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Original Research Article

A two dimensional approach for modelling of pennate muscle behaviour

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1. Introduction

The human movement system consists of striated skeletal muscles that have different architectures. Among these muscles are fusiform muscles and pennate muscles (unipennate muscles, bipennate muscles and multipennate muscles) [1]. The fusiform muscle fibres run generally parallel to the muscle axis (it is line connecting the origin tendon and the insertion tendon). The unipennate muscle fibres run parallel to each other but at the pennation angle to the muscle axis [2]. The bipennate muscle consists of two unipennate muscles that run in two distinct directions (i.e. different pennation angles). The multipennate muscle is composed of a few bundles of fibres that run in distinct directions.

From the physiology point of view, the unipennate muscle consists of three parts: the muscle insertion (insertion tendon), the belly (muscle fibres), and the muscle origin (origin tendon). It is assumed that during contraction the belly maintains the isovolume, each tendon moves only along its axis and muscle fibres become more pennated, i.e. the pennation angle is increased [3].

The spatial arrangement of pennate muscle fibres determines the muscle fibres length, the lengths of tendons and mechanical properties of muscle. That is why the contractile characteristic (i.e. force-generating capacity) depends on the pennation angle [2]. Moreover, one should take into consideration that a real pennate muscle is a non-homogenous structure: the distal muscle fascicles tend to contract more (i.e. they act at greater pennation angles) than the more proximal muscle fascicles.

Applying an imaging technique, such as nuclear magnetic resonance (MRI) or ultrasonography (US), with a motion capture technique, one might perform in vivo non-invasive measurements to estimate volumes of muscles, muscle fibres lengths and pennation angles [2]. However, one should perform invasive measurements to obtain [4]: 1) parameters describing mechanical properties of chosen muscles (by applying tensile tests and sonomicrometry); 2) muscle morphology and its architecture evaluated at the microscopic level (by using a muscle biopsy); 3) muscle static characteristic (length-force dependence); 4) muscle dynamic characteristic (velocity–force dependence); 5) muscle-tendon parameters used in the Hill-type muscle model. That is why a very limited amount of data describing mechanical properties of pennation muscles can be found in literature.

To model behaviour of pennate muscle one should take into consideration that spatial arrangement of muscle fibres influence mechanical properties and contractile properties of this muscle. Nowadays, to describe pennate muscle function in muscle biomechanics there are applied rheological models: Hill-type muscle models and Hill-Zajac muscle models [3,5–11]. However, application of these models is very limited due to

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problems related to the obtainment of model parameters. To deal with these problems an optimization technique (i.e. mathematical optimization) can be applied. However, in this case the problem of compatibility between chosen cost function and an alive muscle physiology should be considered.

The three-dimensional (3D) muscle models that take into consideration spatial muscle fibres arrangement are also proposed [12–18]. To apply chosen 3D muscle model, one needs to define the 3D geometry, interaction between components of this model (e.g. lateral transmission of tension between muscle fibres), boundary conditions and material properties according to the principles of continuum mechanics. The fundamental problem consists in identification of material properties because of constrained range of alive tissue experiments. Moreover, these 3D muscle models are applied for static or quasi-static solutions and are incompatible to solve forward dynamics tasks because these models are computational expenses.

Deliberating an application of high-mentioned Hill-type muscle models, Hill-Zajac muscle models or three-dimensional (3D) muscle models, one should define for each muscle examined: muscle static characteristic, muscle dynamic characteristic, tendon static characteristic, physiological cross section area (PCSA), optimal muscle length and optimal muscle force. Due to limited possibility of an alive muscle examination, these characteristics and parameters are defined by making additional assumptions and presuming that a muscle force can be predicted on the base of the value of PCSA and maximum muscle stress or/and a static characteristic of sarcomere (relationship between a sarcomere length and isometric force of this sarcomere). Moreover, in the case of pennate muscle modelling one should take into consideration that muscle force depends on the spatial arrangement of muscle fibres and that is why above-mentioned characteristics and parameters must be estimated for each pennate muscle in the range of its physiological behaviour.

To model behaviour of chosen flat pennate muscle one should take into account a planar kinematics, which is described by using at least two parameters (two-dimensional approach). The purpose of this study was to elaborate a two-dimensional approach for unipennate and bipennate striated skeletal muscle modelling by applying a method described in [19]. According to this approach, a behaviour of chosen flat pennate muscle is modelled as a rheological system composed of serially linked passive and active fragments having different mechanical properties. Each fragment is composed of three elements: mass element, elastic element and viscous element. Each active fragment furthermore contains the contractile element. Proposed approach takes into consideration that muscle force depends on a planar arrangement of muscle fibres. The scope of presented study was to perform numerical researches and to elaborate a concept of experimental verification.

2. Method of modelling

2.1. Principles of pennate muscle modelling

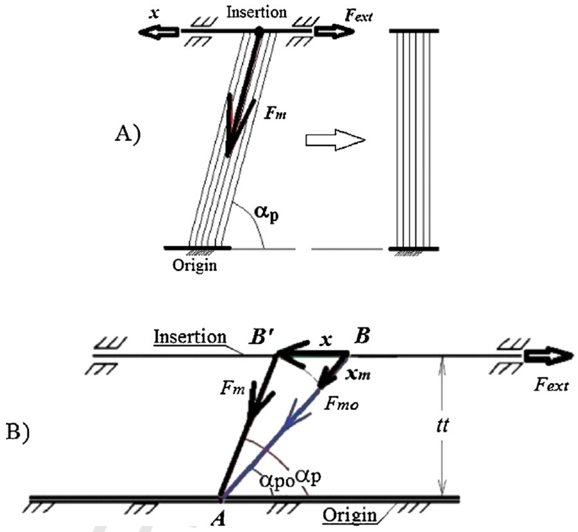

Fig. 1 – Deformation schema of unipennate muscle: A) directions of acting of external force F_{ext} and contractile muscle force F_m towards the muscle insertion displacement x; B) schema of deformation of unipennate muscle (AB – the initial length of muscle (before contraction); AB′ – the finish length of muscle (after contraction); F_{mo} – initial contractile muscle force at the length of muscle equals AB; F_m – finish contractile muscle force at the length of muscle equals AB′; α_{po} – the pennation angle before contraction (at the length of muscle equals AB); α_p – the pennation angle after contraction (at the length of muscle equals AB′); x_m – change of muscle length that is equal to the difference of the length AB and the length AB′) [19].

Assuming a planar deformation schema of unipennate muscle shown in Fig. 1, the mathematical models of unipennate muscle and bipennate muscle were created. According to this deformation schema, the muscle contraction occurs in the plane (two-dimensional space) along muscle fibres directed at the pennation angle α_p towards the line connecting the muscle insertion (it is a movable part with one degree of freedom) and the muscle origin (it is a non-movable part). It is assumed that during muscle contraction the muscle width *tt* is constant (according to [20]) and muscle fibres generate a contractile muscle force F_m, which causes the displacement of muscle insertion x and counterbalances an external force F_{ext}:

$$F_{ext} = F_m \cdot \cos\alpha_p \quad (1)$$

During contraction the muscle fibres are shortening and the muscle insertion is translated from the point B to the point B′ (the distance BB′ is equal to the muscle insertion displacement x). It causes the change of pennation angle: the initial value of pennation angle α_{po} (at the length of muscle equals AB), is changed to the value α_p (at the length of muscle equals AB′). Analyzing the deformation schema of unipennate muscle, the following geometric relation can be derived:

$$tt = AB \cdot \cos\alpha_{po} = AB' \cdot \cos\alpha_p. \quad (2)$$

Taking into consideration a deformation schema of unipennate muscle, five rheological models were created [19]:

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