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Fast generation model of high density surface EMG signals in a cylindrical conductor volume

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ABSTRACT

In the course of the last decade, fast and qualitative computing power developments have undoubtedly permitted for a better and more realistic modeling of complex physiological processes. Due to this favorable environment, a fast, generic and reliable model for high density surface electromyographic (HD-sEMG) signal generation with a multilayered cylindrical description of the volume conductor is presented in this study. Its main peculiarity lies in the generation of a high resolution potential map over the skin related to active Motor Units (MUs). Indeed, the analytical calculus is fully performed in the frequency domain. HD-sEMG signals are obtained by surfacic numerical integration of the generated high resolution potential map following a variety of electrode shapes. The suggested model is implemented using parallel computing techniques as well as by using an object-oriented approach which is comprehensive enough to be fairly quickly understood, used and potentially upgraded. To illustrate the model abilities, several simulation analyses are put forward in the results section. These simulations have been performed on the same muscle anatomy while varying the number of processes in order to show significant speed improvement. Accuracy of the numerical integration method, illustrating electrode shape diversity, is also investigated in comparison to analytical transfer functions definition. An additional section provides an insight on the volume detection of a circular electrode according to its radius. Furthermore, a large scale simulation is introduced with 300 MUs in the muscle and a HD-sEMG electrode grid composed of 16×16 electrodes for three constant isometric contractions in 12 s. Finally, advantages and limitations of the proposed model are discussed with a focus on perspective works.

1. Introduction

The modeling of surface electromyogram (sEMG) signals generation has quickly expanded during the last twenty years [1–7] for purposes of testing decomposition approaches [8], local sensitivity analysis [9], studying the EMG/force relationship [10,11], and assessing processing approaches among the numerous available applications. In fact, models can provide electromyographic data generated in specific physiological and neural configurations. Those configurations can be controlled in models whereas it is hardly estimated in experimental conditions. Advances in sEMG modeling have focused on the description of the volume conductor which can be planar [4] or cylindrical [3,5], the detection system [12], the phenomena of generation and extinction of the intracellular action potentials at the end-plate and myotendinous junction [4], also on the motor units (MUs) recruitment pattern (spatial and rate coding) [1,9]. Both analytical [3,4] and numerical [6,7] models have been proposed for the description of the electrical activity of striated muscles.

Analytical models also considered pennated muscles [13]. Analytical models are usually computationally more efficient than their numerical counterparts but the latter models better describe the complex geometry of the muscle in a patient-specific manner. On the other hand, investigation of the sEMG features changes according to physiological mechanisms are easier and faster with analytical models. Additionally, analytical models are limited to a non-realistic volume that can distort the generated signals and their interpretation. Despite these limitations, analytical solutions are still valuable for the following reasons:

- to express the theoretical relationship of the generated signal according to a specific parameter set (neural, anatomical and physiological);
- to benchmark the accuracy of numerical models in trivial configurations;

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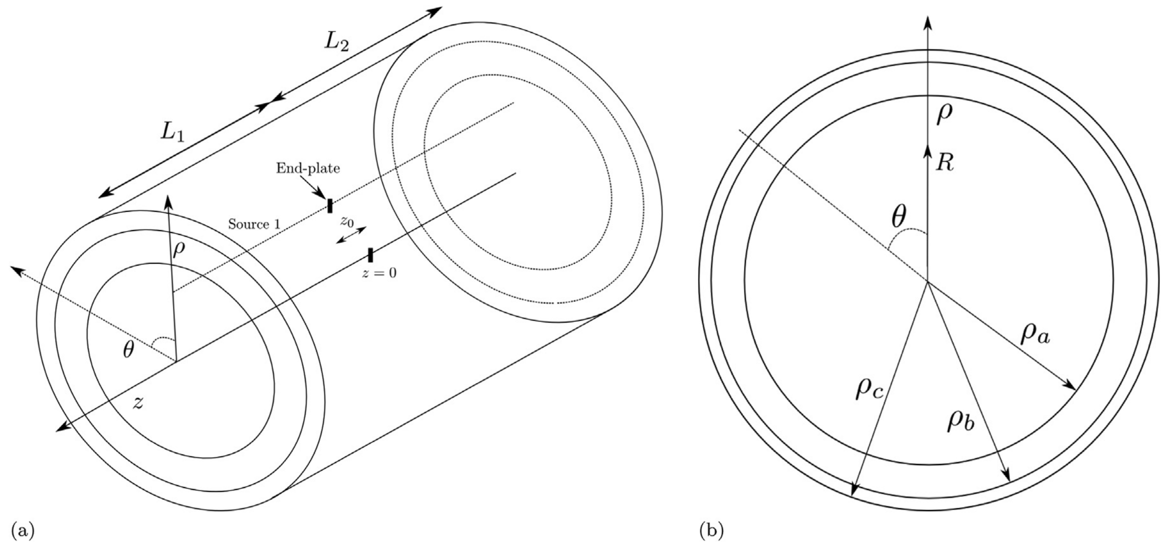

Fig. 1. Muscle geometry in cylindrical coordinates (ρ, θ, z). (a) z_0 represents the position of the fiber's end-plate, L_1 and L_2 are the fiber's semi-lengths from the end-plate to the right and to the left tendon, respectively. (b) Longitudinal cross-section of the cylinder. R is the radial position of the fiber, ρ_a, ρ_b and ρ_c are the muscle, fat and skin radius, respectively.

- to have an approximated solution in a reduced time compared to numerical model.

Even though analytical computation is by definition faster than numerical one, computation time can stepwise go up depending on its precision (e.g. channel number and temporal sampling frequency) and realism (e.g. fiber and MU number). However, this increasing complexity can be managed by optimal programming strategies. Unfortunately, these numerical aspects have never been clearly described in previous analytical sEMG models with no indications of their numerical implementation [3–5].

Recently, a novel electromyographic recording technique has emerged, named High Density (HD) sEMG (HD-sEMG), that provides access to a high number of monopolar channels (up to 128 channels) simultaneously [14]. More significant information about the studied muscle is provided thanks to the increase of recording channels over the muscle. Compared to classical recording techniques, the HD-sEMG makes accessible the analysis of multichannel on the muscle and brain activities (as for EEG recordings) and has already proved encouraging faculties [14]. Still, an efficient incorporation of this multidimensionality in the modeling process should be considered as complex to achieve. Some preliminary works have been proposed imposing a huge computational time [7]. In this study, we overcome this computing complexity by efficient design and programming of an HD-sEMG generation model.

For this purpose, we propose to take inspiration from recent generation models described in [3,5]. In those models, the muscle is considered as a cylinder with the possibility to model multiple anisotropic or isotropic layers. From this geometry, authors developed a 2D transfer function for the conductor volume.

In the models cited above, computation time and numerical implementation for sEMG signal generation were never exposed to evaluate its computing efficiency. Those models can be considered as theoretical starting points for the present work whose objective is to develop a fast, complete and easy-to-use HD-sEMG generation model with a cylindrical conductor volume. In fact, clear description and demonstration of its mathematical formalism and its numerical implementation is provided for managing complexity and computing time. In addition, a different and innovative computation scheme is followed for a fast and optimized computation of the muscle electrical activity over the skin surface using 3D matrices in the Fourier domains and parallel computing (see Section 2). In this study, an analysis of the model computing time will be exhibited in order to evaluate its efficiency (see Section 3). Through several simulation examples, the ability of the model to simulate muscle electrical activity for different type of motor units, fiber velocities, and electrode shapes will be depicted. A study about the volume detection of a circular electrode according to its radius will also be presented. Then, a full scale simulation (300 MUs, 52,200 fibers, 12 s, 4 kHz sampling frequency and 256 circular electrodes computed from a potential map of 131 × 101 points at each time step) using the proposed model will be displayed to show its reliability.

Later on, the abilities and limitations of the proposed model are discussed (see Section 4). A final section (see Section 5) will conclude and brush over the perspectives of futures works.

2. Materials and methods

As mentioned in the Introduction, we took as a starting point the cylindrical representation of the model in [5]. Geometry of the muscle is described in Fig. 1, the cylindrical coordinates (ρ, θ, z) are used in this study. Origin of the cylinder muscle is placed at its center. The cylindrical conductor volume is composed of three layers (muscle, fat, and skin) and sources are placed in the most internal layer, along the z coordinate where four layers (bone, muscle, fat, and skin) have been considered in [5]. The bone layer can be regarded as negligible influence on the simulated signals if the distance between muscle–bone and muscle–fat interfaces are high enough. In [5] the distance between the two interfaces was equal to 5 mm and in this case bone layer has an impact on the simulated signals. However, in the case of a simulation of the Biceps Brachii muscle, this distance turns around 20 mm and therefore bone layer has negligible impact (less than 1% on the simulated signals). This has been checked using the proposed model in a four layer configuration. As for the sources, they are modeled at the microscopic scale and represent fiber intracellular potential generation, propagation and extinction along the fiber. Moreover, all the layers have a finite thickness along the radial direction.