A 3D Finite Element Muscle Model and its Application in Driving Speech Articulators

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SUMMARY

A finite element muscle model has been designed with the Usermat functionality of ANSYS® multiphysics software. It is represented by a transversely isotropic material which its strain energy is a function of I_4 and I_5, invariants of the Cauchy-Green strain tensor due to muscle fibers. Muscle activation is accounted for by adding an active stress to the Cauchy stress in the direction of fibers. An additional isochoric term is included in the strain energy function, to account for lateral normal stiffness. This element has been tested in an existing finite element model of the human face, which has been designed to study interactions between motor control and physical properties of the face in speech production. Some typical facial gestures of speech are studied.

INTRODUCTION

Developing realistic biomechanical models of the articulators used in speech production (jaw, tongue, lips, velum and vocal folds) is a fruitful methodological approach to contribute to study speech motor control and the link between the units of language and their physical realizations in speech communication. The challenges of this research are as follows. What is the potential influence of the physical properties of the vocal tract and facial articulators in the emergence of the language, its evolution and its variability [1,2,3,4,5]? To what extent do these physical properties influence the characteristics of the speech signals that are exchanged between speakers and listeners [6,7,8]? How are speech motor control strategies elaborated? How do they adapt to variations in speech communication conditions, and to possible pathological perturbations [9,10]? For the biomechanical models to be efficient tools in this research approach, it is a requirement to be as realistic as possible, in order to provide a true and reliable account of the impact of the physics in the speech characteristics.

A number of biomechanical models of speech articulators have been designed in the past (e.g. [11,12,13,14,15]). In these models, muscles play a major role, since they are the main driving components of movements (that can be very fast for speech production) and they constitute a significant part of the structure that they deform (e.g. the tongue and face tissues). Hence, working at improving mechanical muscle models is a necessity. In this context, using a nearly incompressible hyperelastic material, which includes an account of a transversely isotropic behavior, is well suited to model passive mechanical properties [16]. An active component is added to model force generation mechanisms and their consequences on movements. This active component should introduce a force which varies as a function of a time varying activation parameter and depends on length and length variation rate of the muscle [17].

METHOD

The muscle model has been created using the Usermat functionality of ANSYS® multiphysics software. Since muscles are composed of bundles of fibers embedded in a matrix of tissues, a transversely isotropic material fits well their mechanical behavior. The strain energy in this material is dependent on the following invariants, as shown in [18],

$$I_4 = \boldsymbol{a_0} . \boldsymbol{C} \boldsymbol{a_0}, \qquad I_5 = \boldsymbol{a_0} . \boldsymbol{C}^2 \boldsymbol{a_0}$$

$\boldsymbol{C}$ is the right Cauchy-Green strain tensor and $\boldsymbol{a_0}$ the initial direction of fibers. This dependence is interesting in the design of a finite element muscle model, since it enables the fiber direction to be specified independently of the mesh geometry and topology. The Cauchy stress ($\boldsymbol{\sigma_f}$) in fiber direction, as extracted from the strain energy function (W) for an incompressible material, becomes:

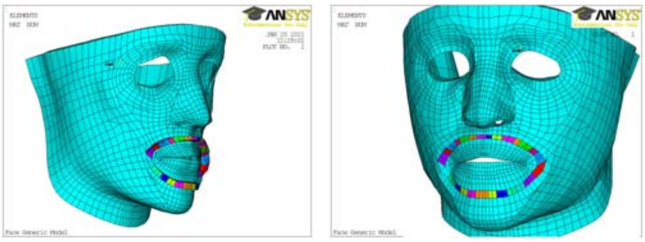
$$\boldsymbol{\sigma}_f = 2 \frac{\partial W}{\partial I_4} I_4 (\boldsymbol{a} \otimes \boldsymbol{a})$$

in which $\boldsymbol{a}$ is the fiber direction in the deformed configuration. Hence, an active stress in fiber direction can be easily added to the Cauchy stress in fiber direction such that:

$$\boldsymbol{\sigma}_f = (2 \frac{\partial W}{\partial I_4} I_4 + \sigma_{active}) (\boldsymbol{a} \otimes \boldsymbol{a})$$

A constitutive law implemented in a nonlinear finite element method is based on the co-rotated stress. In this theoretical context, the objective stress rate is Green-Naghdi stress rate which has been approximated by Jaumann stress rate [19]. Jaumann elasticity tensor is derived numerically by a perturbation method [20]. The strain energy (W) for the muscle is considered as in [16]. Since the proposed energy only takes into account the shear property of the muscle, an additional isochoric term $C_1(I_1\text{-}3)$ is added to account for muscle lateral normal stiffness.

This muscle model is used in a face mesh that has been developed recently [15]. In this mesh, elements are associated with muscles on the basis of anatomical fact and of information extracted from original CT scans of the subject's face. Figure 1 shows, as an example, the implementation of the orbicularis oris peripheralis (OOP). For the surrounding passive tissues in the mesh, a five parameter Mooney-Rivlin hyperelastic model is assumed to apply [15].

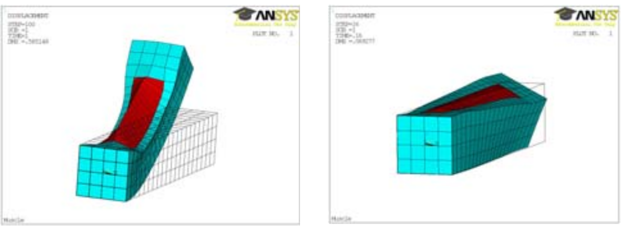


(a) (b)

Figure 1 Orbicularis oris peripheralis muscle (a) on top of first layer (b) surrounded by elements in middle layer

RESULTS AND DISCUSSION

A preliminary qualitative evaluation of the muscle model is provided. First, muscle elements embedded in a hexagonal bar are activated with two assumptions for the fibers directions, a lengthwise one (Fig. 2a) and a diagonal one (Fig. 2b). As expected, the diagonal activation produces a torsional deformation of the bar, while the lengthwise one acts along the main muscle course, with an upward bending due to the top implementation of the muscles fibers.



(a) (b)

Figure 2. Activation of muscle elements embedded on top of a hexagonal bar for 2 fibers orientations; (a) lengthwise (b) diagonal.

In a second test, the muscle model is used to implement the OOP in the face model [15]. Muscle activation produces lip protrusion (Fig. 3).

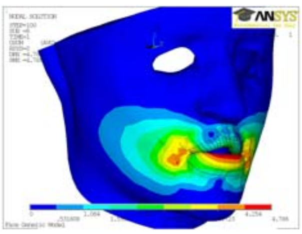


Figure 3 Lip protrusion following OOP activation

CONCLUSIONS

This muscle model is a significant improvement in terms of physical realism. Since the active part in this model can be changed easily, it provides a suitable tool for examining different muscle theories. The model can be used easily in each FE model, and it will be used also in our existing tongue model [13] to unify all our models of vocal tract articulators.

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