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# THREE-DIMENSIONAL MUSCLE MODELLING

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## ABSTRACT

The structure of a skeletal muscle is dominated by its hierarchical architecture in which thousands of muscle fibres are arranged within a connective tissue network. The single muscle fibres consist of many force-producing cells, known as sarcomeres. These microbiological engines are part of a motor unit and contribute to the contraction of the whole muscle. From the mechanical point of view the material behaviour of muscles is highly non-linear. They undergo large deformations in space, thereby changing their shape significantly, so that geometrical nonlinearity has to be considered. The present approach is based on the use of the finite element method. The material behaviour of the muscle is split into a so-called active and a passive part. To describe the passive part special unit cells consisting of one tetrahedral element and six truss elements have been derived. Embedded into these unit cells are further truss elements which represent bundles of muscle fibres. In summary, the present concept has the advantage that a three-dimensional model is developed which allows us take into account many physiological processes at the micro level.

Skeletal muscles can be considered to be a complex organisation of thousands of force-producing muscle fibres arranged within a connective tissue. The muscular system holds about 40% of the total body weight. Muscles are responsible for the movement of the human body, they provide strength, serve as shock absorber and protect the skeleton system against external loads.

One of the first mathematical models was developed by Hill [1]. This phenomenological model is derived from force-velocity measurements on an entire muscle. As an early representative of the group of microstructural approaches the concept of Huxley [2] is crucially based on investigations of the behaviour of the cross bridges which are assumed to have only two possible states: coupled or uncoupled. Both, the phenomenological as well as the micro mechanically-based models are applied to describe the contraction of the whole muscle. These types of models are used in movement analysis and muscle performance studies as known from multibody dynamics systems.

The present contribution differs from earlier approaches insofar as it is formulated at the mesomechanical level, as previously introduced in the framework of rubber-like polymers, cp. [3]. In this way the actual geometry of the muscle, i.e. the directional distribution of the muscle fibres, can be easily taken into account. The mechanical behaviour of muscles is, as earlier mentioned by Van Leeuwen [4], split into a passive and an active part. The here proposed concept is based on the idea of representing the passive part by means of an assembly of non-linear truss elements. In each truss element the force-stretch behaviour of a certain group of collagen fibres is implemented. The truss elements are arranged in such a way that one of them lies on each edge of one finite tetrahedral element. In this way a so-called tetrahedral unit cell is formed. The tetrahedral element of the unit cell serves to model the (near-)incompressible behaviour of skeletal muscles. By using a random assembling procedure we are able to model arbitrary geometries. An ensemble of these unit cells lets us simulate the behaviour of the soft tissue alone. To incorporate muscle activation, bundles of muscle fibres in form of non-linear truss elements are embedded in the before mentioned assembly of unit cells. These trusses contain a mathematical description of the activation at the fibre level. In this way we are able to simulate complex muscle structures with arbitrary muscle fibre distributions, see also [5].

Beside the study of muscle behaviour one main object of this work is to apply the material model to realistic muscle geometries to be responsive to patients-specific questions. Therefore simulations of realistic muscle geometries are shown. Here the longest muscle of the human body, the sartorius muscle, is studied which arises by tendinous fibres from the anterior superior iliac spine, running obliquely across the upper and anterior part of the thigh in an inferomedial direction, see Fig. 1. It descends as far as the medial side of the knee, passing behind the medial condyle of the femur to end in a tendon. This tendon curves anteriorly to join the tendons of the gracilis and semitendinous muscles which together form the pes anserinus, finally inserting into the proximal part of the tibia on the medial surface of its body. The action of sartorius is to cross the legs, by flexion of the knee, and flexion and lateral rotation the hip. Fig. 1 (a) shows the whole sartorius muscle including the tendon (coloured grey).

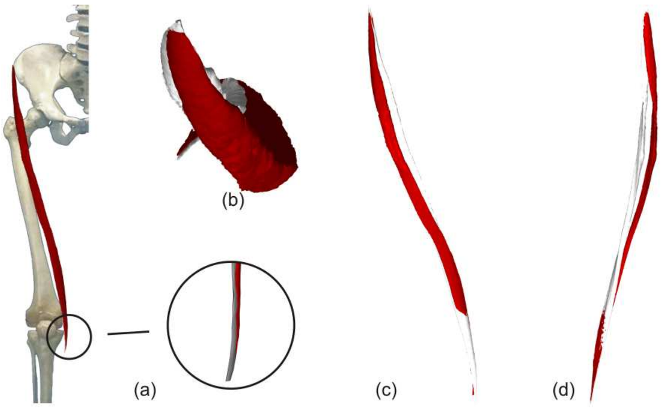

Figure 1: Geometry and simulation results (only tetrahedral elements are shown) of the sartorius muscle: (a) Muscle geometry (red = muscle tissue, grey = tendon), (b) axial, (c) coronal and (d) sagittal view (light-grey = undeformed muscle, red = deformed muscle).

The sartorius muscle belongs to the group of fusiform muscles. That means that the global load direction of the muscle and the muscle fibres are aligned in parallel. Due to the spiral geometry of the muscle also the deformation behaviour is characterised by a torsion-like deformation in combination with a contraction, cp. Fig. 1 (b)-(d). This is conform to the physiological ”function” of the muscle, because it bends the joints of the hip and the knee in combination with a movement of the thigh to the middle while the lower thigh is rotated to the inner site of the thigh.

## References

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