Continuum-mechanical Modelling of the Musculoskeletal System

Röhrle, O.[1,2,3], Bleiler, C.[1], Avci, O.[3]

[1] Institute for Modelling and Simulation of Biomechanical Systems, Chair of Continuum Biomechanics and Mechanobiology, University of Stuttgart, Germany
[2] Stuttgart Center for Simulation Sciences (SimTech), University of Stuttgart, Germany
[3] Fraunhofer Institute for Manufacturing Engineering and Automation IPA, Stuttgart, Germany

1. Motivation and Approach

Most musculoskeletal system models appeal to multi-body simulation frameworks, in which the skeletal muscle force generation is modelled using Hill-type skeletal muscle models. Such modelling frameworks have the advantage that they can analyse and predict movement using musculoskeletal system models with a realistic number of muscle (groups). However, these multi-body simulation frameworks are also based on limiting modelling assumptions. For example, Hill-type skeletal muscle models lump together anatomical and physiological complexity to a few lumped parameters, e.g., the complex muscle fiber architecture to a single parameter at one point in space. Therefore, Hill-type models cannot be used to investigate key phenomena such as, for example, contact with external objects or muscle-muscle or muscle-bone interaction. Musculoskeletal system models appealing to three-dimensional, continuum-mechanical skeletal muscle models could naturally overcome such limitations. However, such models are rare and require sophisticated constitutive models and large computational resources. This is particularly true for forward (dynamics) simulations that are based on solving optimization problems. Based on the currently only published forward simulations of a two-muscle upper limb model, which consists of a Biceps Brachii, Triceps Brachii, the Humerus, and a one-degree-of-freedom elbow joint, cf. [1, 2] and Figure 1 (left), we will discuss the particular challenges in modelling musculoskeletal system models consisting of multiple continuum-mechanical, three-dimensional skeletal muscle models (cf. Figure 1 (right)).

2. Challenges

One of the biggest challenges of using three-dimensional, continuum-mechanical musculoskeletal muscle models is the geometry and particularly functional aspects associated with the geometry. For example, while one can extract the geometry and muscle fibre architecture of a three-dimensional musculoskeletal system from medical imaging techniques such as MRI or diffusion tensor MRI in a rather straight forward fashion, one cannot directly extract functional aspects such as the stress-free configuration (i.e., reference state for the continuum-mechanical framework) from imaging. While this is less important for analysing individual muscles, it is of utmost importance for musculoskeletal system models. We propose to obtain the respective pre-stretches for the individual muscles by setting up an optimization problem, in which the pre-stretch is the variable and the resulting motion part of the objective function. As basis for the pre-stretch calculations, we use a five-muscle upper limb model obtained from segmenting imaging data of the visible male project.

A further hard to overcome challenge is to identify and select appropriate constitutive models. For this purpose, we want to discuss novel homogenisation techniques to derive macroscopic constitutive laws from microscopic material behaviour and microstructural arrangements [3]. The effective constitutive material response is obtained by a homogenisation of mechanical energies and stresses from the micro- to the macroscale. One of the key feature of the new model is that it does not require any constitutive assumptions or calibration on the macroscale and therefore has the potential, e.g. through taking and analysing muscle biopsies and integrating such data into the model, to derive subject-specific constitutive behaviour.

Moreover, we will discuss different computational aspects, in particular the use of surrogate models, to reduce computational cost and to enable forward-dynamics simulations of continuum-mechanical musculoskeletal system models [2].

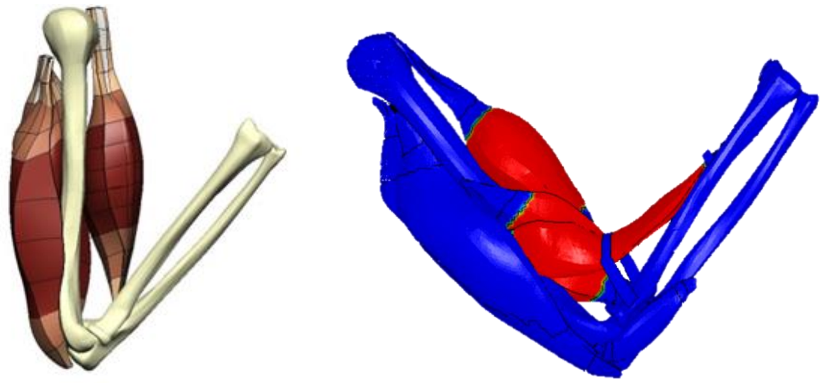

Figure 1 *Computational models of the upper arm consisting out of a two-muscle one-degree-of-freedom upper arm model (left) and a continuum-mechanical upper arm model consisting of 5 skeletal muscles modelled using continuum mechanics (right).*

References

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