A multi-physics multi-scale approach for simulating muscle-tendon systems using OpenDiHu

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Summary

The activation of skeletal muscles is subject to feedback signals from sensory organs. To capture the role of the sensory organs, we use a multi-physics multi-scale muscle model that combines an electrophysiology solver with a finite-element mechanics solver. The model is implemented using OpenDiHu, an scalable open-source framework for neuromuscular simulations. Moreover, we couple our muscle model to a mechanical tendon model with the partitioned coupling library preCICE to achieve more realistic boundary conditions. We use this approach to model a three-tendon-biceps system in detail. We also use it to simulate a muscle-tendon-muscle system, which can be used to model the agonist-antagonist myoneural interface (AMI), a novel method to restore proprioception in amputees.

Introduction

We aim to study the role of the reflex pathways on the activation of skeletal muscles at multiple levels. Thereby we use a multi-physics multi-scale muscle model and couple it to a mechanics tendon model. A relevant clinical case of study is the agonist-antagonist myoneural interface [1], a novel method to restore proprioception in amputees, in which agonist-antagonist muscle pairs are surgically connected with a tendon.

In this talk we present our multi-X muscle model and how it is coupled to a tendon model. We also show the results of our simulation approach in a three-tendon-biceps system and in a muscle-tendon-muscle system, with the latter being used to model the agonist-antagonist myoneural interface.

Methods

Our multi-X muscle model is implemented in OpenDiHu [2]. OpenDiHu is an open-source scalable framework for biophysical simulations of the neuromuscular system developed at the University of Stuttgart. We use the muscle model proposed by [3], which combines a finite-element solver with an electrophysiological solver at the microscopic sarcomere level and complement it with models of the sensory organs and neural stimulation. The geometry of the muscle is described with a structured 3D finite-element mesh and 1D muscle fiber meshes.

To couple the muscle(s) to the tendon(s) we use the partitioned coupling library preCICE [4]. At the surface boundary, preCICE exchanges displacement, velocity and traction values between the tendon model and the mechanics component of the muscle model. The tendon model is also implemented in OpenDiHu, but another finite-element solver could be used. Simulating a muscle-tendon system has the advantage that contact boundary conditions are applied further away of the muscle, which is both more realistic and numerically stable.

Results and Discussion

Preliminary results for the three-tendon-biceps system (Figure 1) and the muscle-tendon-muscle are promising. We observe consistent values across muscle-tendon interfaces. We also observe that the action-potential propagates through the muscle fibers and that the generation of active force in the sarcomeres leads to the macroscopic contraction of the muscle. Moreover, the simulation is sensitive to the initial conditions, e.g., prestretch of the muscle [5].

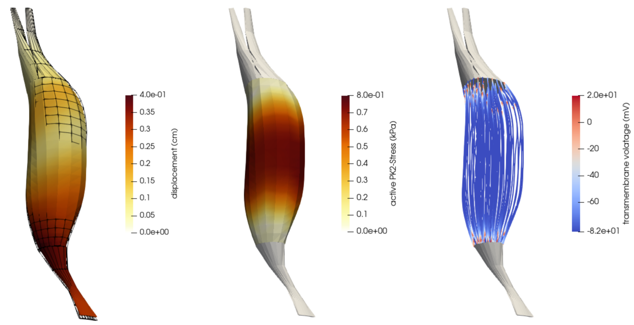

Figure 1: Results of an electrophysiological three-tendon-biceps simulation in OpenDiHu. Plots show displacement (left), active stress (center) and transmembrane voltage propagation (right) at 30ms after firing at the neuromuscular junctions.

Conclusions

We are able to simulate muscle-tendon system using a multi-X model implemented in OpenDiHu. In the next steps, we will study the function of the monosynaptic and dysinaptic reflex pathways. In addition, we will move from cuboid geometries to realistic agonist-antagonist muscle geometries in the lower leg.

Acknowledgments

We thank the Deutsche Forschungsgemeinschaft (DFG) for supporting this work through EXC2075 in Germany's Excellence Strategy and in SPP 2311 (390740016 and 465243391). We acknowledge the support by the Stuttgart Center for Simulation Science (SimTech).

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