EMGSIM: A COMPREHENSIVE SIMULATION TOOLBOX FOR ELECTROMYOGRAPHY

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INTRODUCTION

The electromyography signal (EMG) is the electric signal generated by contracting muscles. It contains important information regarding the physiological properties of underlying neuromuscular systems. When a pool of motoneurons is excited by the efferent neural drive, each active neuron generates a train of neural pulses, which in turn elicits a motor unit action potential (MUAP) train. Since all the action potentials in a MUAP train are identical, the MUAP train can be modeled as the convolution of the action potential and a statistical point process. The latter is usually called the motor unit innervaton process (MUIP). The aggregation of the MUAP trains of all active motor units is called the EMG. Extensive research on EMG synthesis has been focused on the effects of the microscopic properties of muscle fibres, such as muscle fibre length, end-plate dispersion, and tendon dispersion, etc. In these studies, the MUAP trains are usually modelled as simple renewal processes. However, this model is only valid for stationary EMG during isotonic (constant force) contractions, where the neural drive to the motoneuron pool is stationary. Unfortunately, most natural contractions of muscles are anisotonic (changing force). Therefore, it is important to develop a tool that is able to simulate non-stationary EMG. In this paper, a comprehensive EMG simulation toolbox, *EmgSim*, is introduced. It has the capability to simulate both stationary and non-stationary EMG. The object-oriented, modular design of *EmgSim* makes it a universal backend engine for various EMG studies, especially those concerning non-stationary and dynamic EMG, such as those elicited in the control of myoelectric prosthesis. The design and implementation of the toolbox is discussed in the Methodology section. Using the toolbox, a simulation study on different recruitment strategies and their effect on EMG is presented in the Results section.

METHODOLOGY

EmgSim is an object-oriented toolbox with modular and flexible design, developed in MATLAB (version 7.1 or newer). A schematic diagram of the structure of the toolbox is presented in Figure 1. As shown in the figure, it is consisted of two main modules. The first module, innervation process module (IPM), is the module responsible for the generation of the MUIPs. These processes can be used by the second module, volume conductor module (VCM), to generate MUAP trains. The VCM further takes the sum of all the MUAP trains, creating EMG.
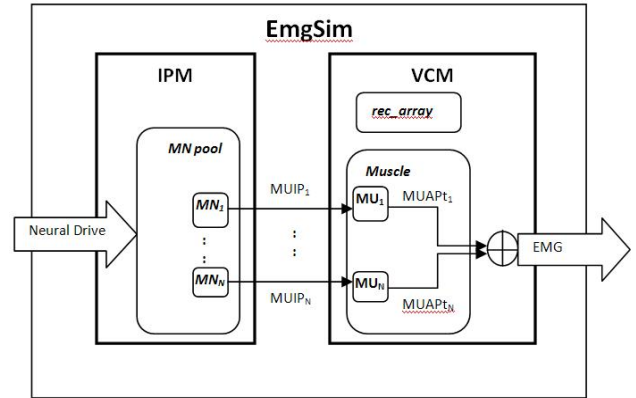

Figure 1 The block diagram of the *EmgSim* toolbox

Innervation Process Module

The function of the IPM is to generate the MUIPs. It has a two-layer object structure. The higher level object, **MN pool**, is the ordered collection of a number of the lower level objects, **motoneuron (MN)**. When creating a **MN pool**, at last three parameters must be specified: *size*, *threshold_curve*, and *model*. The first parameter is the number of **MN** within the pool. The second parameter is the unit recruitment strategy. The recruitment threshold of the i*th* neuron in the pool, namely T_i, is a function, $F(i)$, of its order in the pool, i:

$$T_i = F(i). \tag{1}$$

Two $F(\cdot)$ are implemented to simulate the two types of motor unit recruitment strategy reported in the literature [1]. For smaller muscles, such as those in the hand, all neurons are usually recruited before 50% maximum voluntary contraction (MVC). When this type of strategy is intended, the *threshold_curve* should set to *exp*, under which T_i is assign according to the rule:

$$T_i = \exp(i \ln \frac{T_N - T_1}{N}),\qquad(2)$$

where T_1 is the lowest threshold (the first unit), and T_N is the highest threshold (the last unit). With this strategy, most units have low thresholds.

On the other hand, for larger muscles, recruitment can still happen over 90% of MVC. In this case, *threshold_curve* should be *linear*:

$$T_i = i \frac{T_N - T_1}{N}.\qquad(3)$$

The third parameter, *model*, is the computational model for the neuron. To accommodate the needs of different applications, four different models for the motoneuron are implemented. Ranking by their respective computational complexities, they are random firing model, Yao's enhanced random firing model [2], integrate-to-threshold and fire model (ITF) [3], and a Hodgkin-Huxley-like (HHL) model [4]. To simulate stationary EMG, the random firing model is sufficient. For studies on motor unit synchrony, at least Yao's enhanced random firing model should be applied. To simulate more physiologically realistic MUIPs, the ITF or HHL model should be used, at the expense of higher computational cost. The detail implementations of these models can be found in their respective references.

<u>Volume Conductor Module</u>

The function of the VCM is to generate MUAP trains of all motor units according to an appropriate volume conductor model. The VCM has two top-layer objects: *muscle* and *rec_array*. The object *muscle* corresponds to the object *MN pool* in the IPM. A *muscle* contains a number of sub-objects, *motor_units* (*MU*), which further contains a number of the lowest level object, *fibres*. There are two types of properties of the object *fibre*: electrical and geometrical. The electrical properties define the properties such as conduction velocity, while the geometric properties define its geometric locations. The other top-level object, *rec_array*, contains an array of sub-objects, *electrode*. Each *electrode* specifies the geometric locations of the recording electrodes, as well as other properties of the data collection system, such as sampling rate, data length, etc. With these properties and an appropriate volume conductor model, the action potential of each *fibre*, and consequently the MUAP of each *MU*, detected at each *electrode*, is obtained. Currently, only one simple, yet reasonably accurate volume conductor model is implemented *EmgSim*. The model assumes the finite length muscle fibres are parallel to each other, residing in an infinite isotropic medium [5]. The model has been applied in many studies [5-8]. In

cases where an anisotropic medium and unparallel fibres is necessary, more advanced volume conductor model, such as those employing finite element analysis [9, 10], can be easily implemented, thanks to the flexible design and well defined interfaces of the VCM.

Once the MUAPs are obtained, they are convolved with their corresponding MUIPs from the IPM. The results of the convolution are the MUAP trains of all *MUs*, and the summation of all these MUAP trains is the EMG recorded at a particular electrode.

RESULTS

To demonstrate the functionality of *EmgSim,* a simple case study is presented here. As discussed in the previous section, two types of *threshold_curve* are implemented to simulate the distinct recruitment strategies. An example of these two recruitment strategies is demonstrated in Figure 2. Two *MN pools*, each containing 120 *MUs*, are created by the IPM. The *threshold_curve* of pool A and pool B are *linear* and *exp*, respectively. Both of the pools are subjected to an identical neural drive. As shown in the figure, the two pools demonstrate distinct recruitment patterns.
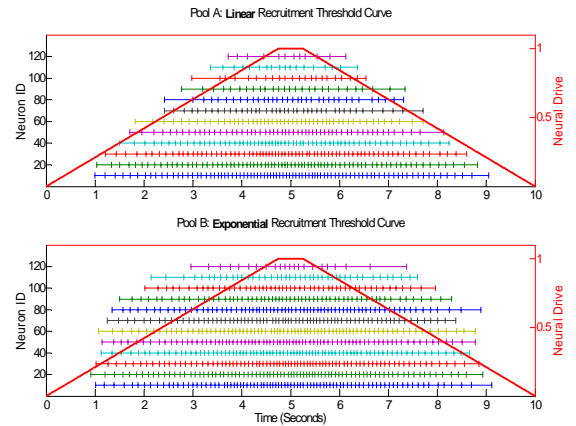

Figure 2 The Inter-pulse interval bar plots of two *MU pools* with different recruitment strategies, receiving the same neural drive (the trapezoidal line in each plot). Each pool consists of 120 *MUs*. The top plot is the linear threshold curve, and the bottom plot is the exponential threshold curve.

To simulate EMG, a *muscle* containing 120 *MUs* is created by VCM. Each *MU* consists of 10 *fibres*, with an average length of 120 *mm.* The center of the end-plate is located at 70 *mm* from one end of the fibres. All motor units are located within an ellipse, centered at 25 *mm* beneath the skin surface. A *rec_array* containing two *electrodes*, located 35 mm and 40 *mm* from the end-plate. The inter-electrode

distance is 5 *mm*. Other details of the geometric configurations of the motor units and the recording electrodes are demonstrated on the left hand side of Figure 3. The MUIPs with the two different recruitment strategies from the IPM (shown in Figure 2), are supplied to the VCM, to generate biopolar surface EMG. The raw EMG signals are plotted in the top-right panel of Figure 3, along with the mean square values (MSV) of the raw EMG in the bottom-right panel. As
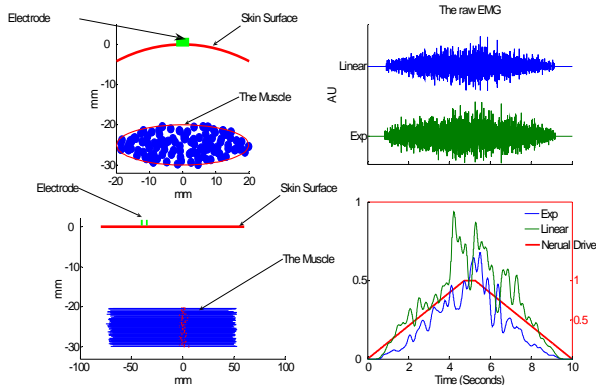

Figure 3 The left panel is the geometric configuration of the simulation in VCM. The top plot is the transverse view, and the bottom plot is the axial view. The right panel is the simulated EMGs. The top plot is the raw EMG, and the bottom plot is their MSVs, obtained by a 200-*msec* Hanning smoothing window.

shown in these plots, the different recruitment strategies result in different EMG patterns. When the underlying recruitment strategy is linear, the magnitude of the resulting EMG is smaller than when the exponential strategy is applied. This is expected, because more units will be recruited with the exponential strategy than with the linear strategy, given the same neural drive.

SUMMARY

A comprehensive simulation toolbox for EMG, *EmgSim*, is presented. This object-oriented toolbox is designed as a flexible and extensible backend engine for EMG synthesis. The toolbox is consisted of two modules: IPM and VCM. In the IPM module, several models for the MUIP are implemented, providing the capability of simulating both non-stationary and stationary EMG. In the VCM module, a simple volume conductor model is implemented, while providing well defined interfaces to incorporate more complex models. With its modular design, the two modules can be used as two independent tools, or they can be used in tandem as one tool. Based on *EmgSim*, front-end applications, such as application-specific graphic user

interfaces (GUI) can be easily developed to suit the needs of different EMG research projects.

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