Teaching a master student how to model the electrical potentials produced by the muscle

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Abstract *— In Electromyography studies, the motor unit is considered as the anatomical and functional unit responsible of the electrical activity related to the contraction of the skeletal muscle. This paper is aimed at showing biomedical engineering master students how to model and study the electrical potentials produced by the activation of the motor unit. The proposed model is based on a mathematical concept familiar to engineers, the convolution. By using computer simulations based on this model we illustrate how to study the effects of changes in the motor unit parameters on the characteristics of generated electrical signal. The paper is useful in showing the students how to identify the different aspects involved in the analysis of biological phenomena.*

Index Terms *— motor unit; muscle fibre; computer simulation; single fibre action potential (SFAP); motor unit action potential (MUAP).*

INTRODUCTION

Biomedical Engineering is the field of Engineering aimed at creating products and services that may have practical use at the fields of clinical medicine and social health care. In the past few decades the industrial sector related to this area has experienced an enormous impulse driven by the maturity of several technologies (radiofrequency, nuclear, computers, signal processing, Internet, nanotechnology, etc) and the advent of a myriad of devices appropriate for diagnosis and therapeutic purposes. Following this trend, Higher Education in Spain has given priority to the development of studies in the fields of Biomedicine and Biomedical Engineering.

The Public University of Navarra (Spain) is relatively young (it was established in 1987) so that it has shown itself to be very dynamic at incorporating changes, and this new environment is no exception. In an attempt to adapt to this framework, our university has promoted the creation the Master's Program of Biomedical Engineering (BME) since 2007. As in other universities, our Master Degree in BME is designed for students who wish to pursue careers in research and development, academia, or industry within the interdisciplinary fields of engineering and medicine. Students are challenged to integrate the engineering and life sciences throughout the curriculum, including quantification of physiological processes, modelling, and computer simulation of biological phenomena.

One of the main subjects treated in the master is Bioelectricity. Indeed, electricity is the cornerstone of the Biomedical Engineering studies as it is essential for the understanding and interpretation of many biological processes. The present work is aimed at showing BME master students how to model and study the electrical behaviour of a well-known biological system: the motor unit. In Electromyography studies, the motor unit represents the functional unit of a skeletal muscle that controls both its electrical activity and contraction mechanism. Our approach to study the motor unit contains several aspects of relevance to the biomedical engineer's background: (1) it identifies the anatomical, physiological and functional properties of the biological system under study, (2) it shows how to develop a mathematical model that comprises the abovementioned system properties, (3) it emphasizes the importance of the recording conditions on the generated electrical signal, (4) it illustrates how to analyse the effects of changes in the system properties on the generated electrical signal, and (5) it shows how to incorporate the inherent variability associated to the system into the mathematical model.

It is generally accepted that students learn an engineering topic best when they see the physical results of the experiments they perform. However, this is not always possible when dealing with a biological system such as the motor unit. In this particular case, the recording of the electrical signals is carried out by a specialist physician using a needle electrode that is inserted into the muscle, which produces a certain degree of pain to the subject. Such tests cannot be performed by the students and this leads teachers to look for educational alternatives such as the use of computers to model and simulate biological processes. Indeed, computer simulation becomes an invaluable tool in teaching the structure and functioning of the motor unit.

In the course of Bioelectricity, simulations were carried out using MATLAB, i.e. a software package well-known by all BME master students. Specifically, the authors have developed a set of simulation programs on MATLAB in order to allow the students: (1) to obtain a better understanding of the generation of electrical potentials produced by the muscle

contraction, and (2) to appreciate how the changes in the motor unit parameters affect the properties of the generated electrical potentials. It has been the believe of the authors that an electrical model of the motor unit together with a carefully designed collection of simulation programs based on this model contribute to a more solid and founded background of the biomedical engineer.

THE STRUCTURE AND FUNCTIONING OF THE MOTOR UNIT

A muscle creates a desire level of force via the repeated contraction of a number of groups of muscle fibres. Each group of muscle fibres is controlled by an alpha-motor neuron. Specifically, the motorneuron governs simultaneously a group of muscle fibres that are attached to its axon terminal branches at the neuromuscular junctions (NMJ) (Fig. 1). The motor unit (MU) is the system formed by a single motorneuron (the axon belongs to it) and all the muscle fibres that it innervates, and represents the anatomic and functional unit of a skeletal muscle (Fig. 1). The end-plate of a motor unit is the region where the neuromuscular junctions of its fibres are located.

Each individual skeletal muscle is activated by electrical impulses coming from the motoneuron through its axon. When an electrical impulse arrives at the neuromuscular junction it is converted into two intracellular action potentials (IAPs) that propagate in opposite directions along the muscle fibre towards the left and right tendons where they extinguish (Fig. 1). The propagation of the IAPs along the muscle fibre generates an electrical potential in the extracellular medium, the so-called single fibre action potential (SFAP), that can be recorded by an electrode. The superposition in time and space of the SFAPs from all the muscle fibres of a single motor unit is the motor unit action potential (MUAP).

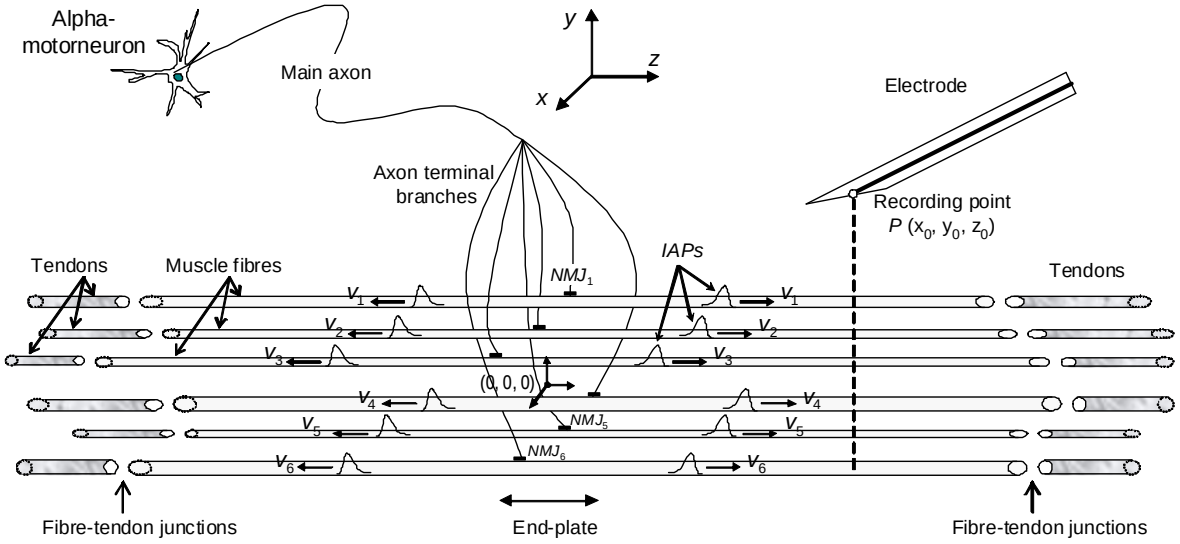

Fig. 1. Schematic representation of the elements of a motor unit

The structure and functioning of the motor unit is described in Fig. 1. For the students to obtain more insight into the architecture of the muscle it is necessary to provide further information on how the motor unit is integrated within the muscle. The different views of the muscle represented in Fig. 2 help the student to establish a solid framework, appropriate for developing their intuition. The following aspects are highlighted in Fig. 2:

- The muscle cross section in which the fibres of a MU are distributed is called *MU territory*. It is important to emphasize that the MU territories of several MUs may overlap as the muscle fibres of one MU are not compactly packed, but are mixed with the fibres of other MUs in the global muscle mass [Fig. 2(a)].
- In Fig. 2(b) we show a cross section of the whole muscle, where the territory of the MUs depicted on the left appears within a small rectangle. In doing so, students can appreciate the relative dimension of the MU territory as compared to the muscle size.
- Fig. 2(c) represents the muscle longitudinal section where the positions of the end-plate and tendons are indicated. The muscle fibres corresponding to MUs depicted in Fig. 2(a) can be recognized easily as they have been plotted using thicker lines than the other fibres.

In each diagram of Fig. 2, the electrode, fibres, MU territory and muscle have been drawn approximately to scale using the dimensions of a normal biceps brachii muscle [1] as a reference. Therefore, these diagrams allow the comparison of the size of the electrode with that of the fibre diameter, fibre length, MU size, and muscle diameter.

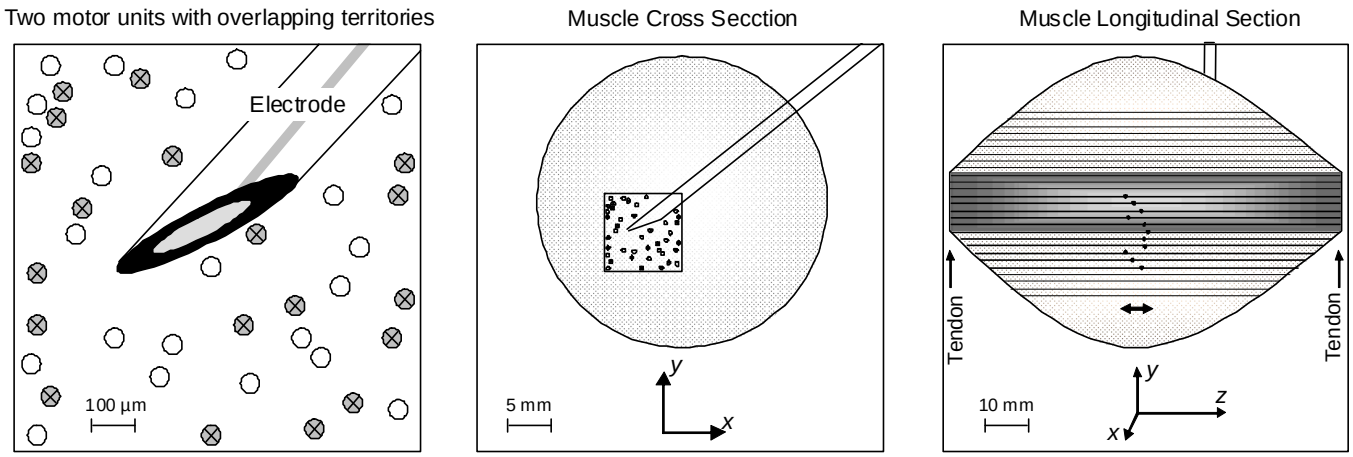

Fig. 2. (a) Muscle fibres (empty and crossed circles) of two different motor units. Cross section (b) and longitudinal section (c) of a normal biceps brachii muscle.

Based on the authors' teaching experience, students tend to think they fully understand the space dimensions of the muscle architecture as soon as they are shown the motor unit picture, depicted in Fig. 1. However, the three dimensions of the problem are barely represented in this picture and students often feel puzzled when they must indentify these three dimensions in the three diagrams shown in Fig. 2. The detail of the motor units, together with the cross and longitudinal sections of the muscle and their corresponding axis are essential to understand correctly the generation of extracellular electrical potentials.

MODELLING SINGLE FIBRE ACTION POTENTIALS (SFAPS) AND MOTOR UNIT ACTION POTENTIALS (MUAPS)

The next step is to show the students how to model mathematically the structure and functioning of the motor unit. As expected, the mathematical descriptions of SFAPs and MUAPs are based on a number of simplifications. If we assume that the shape of the IAP and the propagation velocity are practically not altered along the fibre (which is a reasonable assumption based on [2] and [3]), the skeletal muscle fibre of finite length can be considered as a linear and time-shift invariant system. Under these conditions, the potential generated by a single fibre (SFAP) can be expressed as a convolution of the input signal and impulse response (*IR*) of the corresponding system [3], [4]:

$$SFAP\ (t) = C \cdot d^{\,2} \cdot \frac{\partial^2 IAP(t)}{\partial t^2} * IR\ (t) \tag{1}$$

where C is a coefficient of proportionality that depends on the tissue conductivity (with a typical value of 0.01 $s \cdot m^{-1}$) and d is the fibre diameter (in mm). The input signal is the second temporal derivative of the intracellular action potential, $\partial^2 IAP(t)/\partial t$. One of the most used analytical functions for $IAP(t)$ is [3]

$$IAP\,(t) = 96 t^3 e^{-t} - 90 \tag{2}$$

In (1), the impulse response (*IR*) is computed as

$$IR\ (t) = \frac{1}{\left[\left(z_0 - NMJ - vt_1\right)^2 + r^2\right]^{\frac{1}{2}}} + \frac{1}{\left[\left(z_0 - NMJ + vt_2\right)^2 + r^2\right]^{\frac{1}{2}}},\quad t_1 \in \left[0, \frac{L_1}{v}\right],\quad t_2 \in \left[0, \frac{L_2}{v}\right] \tag{3}$$

In (3), the first and second terms at the right side of the equation correspond to the potentials produced at the recording point by the IAP propagating along the fibre from the end-plate to the right tendon and to the left tendon, respectively. In view of Eq. (3), the students should realise that the propagation of the IAP in the opposite directions is symmetrical. In the definition of the *IR* it is important to notice that the origin of coordinates is assumed to be located at

the geometric centre of the muscle. All the variables appearing in (3) are shown in Fig. 3(a). Specifically, the impulse response comprises:

- Anatomical properties of the fibre: right semilength, L_1 (in mm), left semilength, L_2 (in mm), and neuromuscular junction position, *NMJ* (in mm), with respect to the coordinate origin.
- Physiological properties of the fibre: propagation velocity, v (in m/s).
- Detection conditions: fibre-to-electrode distance, r (in mm), longitudinal position of the electrode in respect to the coordinate origin, z_0 (in mm).
- Duration properties: t_1 and t_2 represent the time elapsed between the onset of IAP at the NMJ and its extinction at the right and left fibre-tendon junctions, respectively.

The propagation velocity and fibre diameter are assumed to have a linear relationship [3] given by

$$v(m/s) = 3.7 + 0.05 \cdot (d - 55) \tag{4}$$

The radial distance (r) in (3) that can be calculated as

$$r = \sqrt{(x_0 - x_j)^2 + (y_0 - y_j)^2} \tag{5}$$

where (x_0, y_0) and (x_j, y_j) are the coordinates of the electrode and the muscle fibre, respectively. Looking to equation (5), students should realize that the radial distance is the minimum distance from the electrode to a certain fibre [calculated within the muscle cross section $z = z_0$, as shown in Fig. 3(a)].

If the physiological properties of the fibre are the same for all fibres of the MU, the IAP in time domain could be accepted as identical, irrespective of the fibre diameter (44,45). Then, the MU could also be considered as a linear time shift-invariant system, whose common impulse response (CIR) is the sum of N impulse responses corresponding to individual muscle fibres:

$$CIR\ (t) = \sum_{i=1}^{i=N} IR_i(t) \tag{6}$$

Instead of N convolutions (one for every fibre), the MUAP as the output signal can be calculated as a single convolution between the IAP second temporal derivative and the CIR:

$$MUAP\ (t) = C \cdot d^2 \cdot \frac{\partial^2 IAP(t)}{\partial t^2} * CIR\ (t) \tag{7}$$

In most cases the students found the equations and formulae above described clear and well-grounded and therfore they were capable of understanding the corresponding mathematical programs on MATLAB. Using this software package, the authors designed a set of simulation programs that enable the students to feel the influence of the motor unit parameters on the amplitude and duration properties of the extracellular electrical potentials (SFAPs and/or MUAPs) generated by the activation of the motor unit.

STUDY OF THE AMPLITUDE-RELATED CHARACTERISTICS OF EXTRACELLULAR ELECTRICAL POTENTIALS

We will start using the models shown in (1) and (7) to illustrate how the electrode position and the physiological properties of the fibre affect the amplitude characteristics of extracellular potentials. For the sake of clarity, the students are suggested to consider a scenario with only one muscle fibre and therefore to use the SFAP model (1). In this simplified scenario, they will analyse the effect of changes in r, z_0 and d on the amplitude of the recorded SFAP (see Fig. 3).

Impulse response parameters

As we have only one muscle fibre, we can make it coincide with the origin of coordinates so that $x_j = y_j = 0$. Moreover, we can assume that this origin is located just at the position of the *NMJ*. It is important that the students understand the implications of these simplifications in the diagram of Fig. 3(a). The default values used for the parameters of the muscle fibre, together with the ranges of variation considered in each of the simulations are summarized in Table 1. The data shown in Table 1 represent real values that were obtained from a normal biceps brachii muscle [1].

Table 1 Parameter values of one muscle fibre of the biceps brachii in different simulations

	L_1 (mm)	L_2 (mm)	*NMJ* (mm)	d (μm)	z_0 (mm)	r (mm)
Varying r	40	50	0	55	20	0.05 - 0.15 (step of 0.05)
Varying z_0	40	50	0	55	0 - 40 (step of 10)	0.10
Varying d	40	50	0	25 - 65 (step of 20)	20	0.10

Effects of varying the radial distance

Students are told to increase r from 0.05 to 0.15 mm, while keeping the other MU parameters unchanged. As shown in Fig. 3(b), they should observe an abrupt decline of the SFAP amplitude when the electrode is moved further away from the fibre. This should not be surprising as Eq. (3) predicts a decrement in the voltage of the EMG signal with increasing r.

Effects of varying the electrode longitudinal distance

The next task is to illustrate the influence of the longitudinal position of the recording point (z_0) on the SFAP amplitude. Students are suggested to change z_0 from 0 to 40 mm in steps of 10 mm. They should notice that, when the electrode is sufficiently far from the end-plate and from fibre-tendon junction, the amplitude of SFAPs is independent of z_0, and their waveforms have three phases [Fig. 3(c)]. However, if the electrode is just above the endplate (z_0 = 0 mm) and/ or above the fibre-tendon junction (z_0 = 40 mm), the SFAP amplitude changes significantly and the SFAP becomes biphasic [Fig. 3(c)].

Effects of varying the fibre diameter

The effects of a varying fibre diameter can be easily predicted from Eq. (1), where d^2 is shown to act as a scale factor. Thus, an increase in d should be followed by an increase in the amplitude of the SFAP, as shown in Fig. 3(d). This figure also reveals that differences in the fibre diameter give rise to different latencies (or delays) of the corresponding potentials. The explanation for this lies in the fact that changes in d not only has an influence on the SFAP amplitude, but also affects the propagation velocity of the IAP along the fibre, as established in (4). According to this equation, a high value of d (65 μm) will allow the IAP travel very fast (v = 4.2 m/s), reaching electrode longitudinal position in a short time [approximately 4.7 ms, as shown in Fig. 3(d)]. In contrast, a low value of d (25 μm) will make the IAP propagate slower (v = 2.2 m/s), which will delay its arrival to the electrode longitudinal position [approximately 9 ms, see Fig. 3(d)].

The differences in the propagating velocities between the different fibres will give rise to time dispersion between the corresponding SFAPs which, in turn, will influence the shape of the resulting MUAP. Further details of the time summation of individual SFAPs are provided in the next section.

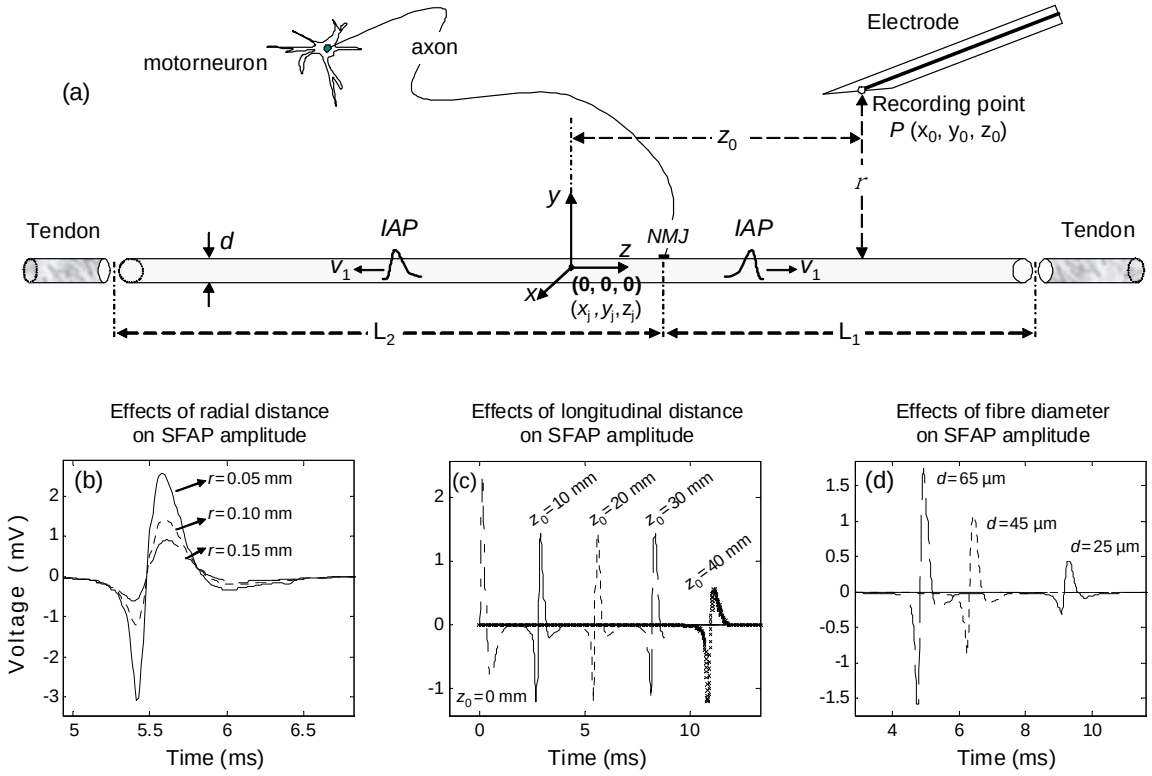

Fig. 3. (a) Schematic representation of a muscle fibre innervated by the axon of a motorneuron. Effects of changes of the radial distance of the electrode (b), longitudinal position of the electrode (c), and diameter of the fibre (d) on the amplitude of SFAPs.

STUDY OF THE TIME-RELATED CHARACTERISTICS OF EXTRACELLULAR ELECTRICAL POTENTIALS

When a scenario with various muscle fibres is considered, such as the one represented in Fig. 1, the students should realize that, at a certain instant of time, the longitudinal positions of the IAPs in the different fibres are not exactly the same; rather, the IAPs of different fibres are dispersed temporally due to a number of factors:

- The differences in length of the axon terminal branches.
- The scattering of the neuromuscular junctions within the end-plate.
- The differences in the propagation velocity of the different fibres.

In order to illustrate the effect of the time dispersion of various SFAPs belonging to different muscle fibres on the shape of the summated potential we will consider the two scenarios shown in Fig. 4. As can be seen, each scenario comprises two muscle fibres whose characteristics are summarized in Table 2.

Table 2 Parameter values of two muscle fibres of the biceps brachii associated to two different scenarios

	L_1 (mm)	L_2 (mm)	NMJ_1 (mm)	NMJ_2 (mm)	d_1 (µm)	d_2 (µm)	z_{10} (mm)	z_{30} (mm)	r (mm)
Scenario (a)	40	50	0	1.5	55 (v_1 = 3.7 m/s)	55 (v_2 = 3.7 m/s)	10	30	0.17
Scenario (b)	40	50	0	1.5	45 (v_1 = 3.2 m/s)	55 (v_2 = 3.7 m/s)	10	30	0.17

In scenario (a), the time dispersion is generated only by the difference in the positions of the neuromuscular junctions (*NMJ*) of fibre1 (0 mm) and fibre2 (1.5 mm). With the two fibres having the same propagation velocities (v_1 = v_2), SFAP2 arrives at z_{10} earlier than SFAP1 because its neuromuscular junction is closer to the right tendon. In this situation, SFAP2 is said to have lower latency than SFAP1. Moreover, since v_1 = v_2, the latency difference between SFAP1 and SFAP2 is the same at different longitudinal positions of the electrode. This explains why the sum of potentials SFAP1 and SFAP2 is the same at z_{10} and at z_{30}.

In scenario (b), the time dispersion is generated by the difference in both the neuromuscular junction positions and propagation velocities of fibre1 and fibre2. Specifically, the neuromuscular junction of fibre 2 is closer to the right tendon than that of fibre 1, and $v_2 > v_1$. In these conditions, the latency of SFAP1 is greater than that of SFAP2 and, more importantly, the latency difference between them increases as they spend more time propagating, i.e. as they approximate to the tendons. This can be appreciated in Fig. 4, where SFAP1 and SFAP2 clearly overlap at z_{10}, whereas they are completely separated at z_{30}.

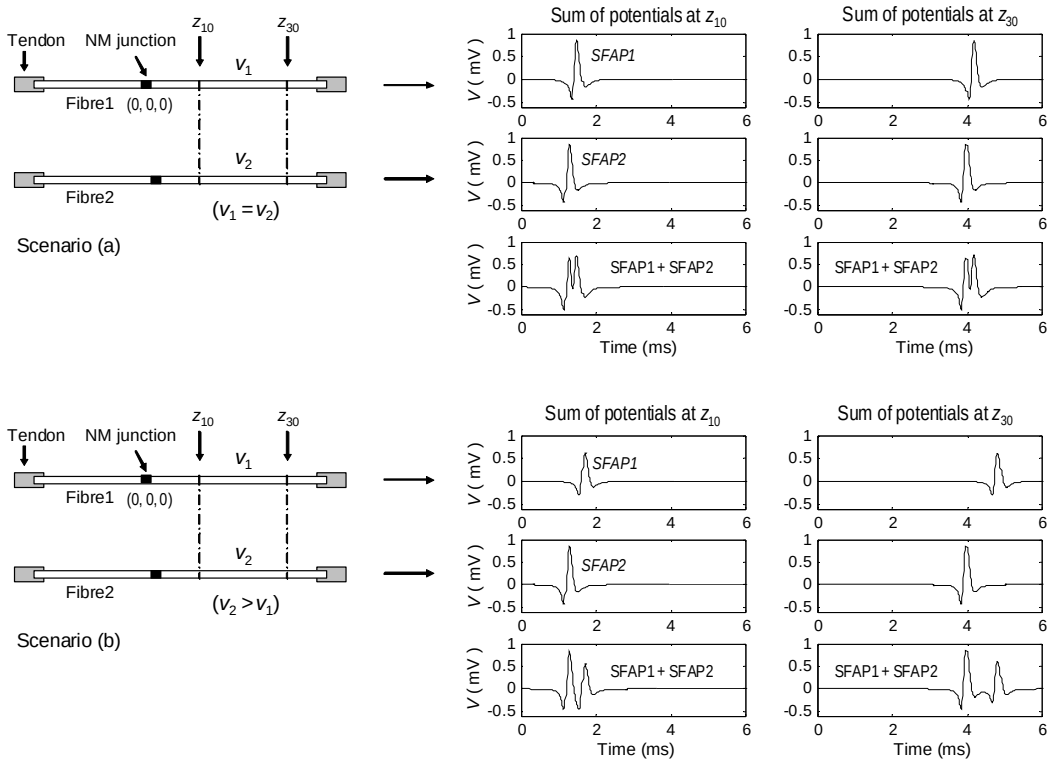

Fig. 4. Upper panel – schematic representation of two muscle fibres with identical properties but different NMJ positions (left) and their corresponding SFAPs recorded at z_0 = 10 mm and z_0 = 30 mm (right). Lower panel – the same as in the upper panel but with the muscle fibres having different propagation velocities.

STATISTICAL DISTRIBUTIONS TO MODEL REALISTIC MOTOR UNIT POTENTIALS

The motor unit is a good example to emphasize the students the importance of using statistical distributions to model the inherent variability of biological structures. Since the motor unit action potential (MUAP) is the superposition in time and space of the SFAPs from all the muscle fibres of a certain motor unit, then the shape of a MUAP will be highly determined by the statistical distribution of the velocities and NMJ positions of the fibres belonging to that motor unit. More specifically, a realistic approach for the motor unit would require statistical distributions to model the variability in the following elements:

1. Diameters: in general, scientists assume that fibre diameters follow a Gaussian distribution (55 ± 2.5 μm) (M ± SD) [3], [5]. Since the propagation velocity is linearly related with the fibre diameter, the statistical distribution of v is indirectly determined by that of d.
2. End-plate: the Gaussian distribution (0 ± 0.5 mm) (M ± SD) is normally used to model the variability in the positions of the neuromuscular junctions within the endplate of a motor unit [5].
3. Fibres' lengths (and semilengths). The variability in the lengths of the different fibres can be assumed to have a Gaussian distribution: right semilength (40 ± 2 mm) and left semilength (50 ± 2 mm).
4. Fibres' position within the motor unit. In a cross section of the muscle, as that shown in Fig. 2(b), the fibres belonging to a certain motor units are considered to fall into circles of a diameter of about 10 mm. Within these circles, fibres are distributed according to a uniform distribution [6].

By considering the abovementioned statistical distributions and using Eq. (7), we simulate the MUAP shown in Fig. 5(a). This MUAP is recorded at a radial distance of 0.1 mm and at a longitudinal position of 20 mm. By taking this MUAP as a reference, we will introduce controlled variation in each of the MU statistical distributions, leaving the other

ones unchanged. In doing so, the students will be able to appreciate the sensitivity of the MUAP waveform to the changes in each distribution.

The MUAPs shown in Figs. 5(b) and (c) are obtained using the same statistical distributions as for the reference MUAP, but with an increase in the dispersion of d (and therefore in the variability of v). As the difference in the conduction velocities between the different fibres increases, the time dispersion of their corresponding SFAPs becomes higher, resulting in a longer and more complex MUAP. The students should note that the number of *turns* (peaks in the waveform) in the MUAPs of Fig. 5(b) and (c) is clearly higher than in the reference MUAP.

The MUAPs shown in Figs. 5(d) and (e) are simulated using the same distributions as for the reference MUAP, but with an increase in the dispersion of the NMJ positions. The widening of the end-plate region also results in higher time dispersion between individual SFAPs, increasing the duration and complexity of the MUAPs. By comparing Fig. 5(d) and (e), the students should appreciate that the three positive peaks of the MUAPs are better distinguished when the end-plate region is wider [higher SD(*NMJ*)].

By increasing the dispersion of both the left and right fibre semilengths we obtain the MUAPs shown in Figs. 5(f) and (g). The students should note that, as compared to the reference MUAP, the shape of the MUAPs main spike is practically unchanged. This is due to the fact that the MUAPs are recorded at a longitudinal position of 20 mm, i.e. sufficiently far from the fibre-tendon junctions.

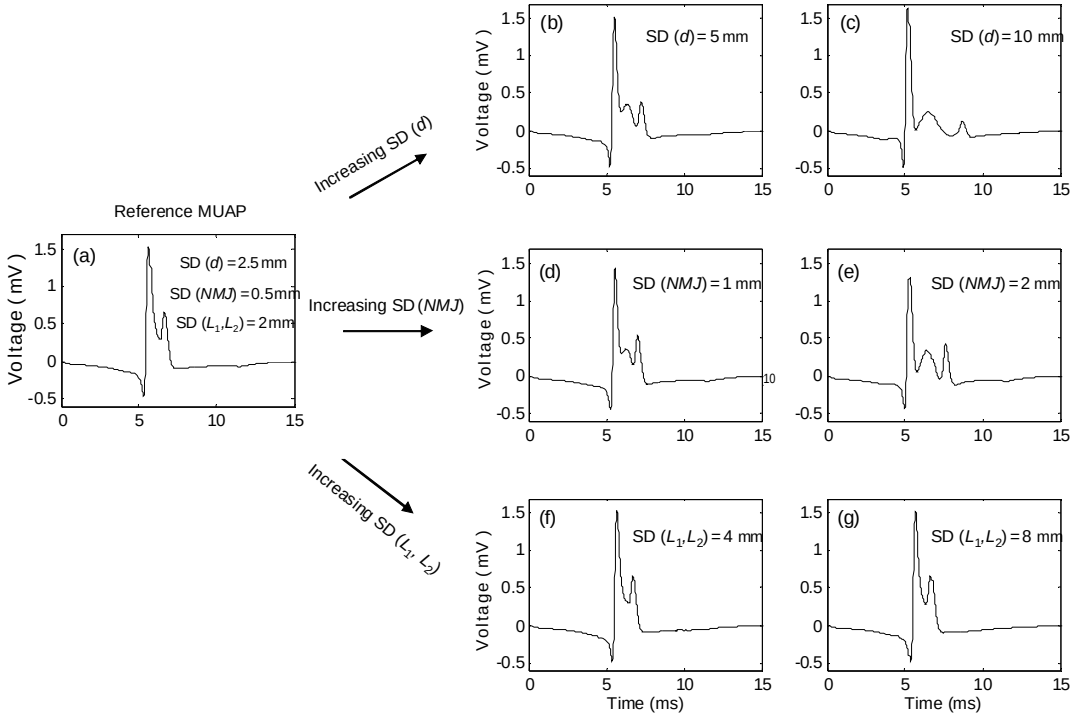

Fig. 5. Simulation of various motor unit action potentials (MUAPs) using different values for the statistical distributions of the fibre diameter (d), neuromuscular junction (NMJ) and right (L_1) and left (L_2) fibre semilengths.

CONCLUSIONS

This paper is aimed at showing biomedical engineering students an example of modelling and computer simulation of the electrical behaviour of the motor unit. Specifically, the authors have proposed a well-known mathematical formulation to describe the extracellular electrical potentials generated by muscle fibres.

The present work allows the students the identification of the different aspects involved in the study of biological phenomena. First, they have to understand the basic anatomic and functional features of the skeletal muscle, motor unit, and the muscle fibre. Next, they have to appreciate the usefulness of the proposed mathematical model in calculating the potentials produced by the contraction of muscle fibres. Using appropriate simulation programs based on this model, they must be able to study of the effects of the detection conditions and fibres' physiological properties on the characteristics of the electrical potential. Finally, they have to learn how to incorporate the inherent variability associated to the motor unit parameters into the model through statistical distributions. The feedback from the students who simulated extracellular potentials following our guidelines was very positive.

It is the desire of the authors to integrate the model presented here within an interactive application in order to help students to obtain a greater insight into the generation of extracellular potentials

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REFERENCES

[1] R.L. Lieber. Skeletal Muscle Structure and Function: Implications for Rehabilitation and Sports Medicine. Williams & Wilkins. Maryland, USA; (1992) 34-35.
[2] G. V. Dimitrov, N. A. Dimitrova. 'Precise and fast calculation of the motor unit potentials detected by a point and rectangular plate electrode'. *Med Eng Phys*, 20 (1998) 374–381.
[3] S. Nandedkar, E. Stålberg. 'Simulation of single muscle fibre action potentials'. *Med Biol Eng Comput*, 21 (1983) 158–165.
[4] J. Rodríguez, A. Malanda, L. Gila, I. Rodríguez, J Navallas. 'A mathematical analysis of SFAP convolutional models'. *IEEE Trans Biomed Eng*, 52(5) (2005) 769-783.
[5] N.A. Dimitrova, G.V. Dimitrov. 'Amplitude-related characteristics of motor unit and M-wave potentials during fatigue. A simulation study using literature data on intracellular potential changes found in vitro'. *J Electromyogr Kinesiol*, 12 (2002) 339–349.
[6] D.W Stashuk. 'Simulation of electromyographic signals'. *J Electromyogr Kinesiol*, 3 (1993) 153–173.

Authors' biographies

Javier Rodríguez was born in Pamplona in 1979. He graduated in 2003, and obtained the PhD in 2007 in Telecommunication Engineering from the Public University of Navarra, Pamplona, Spain. He worked as a Consultant Engineer (2004-2005) and as a System Engineer (2005-2006) in the private sector. He has also worked for the Higher Scientific Investigation Council of Spain during one year (2006). In 2007 he became Assistant Professor in the Electrical and Electronics Engineering Department of the Public University of Navarra. During this period he has been teaching several subjects related to digital signal processing, image processing and biomedical engineering. His research focuses on signal processing applied to biomedical signals, modeling of biological systems, electromyography and sensory-motor interaction studies.

Armando Malanda was born in Madrid, Spain, in 1967. In 1992 he graduated in Telecommunication Engineering at the Madrid Polytechnic University. In 1999 he received his Ph.D. degree from the Carlos III University, Madrid. In 1992 he joined the School of Telecommunication and Industrial Engineering of the Public University of Navarra. In 2003 he became Associate Professor in the Electrical and Electronics Engineering Department of this University. During all this period he has been teaching several subjects related to digital signal processing, image processing and biomedical engineering. His areas of interest comprise the analysis, modeling and simulation of bioelectrical signals, particularly EEG and EMG.

Javier Navallas was born in Pamplona in 1976. He graduated in 2002, and he obtained the PhD in 2008 in Telecommunication Engineering from the Public University of Navarra, Pamplona, Spain. He has also worked as a software engineer. He is presently Assistant Professor of the Electrical and Electronics Engineering Department of this University. His research interests are modeling of biological systems and neurosciences.