JOURNAL OF THE MECHANICAL BEHAVIOR OF BIOMEDICAL MATERIALS 4 (2011) 1299–1310

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journal homepage: www.elsevier.com/locate/jmbbm

Research paper

A coupled electromechanical model for the excitation-dependent contraction of skeletal muscle

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ARTICLE INFO

Article history:
Received 28 December 2010
Received in revised form
8 April 2011
Accepted 21 April 2011
Published online 29 April 2011

Keywords:
Skeletal muscle
Muscle contraction
Electromechanical coupling
Action potential
Skeletal muscle activation
biceps brachii muscle

ABSTRACT

This work deals with the development and implementation of an electromechanical skeletal muscle model. To this end, a recently published hyperelastic constitutive muscle model with transversely isotropic characteristics, see Ehret et al. (2011), has been weakly coupled with Ohm's law describing the electric current. In contrast to the traditional way of active muscle modelling, this model is rooted on a non-additive decomposition of the active and passive components. The performance of the proposed modelling approach is demonstrated by the use of three-dimensional illustrative boundary-value problems that include electromechanical analysis on tissue strips. Further, simulations on the *biceps brachii* muscle document the applicability of the model to realistic muscle geometries.

1. Introduction

It is well known that the depolarisation of a skeletal muscle fibre results in a free calcium ion concentration increase in the sarcoplasm; see, e.g., Melzer et al. (1984) and Ashley et al. (1991). Further, these free calcium ions bind to troponin to enable cross-bridge attachment and consequently muscle contraction. Although many physiological aspects are known, various mathematical muscle models have been developed considering only single aspects of the excitation–contraction process. Further, they are mostly implemented in so-called 'stand-alone' programmes and only capture one-dimensional problems. Hence, no geometry effects can be considered. One-dimensional examples include, for example, calcium (Ca^{2+}) movements/diffusion (Wallinga-de Jonge et al. (1981), Cannell and Allen (1984), Hollý and Poledna (1989), Bugrim et al. (1997), Baylor and Hollingworth (1998), Novo et al. (2003) and Baylor and Hollingworth (2007)), membrane voltage/calcium sparks (Farnbach and Barchi (1977), Hatze (1977), Dorgan and O'Malley (1997), Riener and Quintern (1997), Baylor et al. (2002), Chandler et al. (2003) and Baylor (2005)), and different components that link electrical stimulation to contraction (Cannell and Allen (1984), Ríos et al. (1993), Baylor and Hollingworth (1998), Wallinga et al. (1999), Razumova et al. (2000) and Shorten et al. (2007)).

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1751-6161/$ - see front matter
doi:10.1016/j.jmbbm.2011.04.017

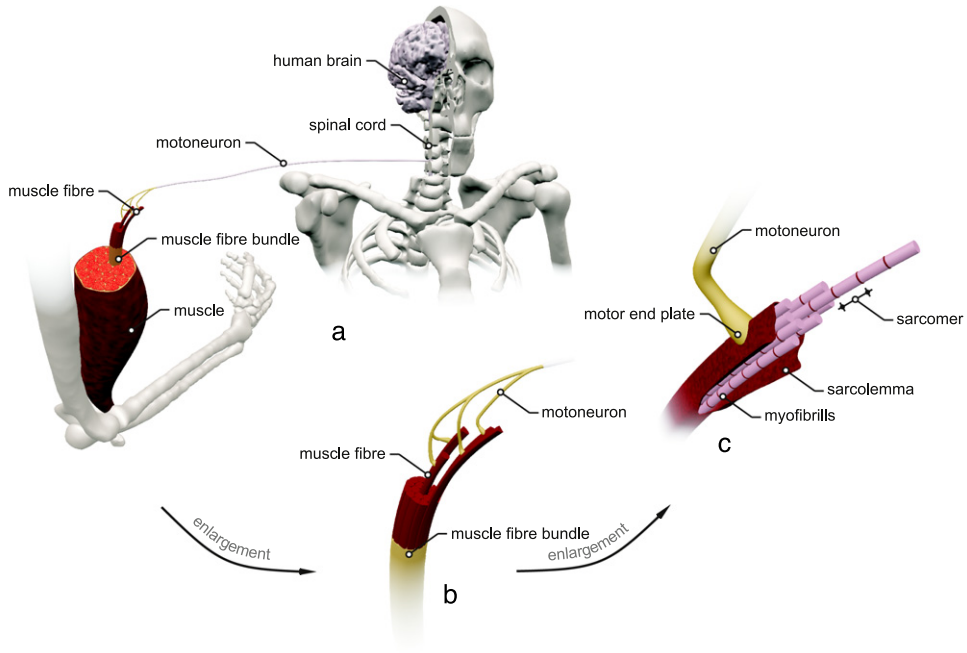

Fig. 1 – Schematic illustration of the connection between the human nervous system and skeletal muscle. (a) The brain sends a signal through the spinal cord and peripheral nerves (motoneuron) to the muscle. (b) The motoneurons are connected to the muscle fibres by neuronal junctions, the motor end plates. (c) A muscle fibre consists of myofibrills that are in turn composed of basic contractile units, the sarcomers.

In contrast to the aforementioned models, to the authors' knowledge there exists only one three-dimensional model, that of Röhrle et al. (2008). This model is based on the classical, additive decomposition of the muscle behaviour into a passive part and an active part. The passive part is specified by the Mooney–Rivlin model (Mooney, 1940) and the active part is rooted on the electrophysiological approach by Shorten et al. (2007) that is based on a system of 51 ordinary differential equations (ODEs). These ODEs control the intracellular and extracellular ion concentrations as well as the binding states of a number of ions and proteins. Consequently, this model depends on a huge number of model parameters that have to be identified primarily.

The aim of the present modelling approach is a numerical tool rooted on the finite element method that allows the study of the excitation–contraction process of skeletal muscles due to external stimuli. To this end, we focus on the main phases in such a process to keep the number of parameters low and thus ensure a satisfying applicability. Hence, the phenomenological approach presented here uses two phases. The first phase entails the electrical propagation of the action potential inside the muscle tissue. The second phase is characterised by the development of an active twitch force of the individual motor units.

The paper is organised as follows. Section 2 gives a brief description of the biophysical mechanisms of skeletal muscle activation. In Section 3, the governing equations of a coupled boundary value problem for skeletal muscle electromechanics are introduced. Before illustrative examples are shown in Section 5, Section 4 considers the coupling procedure of the electrical and mechanical fields used in this modelling approach. We conclude with some closing remarks in Section 6.

2. Biophysical mechanisms of muscle activation

Electromechanical experiments on skeletal muscle are frequently arranged on single muscles or muscle groups, either inside or outside the human body. In both cases, electrodes are connected to the nerves, and thus external stimuli can be applied. This scenario of external stimulation exactly expresses the situation that the modelling approach presented is developed for. However, in order to understand the mechanisms of electromechanical muscle activation, in the first part of this section we give a brief overview of the well-accepted biophysical principles of skeletal muscle activation. The second part focuses on the characteristics of the action potential in order to get a more detailed view of the processes that the approach is based on.

2.1. *Skeletal muscle activation*

The unique feature of skeletal muscles is their ability to contract due to voluntary effort. The spinal cord and parts of the peripheral nervous system carry the electric signals via motoneurons to the muscle in terms of action potentials; see Fig. 1(a). A skeletal muscle is characterised by a hierarchic structure, and it consists of muscle fibres containing bundles of myofibrills; see Fig. 1(b). The myofibrills in turn are composed of basic contractile units, the sarcomers; see Fig. 1(c). They mainly consist of two motorproteins, actin and myosin filaments. A single motoneuron is connected to many muscle fibres of the same type; the exact number depends on the function and size of the respective muscle. The excited fibres and the associated motoneuron build a so-called motor unit. The domain of connection between the