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Modeling of active skeletal muscle

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Abstract. *In this contribution a continuum constitutive model for the passive and active mechanical response of skeletal muscle tissue is presented. Within the verification of the model's predictive capabilities and its numerical behaviour, a benchmark simulation is introduced. The presented model allows for simulation of complex soft tissue structures and their interactions. In a numerical example, an anatomically based representation of the masseter muscle is used to evaluate the maximum bite force during mastication.*

Keywords: Constitutive modeling; Muscle activation; Soft biological tissue

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1 INTRODUCTION

Modeling of skeletal muscle allows to investigate the activated material response of soft tissue structures. Such models are used to study the mechanisms underlying motion, facial expressions, speech and mastication and many other phenomena. As for most biological tissues, muscle may undergo large deformations and is characterized by a highly nonlinear mechanical behavior. Its unique property to produce tensile force upon neural stimulation enables control over several different body functions and voluntary movements.

Physically and phenomenologically based constitutive equations allow to represent the passive and active state of muscle tissue response. In literature, Hill's three element model [1] and Huxley's sliding filament model [2] are probably the most used formulations and many attempts were conducted to extend and modify them in different ways.

Generally, muscle models presented so far consider either the active part as an additive stress term on top of the passive part, or consider an interdependence between active and passive material response. The muscle model adopted in this presentation is a three-dimensional continuum representation that considers the nonlinear, anisotropic, incompressible nature of muscle as one continuous biological material. The constitutive model formulation was then implemented within the commercial software package Abaqus for the simulation of different applications using the finite element environment.

Within this contribution different numerical examples are presented highlighting different aspects such as the models dependence on mesh size, element distortion, different sets of material parameters, etc. Additionally, the model's predictive capability in determining the maximum bite force of the masseter muscle is demonstrated.

2 CONSTITUTIVE MODEL EQUATIONS

On the basis of work by Ehret et al. (2011) [3] and Itskov et al. (2006) [4], a constitutive model formulation is given for the passive and active behavior of skeletal muscles. The constitutive stress is of the form

$$\mathbf{S} = \frac{1}{2}\mu \left\{ \exp\left[\alpha\left(\tilde{I}-1\right)\right]\left(\tilde{\mathbf{L}}+w_a\mathbf{M}\right) - \exp\left[\beta\left(\tilde{J}-1\right)\right] III_C\, \mathbf{C}^{-1}\tilde{\mathbf{L}}\mathbf{C}^{-1} + \left(\tilde{J}\exp\left[\beta\left(\tilde{J}-1\right)\right] - III_C^{-\gamma}\right)\mathbf{C}^{-1}\right\}, \tag{1}$$

where μ, α, β, and γ are material constants. The formulation is given as a function of the right Cauchy Green deformation tensor $\mathbf{C} = \mathbf{F}^T\mathbf{F}$ and the activation parameter w_a, which is a function of current fibre length, state of activation and contraction velocity. Two generalized invariants are considered in this formulation and are given by

$$\tilde{I} = \mathbf{C}\colon \left(\tilde{\mathbf{L}}+w_a\mathbf{M}\right), \quad \tilde{J} = cof\left(\mathbf{C}\right) : \tilde{\mathbf{L}}, \tag{2}$$

which include the structural tensor $\tilde{\mathbf{L}}$ defined by

$$\tilde{\mathbf{L}} = \frac{w_0}{3}\mathbf{I} + w_p\mathbf{M}. \tag{3}$$

The material's anisotropy is governed by the structural tensor $\mathbf{M} = \mathbf{m}\otimes\mathbf{m}$, where $\mathbf{m}$ is the unit vector parallel to the prefered muscle fibre direction in the reference configuration, and the identitiy tensor of second order $\mathbf{I}$ determining the muscle's isotropic properties.

3 NUMERICAL SIMULATIONS

Two numerical examples are considered in this presentation of which one is introduced for verification purposes while the second one allows to understand the extent to which the proposed model can be applied to explore complex muscle tissue structures and their interaction upon activation.
The model's implementation was verified by a comparison of the model's predicted muscle response to an experimental campaign conducted by Hawkins and Bey (1994) [5]. Within their measurements, Hawkins and Bey determined the nominal stress response of rat tibialis anterior muscle in dependence of muscle fibre length. For a parameter set suggested by [3], the propsed muscle model was able to properly reproduce the purely passive, as well as the active muscle behavior as it was observed in the experiments. In particular, the dependence of nominal fibre stress on current fibre stretch as well as fibre contraction velocity is well represented by the adopted model.
As part of the muscle model's verification, a benchmark simulation is proposed that allows to investigate the model's dependence on mesh size, degree of element distortion, sensitivity of material parameters and model response under different types of muscle contraction, i.e. isotonic, isometric or isovelocity contraction. The model considers the muscle to be a rectangular block that is fixed to two rigid bodies at both ends. A schematic representation of the considered setup is given in Figure 1.

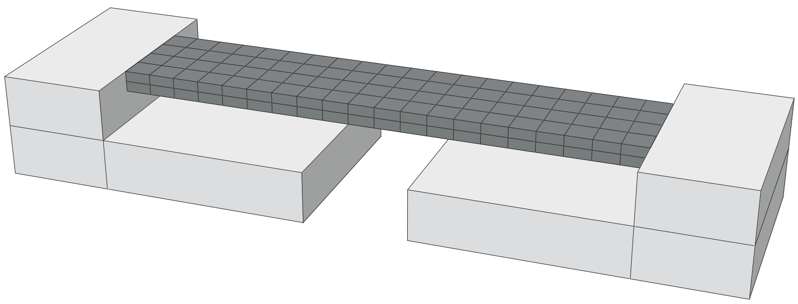

Figure 1: Geometry for numerical benchmark simulation.

Upon activation, the muscle will contract isotonically pulling the two rigid bodies together until they are in contact. Further stimulation of the muscle will result in isometric contraction, since the muscle's overall length remains constant while internal muscle force continues to build up as shown in Figure 2.

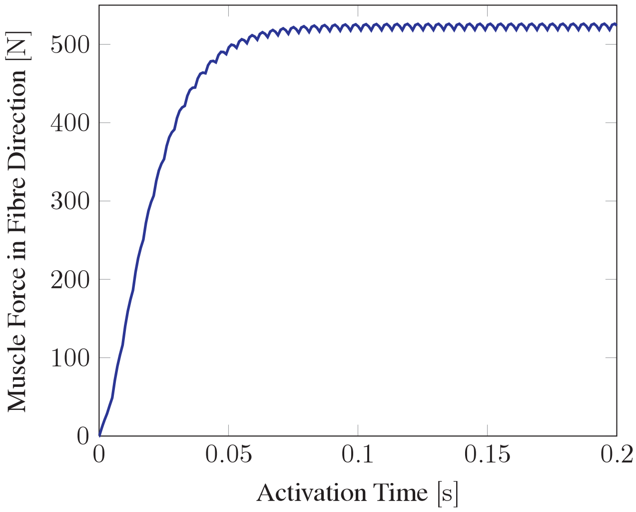

Figure 2: Muscle force response during activation.

This simplified muscle representation can be easily reconstructed and allows to compare the presented model to other muscle model formulations.
This muscle formulation is intended to enable the investigation of complex soft tissue structures involving muscles. The second example in this contribution emblazes the specific tissue response of the masseter muscle during mastication. Based on the segmentation of magnetic resonance imaging (MRI) data of a 27 year old male, an anatomically detailed model of the masseter muscle, skull and mandible are generated [6]. Insertions at the zygomatic arch and the mandible are modeled as fixed boundary conditions at the top and bottom end of the muscle respectively. The jaw is allowed to rotate around the temporomandibular joint. Figure 3 shows the reconstructed muscle geometry in the resting position.

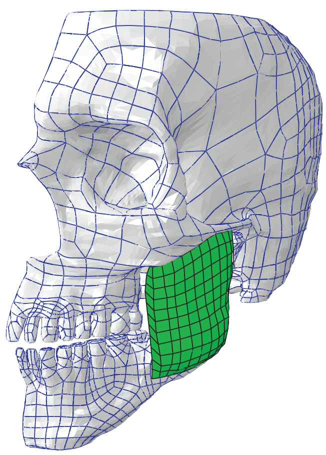

Figure 3: Model representation of the masticatory system including masseter muscle, skull and mandible.

When the masseter is activated, the jaw will close until the teeth are in contact. In this example the muscle is stimulated until it has reached its maximum muscle force. In literature, numerous experimental setups have been proposed in order to quantify the maximum human bite force which is associated with the masseter muscle force. In the simulation presented here, a parameter set was used, that resulted in a maximum bite force of $500N$. Upon activation of the muscle, the bite force increases rapidly to reach its maximum value within $80ms$.

4 CONCLUSION

Within this contribution a novel constituve muscle model formulation is presented. The model's predictive capabilities as well as its numerical behaviour have been thouroughly investigated on the basis of a proposed benchmark simulation for muscle models. Finally, a geomtrically complex simulation was highlighted to demonstrate the model's applicability to relevant problems in medicine.

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REFERENCES

[1] Hill, A.. The heat of shortenning and the dynamic constants of muscle. *Proceedings of the Royal Society B: Biological Sciences* **126**: 136-195, 1938.

[2] Huxley, A.F., Niedergerke, R.. Structural changes in muscle during contraction: Interference microscopy of living muscle fibres. *Nature* **173**: 971-973, 1954.

[3] Ehret, A. E., Böl, M., Itskov, M.. A continuum constitutive model for the active behaviour of skeletal muscle. *Journal of the Mechanics and Physics of Solids* **59**: 625-636, 2011.

[4] Itskov, M., Ehret, A. E., Mavrilas, D.. A polyconvex anisotropic strain-energy function for soft collagenous tissues. *Biomechanics and Modeling in Mechanobiology* **5**: 17-26, 2006.

[5] Hawkins, D., Bey, M.. A comprehensive approach for studying muscle-tendon mechanics. *Journal of Biomechanical Engineering* **116**: 51-55, 1994.

[6] Barbarino, G., Jabareen, M., Trzewik, J., Nkengne, A., Stamatas, G., and Mazza, E. Development and validation of a three-dimensional finite element model of the face. *Journal of Biomechanical Engineering*, 2009.