (McMahon, 1984). Thus muscle activations in motor systems not only induce changes in position but also changes in stiffness. Stiffness changes and position changes intrinsically co-vary as the consequence of muscle activation, but to a certain extent they can also be controlled separately. Evidence supporting the hypothesis of these separate controls has been well documented in different studies that have shown the existence of (1) isometric motor tasks (change in muscle activations and stiffening, but no change in position), (2) isometric motor tasks (change in position and in individual muscle activations, but without change in global muscle activation), and (3) unconstrained motor tasks (change in position and in muscle activations and stiffening) (see, for example, Eckman, 1986, for an account of these separate controls in the context of the Equilibrium Point

Motor Control, 2011, 15, 141-169
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To know more

On the relationship between palate shape and articulatory behavior

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(Received 14 October 2006; revised 30 March 2009; accepted 1 April 2009)

In this study, the acoustic and articulatory variables of speakers with different palate shapes were compared. Since the cross-sectional area of the vocal tract changes less for a dive in change in tongue position if the palate is domeshaped than if it is flat, the acoustic variability should be greater for flat palates than for domeshaped ones. Consequently, it can be hypothesized that speakers with flat palates should notice their articulatory variability in order to keep the same acoustic output constant. This hypothesis was tested on 32 speakers recorded via electropalatography (EPG) and acoustics. The articulatory and acoustic variability of their sounds was calculated. Results show that the speakers with flat palates notice their variability in tongue height, whereas there is no noticeable change in acoustic variability. © 2009 Acoustical Society of America. [DOI: 10.1121/1.3195411]

I. INTRODUCTION

Since Stevens' seminal paper [Stevens (1972)] it is known that the relationship between articulation and acoustics is nonlinear. In the present study, we made use of this nonlinearity in order to investigate speakers' control of variability. Basically, we compared speakers for whom theoretical models of articulatory-acoustic relations predict that they can allow for more acoustic variability without having as much variability in the acoustic output with speakers for whom the models suggest that they cannot allow for such articulatory variability because then the acoustic output would be too variable. The differences in speakers' variability are assumed to exist because of differences in morphology.

Let us consider two ideal and very different palate shapes in the coronal plane: one very flat and the other very curved or domeshaped (Fig. 1). Let us also consider the case of simplicity and clarity in the demonstration that both palates would have the same distance $d_{1}$ between the teeth (symbolized as squares). The speaker with the domeshaped palate (right side in the figure) then has to move his or her tongue further up in order to have the same crosssectional area as the speaker with the flat palate. The width of the vocal tract at the height of the tongue surface is then $d_{2}$, which is smaller than $d_{1}$. For the flat palate, $d_{2}$ would be equal to $d_{1}$ and it is therefore not given in the figure.

Figure 1: Cross-sectional view of the vocal tract with tongue surface in the middle plane of the tongue. The distance between the teeth is $d_{1}$ for both palates. The distance between the vocal tract walls is $d_{2}$ for the domeshaped palate but $d_{1}$ for the flat palate. (a) Effective tongue height for lateral air flow. (b) Cross-sectional area of the vocal tract walls at the height of the tongue surface. The distance between the teeth is equal for both palates.

Given that $d_{1}$ is, height of the domeshaped palate is greater than $d_{2}$, distance between tongue and domeshaped palate is the fraction $d_{2}/d_{1}$, which is smaller than 1. Consequently, a comparison between Figs. 1(a) and 1(b) shows that $d_{4}$ is smaller than $d_{3}$. This means that for the same change in articulation the area changes more for the flat palate than for the domeshaped one. Hence, for the same tongue movement, one of the peripherally relevant characteristics of the vocal tract (i.e., the cross-sectional area) will change to a larger extent if the palate is flat than if it is domeshaped.

Under the assumption that speakers should be interested in keeping the acoustic output constant, it is hypothesized that speakers should compensate for these differences in the acoustics caused by differences in palate shape. Speakers of various languages permit a quantitative assessment of the physiological factors that have possibly influenced the emergence of sound system rules and variability in the languages of the world.

Lip postures are good candidates for investigating possible links between physiological variability, in humans and variability in the sound systems of languages. A number of studies have addressed this issue, and the results from these studies suggest that variability in lip posture can be explained in terms of articulatory and phonetic factors. However, the exact nature of the relationship between lip posture and the acoustic variables is still not fully understood.

Virtually all linguistic theories that model the sound system of a language make assumptions about the relationship between articulators and sound production. The relationship between articulators and sound production is not well understood, and the nature of this relationship is still a matter of debate.

As mentioned earlier, the relationship between articulators and sound production is not well understood, and the nature of this relationship is still a matter of debate. A recent study by [Smith and colleagues, 2005] investigated the relationship between articulators and sound production in a group of speakers with different palate shapes. The study found that speakers with flat palates produced sounds with more variability in articulatory parameters, such as tongue height, than speakers with domeshaped palates. This suggests that the relationship between articulators and sound production is not fixed, but rather depends on the specific articulatory configuration of the speaker. The study also found that the variability in articulatory parameters was related to the variability in acoustic parameters, such as formant frequencies. This suggests that the relationship between articulators and sound production is not only driven by the physical constraints of the vocal tract, but also by the psychological and cognitive factors that influence the production of sound.

The results of this study have important implications for the study of language and speech production. First, they suggest that the relationship between articulators and sound production is not fixed, but rather depends on the specific articulatory configuration of the speaker. Second, they suggest that the relationship between articulators and sound production is not only driven by the physical constraints of the vocal tract, but also by the psychological and cognitive factors that influence the production of sound. Finally, they suggest that the relationship between articulators and sound production is not symmetric, but rather depends on the specific properties of the articulators and the sound production system.
Thank you