CATEGORICAL VARIATION IN LIP POSTURE IS DETERMINED BY QUANTAL BIOMECHANICAL-ARTICULATORY RELATIONS

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1. INTRODUCTION

The labial place of articulation exhibits categorical variation in lip postures corresponding with different manners or degrees of constriction. Specifically, across many languages, stops (complete closures) are most often produced using a flat bilabial constriction; fricatives (critical closures) are produced using labiodental constrictions; and vowels or semivowels (approximant constrictions) are produced using rounded and protruded constrictions (Ladefoged & Maddieson 1996).

The present paper investigates why the lips should adopt such different postures in an attempt simply to modulate degree of constriction. We propose that this categorical variation in lip posture is the result of the speech production system taking advantage of quantal properties (after Stevens 1972) in lip biomechanics. Specifically, we expect to find that assuming different initial settings will allow the lips to achieve the desired speech outcomes with highly variable activation levels and minimal active control.

We test this proposal by simulating lip constrictions using a three-dimensional biomechanical face model in ArtiSynth (www.artisynth.org). The model accounts for passive tissue mechanics as well as active muscle stress and stiffness and can be used to analyze the effect of muscle activation on lip shaping, protrusion, and contact. It will be shown that this hypothesis is supported for stops via ballistic overshoot and for approximants via sphincteric saturation (Nazari et al., 2011). Labiodental fricatives will be treated as stop constrictions against an irregular dental surface.

2. METHODS

We used a model of lip-face dynamics to analyze the effect of muscle activations on lip shaping and opening in different lip configurations. Simulations were made with the ArtiSynth simulation toolkit, which is described in detail by Stavness et al. (2011). The 3D finite-element method (FEM) face model is based on a reference model reported by Nazari et al. (2011) and uses a hyper-elastic, incompressible Mooney-Rivlin material. The face model was adapted and registered to a specific speaker (Bucki et al., 2010) for which we also have jaw, skull, and tongue models (Stavness et al., 2011). Contact between the lips, and between the lips and teeth, is detected and handled as a constraint on the FEM dynamics, allowing for lip compression, as is known to occur in labial stops and fricatives.

The lip musculature is modeled using a transversely anisotropic FEM material (Weiss et al., 1996). The muscle fiber paths for the face muscles are consistent with Nazari et al. (2011), who used simplified line-based muscles with functional isotropic stiffening during muscle activation. Our FEM-based muscles provide a better distribution of muscle stress within the face model and more realistic transverse-anisotropic stiffening during muscle activation. Mesh elements are associated with fibers by finding those elements that are near the muscle fiber paths for each muscle group. The transverse direction of each element is interpolated from the muscle fiber path and represents the muscle's line-of-action. Stress is added in the transverse direction to represent passive muscle stress (varying non-linearly with strain along the preferred direction) and active muscle stress (varying linearly with muscle activation).

Muscle activations were manually set to achieve canonical lip postures for bilabial (stop) and protruded (approximant) constrictions. Lip shapes were achieved by activating muscles up to a maximum stress as indicated in Table 1. The maximum stress values correspond to an average of about 50% of maximum voluntary muscle contraction. Postures for rest position, bilabial constriction and approximant constriction are shown in Figures 1, 2 and 3.

Table 1. Maximum muscle stress (kPa) used for simulated bilabial and approximant constrictions, including the peripheral/marginal fibers of orbicularis oris (OOP/M), risorius (RIS), and mentalis (MEN) muscles.

	Bilabial constriction	Approximant constriction
OOP	–	50
OOM	60	–
RIS	40	–
MEN	40	–

3. RESULTS

The plot in Figure 4 shows that a large range of possible muscle activation levels will produce equivalent degrees of constriction. Closure/protrusion was achieved at relatively low activation (0.2, or ~10% of max. voluntary contraction). Increased activation yielded more compression for stops and more protrusion for approximants, but did not materially affect constriction area or posture.

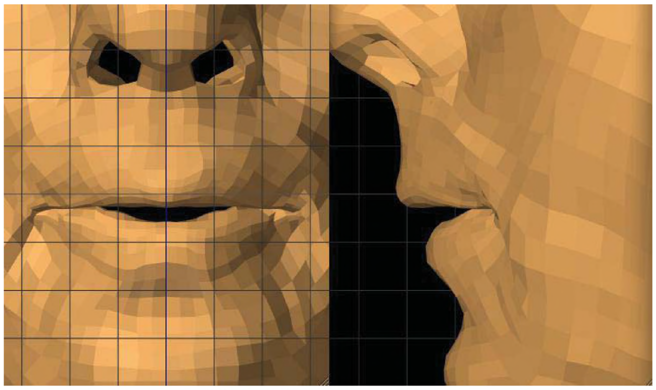

Figure 1. Rest position.

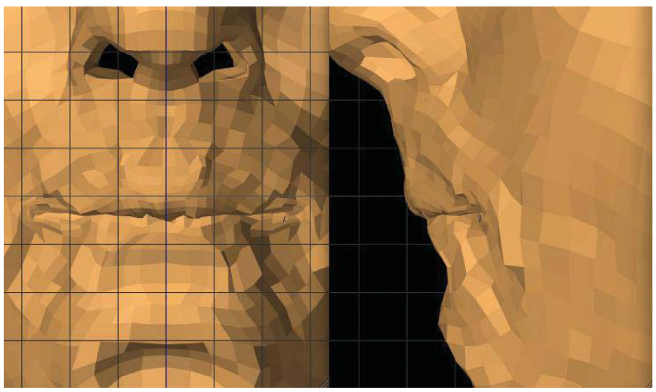

Figure 2. Maximum bilabial constriction.

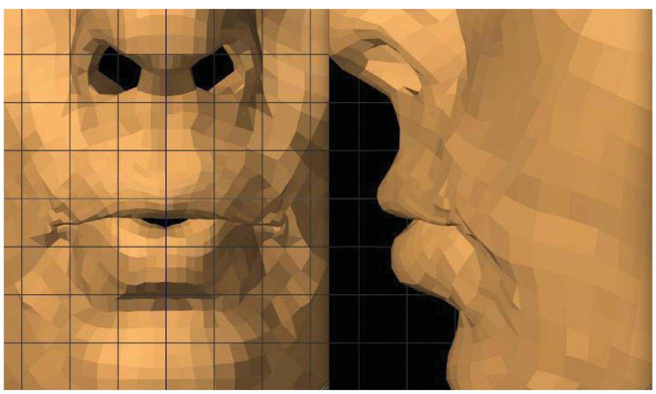

Figure 3. Maximum approximant constriction.

4. DISCUSSION AND CONCLUSIONS

Our results show that different initial muscle settings produce regions in which large variations in input activation yield stably different degrees of constriction, all corresponding to the feature of labial. We consider a labiodental fricative similar in principle to a bilabial stop, except that the teeth constitute an imperfect closure surface.

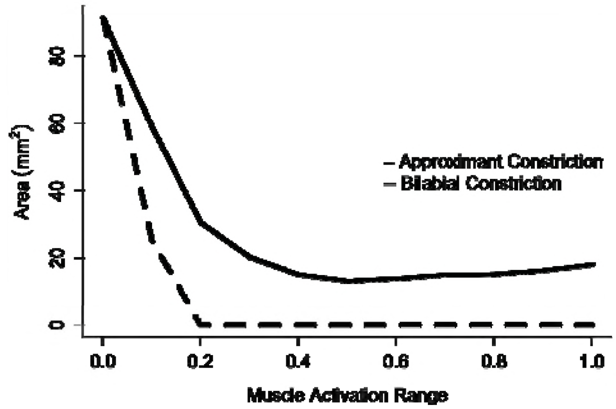

Figure 4. Area of opening as muscle stress increases from 0–1, where 1 is the maximum stress level indicated in Table 1.

We conclude that language speakers use these quantal regions in biomechanical-articulatory space to control constriction degree at the lips. It is important to note that we do not view the lips in this analysis as exceptional. Future work will treat this as a general mechanism driving speech production.

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