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
- Inflluence 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

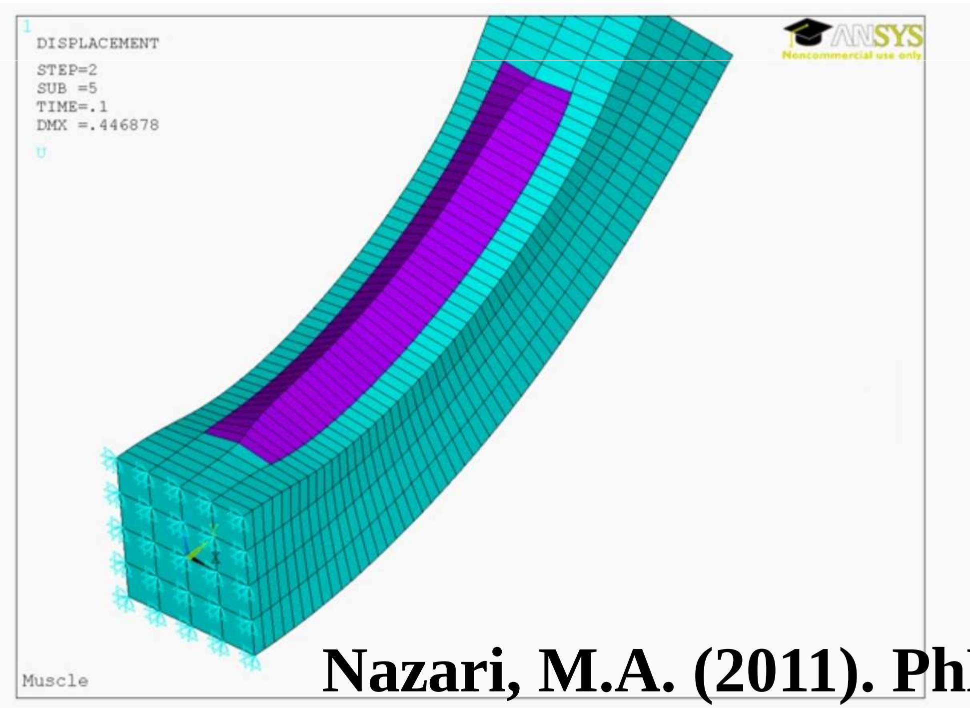
- Little studies about speaker-specific biomechanics and motor control
- Biomechanics: a constraint not a determining factor
- Models: provide information about the constraint
- Evaluation with experimental data requires models of motor control
  - Comparison with data → validates, contradicts hypotheses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

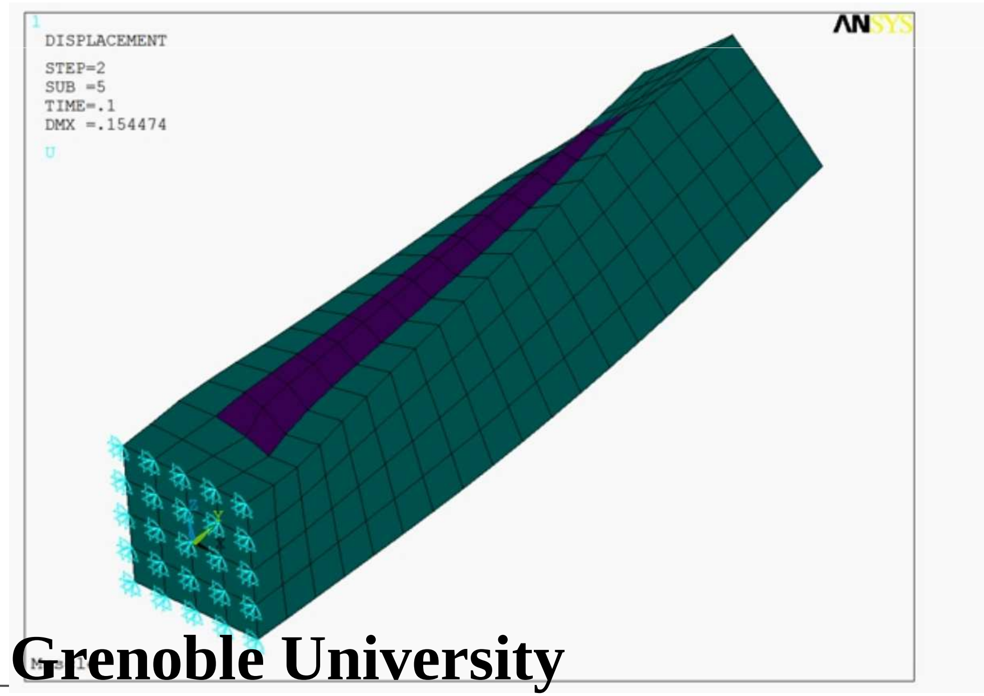
Biomechanics?

- 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



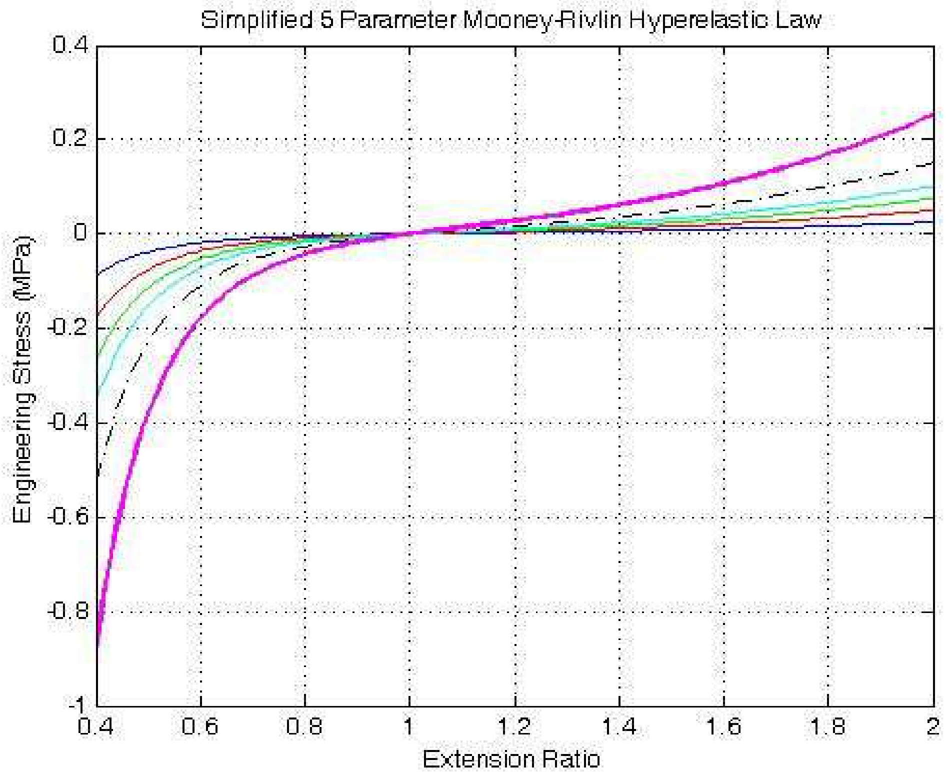


Nazari, M.A. (2011). PhD Grenoble University

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

- Force → Stress
- Displacement → Strain
- Non-linear

  stress –strain relation :

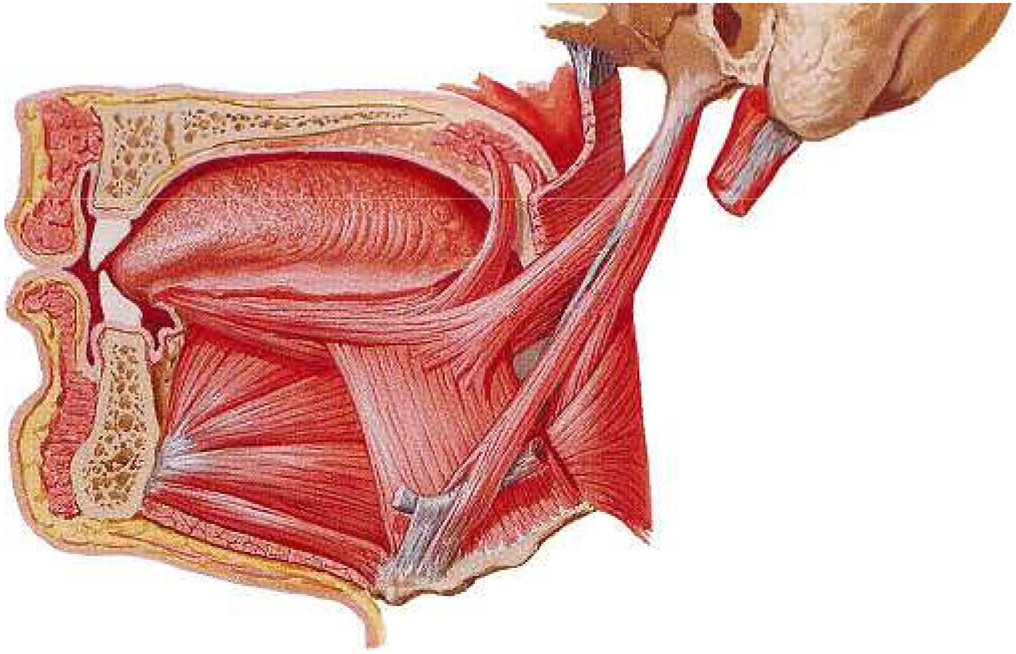


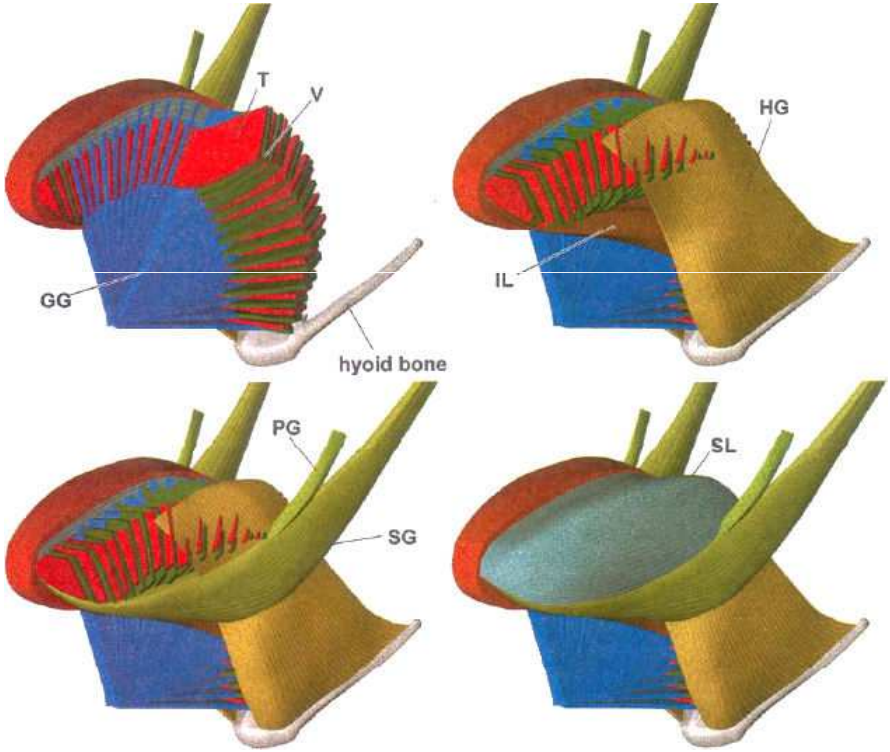
- Non constant stiffness : d(Stress)/d(Strain) (Young Modulus)

Nazari, M.A. (2011). PhD Grenoble University

Tongue anatomy

- Anatomical data



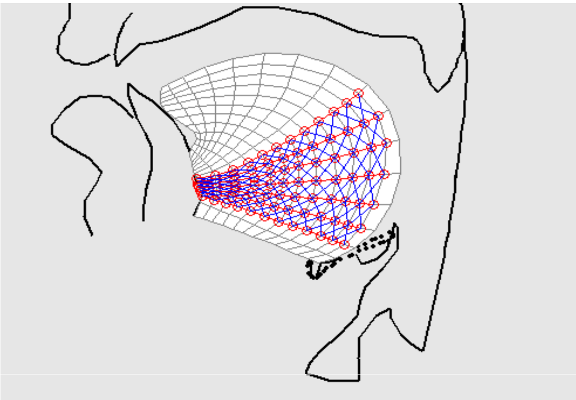


Netter, 2004

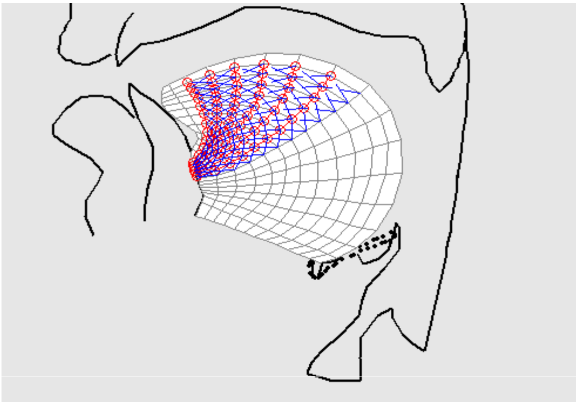
Takemoto, *J. Speech Lang. Hear. Res.*, 2001

2D Tongue Model

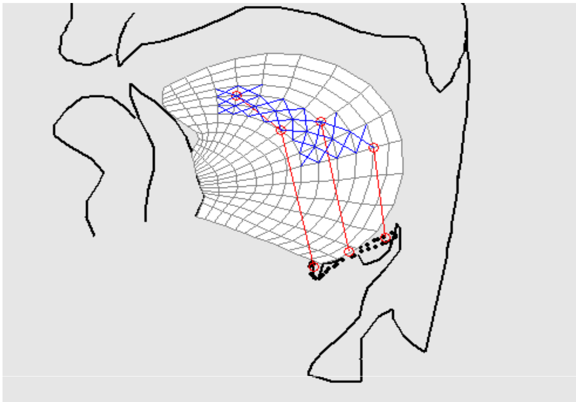
Payan & Perrier, Speech Comm 1997
Perrier et al., JASA 2003



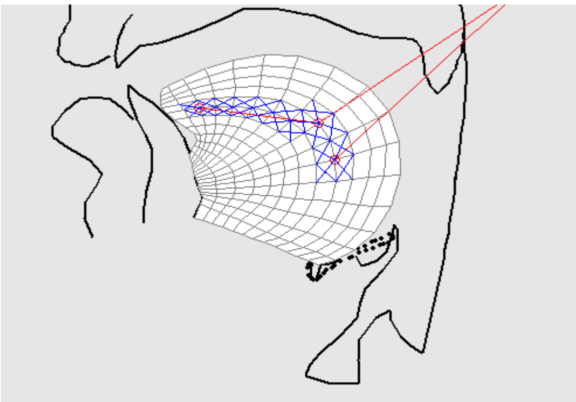
Posterior genioglossus



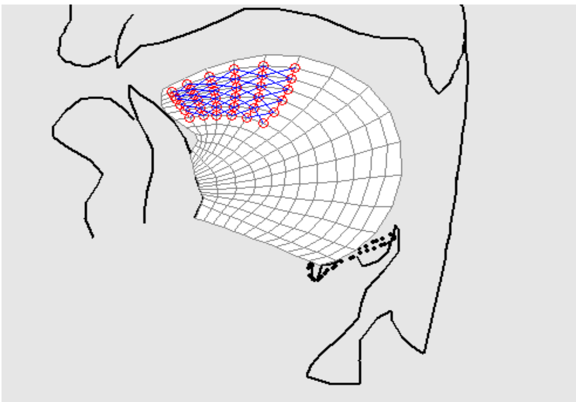
Anterior Genioglossus



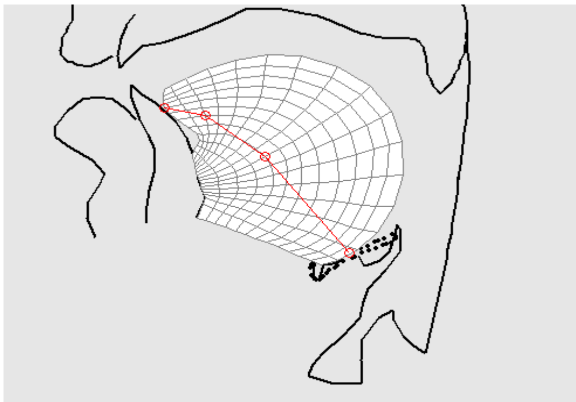
Hyoglossus



Styloglossus



Verticalis

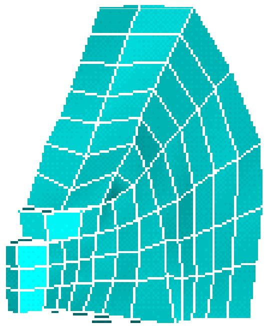


Inferior Longitudinalis

3D Tongue Model

Gerard et al, 2006; Buchaillard et al., JASA 2009

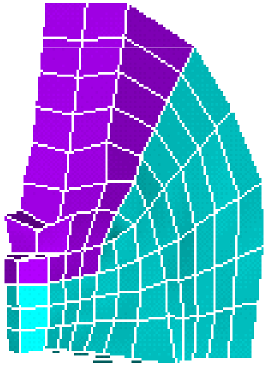
- Posterior Genioglossus



3D Tongue Model

Gerard et al, 2006; Buchaillard et al., JASA 2009

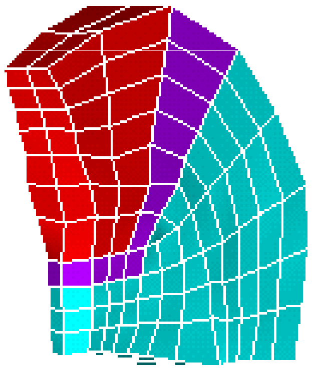
- Medium Genioglossus



3D Tongue Model

Gerard et al, 2006; Buchaillard et al., JASA 2009

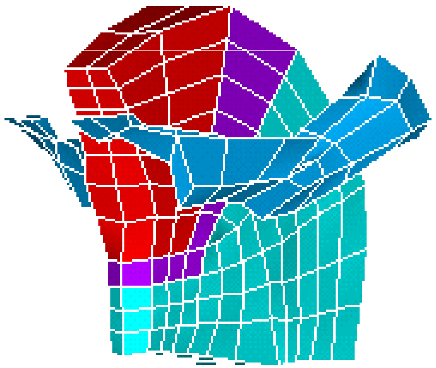
- Anterior genioglossus



3D Tongue Model

Gerard et al, 2006; Buchaillard et al., JASA 2009

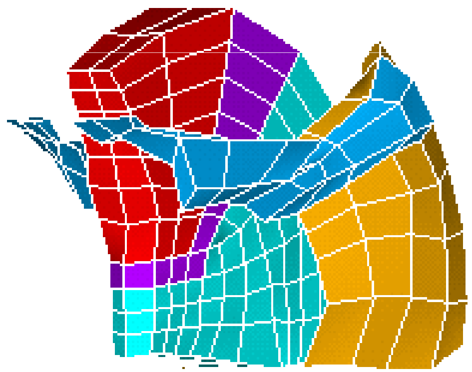
- Styloglossus



3D Tongue Model

Gerard et al, 2006; Buchaillard et al., JASA 2009

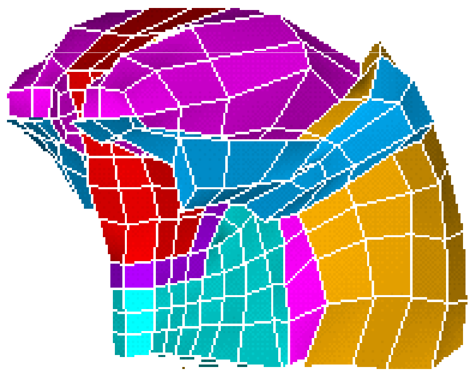
- Hyoglossus



3D Tongue Model

Gerard et al, 2006; Buchaillard et al., JASA 2009

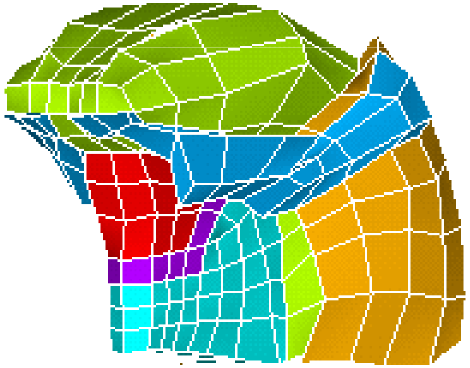
- Verticalis



3D Tongue Model

Gerard et al, 2006; Buchaillard et al., JASA 2009

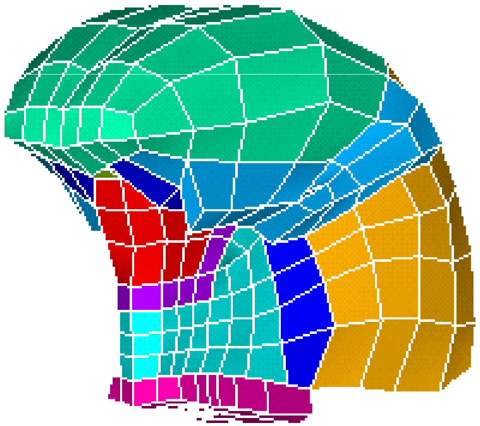
- Transversalis



3D Tongue Model

Gerard et al, 2006; Buchaillard et al., JASA 2009

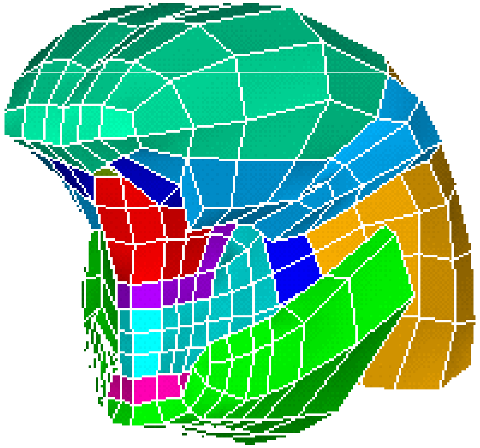
- Geniohyoid



3D Tongue Model

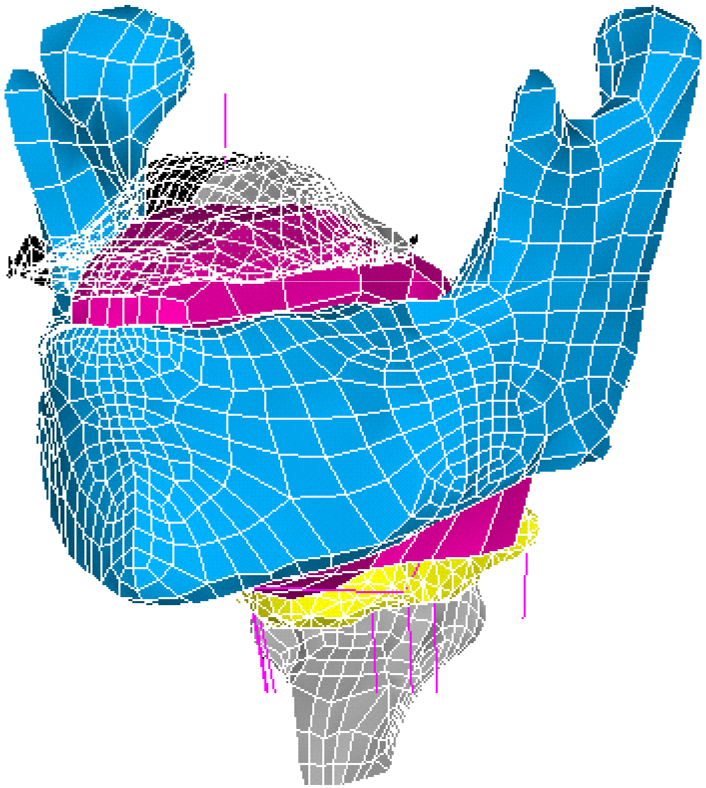
Gerard et al, 2006; Buchaillard et al., JASA 2009

- Mylohyoid



3D Tongue Model

Gerard et al, 2006; Buchaillard et al., JASA 2009



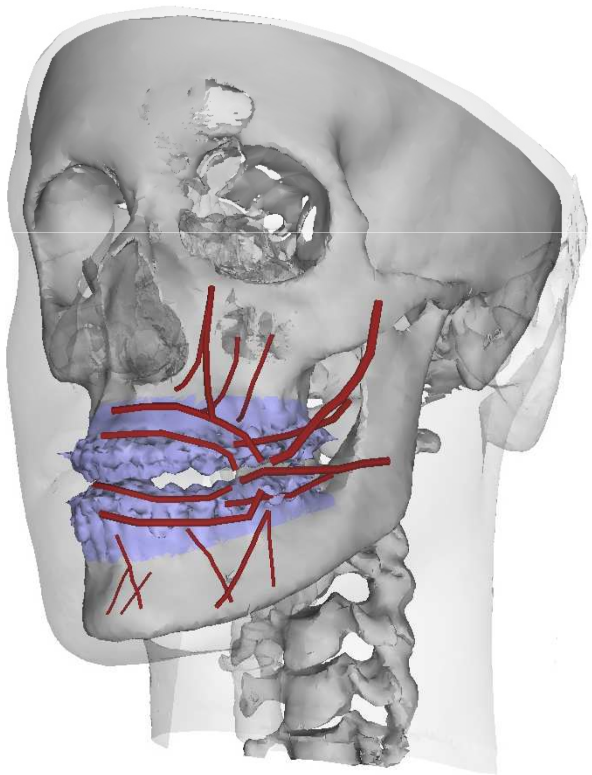
Face anatomy

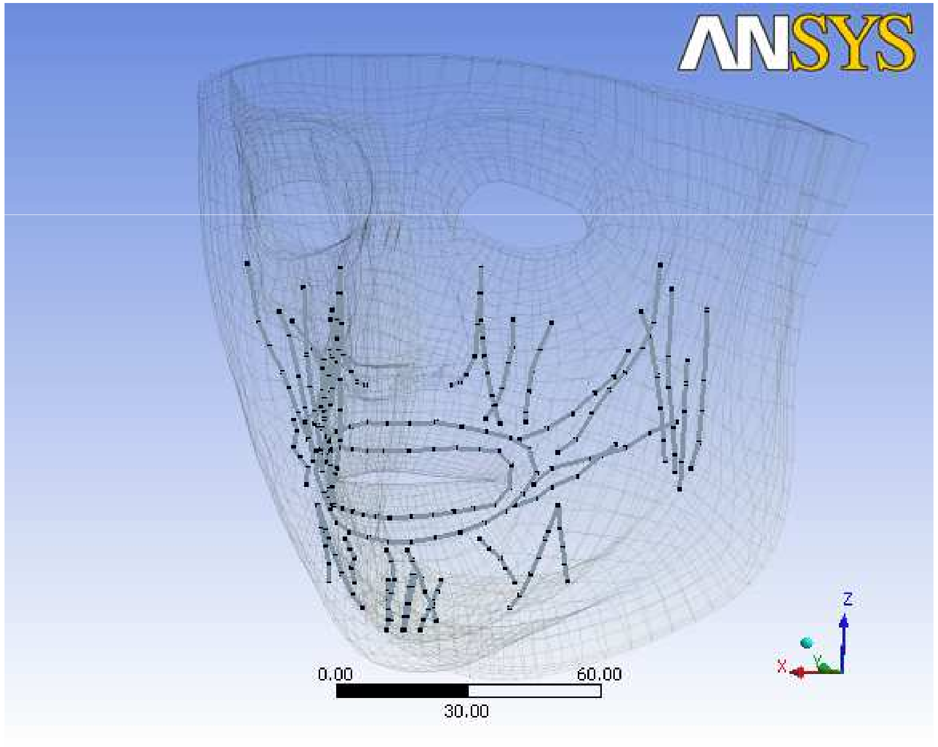
http://www.anatomy.tv

3D Face model

Nazari et al., CMBBE 2010

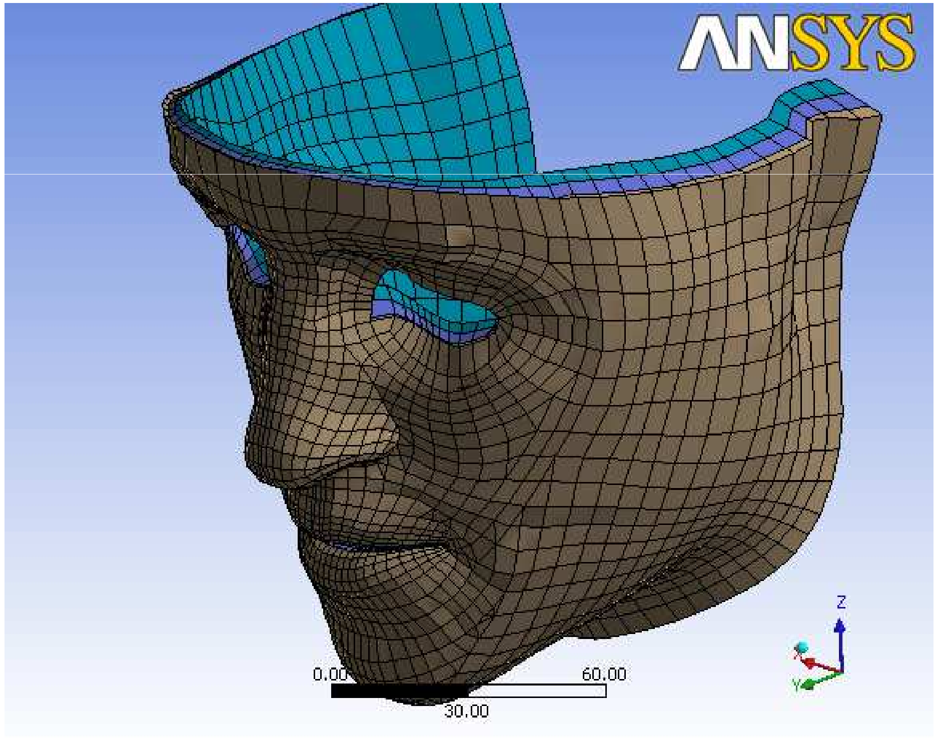
- Implementation of macrofibers in reference to the skull

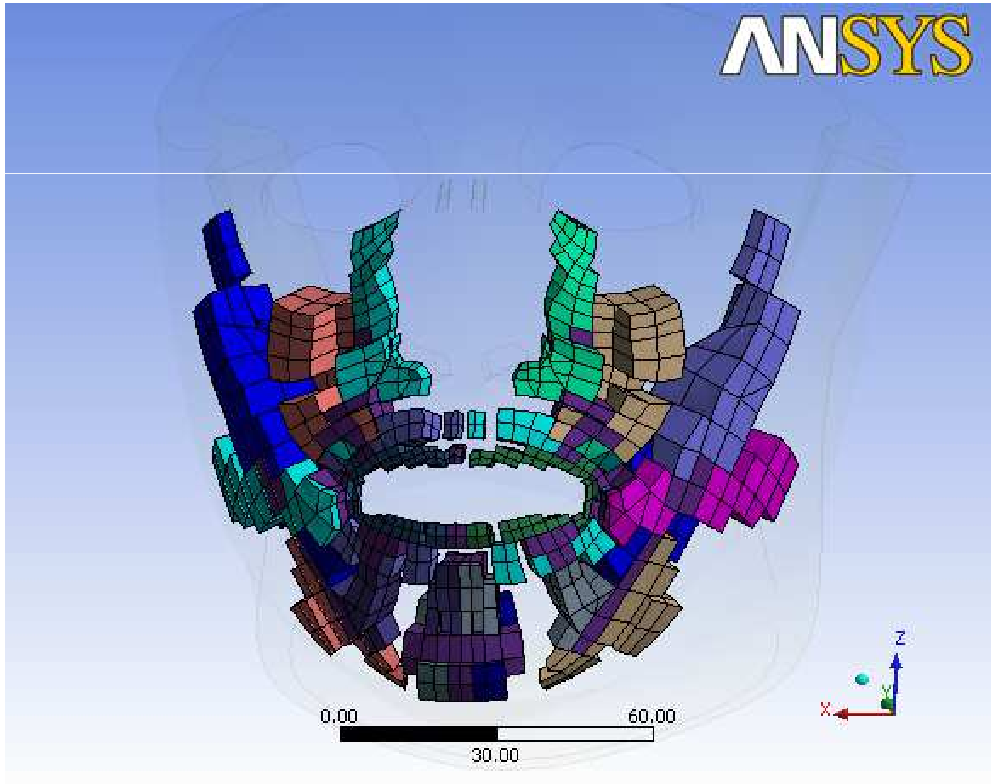




3D Face model

Nazari et al., CMBBE 2010

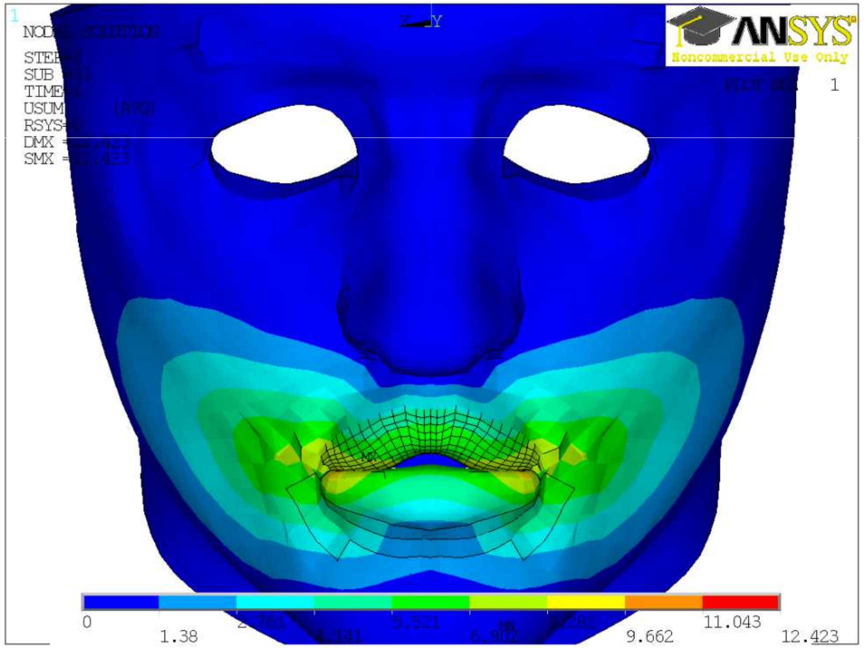


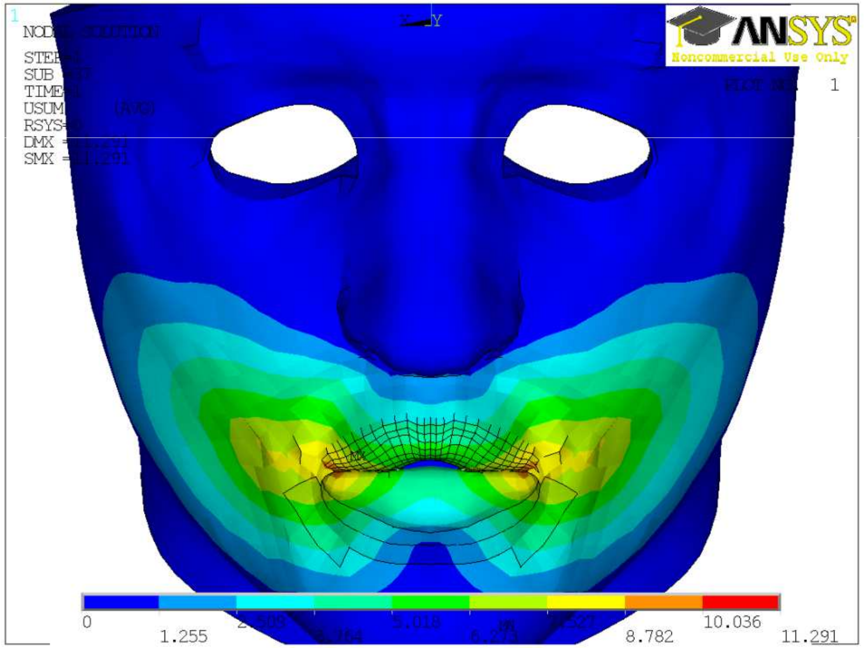


Lip protrusion/rounding: Shaping by stiffening

Nazari et al., Motor Control, 2011

- Results

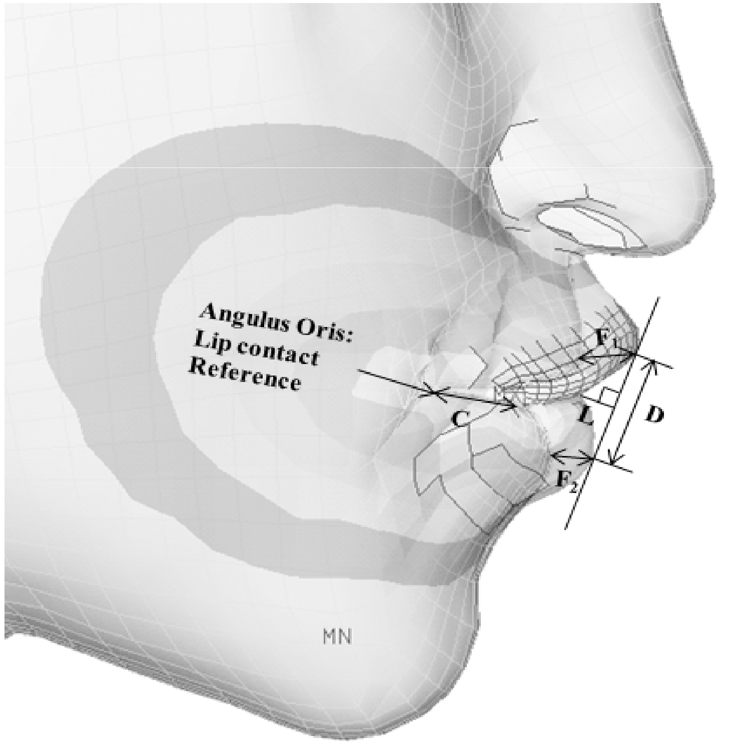


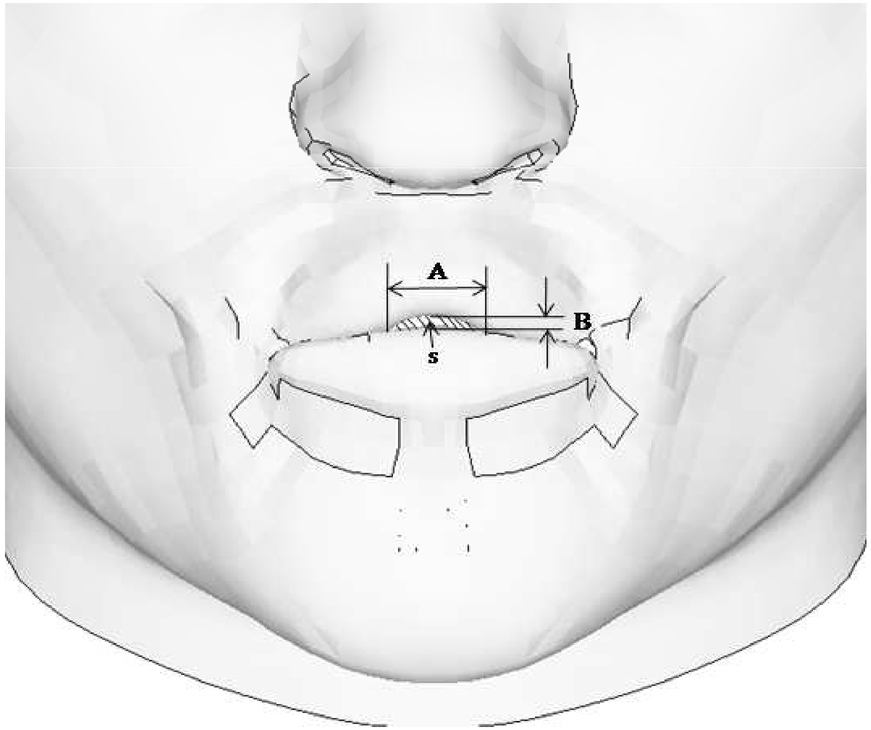


Lip protrusion/rounding: Shaping by stiffening

Nazari et al., Motor Control, 2011

- Lip Parameters for Studying Speech Production



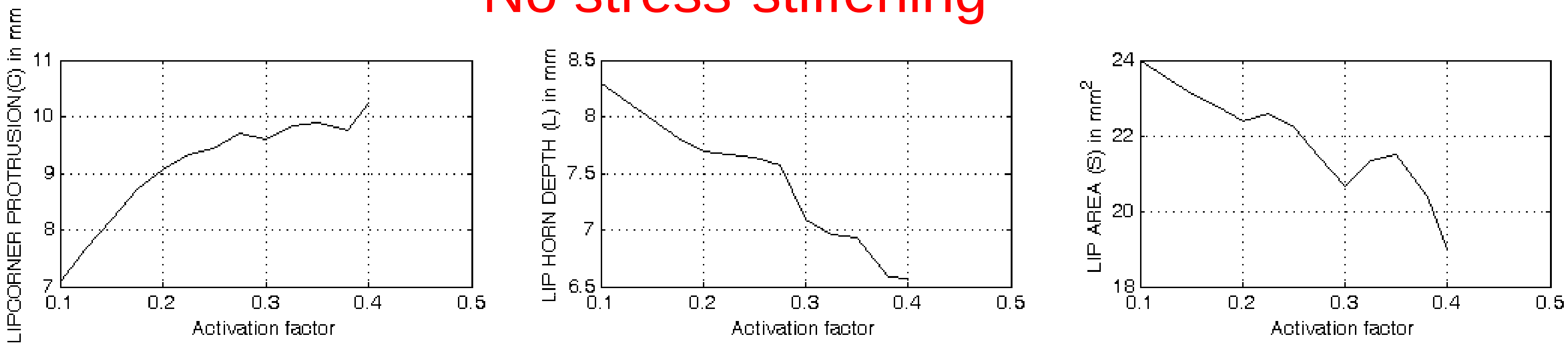


Abry & Boë, 1986

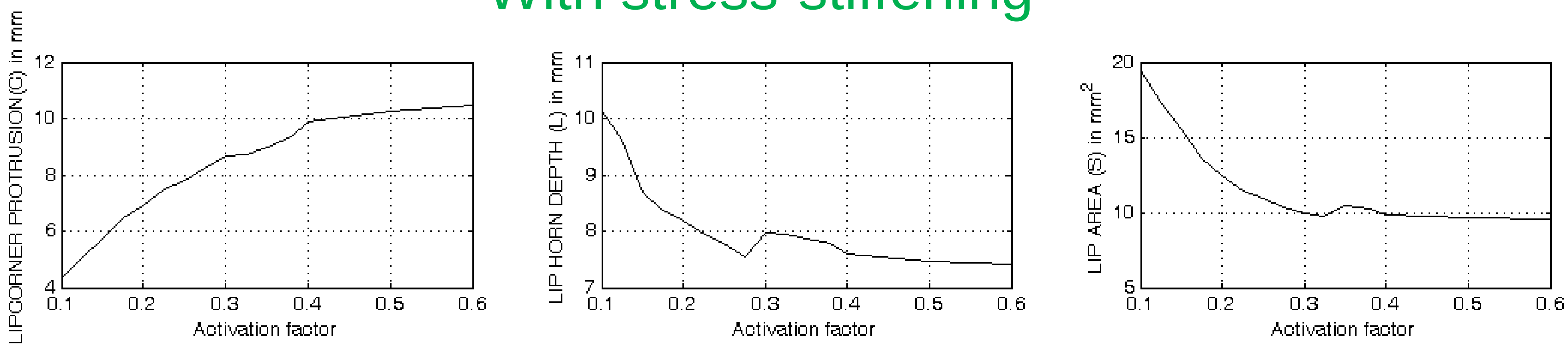
Lip protrusion/rounding: Shaping by stiffening

Nazari et al., Motor Control, 2011

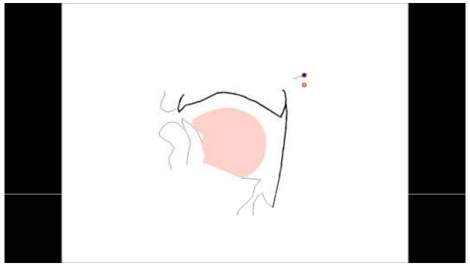
No stress-stiffening

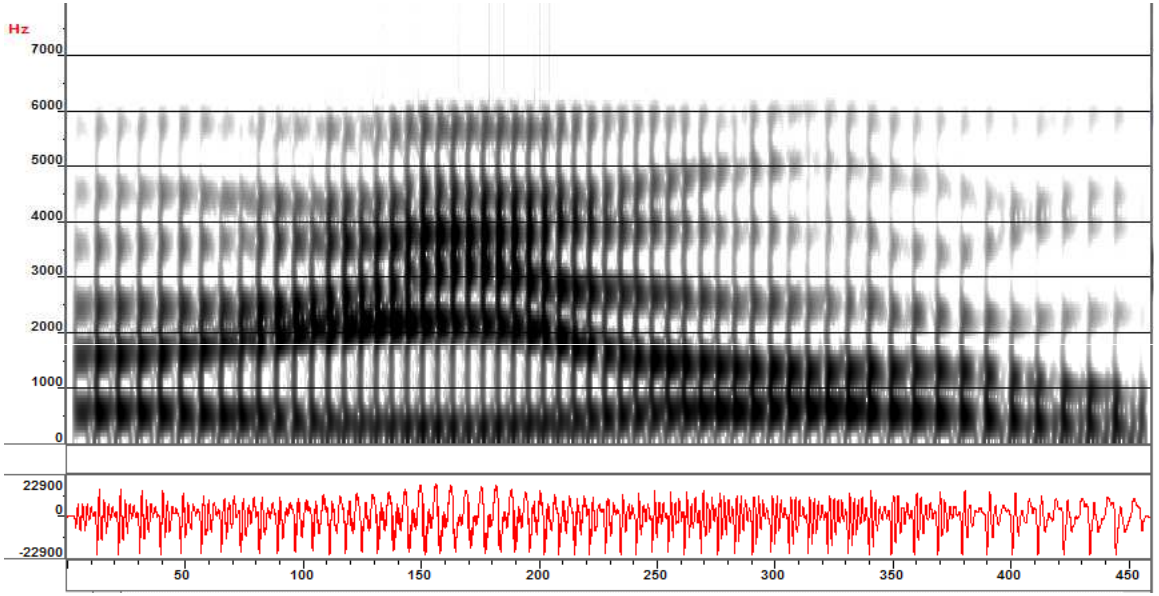


With stress-stiffening



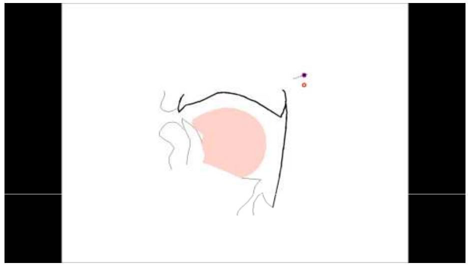
Impact of tissue stiffening (Pathology)

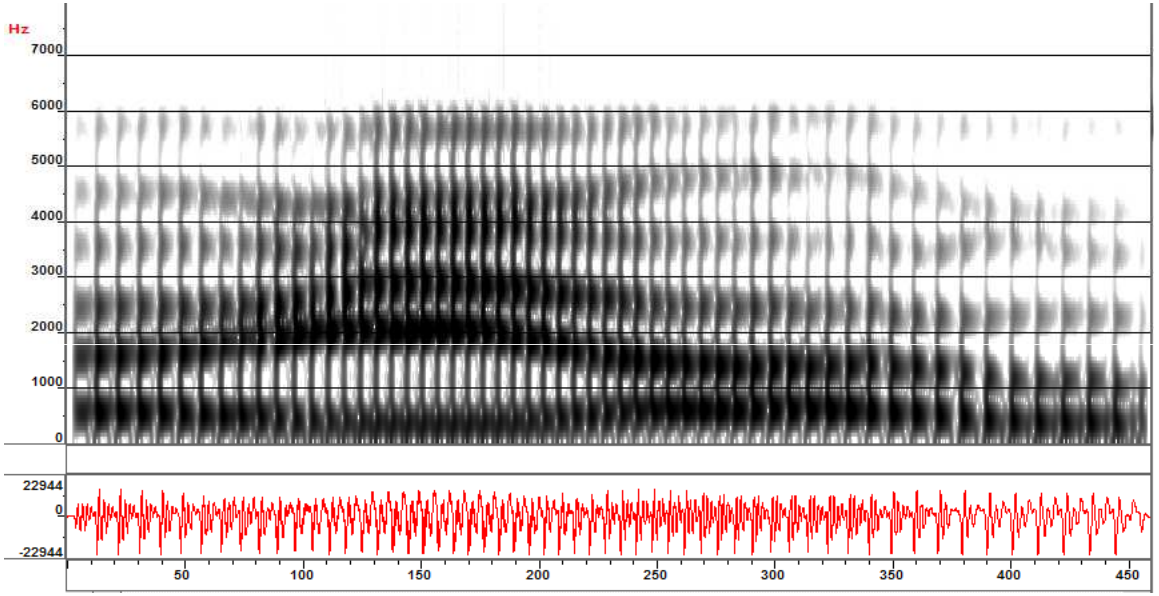




Normal stiffness

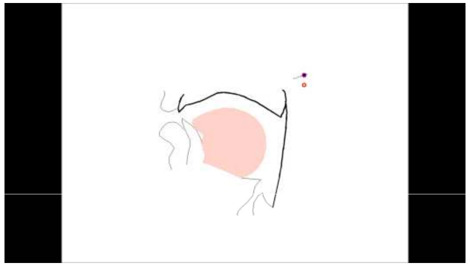
Impact of tissue stiffening (Pathology)

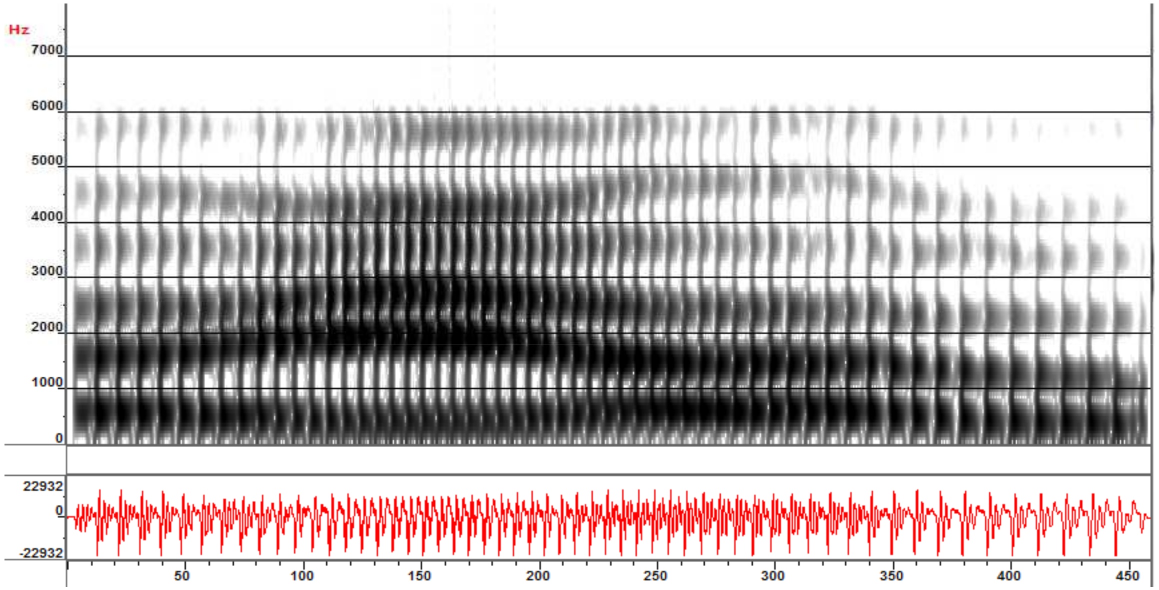




Normal stiffness x 3

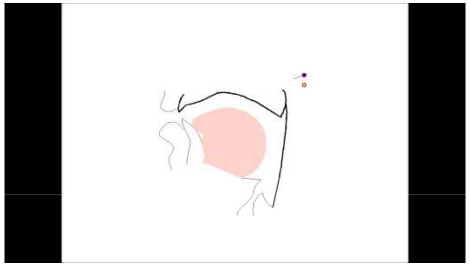
Impact of tissue stiffening (Pathology)

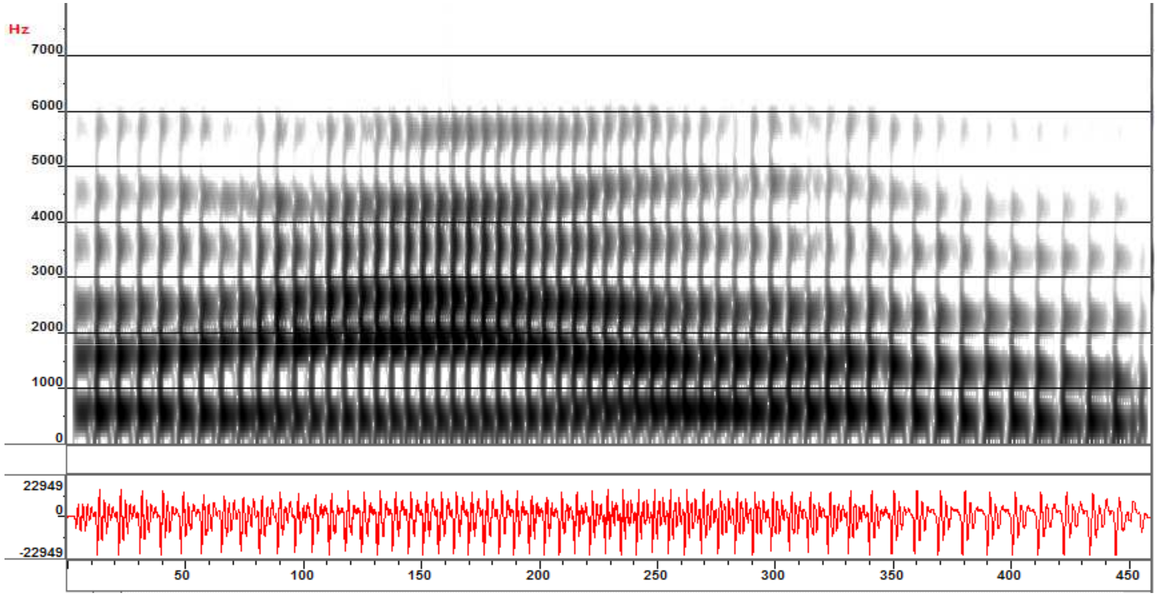




Normal stiffness x 6

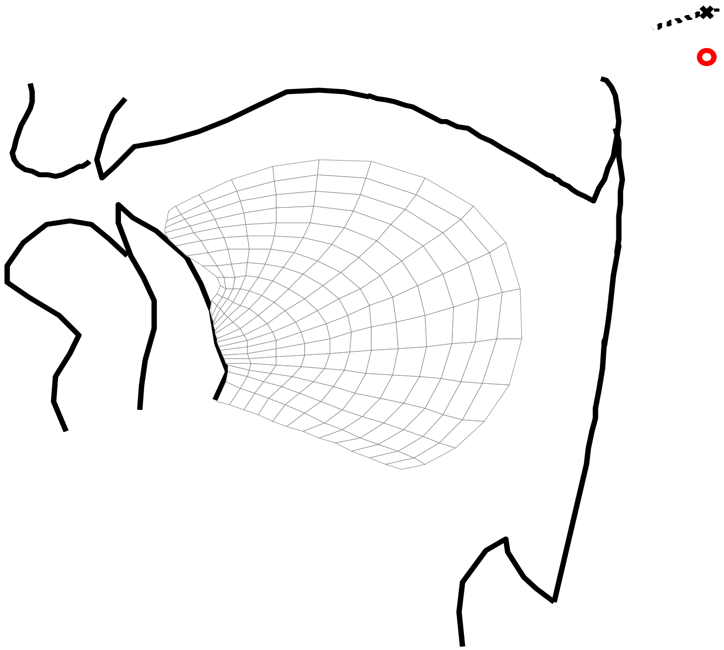
Impact of tissue stiffening (Pathology)

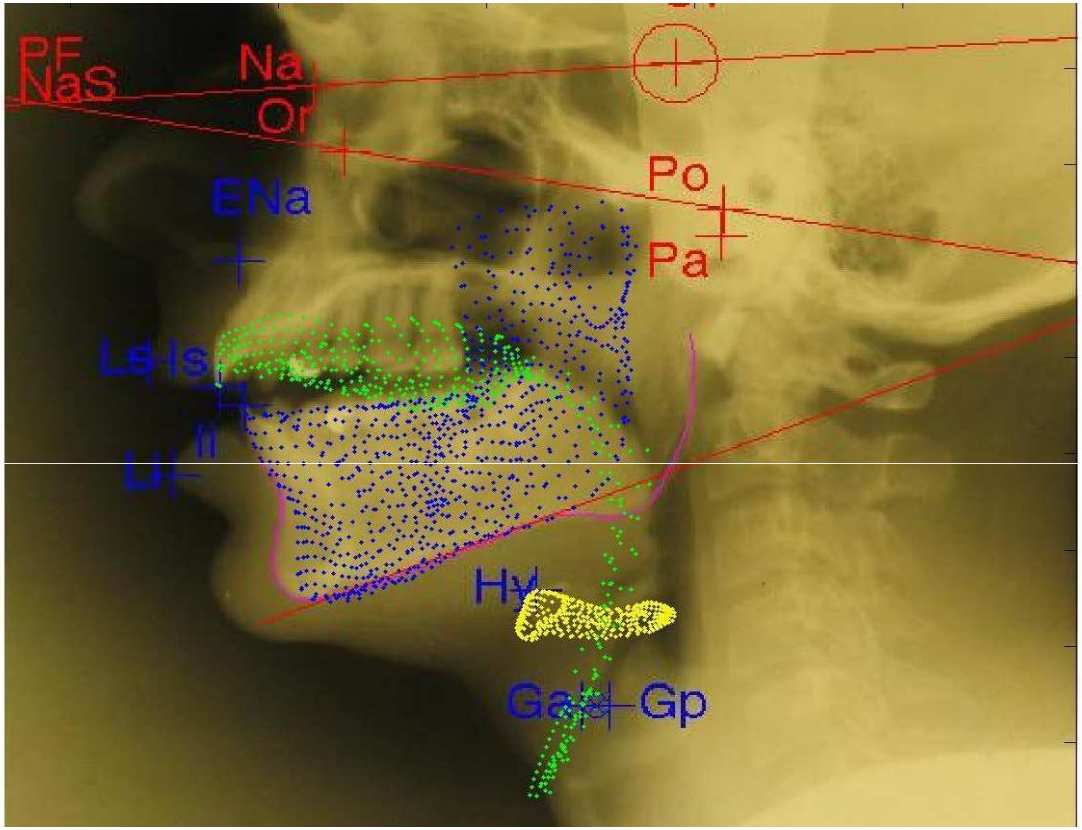




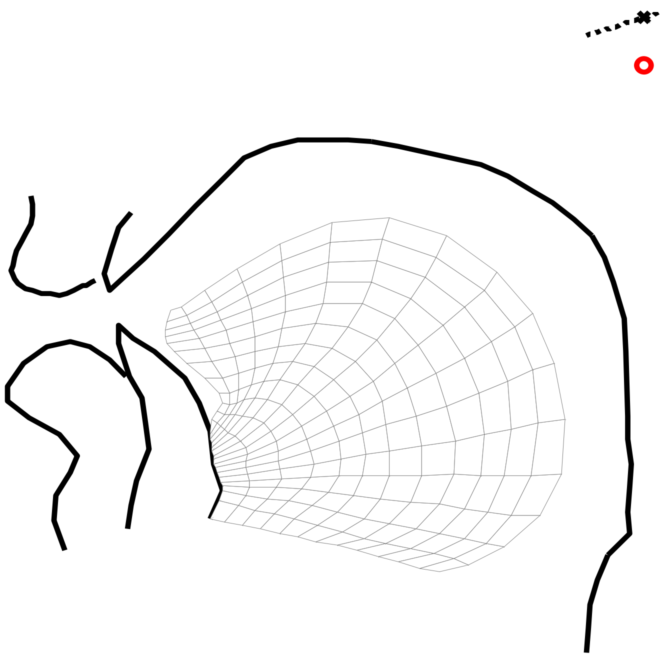
Normal stiffness x 10

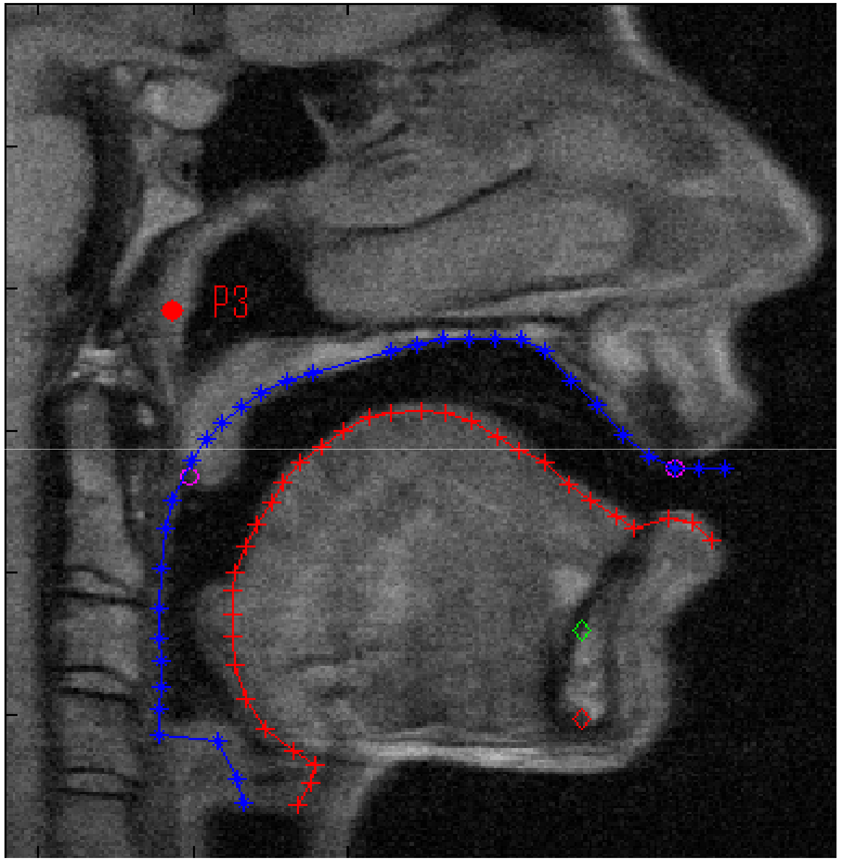
Variability in muscle orientation - YPM



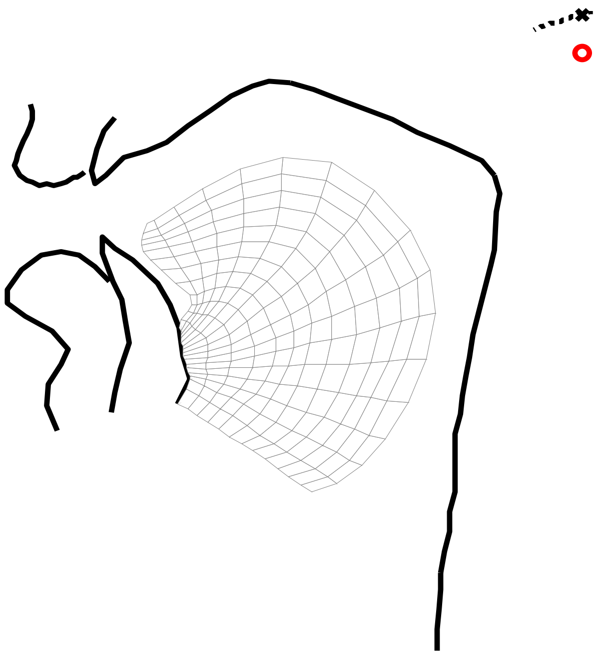


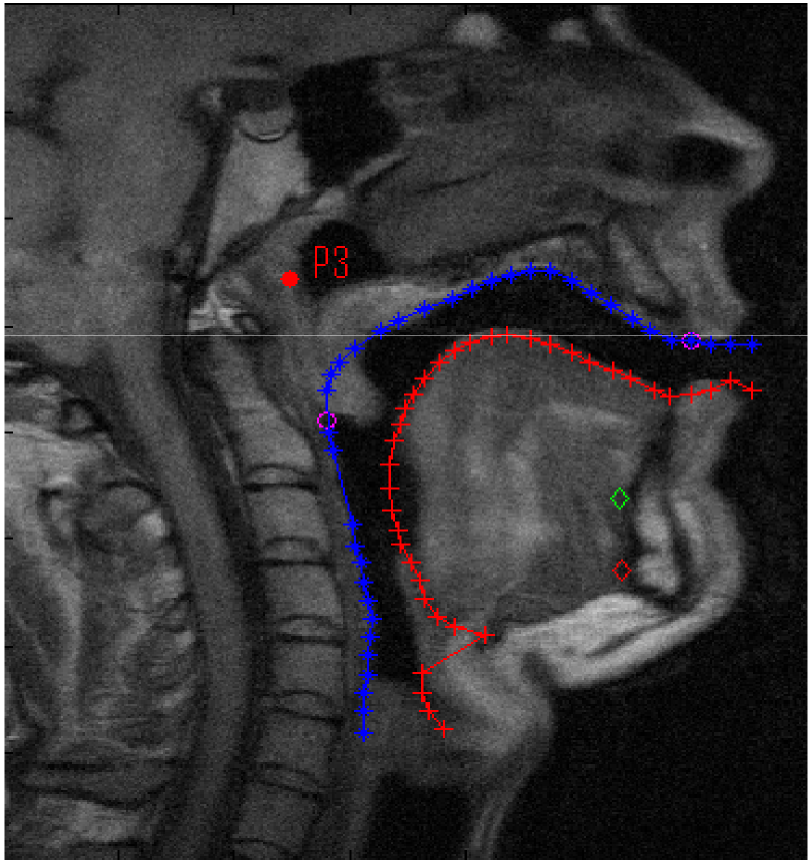
Variability in muscle orientation - AV



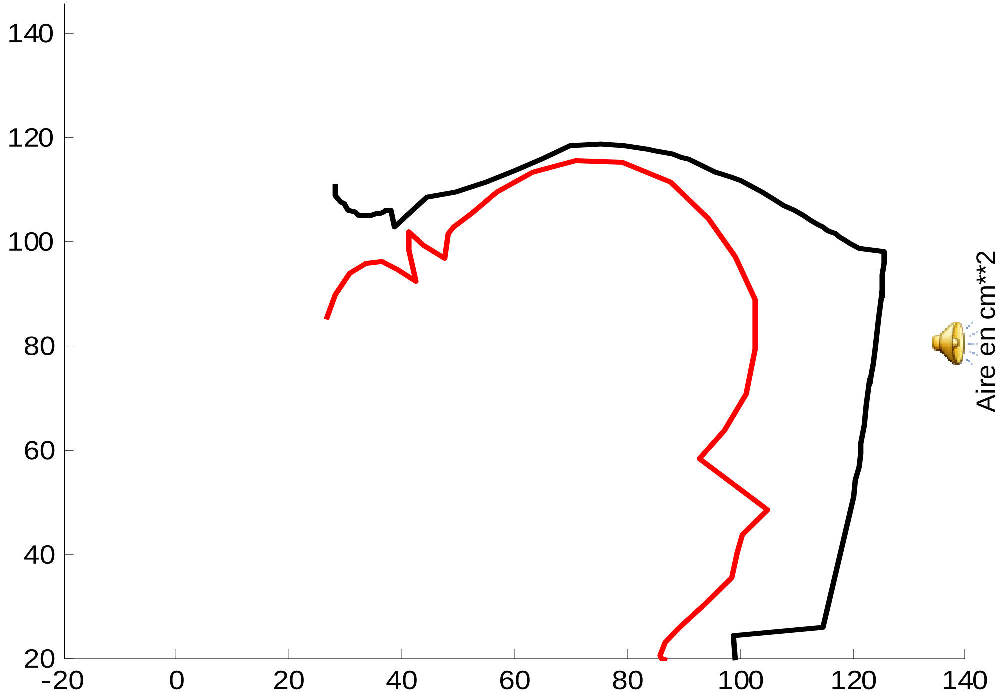


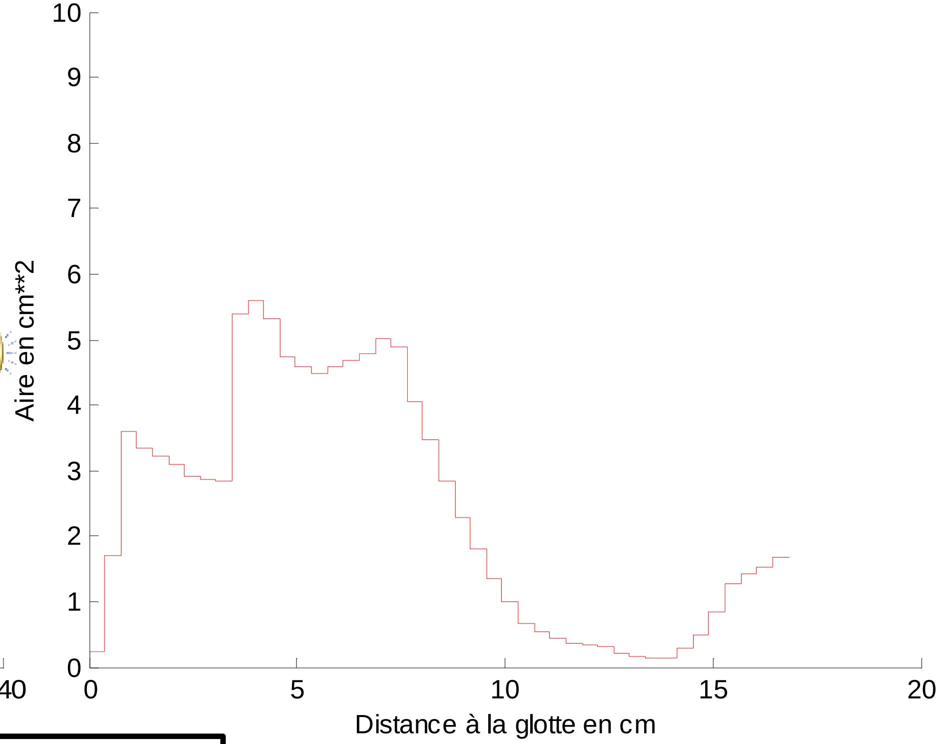
Variability in muscle orientation - CS





Variability in muscle orientation – [i] YPM



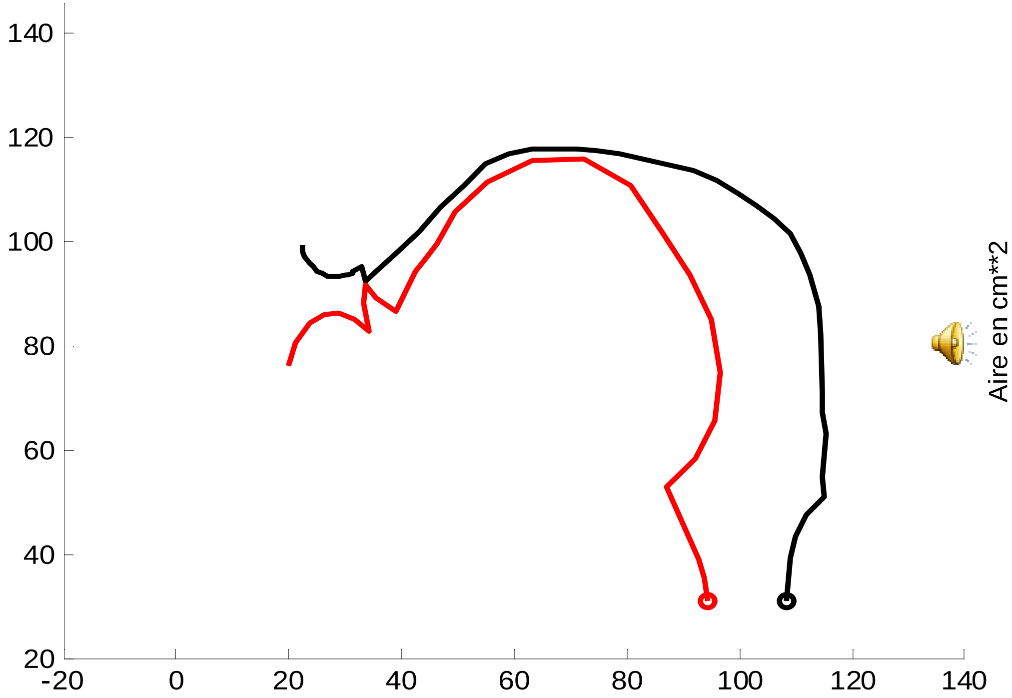


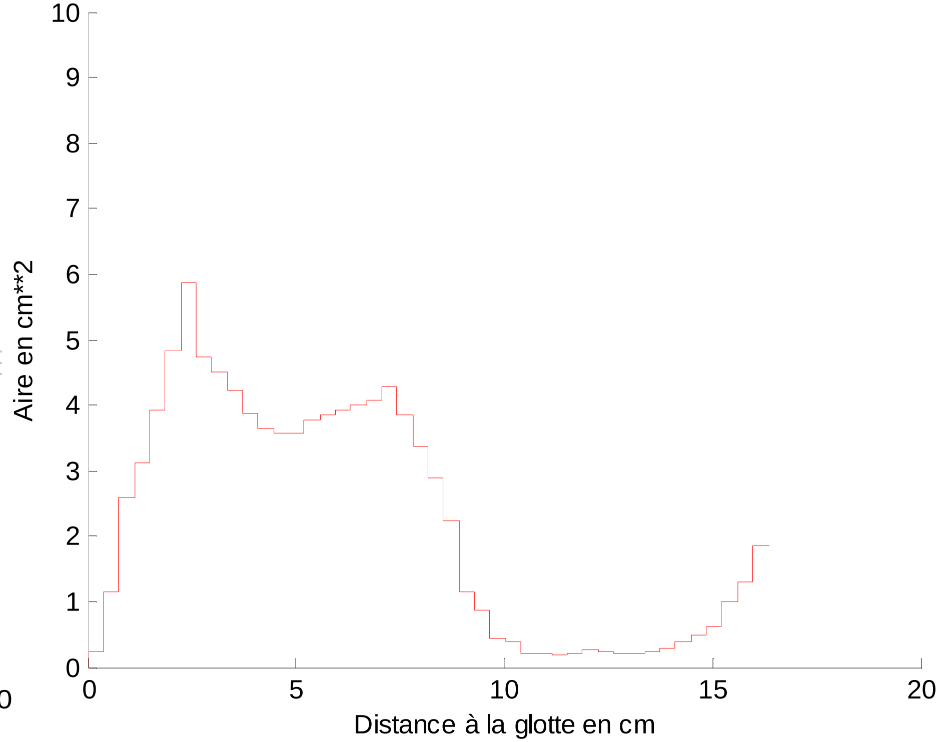
Muscle activations

GGP	GGA	HYO	STY
3.3	0	0	4.4

Ratio GGP/STY = 0.75

Variability in muscle orientation – [i] AV

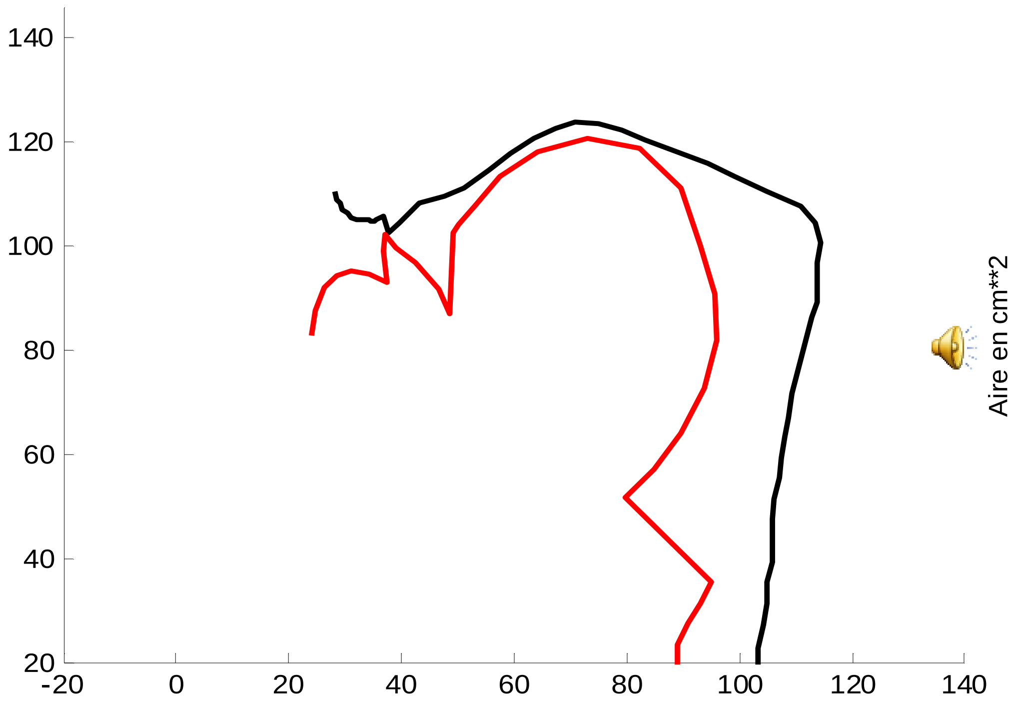


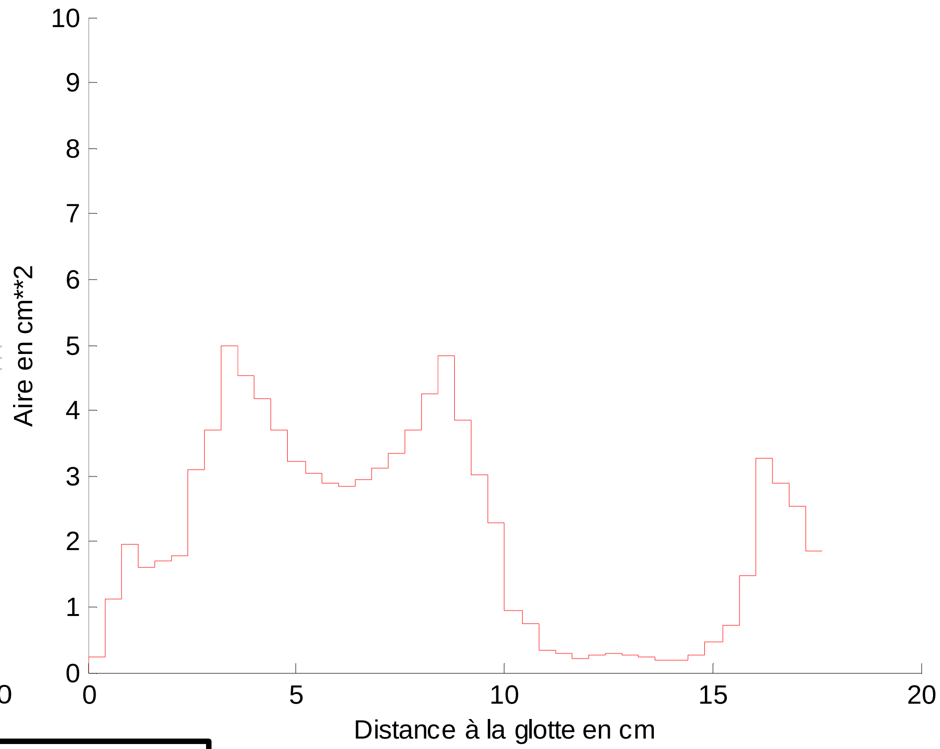


Muscle activations			
GGP	GGA	HYO	STY
4.9	0	0	6.6

Ratio GGP/STY = 0.75

Variability in muscle orientation – [i] CS



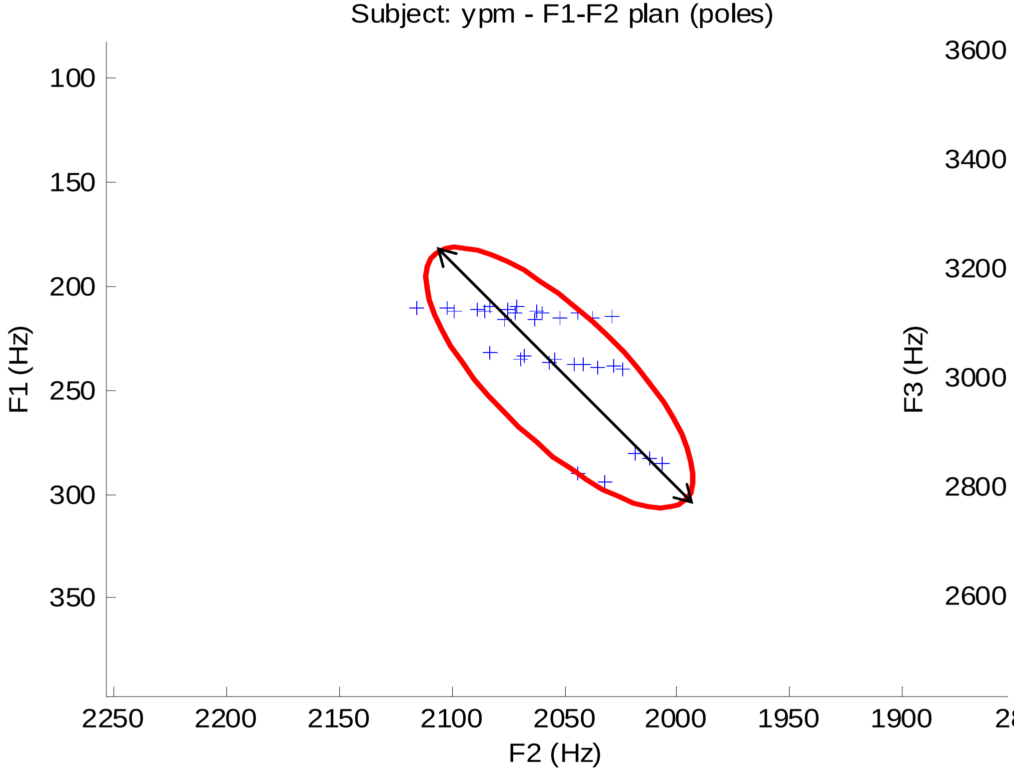


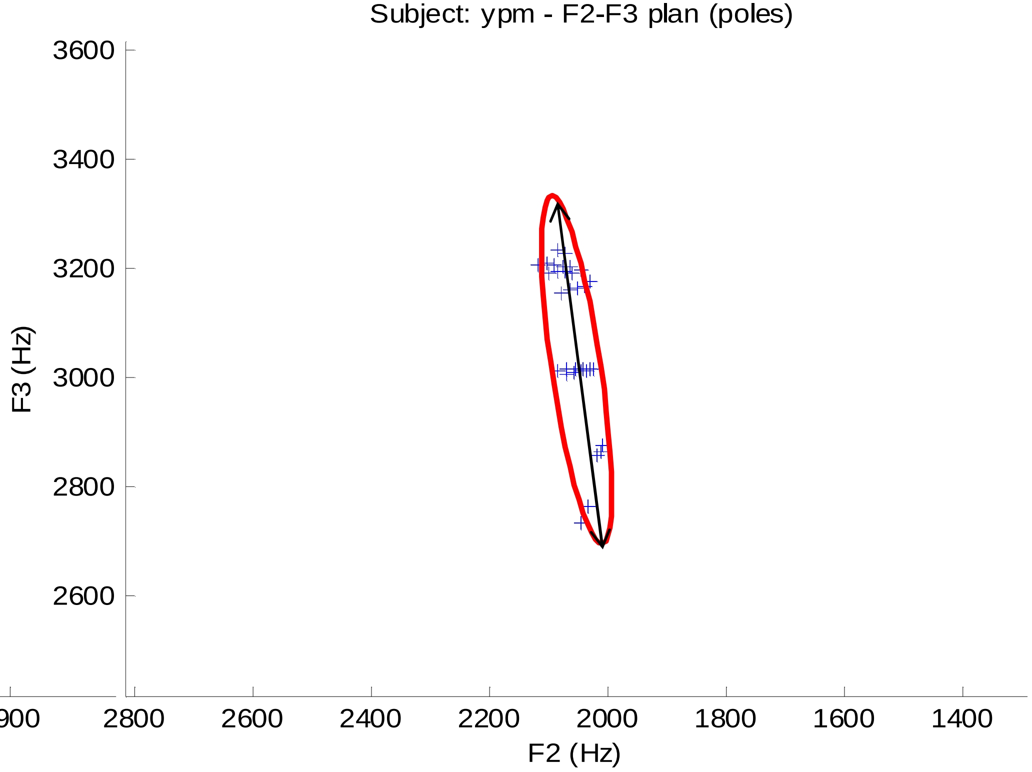
Muscle activations

GGP	GGA	HYO	STY
2.8	0	0	1.5

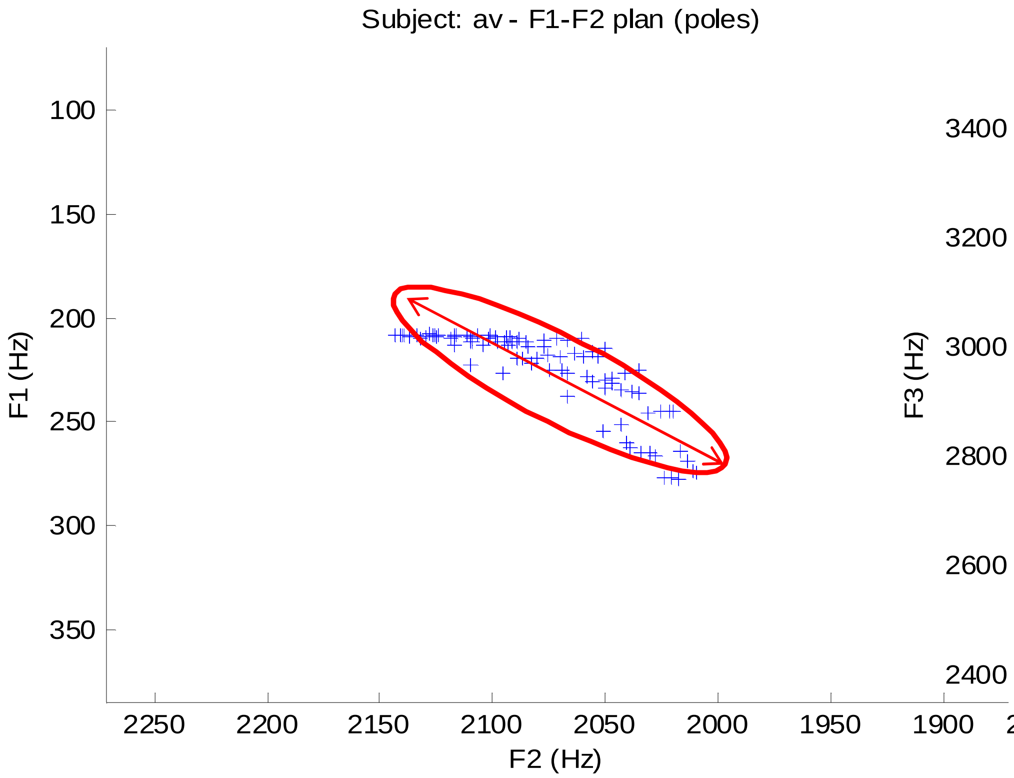
Ratio GGP/STY = 1.9

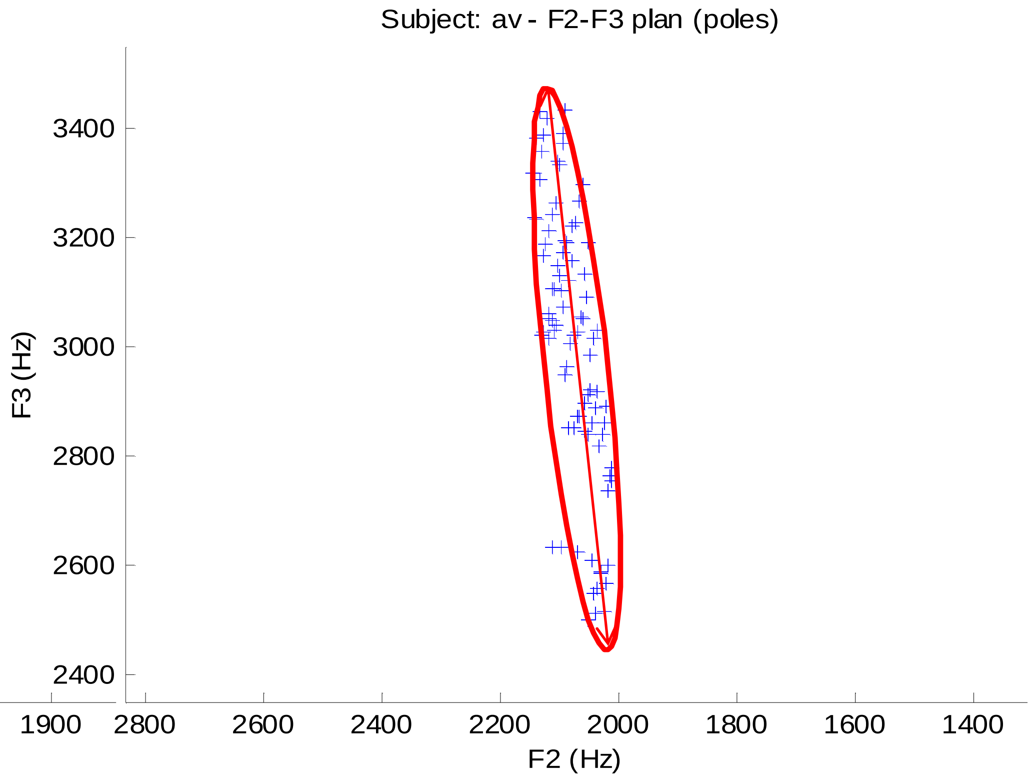
Variability in muscle orientation – [i] YPM



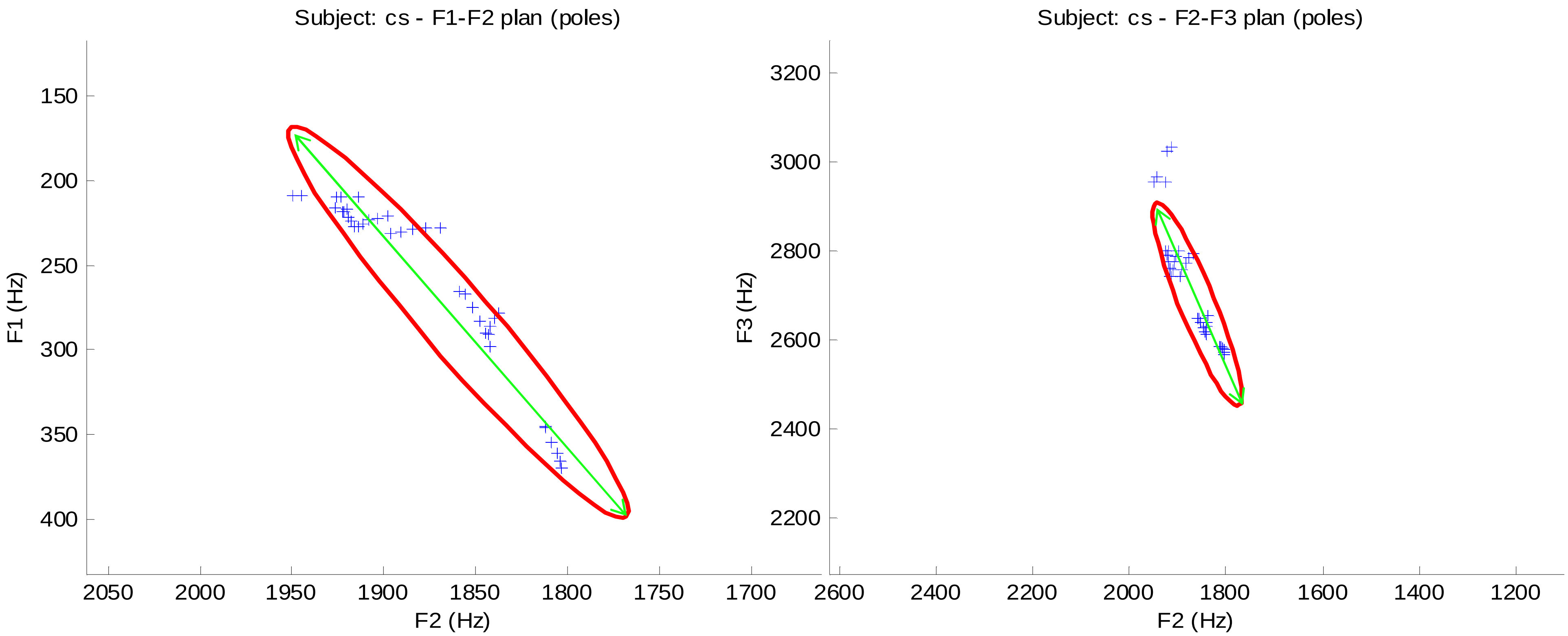


Variability in muscle orientation – [i] AV

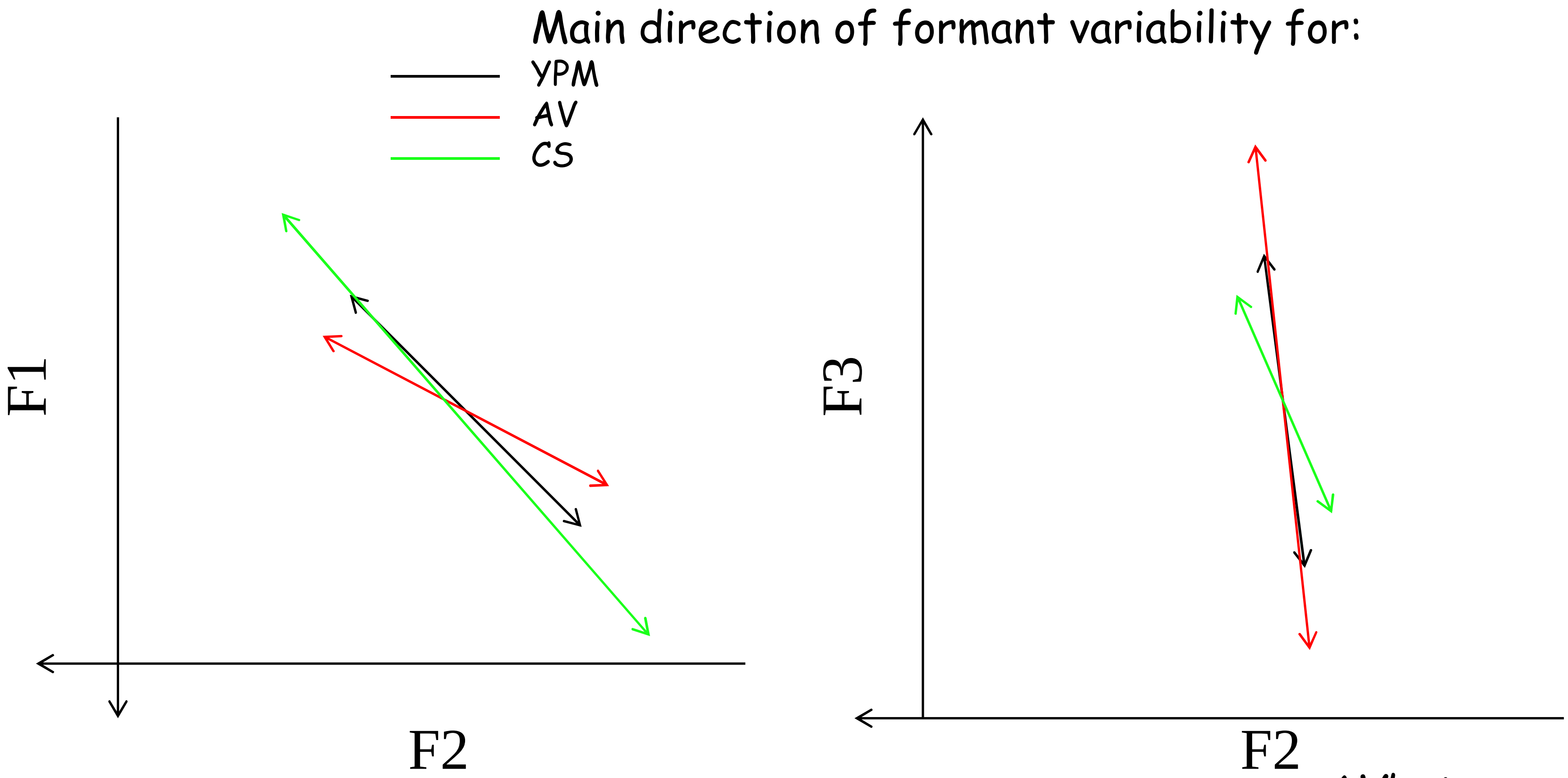




Variability in muscle orientation – [i] CS



Variability in muscle orientation – [i]

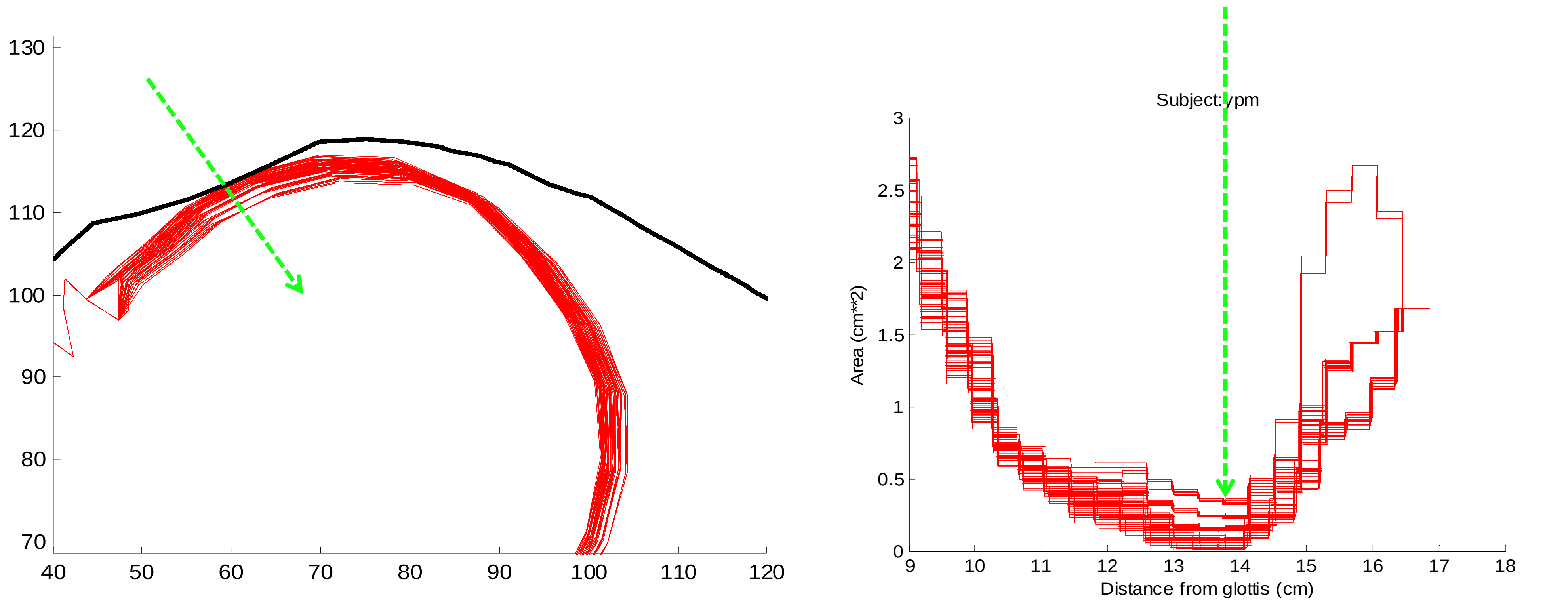


Summary : AV has - the largest ration VarF2/VarF1
- the smallest VarF1
- the largest VarF3

AV's tongue remains very close to the palate while moving backward

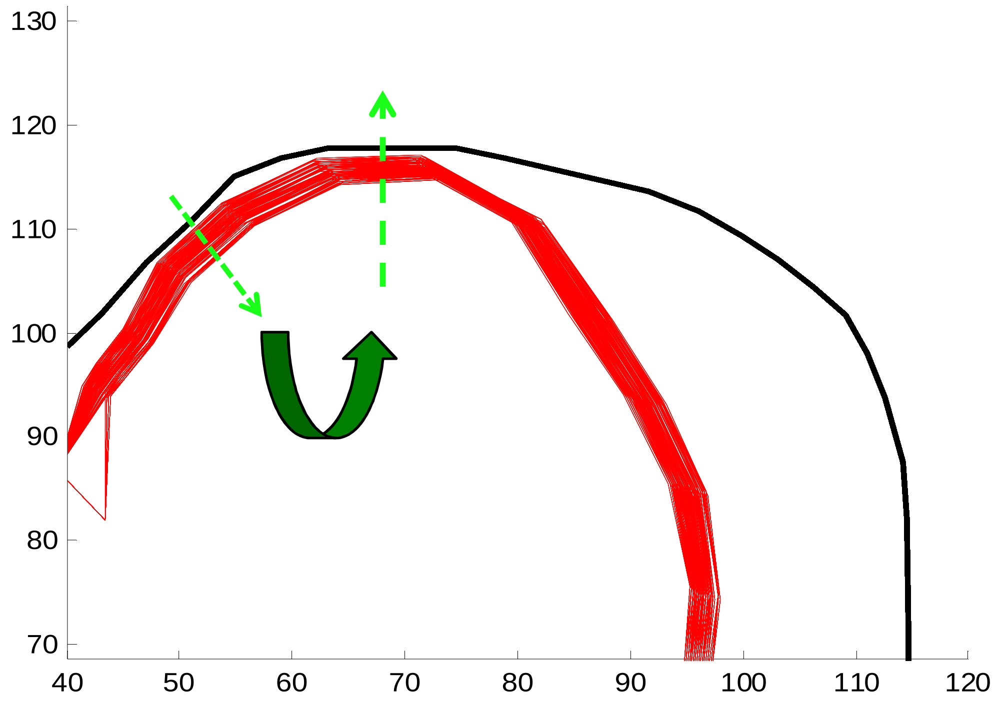
Variability in muscle orientation – [i] YPM

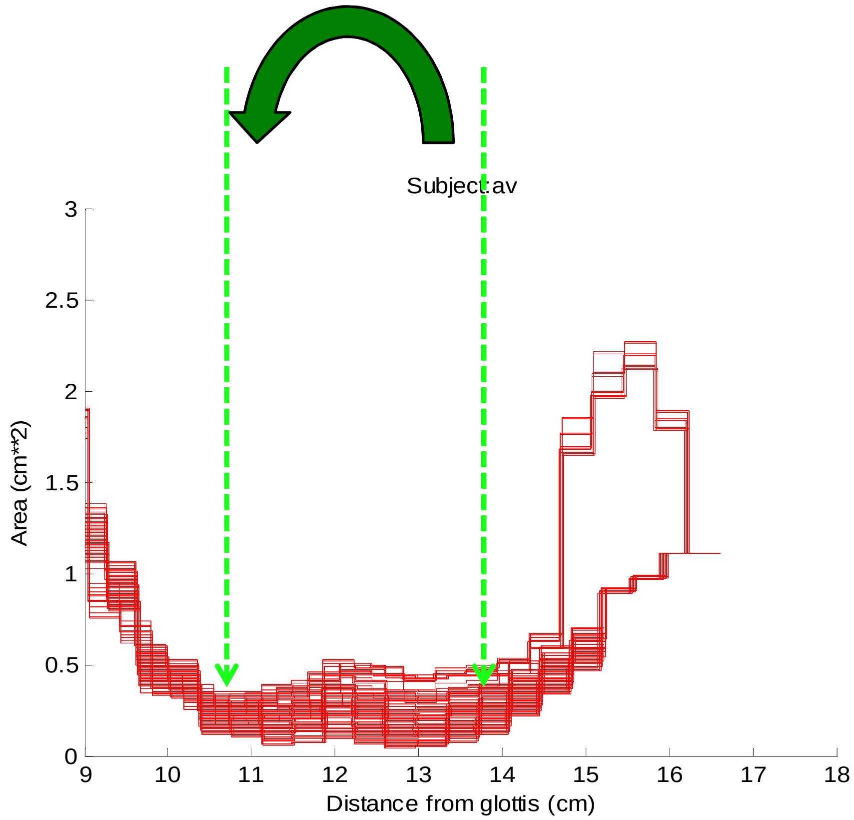
Constriction becomes more open but remains at the same location



Variability in muscle orientation – [i] AV

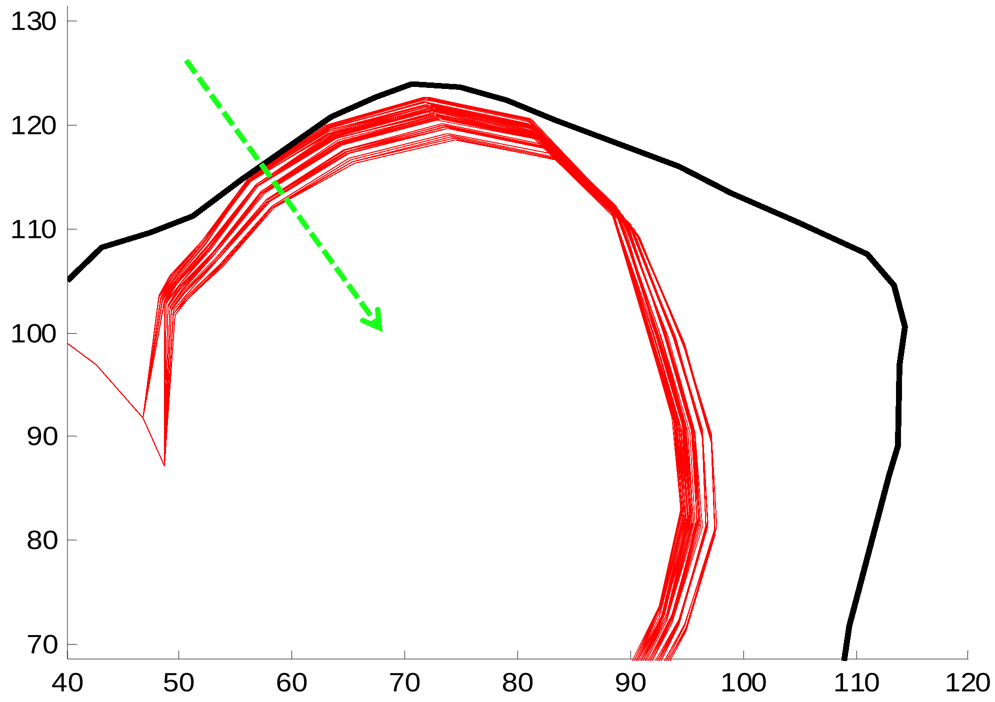
Constriction opens slightly and moves backward

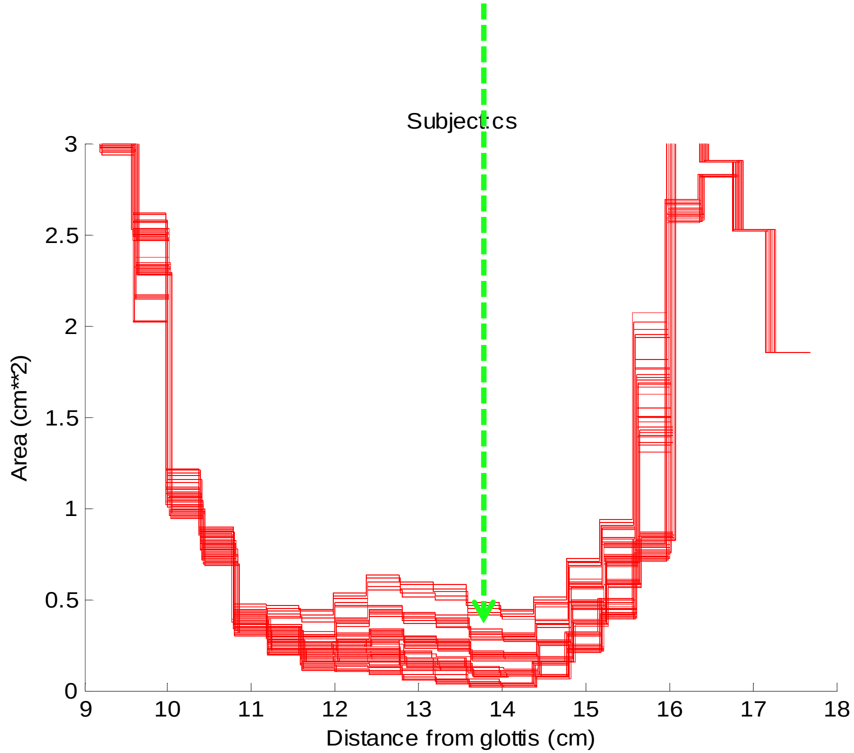




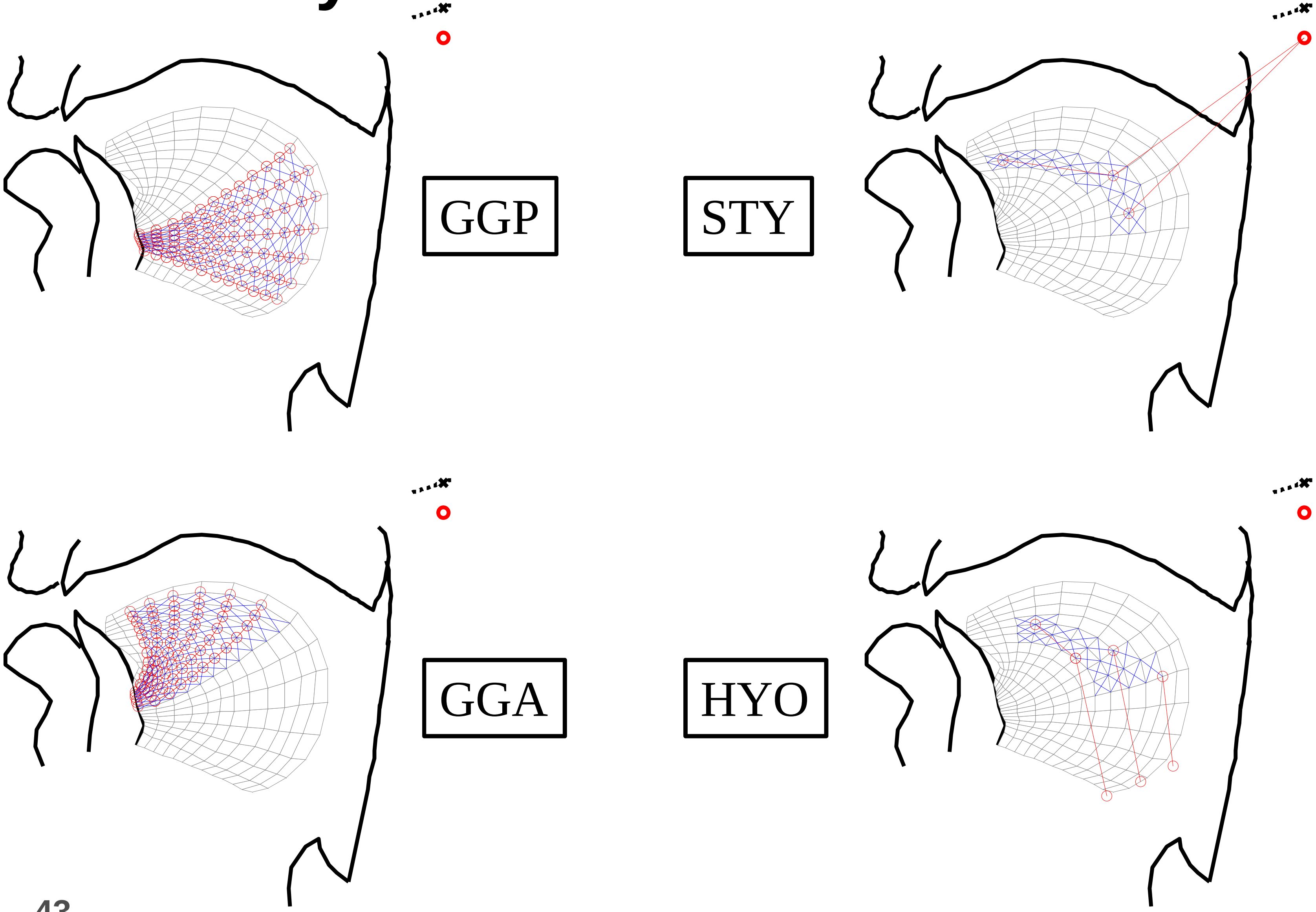
Variability in muscle orientation – [i] CS

Constriction becomes more open but remains at the same location

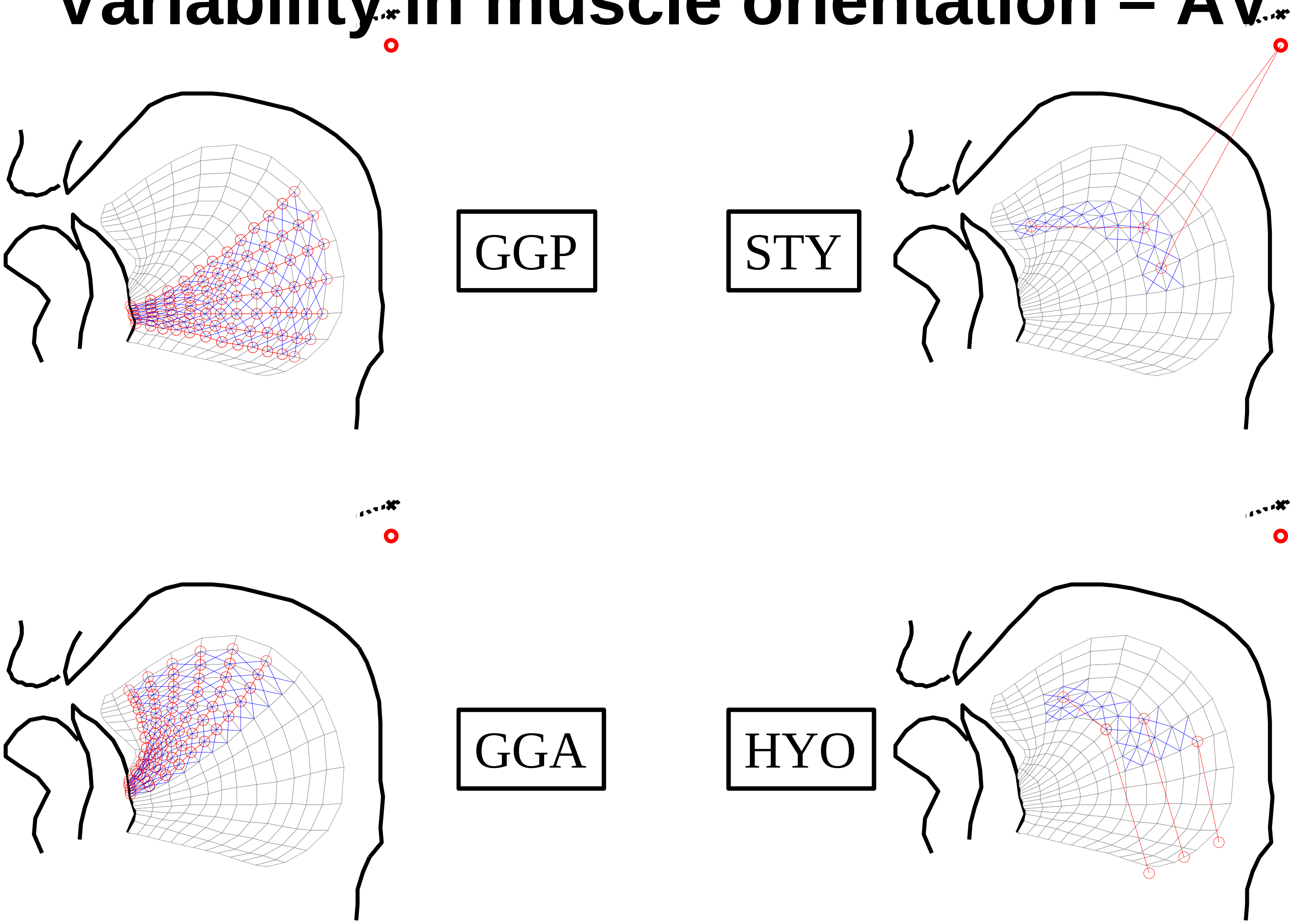




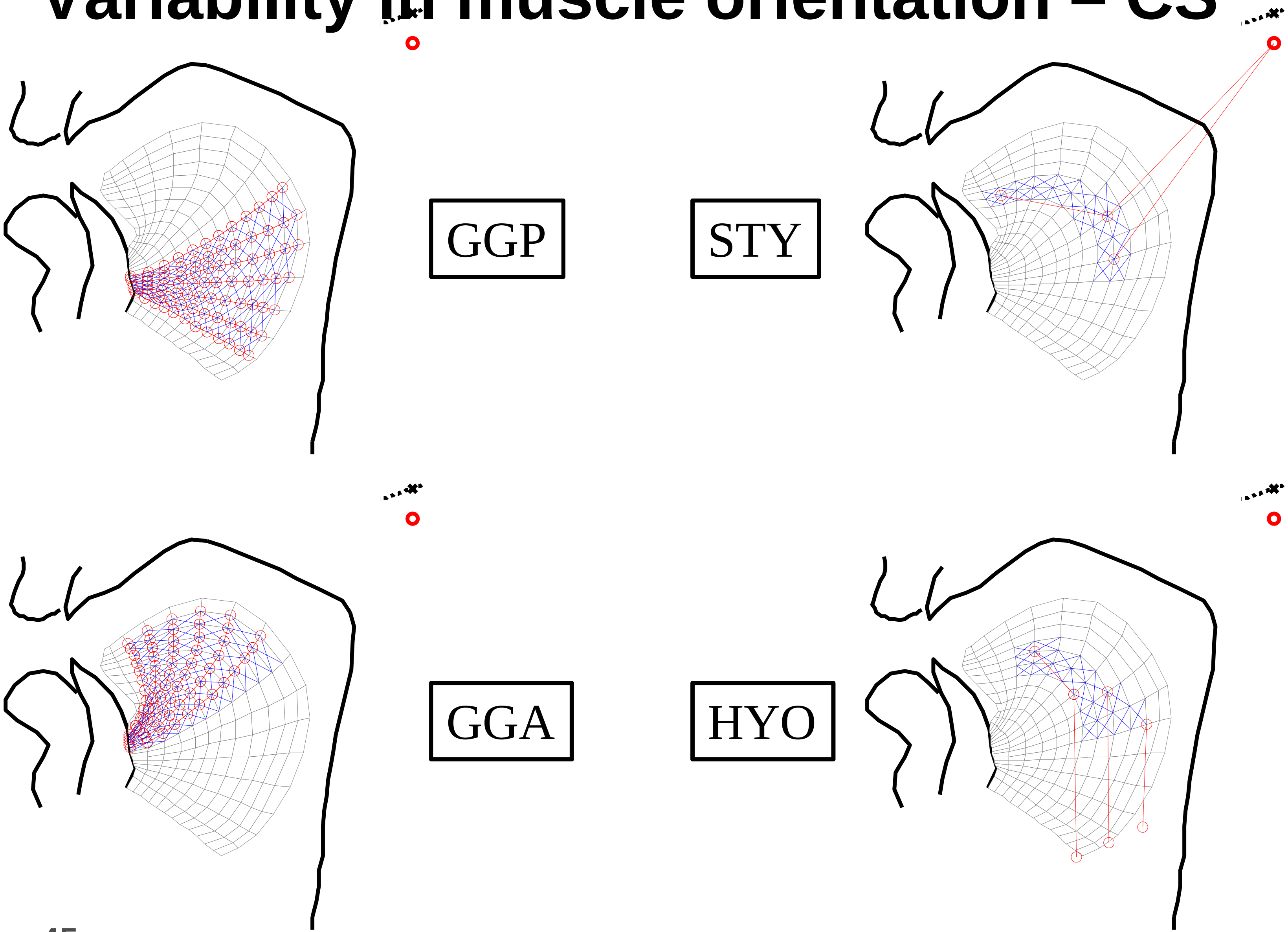
Variability in muscle orientation – YPM



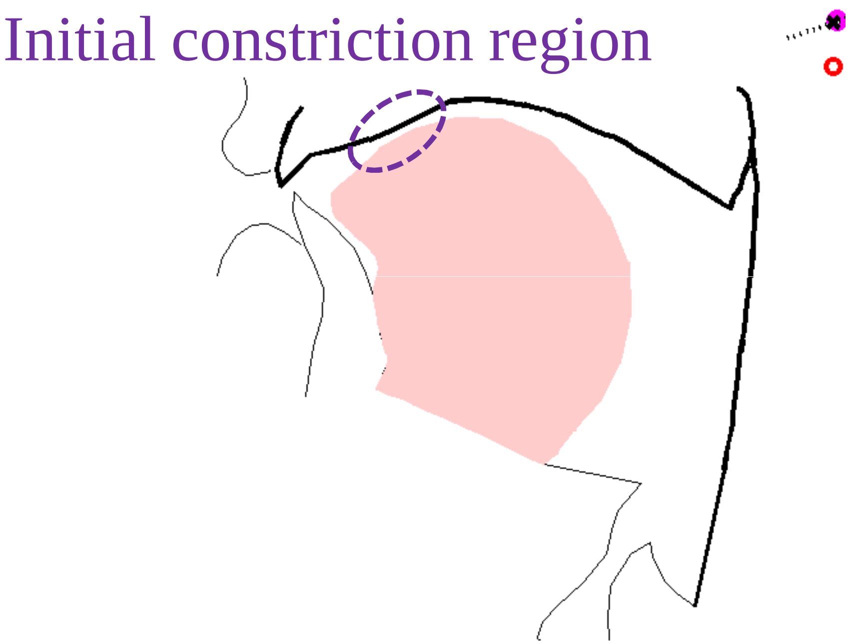
Variability in muscle orientation – AV

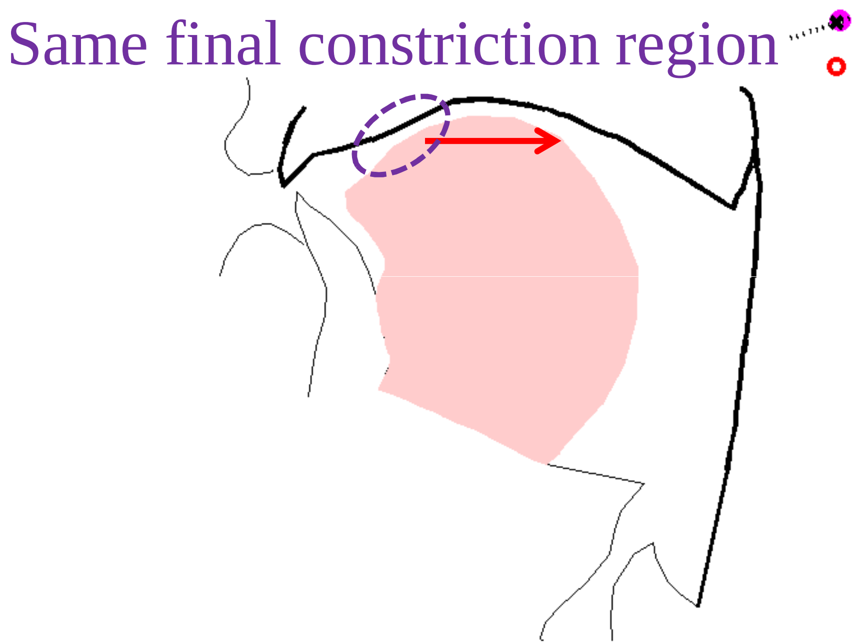


Variability in muscle orientation – CS



YPM – EFFECT of STYLOGLOSSUS

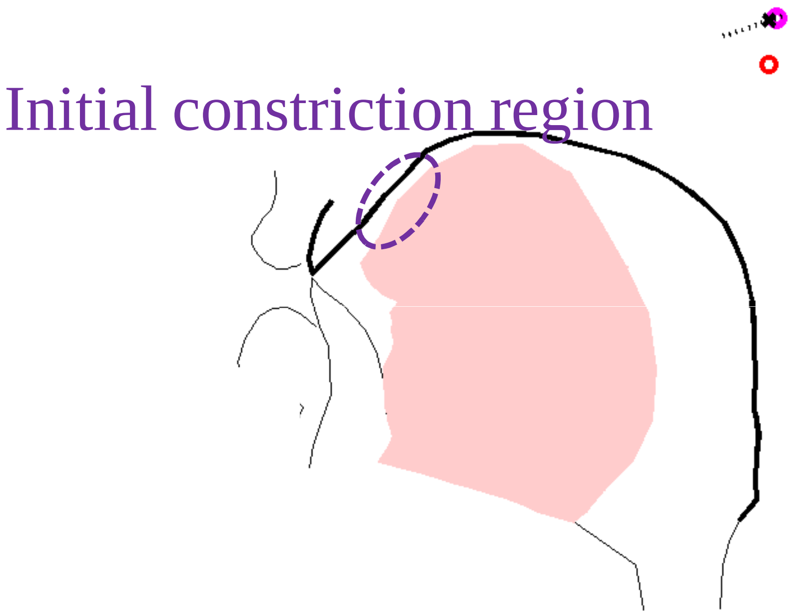




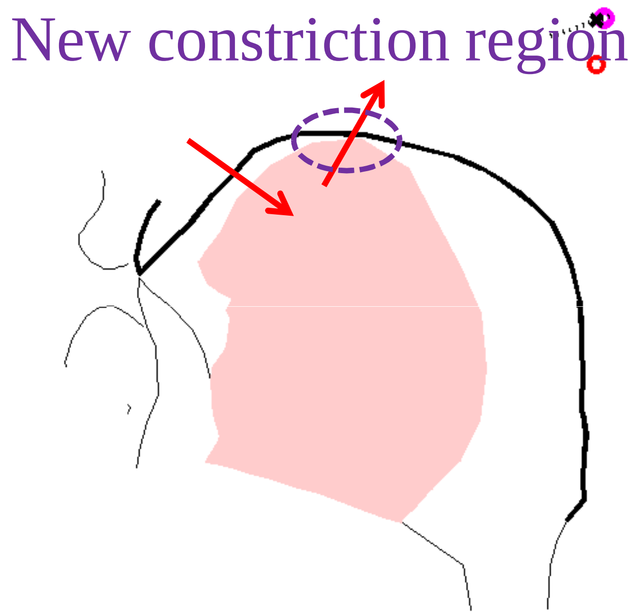
[i] at target

Main direction of displacement associated with STY activation

AV – EFFECT of STYLOGLOSSUS

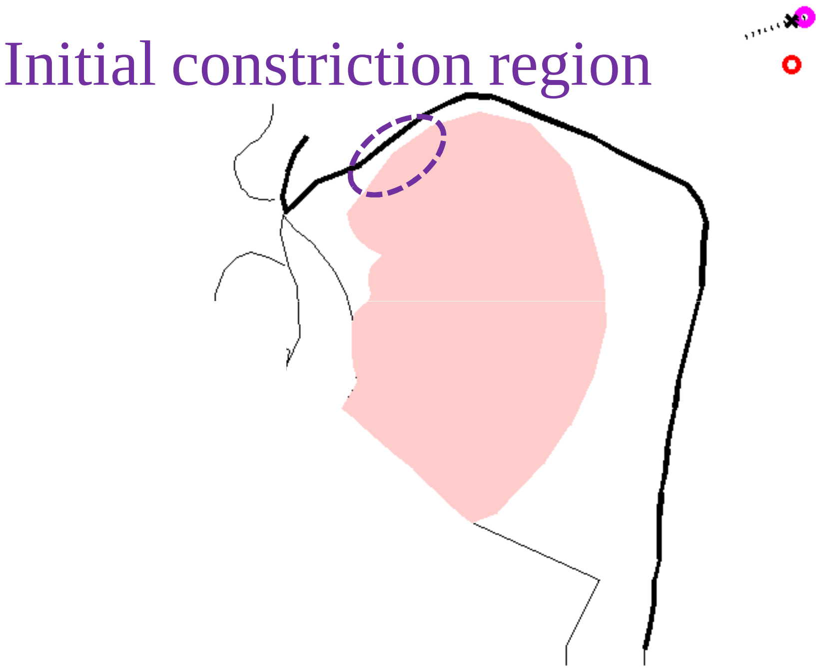


[i] at target

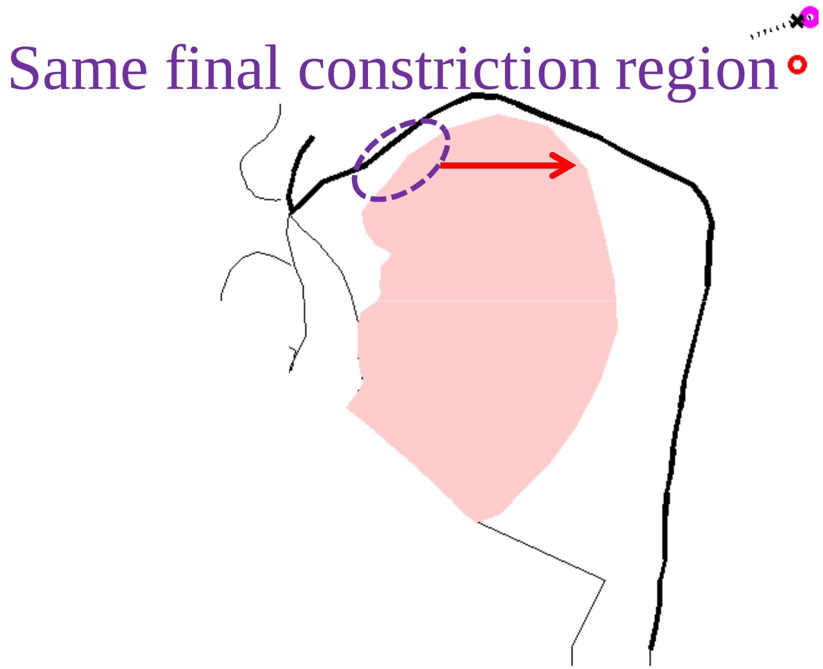


Main direction of displacement associated with STY activation

CS – EFFECT of STYLOGLOSSUS



[i] at target



Main direction of displacement associated with STY activation

First conclusion

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

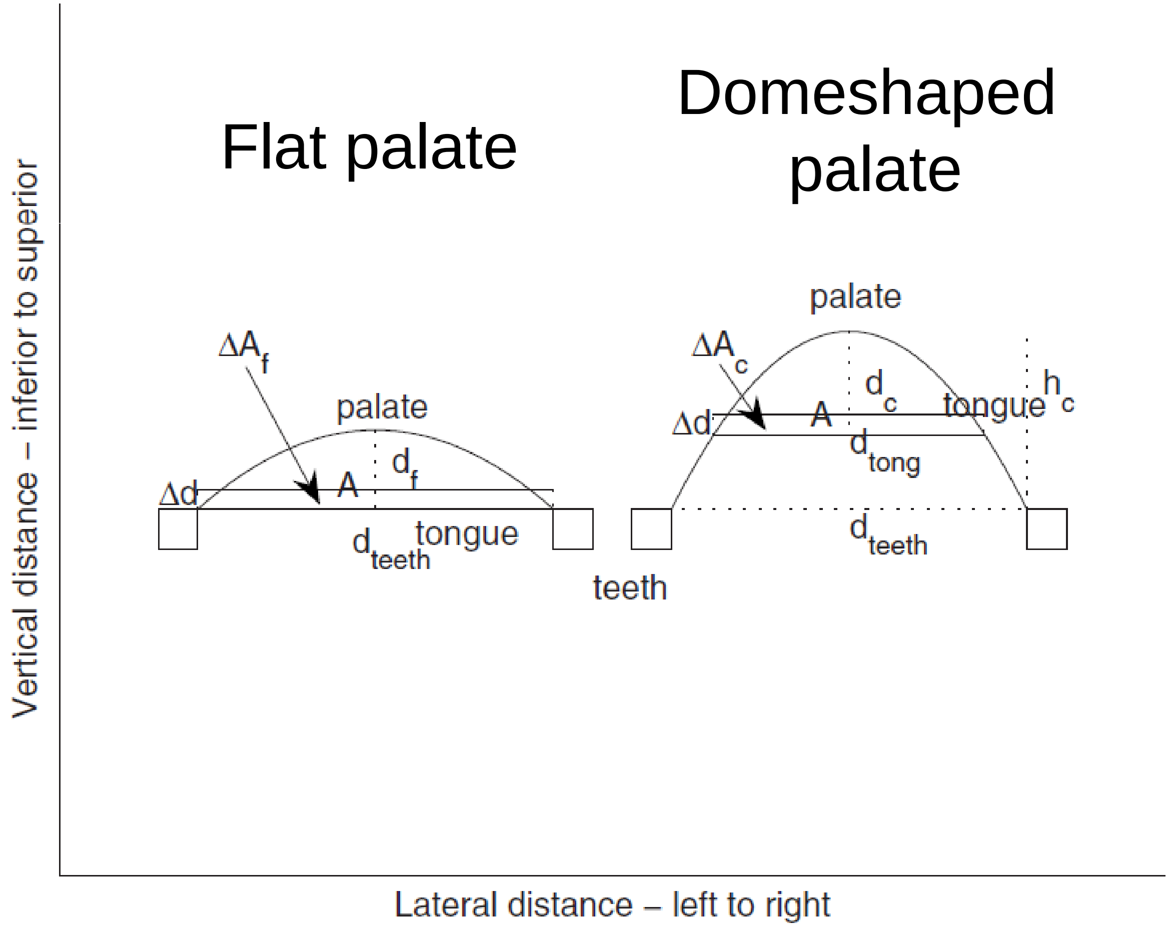
➡

- Does it influence the acoustic speaker-specific variability.
- Does it nfluence motor control strategy/accuracy?

A related issue : palate shape and articulatory variability

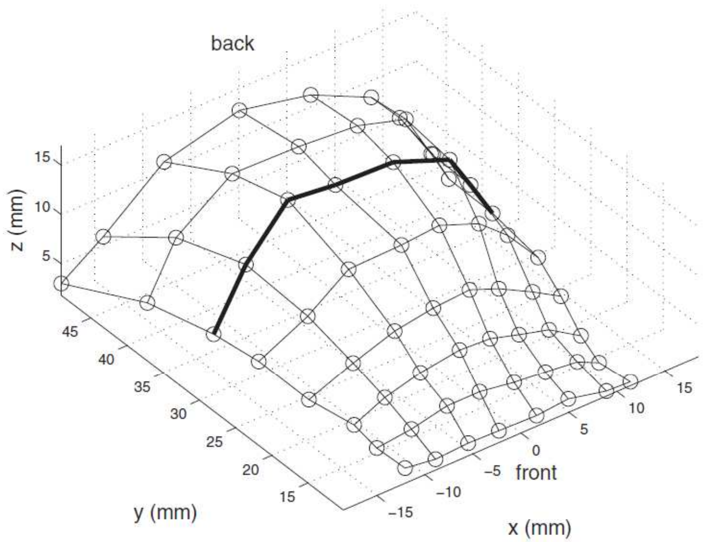
Brunner, Fuchs and Perrier, JASA 2009

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.

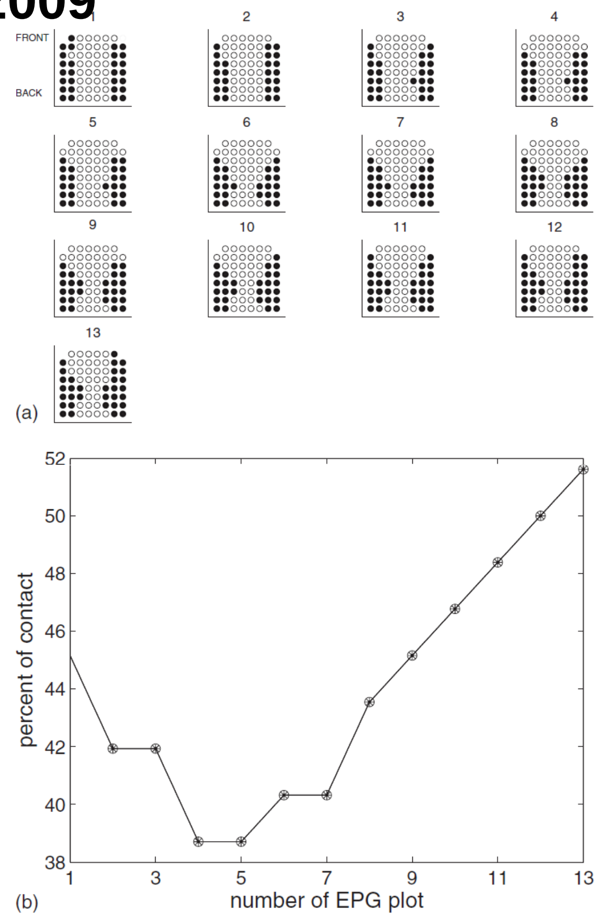


Palate shape and articulatory variability

Brunner, Fuchs and Perrier, JASA 2009



Measure of palate curvature
in the coronal plane : α
a high -value corresponds
to a flat palate
and a low value
to a domeshaped palate.

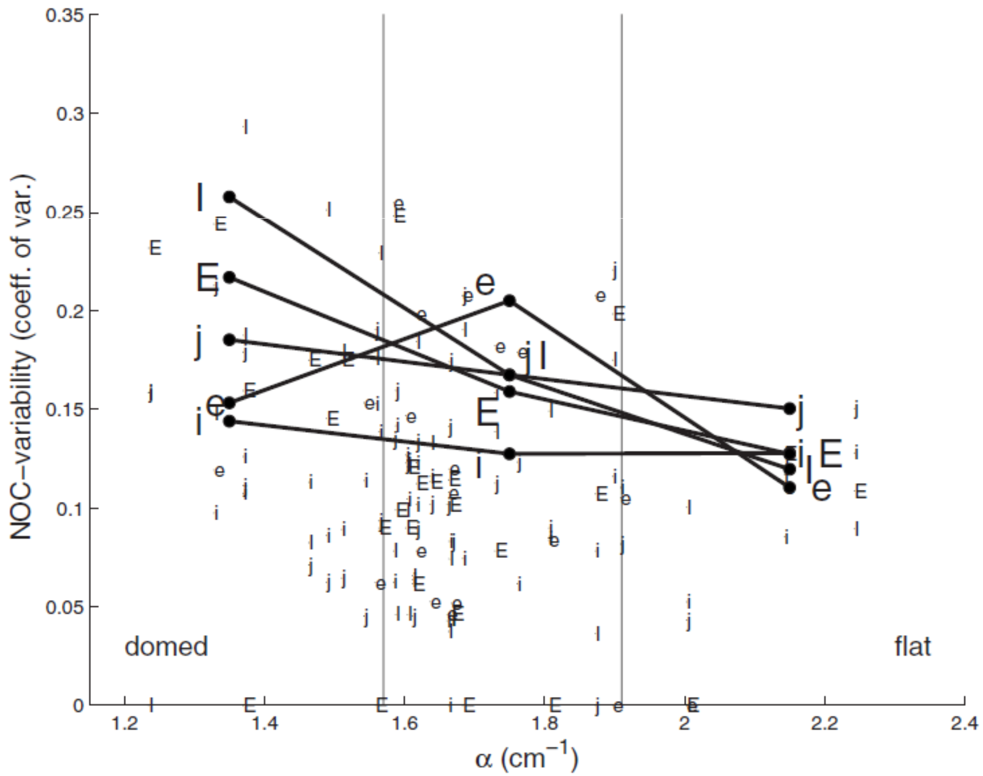


Measure of articulatory
Variability with EPG:
COG & Number of contacts.

Palate shape and articulatory variability

Brunner, Fuchs and Perrier, JASA 2009

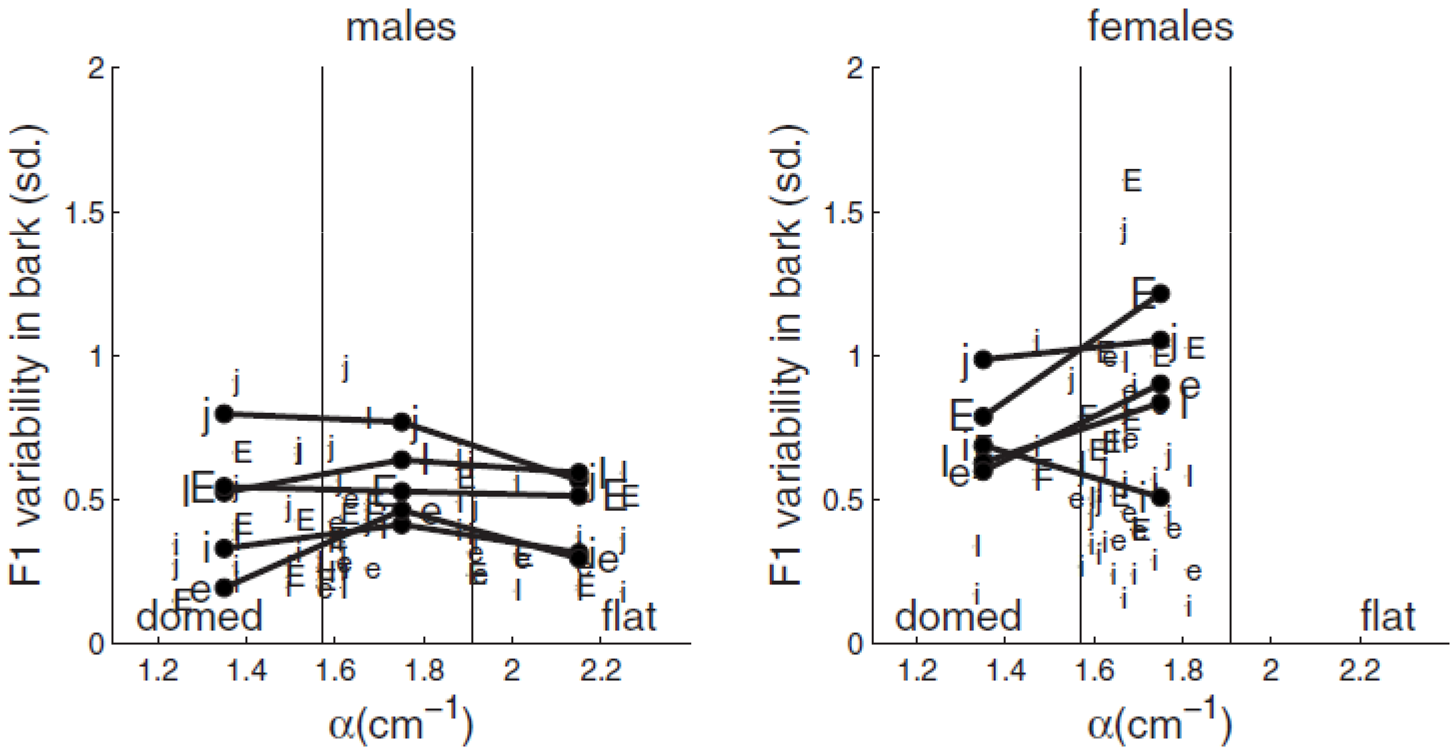
Articulatory variability (32 speakers)



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/

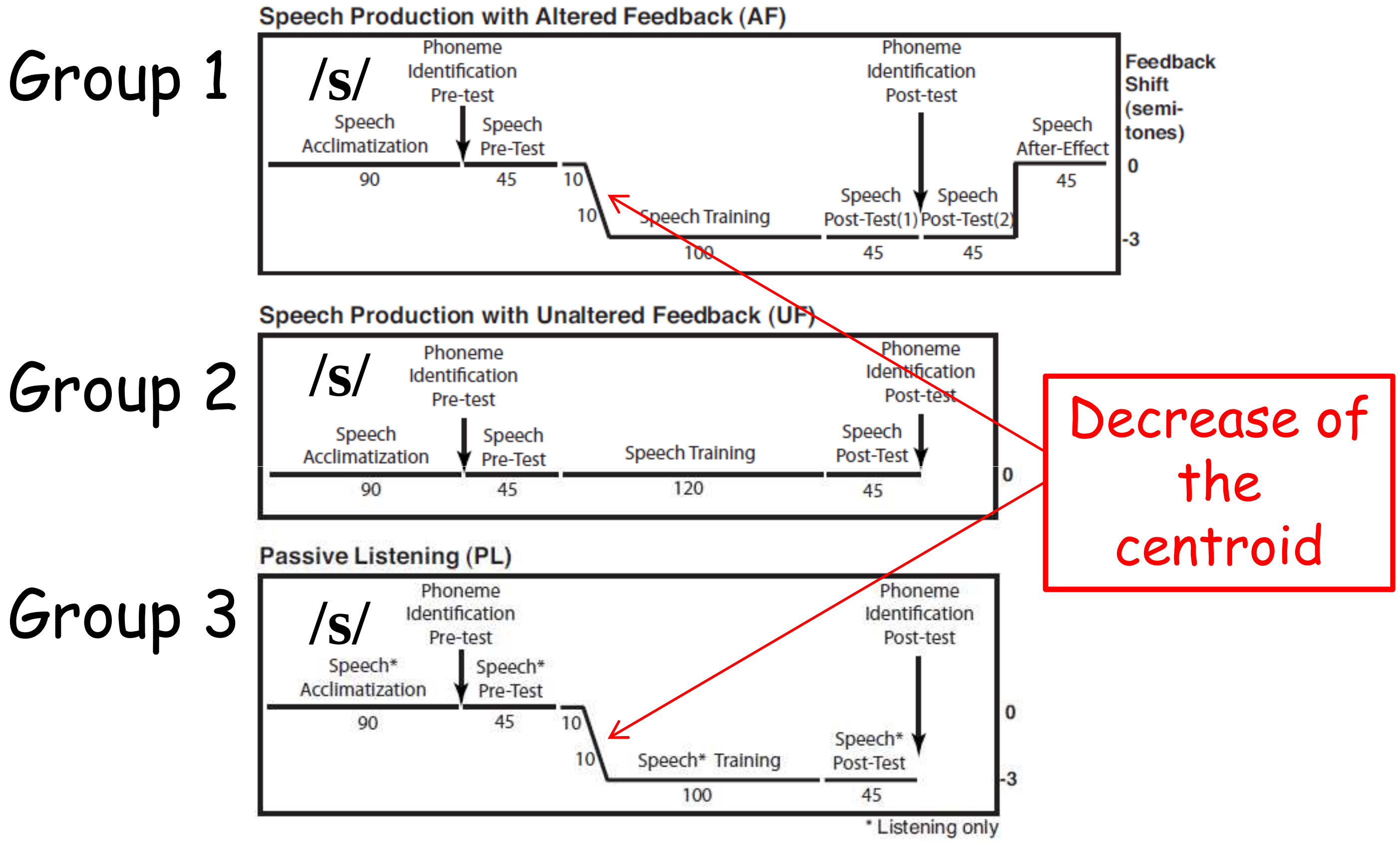
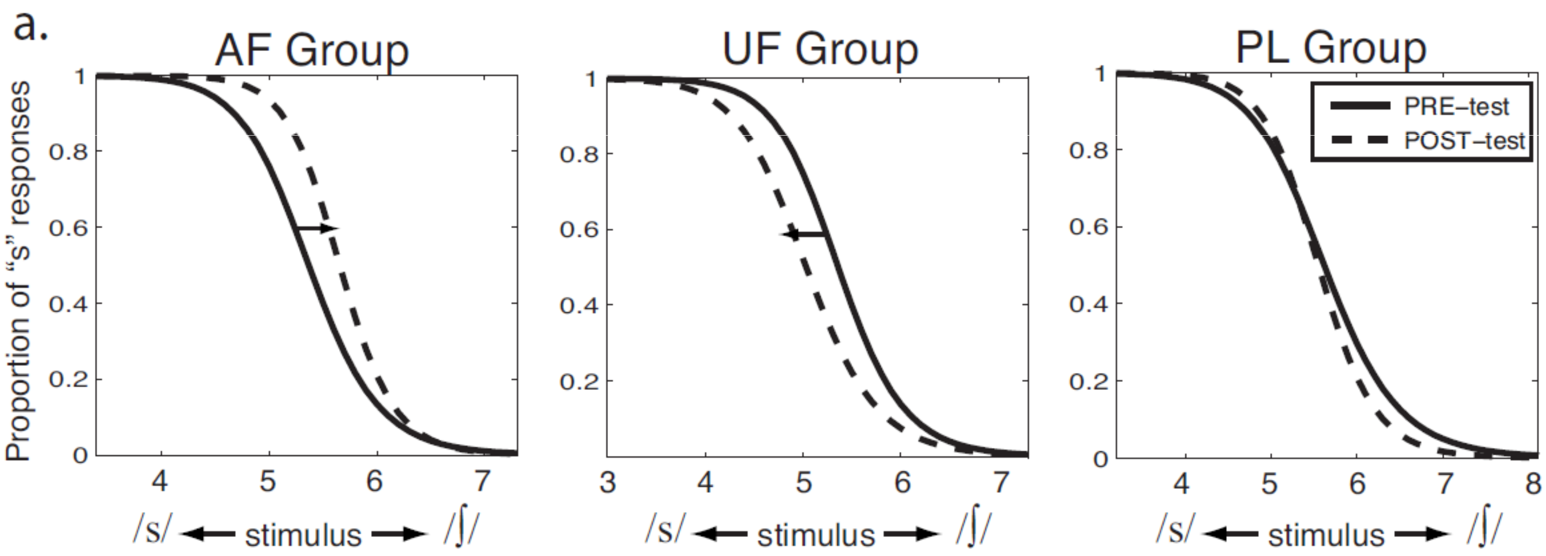


FIG. 2. Schematic depicting the sequence of procedures for each of the three groups of subjects: (1) speech production with altered auditory feedback (AF, top), (2) speech production with unaltered auditory feedback (UF, middle), and (3) passive listening (PL, bottom). The numbers underneath the horizontal 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 | Group 2 | Group 3



Perceptuomotor adapation | Selective adaptation | No effect

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)

    A high sensitivity of speech spectral patterns to motor variability increases the intolerance to motor vatiability 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)

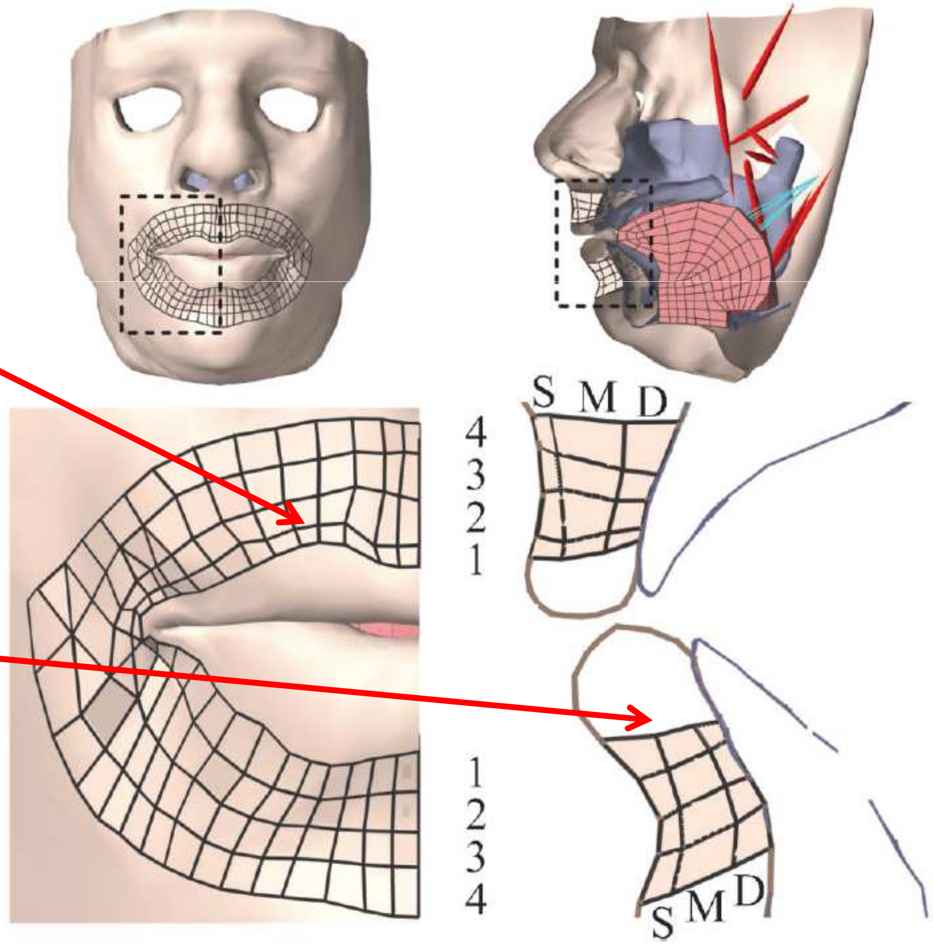
Variation in orbicularis oris implementation and lip protrusion

Stavness, Nazari, Perrier, Demolin, Payan, JSLHR, 2013

Modeling variation in OO Implementation

1,2,3,4: marginal to peripheral

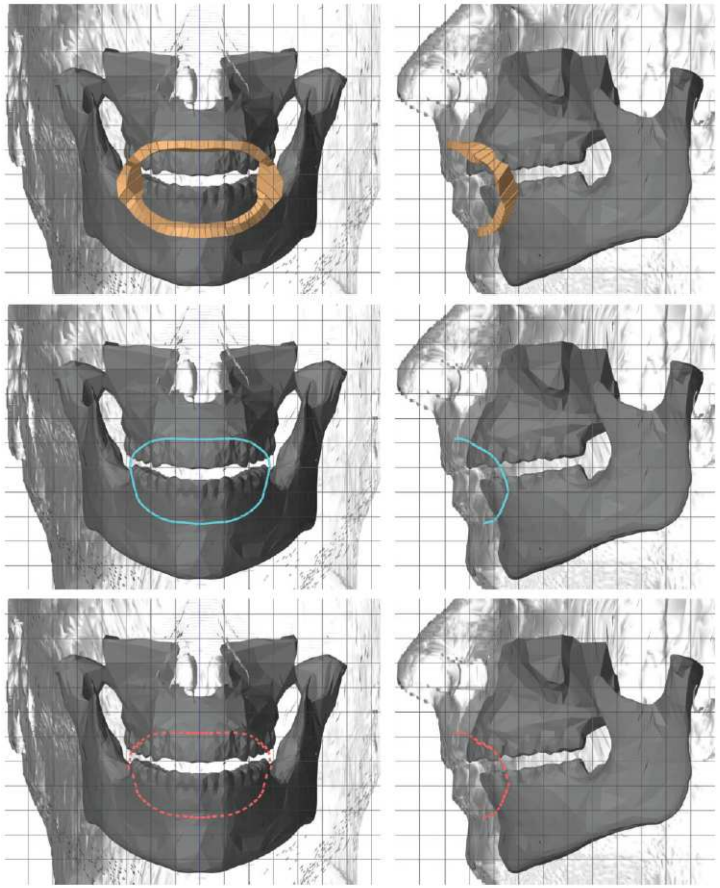
S,M,D: Superficial to depth



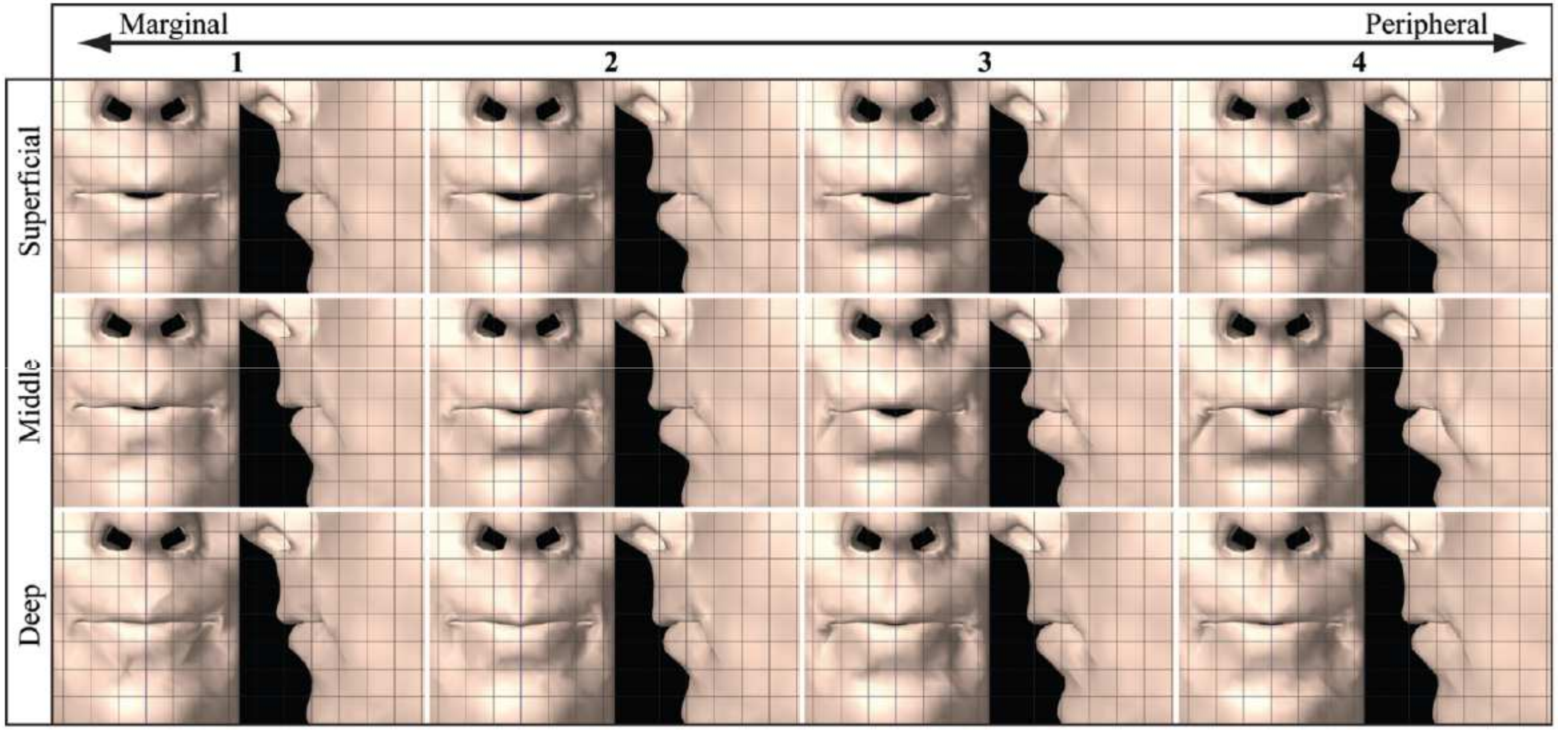
Variation in orbicularis oris implementation and lip protrusion

Stavness, Nazari, Perrier, Demolin, Payan, JSLHR, 2013

Example of OO
Implementation
M3



Variation in orbicularis oris implementation and lip protrusion

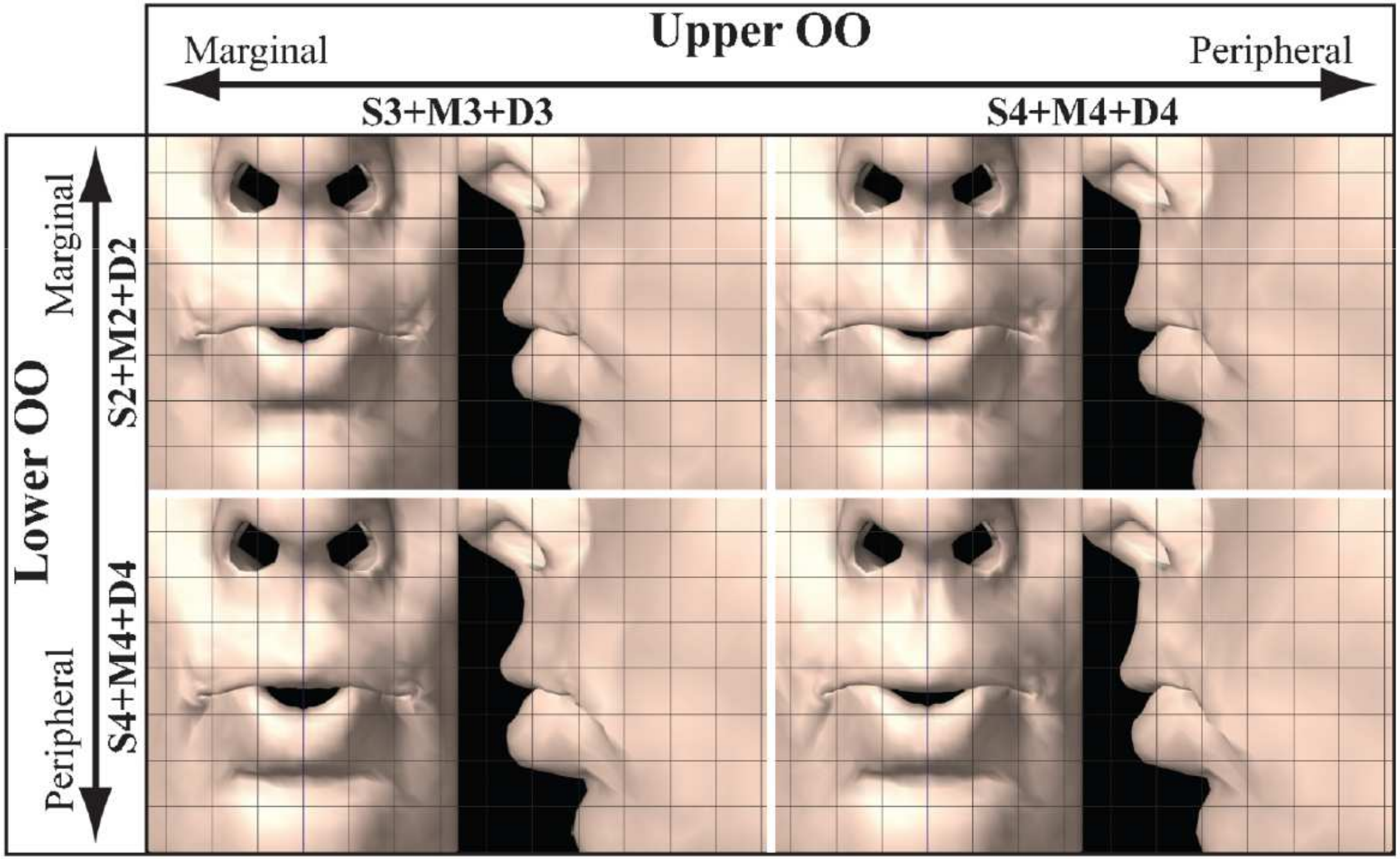


Middle and peripheral implementation generates protrusion and rounding

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

Stéphanie Buchaillard[a)] and Pascal Perrier
ICP/ GIPSA-Lab, UMR CNRS 5216, Grenoble INP, 38402 Saint Martin d'Hères, France

Yohan Payan
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(Received 18 March 2008; revised 21 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 (λ-model of the equilibrium 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, electropalatographic, and cineradiographic 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 transversalis, 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 motor command variations for the main tongue muscles revealed a non-negligible modification of the alveolar groove in contradiction to the saturation effect hypothesis, due to the role of the anterior genioglossus. Finally, the impact of subject position (supine or upright) on the production of French cardinal vowels was explored and found to be negligible.
 [DOI: 10.1121/1.3204306]

PACS number(s): 43.70.Bk, 43.70.Aj [AL] Pages: 2033–2051

I. INTRODUCTION

Speech movements and acoustic speech signals are the results of the combined influences of communicative linguistic 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 and/or speech perception systems. The predictions of these models can then be compared with experimental data, and used to infer information about parameters or control signals that are not directly measurable or the measurement of which is difficult and not completely reliable. Such a methodological approach underlies 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 token-to-token variability, and its consequences for tongue shape sensitivity to changes in head (supine versus upright) 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 anatomical, neurophysiological, and physical characteristics of the tongue, as well as with the vast growth in the computational capacities of computers. All these models have significantly contributed to the increase in knowledge about tongue behavior and tongue control during speech production, and more specifically about the relations between muscle recruitments and tongue shape or acoustic signal (see, in particular, Perkell, 1996, using his model presented in Perkell, 1974; Kakita *et al.*, 1985; Hashimoto and Suga, 1986; Wilhelms-Tricarico, 1995; Payan and Perrier, 1997; Sanguineti *et al.*, 1998; Dang and Honda, 2004). With a more sophisticated three-dimensional (3D) vocal tract model, based on non-linear continuum mechanics modeling, and taking into consideration 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 the oral cavity, controlled by a functional model of muscle force generation [λ-model of the equilibrium point hypothesis (EPH)] and coupled with an acoustic model. It is a significantly improved version of the model originally developed in GIPSA-Lab by Gérard and colleagues (Gérard *et al.*, 2003, 2006). The oral cavity model was developed so as to give as realistic a 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 this subject, different kinds of data [x-ray, computed tomography (CT) images, and acoustic data] were available. The parameters used in this model were either extracted from the literature, derived from experimental data, or adapted from the literature. This modeling study is inseparable from a thorough experimental approach. In addition to

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Motor Control, 2011, 15, 141-168

Shaping by Stiffening: A Modeling Study for Lips

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

On the basis of simulations carried out with a finite element biomechanical model of the face, the influence of the muscle stress 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 lip shape. When stress stiffening 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 shaping associated with the absence or presence of stiffening have consequences for the spectral characteristics of the speech signal obtained for the French vowel /u/. These results are interpreted in terms of their consequences for the motor control strategies underlying the protrusion/rounding gesture in speech production.

Keywords: speech motor control, stiffness, biomechanics, orofacial 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 activations, 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-occur as the consequences 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) isotonic 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 Feldman, 1986, for an account of these separate controls in the context of the Equilibrium Point

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To know more

On the relationship between palate shape and articulatory behavior

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In this study the acoustic and articulatory variabilities of speakers with different palate shapes were compared. Since the cross-sectional area of the vocal tract changes less for a slight 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 reduce their articulatory variability in order to keep the acoustic output constant. This hypothesis was tested on 32 speakers recorded via electropalatography (EPG) and acoustics. The articulatory and acoustic variability of some of their vowels and /j/ was measured. Indeed, the results show that the speakers with flat palates reduce their variability in tongue height. There is no such trend in acoustic variability. © *2009 Acoustical Society of America.* [DOI: 10.1121/1.3125313]

PACS number(s): 43.70.Bk, 43.70.Mn [CHS] Pages: 3936–3949

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 make use of this nonlinearity in order to investigate speakers' control of variability. Basically, we compare speakers for whom theoretical models of articulatory-acoustic relations predict that they can allow for much articulatory variability without having as much variability in the acoustic output with speakers for whom the models suggest that they cannot allow for so much 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, the one very flat and the other very curved or domeshaped (cf. Fig. 1). Let us also consider for the sake of simplicity and clarity in the demonstration that both palates would have the same distance d_{teeth} between the molars (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 cross-sectional area A as the speaker with the flat palate. The width of the vocal tract at the height of the tongue surface is then d_{tong}, which is smaller than d_{teeth}. For the flat palate d_{tong} would be equal to d_{teeth} and is therefore not given in the figure.

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If the tongue is now raised by Δd, the distance between tongue and palate changes to $d_c-\Delta d$ for the domeshaped palate (c stands for *curved*) and $d_f-\Delta d$ for the flat palate. The difference between the original and the new area is for the flat palate

$$\Delta A_f = d_{teeth} \times \Delta d. \tag{1}$$

For the domeshaped palate, if we approximate the palate sides with straight lines,

$$d_{tong} = \frac{d_{teeth} \times d_c}{h_c} \tag{2}$$

the difference in the cross-sectional area is

$$\Delta A_c = d_{teeth} \Delta d \frac{d_c}{h_c}. \tag{3}$$

Given that h_c (height of the domeshaped palate) is greater than d_c (distance between tongue and domeshaped palate) the fraction d_c/h_c is smaller than 1. Consequently, a comparison between Eqs. (1) and (3) shows that ΔA_c is smaller than ΔA_f. 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 perceptually relevant characteristics of the vocal tract (i.e., the constriction 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

JSLHR

Article

A Biomechanical Modeling Study of the Effects of the Orbicularis Oris Muscle and Jaw Posture on Lip Shape

Ian Stavness,[a] Mohammad Ali Nazari,[b,c] Pascal Perrier,[b] Didier Demolin,[b] and Yohan Payan[d]

Purpose: The authors' general aim is to use biomechanical models of speech articulators to explore how possible variations in anatomical structure contribute to differences in articulatory strategies and phone systems across human populations. Specifically, they investigated 2 issues: (a) the link between lip muscle anatomy and variability in lip gestures and (b) the constraints of coupled lip/jaw biomechanics on jaw posture in labial sounds.
Method: The authors used a model coupling the jaw, tongue, and face. First, the influence of the orbicularis oris (OO) anatomical implementation was analyzed by assessing how changes in depth (from epidermis to the skull) and peripheralness (proximity to the lip horn center) affected lip shaping. Second, the capability of the lip/jaw system to generate protrusion and rounding, or *labial closure*, was evaluated for different jaw heights.
Results: Results showed that a peripheral and moderately deep OO implementation is most appropriate for protrusion and rounding; a superficial implementation facilitates closure; protrusion and rounding require a high jaw position; and closure is achievable for various jaw heights.
Conclusions: Models provide objective information regarding possible links between anatomical and speech production variability across humans. Comparisons with experimental data will illustrate how motor control and cultural factors cope with these constraints.

Key Words: biomechanics, articulation, physiology, speech production, lip shape, orbicularis oris, jaw, face

Variations and regularities found in the sound systems of human languages might be due, at least in part, to the intrinsic properties of the orofacial motor system. Variability in vocal tract anatomy across human populations could have initiated differences in articulatory gestures across languages. Likewise, properties shared by all human orofacial motor systems could have been the basis for common articulatory and motor trends observed in a large number of languages. In this context, models of the orofacial motor system can be used to evaluate the influence of variations in physiological and anatomical properties on articulatory speech gestures. Comparing predictions made with models to data collected from speakers of various languages permits a quantitative assessment of the physiological factors that have potentially influenced the emergence of sound system rules and variability in the languages of the world.

Lip gestures are good candidates for investigating potential links between physiological variability in humans and variability in the sound systems of languages because significant differences in facial muscle morphology are known to exist across subjects. These anatomical variations could explain differences in speech-specific lip gestures, such as lip protrusion and lip rounding. In a discussion of anthropophonetic variations, Brosnahan (1961) and Catford (1977) quoted the studies of Huber (1931) and stated that the risorius muscle is found in about 20% of Australians and Melanesians, 60% of Africans, 75% to 80% of Europeans, and 80% to 100% of Chinese and Malays. More recently, Pessa et al. (1998) showed that as many as 22 of their 50 cadaver specimens lacked the risorius muscle. Although based on small samples of data, these studies suggest that such genetic anatomical characteristics could be consistent, or even occur with increasing frequency, over successive sections of populations of the African-European-Asian land mass. Pessa et al. (1998) also found that, in 17 of their 50 specimens, the zygomaticus major presented a bifid structure with two insertions points. The two insertion points of this

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Thank you