A Continuous Biomechanical Model of the Face: A Study of Muscle Coordination for Speech Lip Gestures

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Abstract

A 3D finite element face model which geometry has been extracted from CT data is being used for implementing orofacial speech gestures and studying underlying muscle activations. This model consists of 3 layers of full and degenerated hexahedral elements. The simplified 5-parameter Mooney-Rivlin hyperelastic law has been used to account for nonlinear elastic properties of face tissues. Contact elements model the contacts between upper and lower lip and between lips and teeth. Muscle fibres are modelled by macrofibres which are implemented in reference to anatomical key points, independently of the mesh structure, by cable (tension only) elements. The muscles themselves are determined by a proximity algorithm through face elements surrounding the cable elements. The effect of some muscle activations on lip shaping has been studied. It is shown that in particular muscle stiffening associated with muscle activation has a noticeable influence on lip protrusion and rounding. The effect of muscles coordination for producing realistic lip shapes has been investigated.

1 Introduction

Many biomechanical models of the human face have been proposed in the literature, mainly developed in the context of computer graphics animation [1, 2], computer-aided maxillofacial surgery [1, 3], or speech production [4, 5, 6]. Most of them propose to model the face with a volumetric mesh defined by an external (the "visible" part of the face) and an internal surface (the part in contact with the skull), with some point/nodes or layers in between. Mechanics of the tissues (epidermis, dermis, hypodermis, fat and muscles) have, thus, been modelled through the relationship between displacements and forces acting on mass points (mass-spring models) or between strains and stresses acting on nodes (finite element models). When using these models to generate movements, two main problems are faced to simulate muscular activations and their impacts on face geometry: (1) how to model muscles fibres and transmit forces or stresses on the mesh; (2) how to coordinate muscles in order to produce realistic mimics or speech gestures.
This paper aims at contributing to these two issues by presenting a realistic continuous face model in which muscles are implemented as force generating cables between specific anatomical key-points and by studying muscle coordination required for the production of lips speech gestures.

2 Model and its specifications

A 3D Finite Element model of the face soft tissues has been built (with ANSYS™ v11 software) out of CT scan of a single subject. The model consists of a 3-layer mesh, contact elements and cable elements.

The 3-layer mesh

The elements are full and degenerated hexahedral elements and have no midside nodes. Since biological soft tissues are known to behave non-linearly [7], a simplified 5- parameter Mooney-Rivlin hyperelastic model has been used for the material property. According to this model there is a strain-energy function, *W,* which derivative with respect to strain gives stress:

$$W=c_{10}(\bar{I}_1-3)+c_{01}(\bar{I}_2-3)+c_{20}(\bar{I}_1-3)^2+c_{11}(\bar{I}_1-3)(\bar{I}_2-3)+c_{02}(\bar{I}_2-3)^2+\frac{1}{d}(J-1)^2$$

Where $\bar{I}_1$ and $\bar{I}_2$ are respectively the first and second invariant of the right Cauchy-Green strain tensor and J is the determinant of elastic deformation gradient. In the simplified model only two constants, c_{10} and

c_{20}, are different from zero while $d = \dfrac{1-2\nu}{c_{10}+c_{01}}$ where ν is Poisson's ratio. According to [9] $c_{10} \cong \dfrac{E}{6}$ where E is the Young's modulus. The two coefficients c_{10} and d have been calculated from the data reported in [8] with the assumption of mechanical linearity and incompressibility of muscle namely E=15 kPa and ν =0.499. The c_{20} coefficient has been determined according to [7]. The computed constants are shown in table 1.

Table 1. *Constants of simplified 5-parameter Mooney-Rivlin model for inactive muscle*

c_{10} (MPa)	c_{20} (Mpa)	d (1/MPa)
2.5e-3	1.175e-3	0.8

As a first estimate the constants in active muscle have been assumed to be 10 times greater than inactive case.

The mesh has three distinctive layers which give a good ability to define the extent of each muscle more accurately. The geometry has been assumed symmetrical. The plane of symmetry is the midsagittal plane (yz plane) (fig. 1). For simulating face gestures the full model (fig. 2) is used to allow simulating unsymmetrical face gestures through unsymmetrical muscle activation.

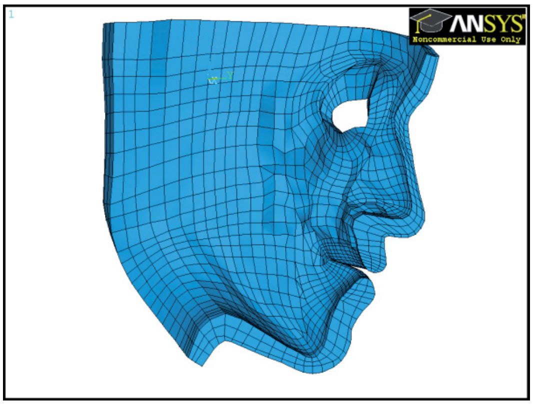

Fig. 1: *The mesh which has been cut through the midsagittal plane (yz plane).*

Cable Elements

The main lines of action of muscles have been modelled by straight cable elements which only withstand tensile forces. Each muscle "fiber" is represented by a set of constant-length cables, to accurately conform with its geometry. Muscle courses have been defined from CT data of face and skull and anatomical books with the assistance of a maxillofacial surgeon (fig. 3). Some of the muscles have been defined with one fiber and some of them with two to four fibers. The difference depends on the muscle geometry.

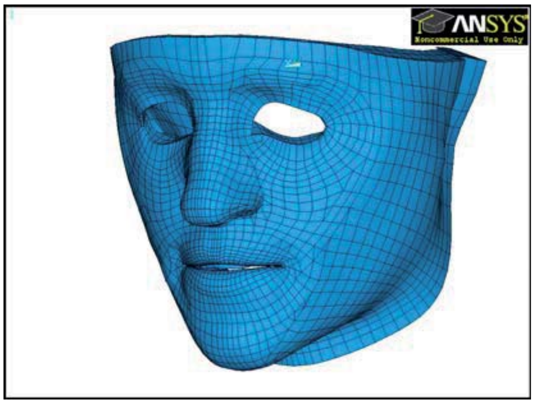

Fig. 2: *The complete symmetrical mes*h.

Since the muscle definition by these cable elements is independent of the mesh further refinement of the mesh geometry can be done without redefining the muscle implementations.

The boundary conditions are applied through fixed nodes on skull and muscle insertions and coupling elements.

Contact Elements

Contact elements have been used for modelling contacts between lower and upper lip and between lips and teeth. The surface of teeth on mandible and maxilla has been approximated with a spline surface (fig. 3) and discretized with quadrilateral contact elements. The contact elements have no initial interpenetration and are of sliding type without friction.

Fixed Nodes

The inner nodes of the mesh corresponding to face tissue attachments to the skull are fixed. Those ends of cable elements corresponding to muscle insertions on skull also have been fixed.

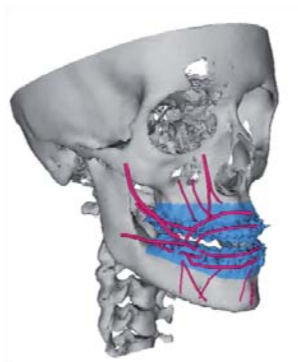

Fig. 3: *The course of orofacial muscles (red lines) and the spline surfaces (blue surfaces) which show teeth contact surface.*

3 Method

The cable elements activation is controlled by a differential parameter ΔT. Their stiffness has been taken as an activation parameter for controlling the level of muscle activation. Muscular fibre tips are coupled with the facets of the surrounding mesh elements through pilot nodes (fig. 4). They generate forces, that are transferred to the soft tissue mesh.

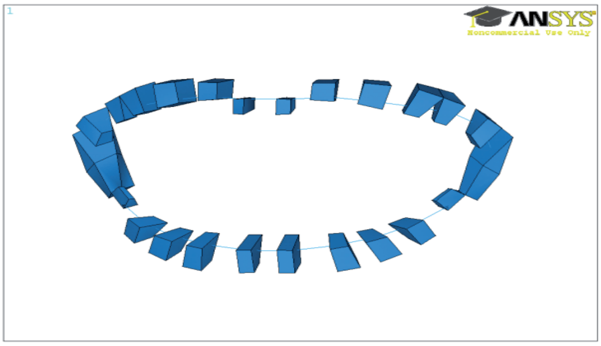

Fig. 4: *Coupling elements between cable elements and the surrounding mesh for orbicularis oris peripheralis (OOP) muscle*

If an initial parameter difference ΔT is applied on the model with the coefficient of expansion α the resulting force will be

$$F = AE(\varepsilon - \alpha \Delta T)$$

in which A is the cross section area and E is the Young's modulus of the cable elements. This means that an equivalent initial strain equals to

$$\varepsilon_0 = -\alpha \Delta T$$

When a muscle is activated, the corresponding cable elements pull the mesh elements, causing soft tissue deformations.
If material properties of face tissues are taken as a function of the T parameter, muscle stiffening can be modelled in parallel to muscle activation [8]. The remaining question is on which region of the mesh surrounding each muscle fibers this dependency will apply? In this regard a proximity algorithm has been defined to select the elements that are in spherical proximity of cable elements (fig. 5). The muscle stiffening accompanying muscle activation has been modelled by specifying the radius of this spherical neighbourhood estimated from anatomical data and changing the stiffness of the corresponding elements to be a function of T parameter.

4 Results

The activation of muscles individually and in coordination has been investigated. This activation has been done with and without muscle stiffening for orbicularis oris peripheralis (OOP) muscle.

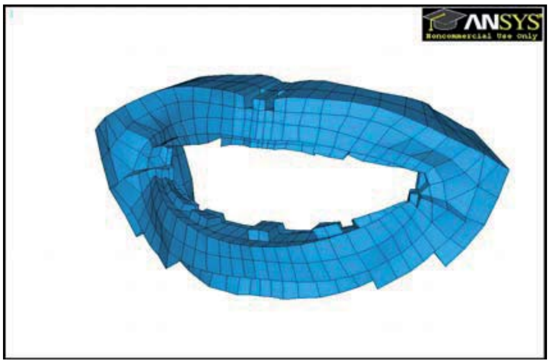

Fig. 5: *The face elements which are in spherical neighbourhood of OOP*

These results well comply with the anatomical predictions in the related literature [10]. The result of activating zygomaticus draws the angle of the mouth upwards and laterally (fig. 6).

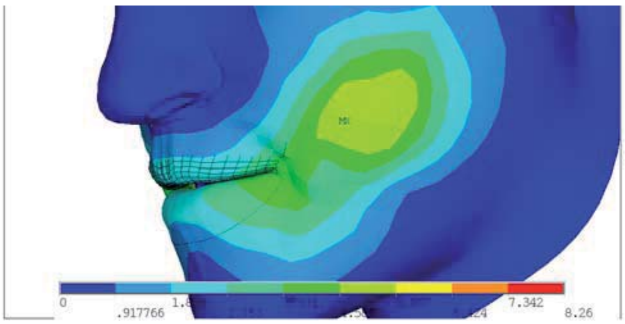

Fig. 6: *Activation of zygomaticus muscle*

Levator labii superioris elevates the upper lip. Acting with other muscles, it modifies the nasolabial furrow. In some faces, this furrow is a highly characteristic feature often deepened in expressions of sadness or seriousness.

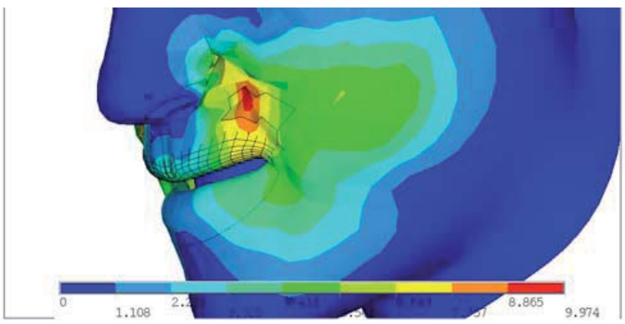

Fig. 7: *Coordinate action of zygomaticus, levetor labii superioris alaeque nasi and levetor angulai oris*

The activation of the levator labii superioris with zygomaticus and levetor labii superioris alaeque nasi in fig. 7 well satisfies that hypothesis.
The effect of OOP in protruding and rounding the lips has been shown (fig. 8).
But without muscle stiffening the shape of lips looks like fig. 9 which is mainly protrusion without rounding. This result is in agreement with [6]. Accounting for muscle stiffening to produce rounding is thus a significant achievement.

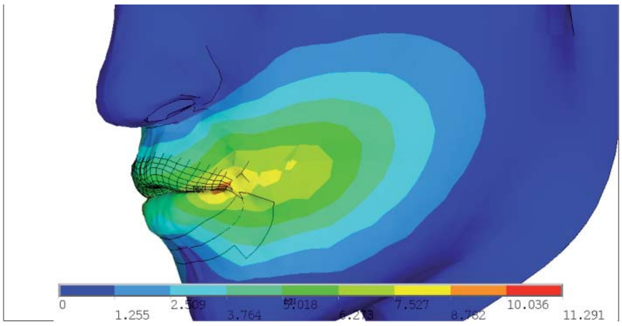

Fig. 8: *Orbicularis oris peripheralis activation*

Mentalis raises the lower lip, wrinkling the skin of the chin. Since it raises the base of the lower lip, it helps in protruding the lower lip in drinking and also in expressing doubt. Fig. 10 shows this coordinate action of mentalis and OOP.

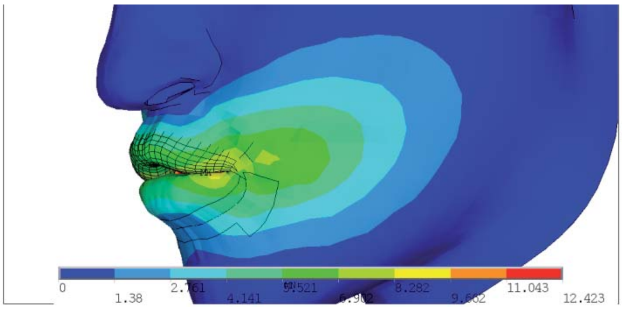

Fig. 9: *OOP activation without muscle stiffening*

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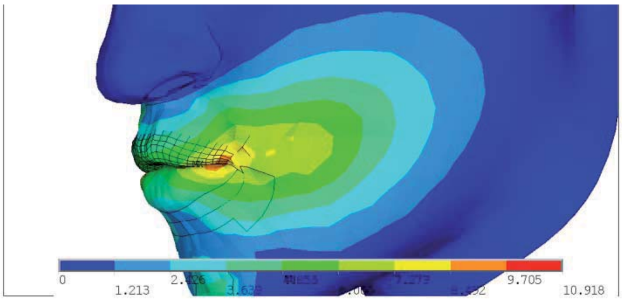

Fig. 10: *Coordinate activation of mentalis and OOP*

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