Interwoven muscle fibers: a 3D two-fiber muscle active model

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1. Introduction

Muscles are involved in all voluntary movements in humans, and their influence is crucial since they generate the forces that guide movements. Therefore their presence in modeling is essential. Muscles are often modelled as a one-dimensional spring with a dashpot and a contractile element. Most musculoskeletal models use this type of modeling (Uchida and Delp 2021). Such a 1-D model, connecting the muscle's insertion points on bony rigid structure, suffers from shortcomings. Primarily the 3D shape of the muscles and its influence on movement are ignored. Moreover, muscles without osseous attachments, in particular muscular hydrostats, cannot be modelled. This is the case for muscles that build the largest part of tentacular organs like human tongue, lips or face.

The 3D fibrous structure of muscles has been mostly modeled by a transversely isotropic material with a one family of fibers (Blemker 2017). The activation force is added to the direction of fibers consequently as an additive stress. The activation mechanism can vary from a calcium-based model to an equilibrium point hypothesis (Nazari et al. 2013). This type of modeling is usually done using Finite Element Method via a user defined material property at integration points.

Some muscular organs exhibit regions where two different muscles get interwoven fibers at the same location. This is for example the case for tongue tissues where intrinsic muscles like the verticalis and the transversalis cross under the surface (Gilbert et al. 2007). These two fiber directions can act independently or at the same time to create a desired tongue shape. This introduces a two-fiber muscle model (TFM) that should allow to study synergies or antagonisms between interwoven muscles.

TFM was developed as a user material (UserMat) subroutine in ANSYS© Mechanical. It uses a Hill-type activation along muscle fibers and takes into account the interaction between muscle fibers. It is evaluated here for an isometric activation.

2. Method

As usually done for hyperelastic materials, a muscle is often modelled using a strain energy density function ψ such that the stress can be derived from the derivative of this energy with respect to a strain tensor. This energy function consists in the addition of two components. One component models the passive surrounding soft tissues and the other one represents the active part:

$$\psi(\mathbf{C},\alpha) = \psi_{passive}(\mathbf{C},\mathbf{a}_0) + \psi_{active}(\mathbf{C},\ \mathbf{a}_0,\alpha,par) \quad (1)$$

where $\mathbf{C}$ is a measure of strain, $\mathbf{a}_0$ shows initial tangent vector at a point along muscle fiber, α is a measure of the activation level, and par is a collection of parameters and variables which depends on the utilised activation scheme. The passive part is assumed to be made of a transversely isotropic material with a strain energy density defined as a function of the five invariants:

$$I_1 = tr(\mathbf{C}),\ I_2 = \frac{\left[(tr(\mathbf{C}))^2 - tr(\mathbf{C}^2)\right]}{2},\ I_3 = \det(\mathbf{C}),$$
$$I_4 = \mathbf{a}_0.\mathbf{C}\mathbf{a}_0,\ I_5 = \mathbf{a}_0.\boldsymbol{C}^2\mathbf{a}_0 \quad (2)$$

For a muscle, Cauchy stress at current time is known so there is no need to compute the corresponding strain energy. The muscle stress tensor $\boldsymbol{\sigma}_{muscle}$ is expressed as:

$$\boldsymbol{\sigma}_{muscle} = \sigma_{muscle}(\mathbf{a}\otimes\mathbf{a}) \quad (3)$$

where σ_{muscle} shows the muscle stress along fiber direction at current time which is shown by the tangent vector $\mathbf{a}$.

For a two-fiber muscle an additional stress tensor corresponding to a second fiber direction is added to the first one:

$$\boldsymbol{\sigma}_{muscle} = \sigma_{muscle}(\mathbf{a}\otimes\mathbf{a}) + \sigma_{muscle}(\mathbf{b}\otimes\mathbf{b}) \quad (4)$$

And the passive part is augmented with corresponding invariants related to $\mathbf{b}$ direction:

$$I_6 = \mathbf{b}_0.\mathbf{C}\mathbf{b}_0,\ I_7 = \mathbf{b}_0.\mathbf{C}^2\mathbf{b}_0 \quad (5)$$

We propose to model the interaction between the two fibers using the following invariant:

$$I_8 = (\mathbf{a}_0.\mathbf{b}_0)\mathbf{a}_0.\mathbf{C}\mathbf{b}_0 \quad (6)$$

with the addition of the following term to the strain energy:

$$\psi_{passive_interaction}(\mathbf{C},\mathbf{a}_0) = c_8(I_8 - I_{8i})^2 \quad (7)$$

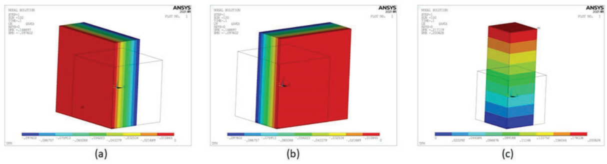

Figure 1. One-element model activation along (a) x direction (x displacement contours) (b) y direction (y displacement contours) (c) simultaneous x and y direction (z displacement contours).

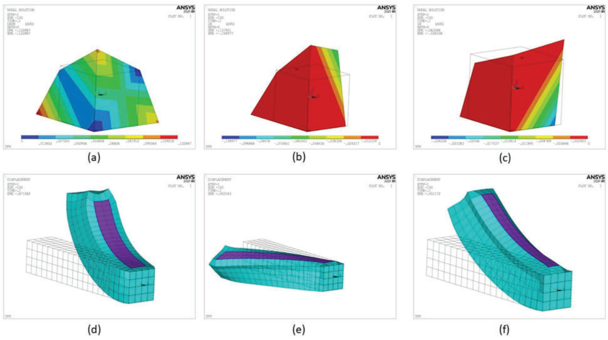

Figure 2. (a) Activation along the diagonal (b) activations along the diagonal and x directions were combined without interaction and (c) with interaction. (d) Beam model with a central muscle having fibers along beam axis, (e) diagonally oriented fibers and with (f) two families of orthogonal fibers.

where I_{8i} shows the initial value of I_8 which is the square of cosine of the initial angle between the two fibers and c_8 is a material constant. This invariant does not change the initial strain energy associated with orthogonal muscle fibers.

The implemented UserMat was defined with a separated volumetric and isochoric formulation. Since this constitutive model is meant to be used for muscle modeling, the nearly incompressible assumption was applied using a large bulk modulus. To evaluate this UserMat a one-element model was deformed along two orthogonal directions separately (Figure 1a and b) and at the same time (Figure 1c) using a Hill-type activation. Then the same one-element model was evaluated by activation first along the diagonal direction of one family of fibers (Figure 2a) and then along both diagonal and x direction which are not orthogonal (Figure 2b and c). In this last case, the interaction between fibers was first ignored (Figure 2b) and then was considered through the parameter c_8 (Eq. (7)) (Figure 2c).

3. Results and discussion

As it can be seen in Figure 2, the interaction between fibers significantly changes the model behaviour. As an example, a beam with a muscle in its center was modelled. As can be seen on Figure 2d, varying the fiber direction from longitudinal (y axis)) to diagonal (45 degrees with respect to y axis) (Figure 2e) changes the model behaviour completely. Having two families of orthogonal active fibers (along x and y axes) results in a specific shape (Figure 2f): the activation along fibers in the x direction creates a dip in the side part of the beam.

As it can be seen, the model does not consider the interaction between two orthogonal families of fibers if there is any. In order to implement this phenomenon more invariants are needed. The assumption about the strength of the interaction between the two families of fibers are not based on any experimental observation. To account for the exact amount of interaction in-vivo measurements on subjects would be highly required.

Finally, to evaluate the active muscle behavior, an isometric test was designed which includes simulations applying (1) an initial imposed displacement on the one-element model without muscle activation and (2) an additional activation to get the maximum force, simulating isometric activation. The corresponding stretch and forces were computed (Table 1). These values verify the activation trend of a muscle. As it can be seen, decreasing the stretch from the initial value ($\lambda = 1$) reduces muscle force of which represents a concentric activation. Increase of isometric force in an eccentric activation pattern matches also well with muscle behavior.

Table 1. Variation of isometric muscle behaior.

Stretch ratio (λ)	0.5	0.9	1	1.1	1.5
Maximum Isometric Force	0.075	0.215	0.24	0.245	0.26

4. Conclusion

A new active muscle model was introduced as a user material in ANSYS© to model the behaviour of muscles with two families of fibers. This model can be used for studying tentacular organs (like the human tongue) with a complex geometry of interwoven muscles. The model also works as a muscle with one family of fibers. The interaction between non-orthogonal fibers were implemented with the introduction an additional strain energy term. The model seems to behave correctly with a standard one-element test and through a simple beam simulation.

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KEYWORDS Two-fiber muscle active model; transversely isotropic; tentacular organs; user material; finite element method

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