A LIP PROTRUSION MECHANISM EXAMINED BY MAGNETIC RESONANCE IMAGING AND FINITE ELEMENT MODELING

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ABSTRACT

The lips are regarded as a paired organ for audiovisual speech communication that modulates speech sound and facial shape together in speech production. Despite the long research, the mechanism of lip protrusion is still an open question. This study aims at exploring physiological mechanisms of lip protrusion based on muscle visualization and finite element simulation of lower lip deformation. A special focus is placed on the peripheral part of the orbicularis oris among the lip muscles because it is located closer to the lip's oral surface. This geometry suggests enhancement of lip tissue convexity by medial shortening the teeth-side lip tissue disproportionately. This hypothesis is examined by a simulation using a finite element model of the lower lip built based on high-resolution magnetic resonance imaging (MRI) data. Lower lip deformation obtained by the simulation conforms to the hypothesis of lip tissue advancement with enhanced anterior convexity.

Keywords: lip protrusion, speech production, FEM, orbicularis oris muscle.

1. INTRODUCTION

The lips are unique speech organs of humans consisting of many orofacial muscles that perform hydrostatic deformation. While the lips contribute to acoustic realization of speech by forming the open end of the vocal tract, they change in shape co-varying with the tongue, thus enhancing visual perception of speech. Lip deformation can be roughly classified into three action components: opening-closing, narrowing-spreading, and protrusion-nonprotrusion. While the former two are naturally explained by corresponding antagonistic activations of the perioral muscle pairs and jaw movement, lip protrusion is not. This is because no direct muscle is found to advance the lip tissue, and its mechanism must be accounted for by the hydrostat of the lip tissue. The typical lip protrusion observed for English vowel /u/ for example may be explained by three components of deformation: (1) medial approximation of the lip corners keeping their inside in contact with the teeth surface, (2) advancement of mid-line lip tissue partly being apart from the front teeth, and (3) narrowed lip aperture with thickened or partially herniated vermillion regions. In this study, we examine the mechanism involved in lower lip protrusion based on magnetic resonance imaging (MRI) data and finite element model (FEM) simulation, mainly focusing on the first two factors noted above.

With recent development of observation and analysis techniques, a common way to investigate lip deformation mechanisms is to reproduce lip deformations using three-dimensional (3D) computational models. In the previous reports, a 3D biomechanical face model was built using the ANSYS™ software with a simulation of the lips in smile [6]. Another study aimed at demonstrating the effect of orbicularis oris (OO) morphology on simulated lip protrusion using a biomechanical model of the orofacial system implemented in ArtiSynth [13], but their definition of the OO muscle was not consistent with anatomical literature or MRI observation. A protrusion-like shape was reported using a perioral dynamic model, which concerned with a discrete particle system to simulate continuum deformation [5], but no causal mechanism was described for lip protrusion. Thus, so far, the previous studies have been unsuccessful at modeling realistic lip protrusion or proposing convincing physiological mechanisms.

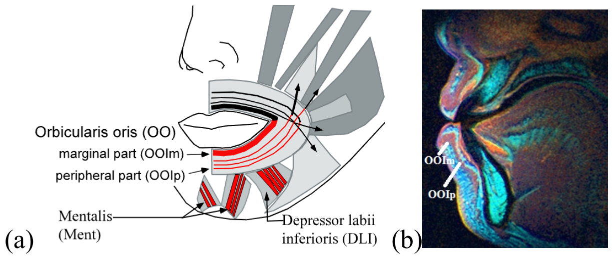
The aim of our study is to discover physiological mechanisms of lip protrusion. In this report, we review anatomical and physiological findings of the lip muscles in detail and propose a possible mechanism of lip protrusion by the action of the orbicularis oris muscle (OO). To do so, a hypothesis was formulated based on the previous work with electromyography (EMG) [7] and magnetic resonance imaging (MRI) [11]. In order to test the hypothesis, a 3D biomechanical finite element model of the lower lip, including the orbicularis oris inferior (OOI) muscle and soft tissue, was built to simulate the protrusion of the lower lip tissue.

2. HYPOTHESIZING LIP PROTRUSION

Anatomical literature suggests that the OO muscle consists of four substantially independent quadrants (upper, lower, left and right), each of which contains the distributed peripheral part and the compact marginal part [12]. Figure 1(a) is a schematic drawing illustrating the perioral muscles, with the red lines indicating the two parts of the orbicularis oris inferior (OOI) muscle in the lower lip: the peripheral part (OOIp) is arranged to surround the marginal part (OOIm). The mentalis (Ment) and depressor labii inferioris (DLI) are two large perioral muscles in the lower lip, which arise from the mandible and end into the skin or the mucosa of the lower lip.

Recent findings suggest that lip protrusion may be suppressed by powerful contraction of the OO muscle or enhanced by selective activation of parts of the labial tractors that insert directly into the tissue of the lips [12]. The actions by the Ment and DLI muscles for lip protrusion can be naturally interpreted by their anatomy, the former elevating the base of the lower lip tissue, and the latter keeping lip aperture while turning out the vermilion. However, no detailed mechanisms have been proposed regarding how the muscles interact to perform lip protrusion or why the lip tissue advances.

Figure 1: (a) Perioral muscles and two parts of the orbicularis oris. (b) A pseudo-color midsagittal MR image composed by three midsagittal images obtained from different scan parameters. (This figure is made from the data prepared for the previous study [11].)



The functional differentiation between the marginal and peripheral parts of the OO muscle has not been clarified. According to the EMG study by Honda, et al. [7], the two parts of the OOI muscle are differentially activated for lip narrowing and protrusion. The OOIm showed increased activity equally for lip narrowing and moderate protrusion in Japanese vowel /u/, while the OOIp showed the higher activity for obvious lip protrusion in Japanese vowel /o/. This result suggests that the OOIp contributes to lip protrusion to a greater extent than the OOIm. The authors discuss the lip protrusion mechanism by differential thickening of the muscle tissue near the vermillion region between the OOIp and OOIm. However, their assumption on the geometrical arrangement of the two parts does not appear to be anatomically plausible.

In the MRI study by Murano, et al. [11], the inner structure of the lower lip was visualized based on high-resolution MRI data, showing evidence that the OOI muscle is hook-shaped, and the marginal part (OOIm) is dense and runs along the vermilion, while the peripheral part (OOIp) distributes widely along the entire lip tissue forming a broad layer located closer to the teeth side of the lip tissue, as shown in Figure 1(b). This muscle distribution pattern of the OOIp suggests that this part contributes to advancing the lip tissue by the greater mechanical effect on the thinner mucous layer on the oral side of the lip tissue rather than on the outer side of the lower lip tissue.

Figure 2: Tracings of transverse MRI images of lower lip during Japanese vowel /i/ and /u/. Contraction of the OOI muscle may apply the larger force on the oral side tissue to cause the greater tissue shortening, which leads to make the entire tissue convex forward.

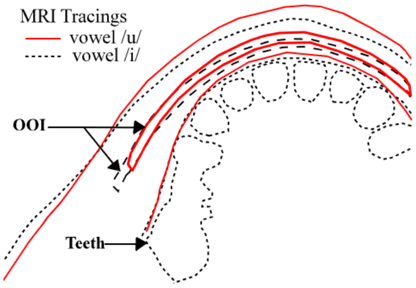
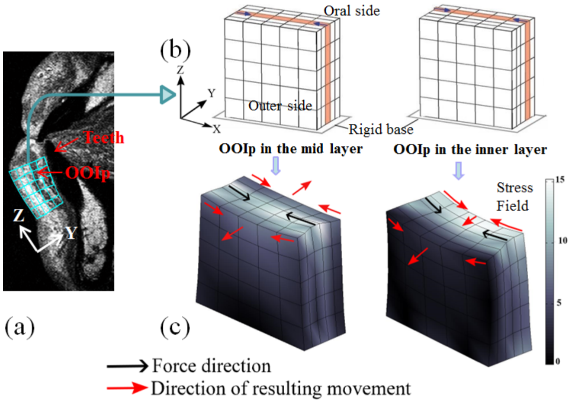


Figure 2 shows tracings of transverse MRI images of the lower lip during Japanese vowel /i/ (non-protrusion) and /u/ (protrusion). In the figure, advancement of lip tissue from vowel /i/ (dash line) to vowel /u/ (solid line) is obvious together with the shortening of the OOI muscle. Based on the previous discussion, a possible mechanism is proposed to account for the tissue deformation for lip protrusion: When the OOIp contracts, the tissue layer behind the muscle on the teeth side is more compressed due to muscle fiber shortening than the layer in front of the muscle on the skin side. The resulting stress deforms the midline region of the lip tissue to advance while keeping the lip corner tissue in contact with the rigid wall of the teeth, thus shaping the lip tissue for protrusion.

This hypothesis has been preliminarily tested by a simple model based on static finite element analysis [9] using a meshed block of a five-layer structure composed by the quasi-incompressible elastic tissue. Figure 3 shows the mesh model that was implemented by using an FEM toolbox [4]. In this simulation, when the force is applied to the inner layer that is closed to the teeth side, it generates the larger stress on the teeth side than on the outer side. This stress difference causes disproportionate tissue shortenings between the outer and inner layers of the lip tissue, which results in the anterior convexity of the block model.

Figure 3: A speculated mechanism for bending an elastic material by a contractile layer. In a five-layer mesh structure composed by the quasi-incompressible elastic tissue, the force applied to the layer if deviating from the mid layer would generate the larger stress on the side of the contractile layer, leading to the convexity of the mesh (right panel in figure c).



3. PHYSIOLOGICAL MODELING

In order to further verify the role of the OOIp in lip protrusion, a physiological model of the lower lip was constructed using the modeling and numeric library support of ArtiSynth [10]. This modeling toolkit provides a framework for creating and interconnecting various kinds of dynamic and parametric models to form an integrated biomechanical system.

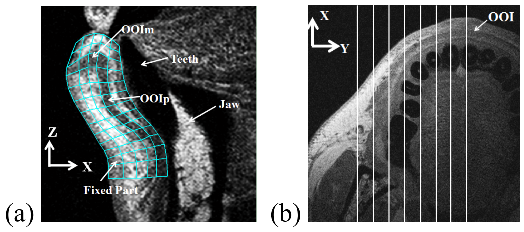
3.1 Model construction

We employed two sets of high-resolution 3D MRI data of the orofacial region obtained from a male Japanese subject to extract the geometric features of the lower lip. Details of the OO muscle in the lower lip were analyzed so that the 3D geometrical structure of the model could match as closely as possible the muscle morphology within the lower lip.

Figure 4(a) shows a midsagittal slice of the MRI data around the perioral region, including the lower lip and teeth. The XZ plane of the 3D mesh was composed of five layers in the front-back (X) direction and 13 layers in the vertical (Z) direction. The OOIp is represented mainly by the elements in the fourth layer (X direction), and the OOIm by the elements in the second and third layer (X direction). The bottom two layers in the Z direction are regarded as fixed regions, which are connected to the jaw.

Figure 4(b) shows a horizontal slice of the MRI image around the lower lip, and the eight vertical white lines indicate the locations of the parasagittal slices used for modeling. The mesh of the right side is a copy of the left side based on a common assumption that the left and right sides of the lower lip are symmetrical.

Figure 4: High-resolution lip MRI. (a) Midsagittal MRI slice (XZ plane of 3D mesh); (b) Transverse MRI slice (XY plane of 3D mesh).



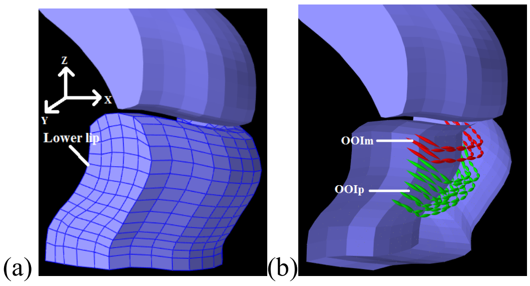
3.2 Implementation

The dynamic finite element method [8] was adopted as the basis of modeling to simulate node displacements to describe 3D deformation of a continuum in the time domain. In our model, the lower lip was divided into 910 hexahedron elements with 1260 nodal points.

Figure 5(a) shows the 3D biomechanical model of the lower lip constructed by the mesh extracted using the above procedure based on the hexahedron elements with a density of 1040 kg/m^3, which was implemented in ArtiSynth. A five-parameter hyperelastic Mooney-Rivlin material and the Rayleigh damping model, with parameters and damping coefficients consistent with a reference face model [2] (c_{10} = 2500 Pa, c_{20} = 1175 Pa and $c_{01} = c_{11} = c_{02}$ = 0 Pa; $\partial = 19s^{-1}$ and $\beta = 0.055s$), were adopted to simulate the non-linear and visco-elastic properties of biological soft tissues [3]. Incompressibility was implemented using a constraint based on the mixed u-P formulation [8].

The lines corresponding to the muscle layer between each parasagittal slice are selected to act as "muscle fibers", along which a uniform muscle–activated force is exerted. Parameters for the muscle fiber behavior were chosen based on the parameters for muscle provided by Blemker et al. [1]: $C_3 = 0.05$, $C_4 = 6.6$, $C_5 = 1$, $\lambda^* = 1.4$. The maximum active fiber stress was 100 kPa. The OOIm and OOIp were designed as two independent muscle fiber bundles for testing the functional differentiation between the two parts of the OO muscle in the lower lip, as shown in Figure 5(b).

Figure 5: A model of the lower lip. (a) 3D mesh of lower lip reconstructed from sectional MRI images; (b) Arrangements of the OOI muscle in the model. The shapes of the lateral lip tissues were simplified in the model.



3.3 Simulations

Our primary aim is to determine the role of the OOIp in lip protrusion and further to unveil the mechanism of lip protrusion. Our interests also include the functional differentiation between the two parts of the OO muscle.

Figure 6: Simulation results. (a) Neutral lip state. (b) Lip deformation only by activating the OOIp. (c) Lip deformation only by activating the OOIm. (d) Lip deformation by activating the OOIp and OOIm together.

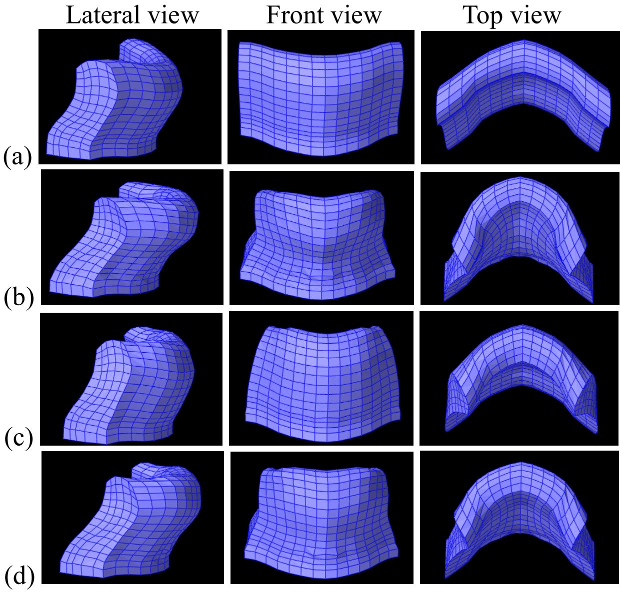


Figure 6(a) shows the rest state of the lower lip without muscle activation. For testing our hypothesis of OOIp muscle function, the first simulation was conducted only by activating the peripheral parts of the OO muscle in the lower lip. The result indicates that the lower lip narrows in the transverse direction causing an obviously anterior convexity, as shown in Figure 6(b).

In the second simulation, the OOIm was activated with the result showing no apparent forward movement but causing deformation with narrowing near the vermilion region, as shown in Figure 6(c).

Figure 6(d) shows the deformation of the lower lip under the activation of both OOIp and OOIm, which demonstrates plausible deformation for lip protrusion.

4. CONCULSION AND DISCUSSION

A hypothesis was proposed for lip protrusion mechanism by the OO muscle, which was examined by a model-based simulation. The biomechanical model of the lower lip presented in this report was composed of five soft tissue layers with fiber-based muscle force generation in a 3D mesh based on the finite element method. The lip shapes and muscle locations were extracted from 3D high-resolution MRI data, and the OOI muscle was precisely modeled for the two parts (OOIp and OOIm) so that they were independently controlled. This model was used to examine our hypothesis for lip protrusion produced by the OOIp. The OOIp is located closely to the teeth side of the lip tissue, which causes disproportionate tissue shortenings between the outer and inner layers of the lip tissue. From the simulation by activating the OOIp alone, the lower lip model demonstrated deformation toward an anterior convexity. The role of the OOIp in lip protrusion was thus supported as estimated by the hypothesis, while simulation on the other part, the OOIm, resulted in the lip shape for narrowing. Thus, the hypothesis-based simulation attempted in this study promises a better understanding on the physiological mechanism of lip protrusion.

There remain further factors, however, that need to be considered. As mentioned earlier, the Ment and DLI muscles must also be involved in lip protrusion, which are not considered in the current model. In addition, the inside of the lip corners must keep in contact with the front surface of the teeth, when the mid-line lip tissue advances. Therefore, the interaction between the lips and teeth is another issue to be incorporated into the model in the future studies.

5. ACKNOWLEDGEMENT

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