International Journal of Engineering Education Vol. 28, No. 3, pp. 674–685, 2012
Printed in Great Britain

0949-149X/91 $3.00+0.00

A New Way to Describe Intra- and Extra-cellular Electrical Potentials and their Generation by Excitable Cells*

JAVIER RODRIGUEZ-FALCES**, JAVIER NAVALLAS and ARMANDO MALANDA
Department of Electrical and Electronic Engineering, Public University of Navarra, Campus de Arrosadía, 31006 Pamplona, Spain.
E-mail: javier.rodriguez.falces@gmail.com

A fundamental aspect of bioelectricity studies is the process by which activation of an excitable cell results in the generation of a transmembrane voltage (the intracellular action potential) and an extracellular electrical potential in the surrounding medium. Traditional methods for teaching how to calculate the potentials do to provide biomedical engineering students with a means to appreciate the progressive nature of the generation of the extracellular potential as the intracellular potential propagates along the fiber. The objective of this paper is to propose a new approach, based on electrostatic theory, to teach students the basics of the formation of the intra- and extra-cellular potential around a fiber. The paper reports on the application and testing of this approach, which is demonstrated to enhance the ability of students to predict the shape (waveform) of the extracellular potential at different electrode positions relative to the fiber. In addition, the new approach helps students to create a mental picture of bioelectrical potentials in the context of the biological structures in which they occur and interact. The paper also emphasizes the necessity of considering the spatial profile of the intracellular potential, in conjunction with its temporal profile, for a correct interpretation of the amplitude and temporal characteristics of extracellular potentials.

Keywords: biomedical engineering; bioelectricity; excitable cell; electrostatic theory; intracellular potential; extracellular potential

1. Introduction

In recent decades, the field of Biomedical Engineering has significantly advanced, mainly as a result of the development of existing areas of study such as Neuroengineering, Biomedical Imaging, Bioinformatics, Tissue Engineering [1–7]. The European Higher Education Area, established in June 1999 and consolidated with the signing of the Bologna declaration, has supported growth in Biomedical Engineering [8]. In the past ten years, the Public University of Navarra (Spain) has endeavoured to follow the Bologna process directives and thus promote harmonization of higher education in Europe within the field of Biomedical Engineering. Since 2007, our university has offered a Master Degree Program in Biomedical Engineering (BME), and this encompasses most of the key areas suggested by Bronzino for the BME curriculum [9, 10], such as Biomechanics, Biomedical Instrumentation, Biosystems, Computational Biology and Biomedical Imaging.

One of the key subjects treated in the master degree is Bioelectricity. The Bioelectricity course begins with the topic of excitable cells, of both myelinated and demyelinated fibers, which provides the basis for the understanding of more complex biological systems and processes [10–13]. Activation of a muscle excitable cell results in the generation of a transmembrane voltage (intracellular potential), and the propagation of this voltage along the fiber gives rise to an extracellular potential in the surrounding medium. Traditionally, a number of methods have been used to teach and study the generation of intra- and extra-cellular potentials [13–18]. Although these methods (which include mathematical models, computer-based modelling, and simulation programs) have proved to be valuable pedagogical tools [18], they are deficient in terms of representing how electrical potentials develop around a fiber. In our experience of teaching, the main limitation of the abovementioned methods is that they do not allow the students to visualize how the extracellular potential is progressively generated as the intracellular potential propagates along the fiber.

Textbooks on Bioelectricity [12, 13] usually present extracellular potentials as a convolution between an input signal and an impulse response. Use of convolution models is considered suitable for biomedical engineering students as they are familiar with this mathematical operation [15, 17]. Whilst the convolution approach offers many advantages, it does not facilitate an intuitive perception of how the different portions of the intracellular potential give rise to the different phases of the extracellular potential. Convolution models provide no direct way to associate changes in the shape of the extracellular potential with the position of the intracellular potential or with the location of the electrode. Simulation programs based on convolution can overcome some of the above-mentioned

** Corresponding author.

* Accepted 17 July 2012.

limitations by offering the possibility to change the position of the electrode in respect to the fiber and display the shapes of both intra- and extra-cellular potentials. However, such programs still fail to provide a mental schema with which to visualize what is happening.

Another shortcoming in traditional teaching methods is that they focus on the temporal characteristics of biological signals. This is the consequence, and surely also the cause, of the widespread belief among students, as well as clinicians, that interpretation of bioelectrical potentials must be performed in the temporal domain [19, 20]. Actually, the formation of an electrical potential around a fiber is an inherently spatial matter [21–26], and therefore both the temporal and spatial profiles of the excitation source (i.e., the intracellular potential) should be taken into account. Students and clinicians usually find their first experience of analysis in the spatial domain confusing: they cannot fully appreciate or understand the implications of the signal in this new framework.

In order to overcome the limitations of traditional teaching methods, which are based on the above arguments, we propose a new approach to the conceptualization of the intracellular potential based on electrostatic (and biophysical) theory and grounded on the pioneering work of Wilson [27] and subsequent studies of other authors [21, 25, 28–30]. The approach addresses the two major goals of the present paper: (1) to provide students with a simple and intuitive way to understand and visualize how extracellular potentials are generated from intracellular ones; and (2) to justify the assertion that students need to consider the spatial domain of an intracellular potential in order to attain a correct perception of the amplitude and temporal characteristics of extracellular potentials.

In our experience, an electrostatic model of the intracellular potential helps biomedical engineering students to develop a feel for bioelectric signals and prepares them for more sophisticated methods of signal modelling and processing.

2. An electrostatic model of the intracellular potential

The striated skeletal muscle is composed of a large number of parallel striated muscle cells or fibers, which spread out along the whole muscle [31]. Their diameters vary from 10 to 80 μm. The muscle fibers are composed of several microstructures: the sarcolemma, the myofibrils, the sarcoplasm, and the sarcoplasmic reticulum [31]. Muscle fibers are bound together into bundles called fascicles; the bundles are then grouped together to form the muscle mass.

Skeletal muscle fibers are linked to large nervous myelinated fibers originated in motorneurons in the spinal cord. Motorneurons are efferent neurons that have their cell bodies in the spinal cord and their axons run along the perpiheral nerves and synapse with muscle fibers to activate the muscle contraction [32]. Each nervous fiber is split into several terminal branches, which stimulates between three and hundreds of skeletal muscle fibers. The nervous endings (terminal axons) and the muscle fibers join in the so-called neuromuscular junction (end-plate) [33], which tends to be located approximately in the middle of the muscle fiber length [Fig. 1(a)]. The neuromuscular junction is responsible for the transmission of electrical impulses from the nervous fibers to the muscle fibers.

2.1 Depolarization and repolarization of a muscle fiber membrane

A muscle fiber contraction (also known as a muscle fiber twitch) occurs when a muscle fiber shortens. For skeletal or voluntary muscles, contraction occurs as a result of conscious effort originated in the brain. The brain sends signals, in the form of action potentials, through the central nervous system to the motorneuron that innervates the muscle fiber [31]. Muscle contraction is created via the repeated activation of several groups of muscle fibers, each of which is governed by a single motorneuron through its axon [31].

The activation of the fiber cell brings about its depolarization and the generation of a transmembrane voltage (normally defined as the extracellular electrical potential minus the intracellular one). Under normal conditions, the extracellular potential is practically zero [13], and so the transmembrane voltage resultant on depolarization can be assumed to be approximately the same as the intracellular action potential (IAP). Membrane depolarization starts at the end-plate and extends along the muscle fiber towards both ends of the cell. As a result, two IAPs propagate in an all-or-nothing way (i.e., without attenuation), with constant velocity v, along the muscle fiber towards the tendons, where they extinguish [25] [Fig. 1(a)].

The plasma membrane of a muscle cell at rest maintains an electrical potential difference between its external and internal surfaces. This voltage, called the resting potential, is typically about –80 mV. The negative sign indicates that the interior is more negative than the exterior (negative polarization). In Fig. 1(a) the polarization of the fiber membrane is represented by a number of layers of negative signs. Note that, at rest, the number of negative-signed layers is constant.

After the fiber activation, two potential profiles exist across the fiber membrane that are called

waves of excitation or depolarized zones [Fig. 1(a)]. Consequently, in the representation, the number of negative-signed layers within the depolarized zones of the fiber membrane is changed. Specifically, an IAP profile has gradual depolarization and repolarization transitions, as shown in Fig. 1(b) [25, 29], and these progressive changes with axial distance (the x-axis in the figure) can also be reflected in the representation. The length of the IAP profile along the fiber, L, is defined by the product of the IAP duration, T_{in}, and the propagation velocity v [Fig. 1(b)]. The specific mechanisms of the ionic currents that give rise to the IAP were first described by Hodgkin and Huxley [34].

2.2 *The dipole-based presentation of the IAP*

In order to model the electrical behaviour of fiber membrane affected by the IAP, let us divide the fiber into portions or cylinders of equal-infinitesimal length dx as represented in Fig. 2(a). In this figure, it can be seen that the voltage of the IAP varies across each cylinder so that its faces have different voltage values (V_A, V_B). The steeper the profile of the IAP, the higher the voltage change across the corresponding membrane portion. On the basis of Wilson's studies [27], the variation of the electrical potential across each of these cylinders produces in the extracellular medium an electrical field that can be assumed to be equivalent to that produced by a lumped dipole. Thus, for a certain cylinder (i.e., membrane portion), the higher the voltage variation between its faces, the stronger the dipole field generated. It follows from this that the formation of the potential field around a fiber depends on the spatial profile of the IAP de- and re-polarization phases [25].

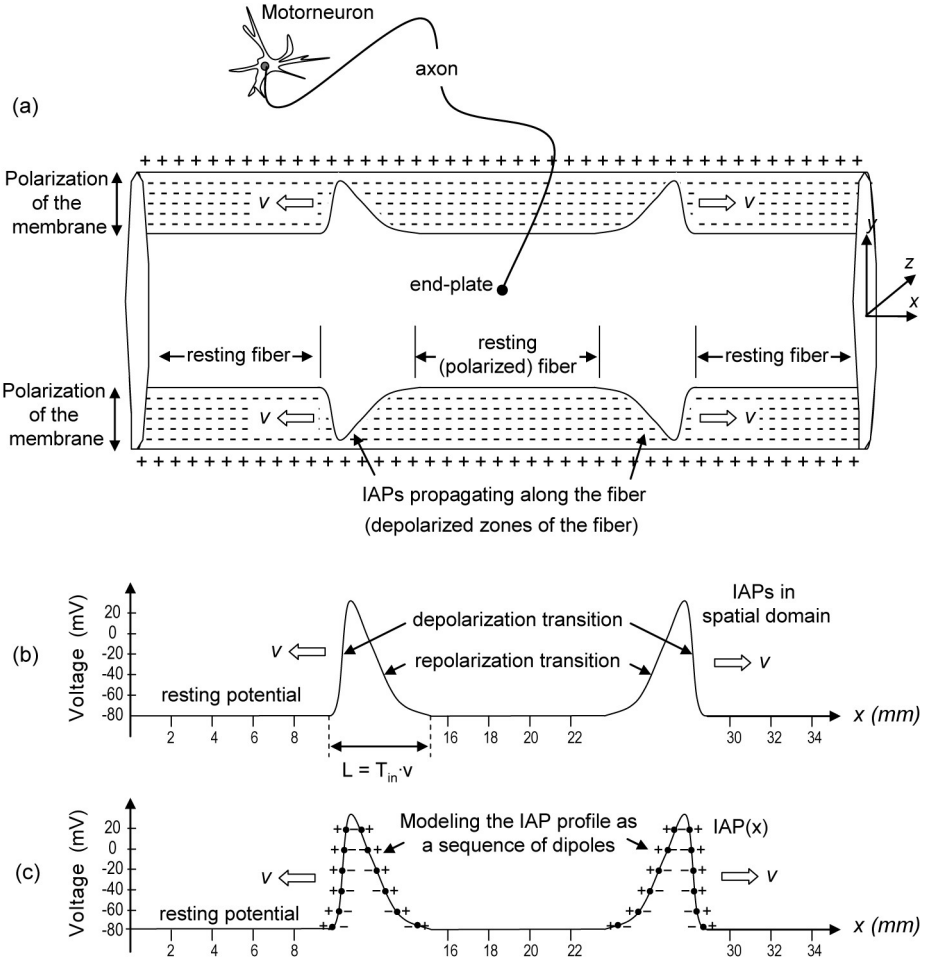

Fig. 1. (a) Schematic representation of a muscle fiber innervated by the axon of a motorneuron at the end-plate. Polarization of the fiber membrane is represented by several layers of negative signs. Two depolarized zones propagate along the fiber from the end-plate region to the fiber ends. The number of negative-signed layers within the depolarized zones changes gradually with axial distance and is constant within the regions where the fiber is at rest. (b) Spatial profile of the intracellular action potential (IAP) with its de- and re- polarization phases. (c) Approximation of the IAP through a collection of lumped dipoles distributed along its profile.

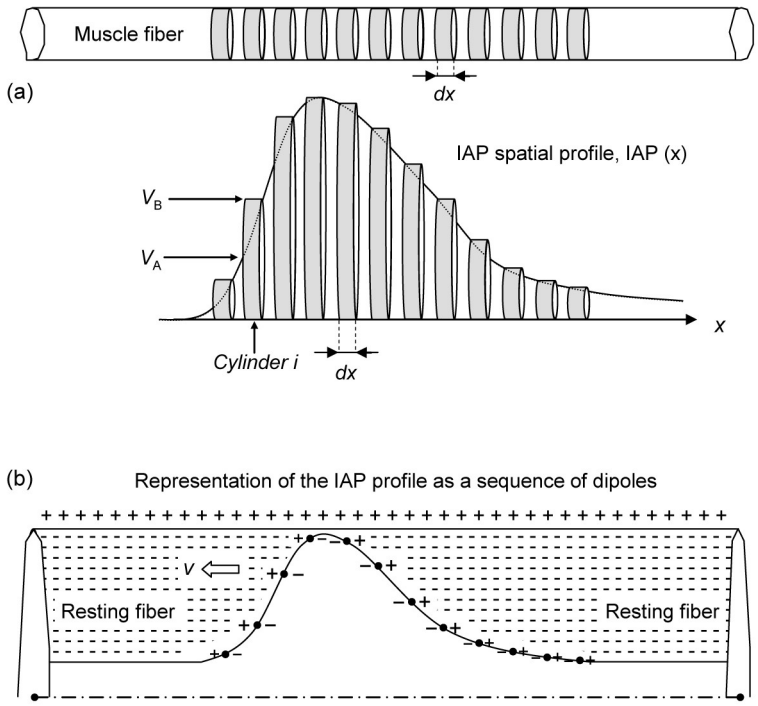

Fig. 2. (a) Schematic representation of a fiber as a sequence of cylinders of equal infinitesimal length *dx*. Accordingly, the IAP spatial profile can be approximated through a number of cylinders of equal length. The IAP voltage varies across each cylinder. (b) Representation of the IAP spatial profile along the fiber membrane as a sequence of dipoles oriented according to the sign of dIAP(x)/dx.

As follows from the above explanation, each cylinder can be substituted for a lumped dipole and thus the IAP spatial profile, IAP(x), can be represented as a sequence of dipoles distributed equidistantly along its profile [29], as shown in Figs. 1(c) and 2(b). The strength of each of the dipoles (or the dipole moment) is determined by the spatial derivative of the potential profile along the fiber [dIAP(x)/dx]. Orientation of the dipoles is determined by the sign of dIAP(x)/dx. This explains why the orientation of the dipoles lying on the IAP depolarization phase is opposite to that of the dipoles in the repolarizaton phase [Fig. 2(b)]. This electrostatic description of the IAP, as a collection of lumped dipoles, will be used in the next section to show how the extracellular potential is generated at a detection point outside the fiber.

3. Applying the dipole-based IAP model to calculate extracellular potentials

3.1 Extracellular potentials resulting from propagation of an IAP along the fiber

The propagation of an IAP along a muscle fiber generates in the extracellular medium an electrical potential, the single fiber action potential (SFAP) that can be recorded by an intramuscular electrode (Fig. 3). In this section the dipole-based presentation of the IAP, shown in Figs. 1(c) and 2(b), will be used to illustrate how the different portions (phases) of the SFAP are generated as the IAP(x) propagates along the fiber. To this end an IAP of T_{in} = 2 ms, propagating at v = 3 mm/ms along a muscle fiber with a right semilength of 20 mm (Fig. 3) will be assumed. The spatial extension of this IAP is 6 mm. The longitudinal position of the electrode is x_0 = 10 mm. The fiber-to-electrode (radial) distance, defined as $r = \sqrt{(y_0^2 + z_0^2)}$, is 0.2 mm. For such a short radial distance, the IAP propagating to the left can be assumed to make negligible contribution to the SFAP [30].

The polarity of the extracellular potential produced at a recording point (electrode) by the IAP(x) is determined by the sign of the field generated by the dipoles of this IAP as they are 'seen' from this point. In the scenarios of Figs. 3(a) and (b), for example, the recording point (P) is only directly exposed to the positive field of the dipoles that lie on the IAP rising (depolarization) phase. As a result, in these scenarios, the extracellular potential produced at P is positive. In contrast, in Fig. 3(c) the recording point is exposed to both the positive and negative charges of the dipoles in the IAP rising phase. Since the fields produced by these dipoles have approxi-

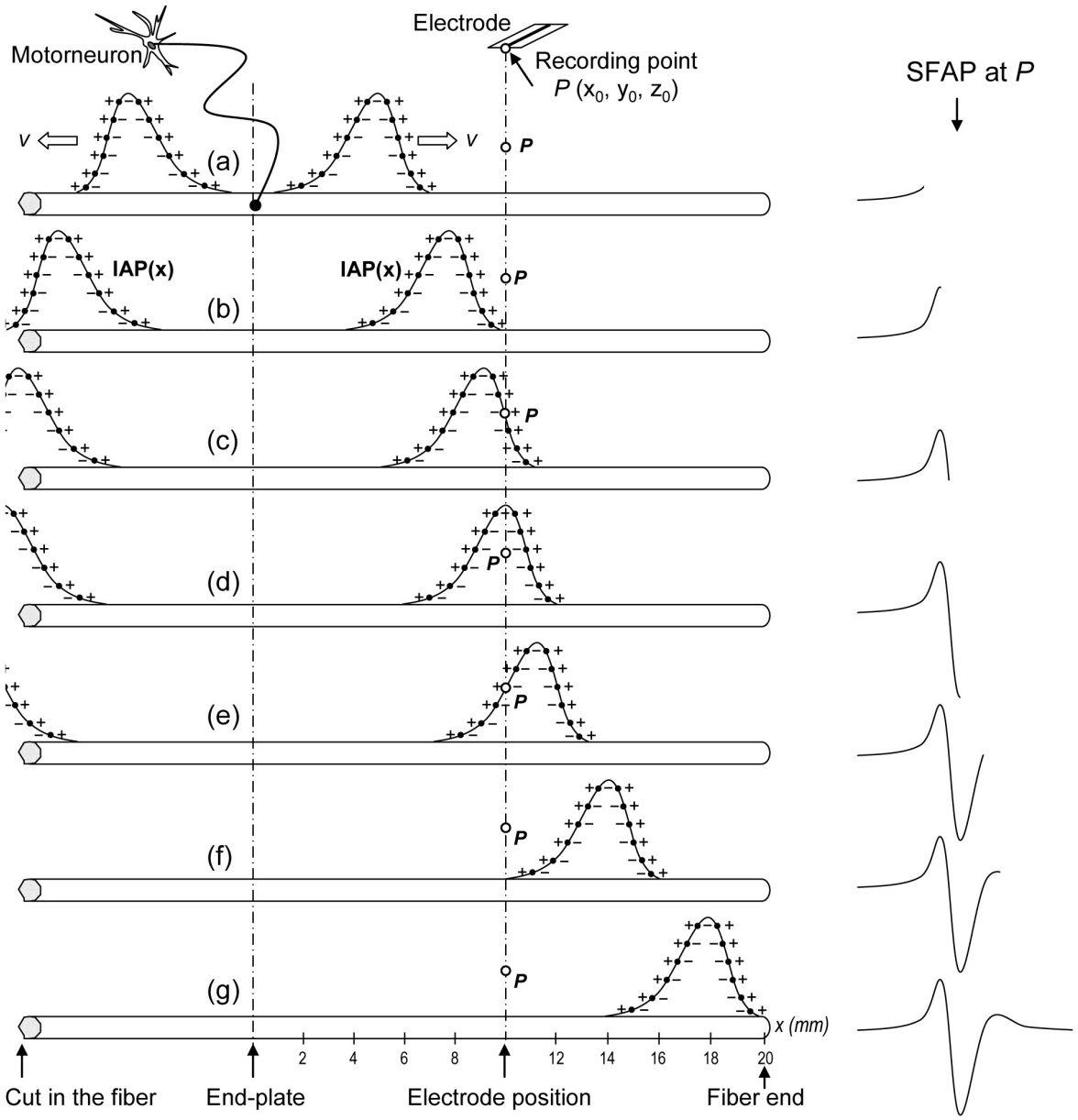

Fig. 3. (a) Schematic representation of two IAPs propagating along a muscle fiber, showing the corresponding single fiber action potential (SFAP) detected at 10 mm to the left of the end-plate. In (a) to (c), propagation of the IAPs gives rise to the first positive phase of the SFAP. In (c) to (e), the negative phase of the SFAP is generated. In (e) to (g), IAP propagation results in the second positive phase of the SFAP. For the sake of clarity, the left semi-half of the fiber has been truncated. The amplitudes of the IAP and SFAP and the distance from the recording point *P* to the fiber are not to scale.

mately the same magnitude but opposite sign [note that in Fig. 3(c) the point of steepest rise of the IAP rising phase is lined up with the x-coordinate of the electrode (x_0)], the net potential recorded by the electrode is zero.

When the peak of the IAP is lined up with the electrode (x_0), as in Fig. 3(d), the recording point is exposed to only the negative charges of dipoles, whether they are lying on the rising or falling phases of the IAP. In this case, the negative field produced at the electrode is at its strongest and so the SFAP exhibits its deepest trough (negative peak). From here, as the IAP propagates to the right, the recording point is exposed to an increasing number of positive charges and a decreasing number of negative charges. When the point of steepest decay of the IAP falling phase coincides with x_0 [Fig. 3(e)], the positive field approximately cancels out the negative field, and the net potential registered by the electrode is zero. As the IAP moves further to the right of this point, the positive field at the electrode is stronger than the negative field, and the electrical potential produced at the electrode is positive, as shown in Figs. 3(f) and (g).

3.2 Extracellular potentials resulting from the origination and extinction of the IAP

The initiation of the IAP at the end-plate [Figs. 4(a), (b) and (c)] and its extinction at the tendon [Figs. 4 (e), (f) and (g)] give rise to non-propagating components of extracellular potentials. Traditional approaches to SFAP modelling, such as convolution, do not provide students with a means to achieve an intuitive understanding of the generation of these particular components. The dipole-based representation of the IAP, on the other hand, provides an accessible way to perceive how the SFAP is affected by origination and extinction. Let us take an IAP with the same characteristics as before, and a muscle fiber with a right semilength of 14 mm (Fig. 4). In this explanation there are two electrodes, one located just above the end-plate (recording point *P1*, $x_1 = 0$ mm) and the other to the right beyond the fiber end (recording point *P2*, $x_2 = 16$ mm). To obtain non-propagating components of sufficiently large amplitude (relative to the propagating components), a radial distance of 2 mm is assumed [30].

During the first stages of the initiation of the two IAPs at the end-plate [Figs. 4(a) and (b)], the recording point *P1* registers only the influence of the negative fields of the dipoles lying on the depolarization phases. As a result, the recorded SFAP begins with a negative phase. As initiation progresses, the recording point *P1* begins to be exposed to the positive fields of the dipoles lying on the repolarization phases [Fig. 4(c)], and, when the IAP profile is totally generated [Fig. 4(d)], *P1* registers only these positive fields. Fig. 4(d) represents the moment when repolarization has just completed and the whole IAP profile has just been generated; all the dipoles of the IAPs are presenting

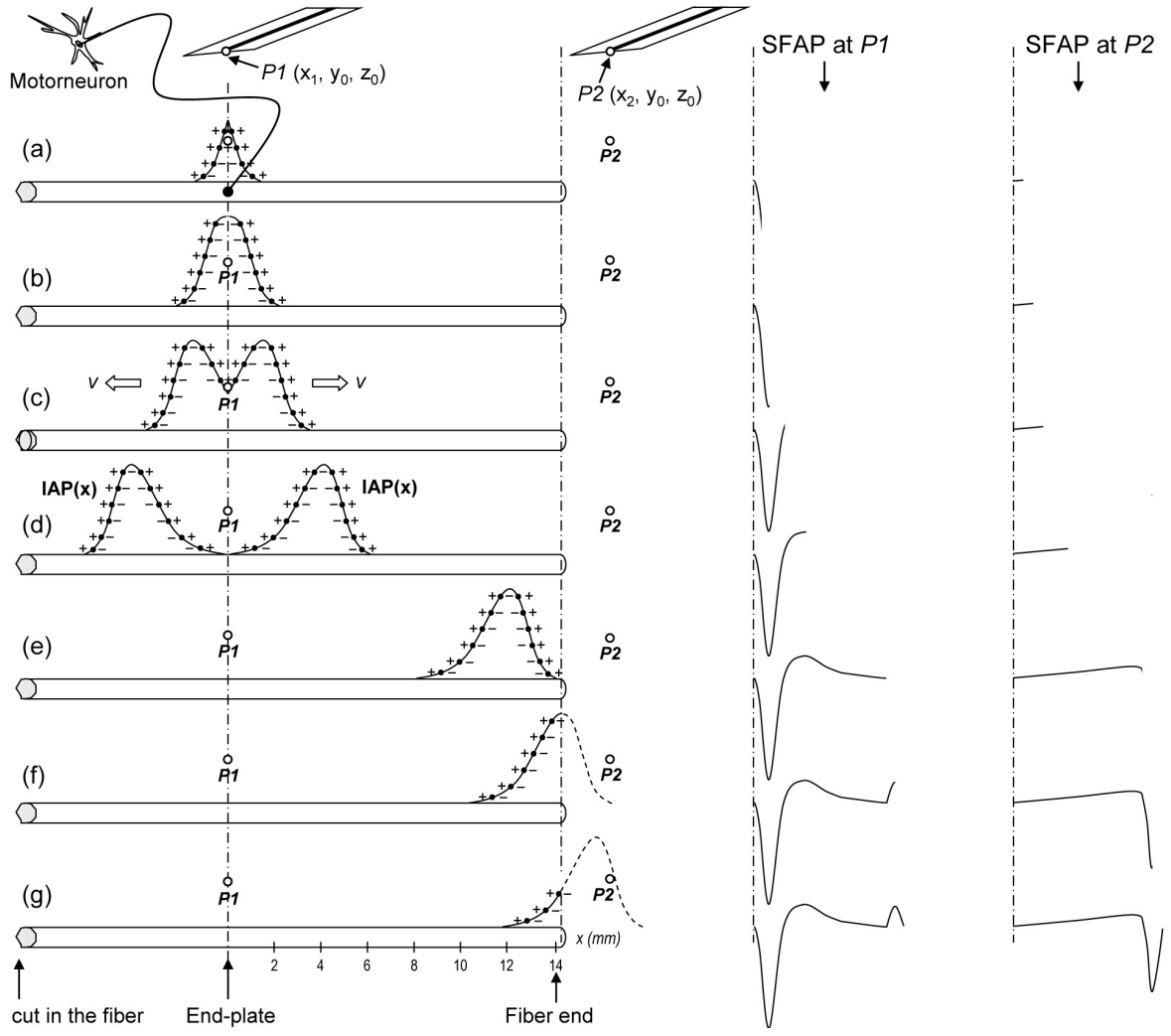

Fig. 4. (a) Schematic representation of the alterations in the IAP profile (left panel) during its initiation at the end-plate (a-d) and its extinction at the fiber-tendon junction (e-g). Extracellular potentials resulting from IAP initiation and extinction recorded by two electrodes located just above the end-plate (middle panel) and beyond the fiber end (right panel). The left side of the fiber has been truncated. The amplitudes of the IAP and SFAP and the distance from the recording points P_1 and P_2 to the fiber are not to scale.

their positive sides towards *P1* and the distance of the whole set of dipoles from *P1* is at its minimum. This generates the positive peak in the extracellular potential. As the IAPs propagate towards the tendon [Fig. 4(e)], the magnitude of the positive potential field recorded at *P1* decreases. Finally, the extinction of an IAP at the fiber end [Figs. 4(f) and (g)] generates a characteristic terminal waveform (see [28] for more details).

With regard to the recording point located to the right of the fiber end (*P2*), during the excitation initiation [Figs. 4(a), (b) and (c)] and its propagation along the fiber [Figs. 4(d) and (e)], this point is exposed only to the positive potential field produced by the dipoles lying on the leading edge of the IAP. As the leading edge dies at the fiber-tendon junction [Fig. 4(f)], the recording point *P2* becomes exposed to the negative field of the dipoles lying on the IAP repolarization phase. Consequently, the extracellular potential becomes negative. The final disappearance of the IAP profile at the fiber end [Fig. 4(g)] gives rise to the terminal wave.

4. How changes in the temporal and spatial profiles of the intracellular potential affect extracellular potentials

Having explained to students the basics of the formation of the SFAP waveform, the next educational goal is to illustrate how the temporal and amplitude characteristics of an SFAP are affected by different temporal and spatial IAP profiles. This objective further consolidates in the student's mind the need to consider both the temporal and spatial aspects of the IAP in order to fully understand and interpret changes in the SFAP waveform. For the sake of simplicity, the following explanation is limited to extracellular potentials measured at short radial distances (less than 0.3 mm), which reflects the reality of single fiber studies. The general case is described succinctly in [25].

4.1 Changes in the spatial profile of the IAP

Let us consider a scenario representing a slow muscle fiber, as shown in the first row of Fig. 5, where an IAP of $T_{in} = 2$ ms [Fig. 5(a)] is propagating

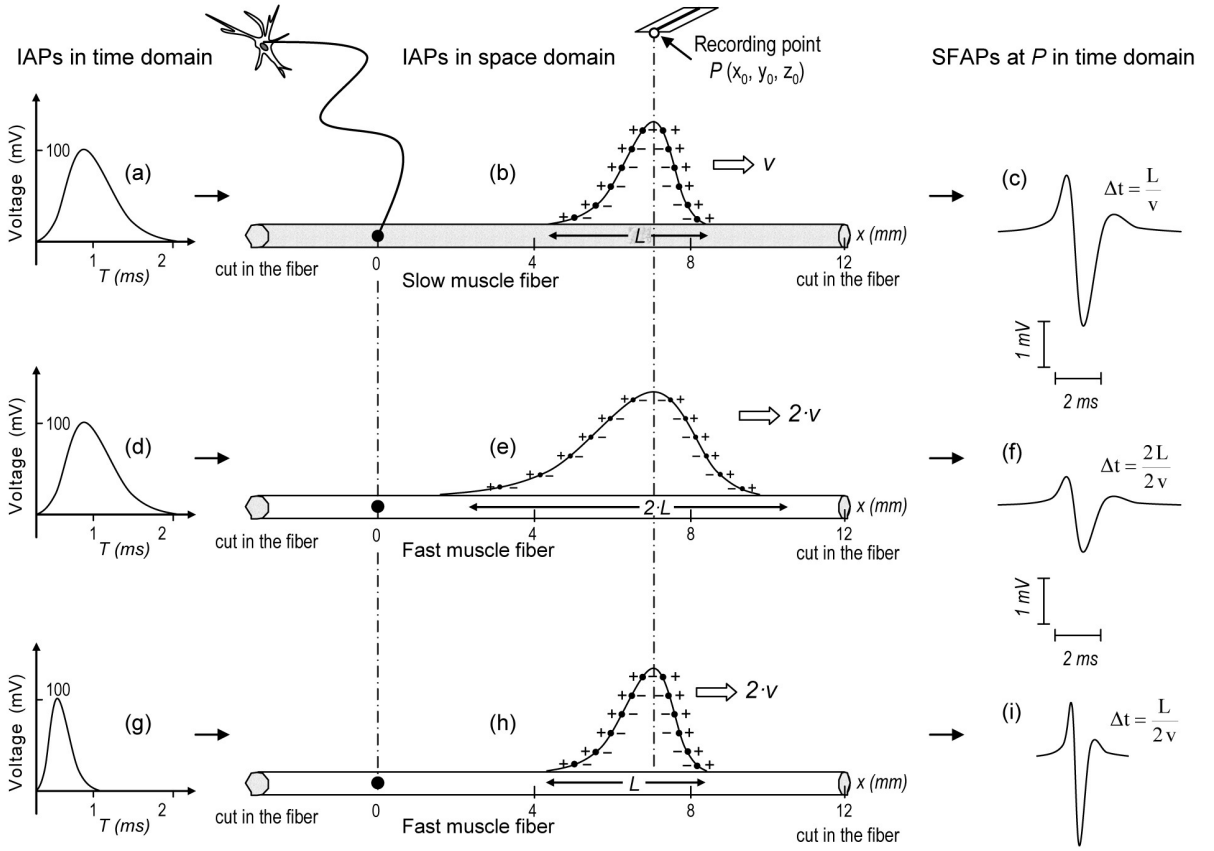

Fig. 5. First row—schematic representation of the temporal (a) and spatial (b) profiles of an IAP recorded from a slow muscle fiber and the corresponding SFAP (c) at an extracellular point *P*. Second row—representation of a fast-propagating fiber, where the IAP maintains its temporal profile (d) but travels two times faster (e), resulting in an SFAP (f) with the same duration but lower amplitude. Third row - representation of a fast fiber (third row), in which the duration of the IAP temporal profile is halved (d) but the IAP travels twice as fast (e), resulting in an SFAP (f) with the same amplitude but shorter duration.

at $v = 2$ mm/ms along the fiber. The spatial extension of the IAP is $L = 4$ mm [Fig. 5(a)]. Let us take another fiber with faster propagation characteristics [second row of Fig. 5] where the IAP has the same time-course as before [$T_{in} = 2$ ms, Fig. 5(d)], but travels twice as fast [$2v$, Fig. 5(e)]. It is assumed that other fiber characteristics, such as diameter, length, and shape, remain unchanged. In the fast fiber, therefore, the spatial extension of the IAP ($2L$) doubles that in the slow fiber (L). With the amplitude of the IAP practically the same and its spatial profile significantly widened, the strengths of the dipoles lying on this profile are considerably reduced. As a result, the amplitude of SFAPs derived from the fast fiber [Fig. 5(f)] is expected to be smaller than that of SFAPs derived from the slow one [Fig. 5(c)].

With regard to the time characteristics of the SFAP, students' attention should be drawn to the fact that the duration of the slow-fiber SFAP [L/v, Fig. 5(c)] is approximately the same as that of the fast-fiber SFAP [$2L/2v$, Fig. 5(f)]. This is because the fast-fiber IAP, whilst moving at twice the velocity ($2v$) of the slow-fiber IAP, is twice as long ($2L$) as the slow-fiber IAP.

4.2 Changes in both the spatial and temporal profile of the IAP

Let us now consider a new scenario (third row of Fig. 5) in which the time-course of an IAP in a fast fiber is half [$T_{in} = 1$ ms, Fig. 5(g)] that of a slow IAP and travels along the fiber twice as fast [$2v$, Fig. 5(h)] as the reference slow-fiber IAP (first row of Fig. 5). The simultaneous changes in the time-course and propagating properties of the new fast-fiber IAP leave its spatial extension along the fiber (L) unchanged as compared to that of the reference, slow fiber IAP. This means that the moments of the dipoles lying on the spatial profile of the new fast-fiber IAP are the same as those on the spatial profile of the slow-fiber IAP, and so the amplitude of its corresponding SFAPs [Fig. 5(i)] is expected to be the same as that of slow SFAPs [Fig. 5(c)].

With regard to the time characteristics of the SFAP, students should note that in the new fast-propagating fiber, an IAP with the spatial extension (L) moves beneath the electrode with a velocity that is twice as high ($2v$) as that with which the corresponding IAP in the slow fiber would move, and so the duration of the detected potential [$L/2v$, Fig. 5(i)] is approximately half that of an SFAP recorded from a fiber in slow condition [Lv, Fig. 5(c)].

5. Learning objectives of the topic

At the Public University of Navarra, Bioelectricity is a compulsory course taught in the first semester of the Master Degree Program for Biomedical Engineering. The course has been run since the academic year 2007/2008, and averages of 20 students (standard deviation of $\pm$ 6) have done it each year.

The generation of intra- and extra-cellular electrical potentials by excitable cells is an essential topic of the Bioelectricity course. The learning objectives for this topic are defined in three groups, as below.

(a) To understand the electrostatic description of the intracellular potential and its representation as a collection of lumped dipoles:
   1. To become familiar with the concepts of membrane polarization and resting potential.
   2. To realize how the transmembrane voltage alters the polarization of the membrane. Revision of the Hodgkin and Huxley model for the cell membrane.
   3. To understand that the potential produced by an infinitesimal portion of depolarized membrane is equivalent to the potential produced by a dipole.

(b) To understand the formation of the extracellular potential around a fiber produced by the propagation of the intracellular potential along this fiber:
   1. To appreciate that an active fiber generates an electrical potential in the extracellular medium and that this potential can be described in terms of the intracellular potential.
   2. To realize that the extracellular potential is the result of the propagation of the intracellular potential along a fiber.
   3. To know the relationship between the profiles of intra- and extra-cellular potentials.
   4. To be able to predict the profile of an extracellular potential as recorded at various positions relative to the fiber.

(c) To appreciate the necessity of considering both the temporal and spatial profiles of an intracellular potential:
   1. To understand that the strengths of the dipoles characterizing the intracellular potential are proportional to the slopes of its spatial profile.
   2. To comprehend that the amplitude characteristics of an extracellular potential depend on the spatial profile of its corresponding intracellular potential.
   3. To understand that the temporal characteristics of an extracellular potential depend on both the spatial and temporal profile of its corresponding intracellular potential.

6. Teaching plan and evaluation of the topic

A total of six lectures (of approximately fifty minutes each) were devoted to showing students the theoretical knowledge presented in the previous sections. These informational lectures covered the learning objectives as follows: the first two lectures were focused on the electrostatic description of the IAP, putting special attention to the model of the fiber membrane of Hodgkin and Huxley [34]. The third and fourth lectures addressed the generation of the different phases of extracellular potentials, and the last two lectures explained the effect of combined changes in the temporal and spatial profiles of the IAP on the SFAP characteristics.

Knowledge acquired during the theoretical sessions was evaluated by means of a closed-book 60-minute written exam consisting of ten questions, each of which corresponded to one of the learning objectives outlined in Section 5. Most of the questions were concerned purely with theory; inclusion of mathematical expressions was not precluded.

To measure the degree of student satisfaction with the teaching approaches described in the present paper, in the last session, students were asked to fill in a short questionnaire consisting of the points listed in Table 1.

7. Results

The results of applying the theoretical knowledge and approaches presented here to teaching the generation of intra- and extra-cellular potentials are summarized in Table 2. This table shows that students reached an acceptable understanding on the electrostatic behaviour of the excitable cell (learning objectives a1–a3). Feedback from the students revealed that, in general, they were able to create a mental picture of the membrane polarization and bioelectrical potentials. Table 2 also indicates that students obtained the highest marks in questions pertaining to the formation of the extracellular potential (learning objectives b1– b4). This suggests that our dipole-based IAP model was useful in illustrating the relationship between the waveforms of intra- and extra-cellular potentials. Despite our effort to show the students the necessity of considering both the temporal and spatial profiles of the IAP to predict the characteristics of extracellular potentials, they obtained relatively low grades in the questions related to the learning objectives c1–c3. This is probably explained by the fact that the relationship between the spatial extent of the IAP profile and the amplitude of the extracellular potential is somewhat counterintuitive and therefore requires an additional effort from the student.

The results from the evaluation form filled in by the students at the end of the last session are presented in Table 3. This table indicates that most students were highly satisfied with the theoretical approaches proposed (point 5) and that, in general, they were interested in the topic (point 4). In addition, they considered that the lectures provided a thorough understanding of the generation of intra- and extra-cellular potentials (point 1), which contributed to enhance their motivation (point 3).

Table 1. Evaluation form for students

Evaluation points	**Grade from 1 to 10**
(1) Do you think these lectures provide a deep understanding of the subject of interest?	
(2) Do you think the educational materials used in the context of these lectures are sufficient?	
(3) How does this topic affect your motivation to continue your education in the biomedical engineering field?	
(4) Does this topic attract your attention?	
(5) Overall, I am satisfied with the sessions	

Table 2. Assessment of the learning objectives of the topic as a function of year (N = number of students)

	Examination Grades, Mean ± SD (from 1 to 10)			
Learning objectives	**2007/2008 (N = 13)**	**2008/2009 (N = 18)**	**2009/2010 (N = 26)**	**2010/2011 (N = 24)**
(A) Understanding of the electrostatic description of the intracellular potential and its representation as a collection of lumped dipoles	6.9 ± 1.2 [5.2 – 8.9]	6.3 ± 1.4 [4.3 – 8.6]	7.0 ± 0.9 [5.5 – 8.9]	7.6 ± 1.3 [5.2 – 9.1]
(B) Understanding of the formation of the extracellular potential around a fiber produced by the propagation of the intracellular potential along this fiber	7.7 ± 1.4 [5.2 – 8.9]	7.3 ± 1.3 [4.9 – 8.7]	8.6 ± 1.1 [5.7 – 8.9]	8.1 ± 1.2 [6.6 – 9.5]
(C) Using the temporal and spatial profiles of the intracellular potential to calculate the extracellular potential	5.3 ± 1.8 [3.5 – 7.8]	5.9 ± 1.6 [4.0 – 7.8]	6.5 ± 1.9 [4.9 – 8.2]	6.3 ± 1.5 [4.8 – 7.9]

Table 3. Students' evaluations of their satisfaction with the teaching approaches

	Degree of Satisfaction, Mean ± SD (from 1 to 10)			
Evaluation point	**2007/2008 (N = 13)**	**2008/2009 (N = 18)**	**2009/2010 (N = 26)**	**2010/2011 (N = 24)**
(1) Lectures provide a deep understanding of the subject of interest	8.1 ± 1.1 [5.9 − 9.5]	8.4 ± 1.2 [5.8 − 9.6]	7.6 ± 1.3 [5.2 − 8.9]	8.6 ± 0.7 [6.9 − 9.5]
(2) Educational materials used in the context of these lectures are sufficient	6.7 ± 1.3 [5.2 − 8.7]	6.3 ± 1.1 [4.9 − 7.8]	7.1 ± 1.1 [5.3 − 8.1]	6.8 ± 1.0 [5.3 − 8.5]
(3) The topic affects your motivation to continue your education in the biomedical engineering field	7.7 ± 1.3 [5.6 − 8.9]	7.2 ± 1.0 [4.7 − 8.9]	7.7 ± 1.0 [5.7 − 8.5]	8.3 ± 0.9 [6.5 − 9.3]
(4) The topic attracts your attention	8.3 ± 0.7 [6.9 − 9.6]	8.1 ± 1.0 [6.1 − 9.4]	8.5 ± 0.9 [7.1 − 9.5]	8.6 ± 0.8 [7.3 − 9.6]
(5) Overall, I am satisfied with the sessions	8.0± 1.3 [5.9 − 9.2]	7.7 ± 1.2 [6.1 − 9.3]	8.2 ± 1.4 [5.5 − 9.2]	8.4 ± 1.1 [6.5 − 9.6]

8. Discussion

8.1 Innovative contribution

After the pioneering studies of Wilson [27], Plonsey [21] was the first to propose that the excitation source of excitable cells can be considered as 'stacks of double layer disks'. Such an IAP description was used by Dimitrov and Dimitrova in a modelling study [21], but their representation of the IAP was unsuitably complex for teaching purposes. In recent works, Todor et al. [28] and Rodriguez et al. [29, 35] have represented the IAP as a sequence of lumped dipoles in the spatial profile and have calculated the potential field generated by these dipoles, providing a representation of the IAP that is more accessible and amenable to adaptation for teaching purposes.

Despite these studies, description of the IAP as a collection of dipoles (or double-layered disks) is not prevalent in academia or among researchers in the field; following the studies of Rosenfalck [36], most post-graduate reference texts on bioelectricity [12, 13, 15, 28, 37, 38] use analytical functions to model the intracellular potential. Whilst such analytical expressions calculate extracellular potentials with high computational efficiency (which is of importance in research), they do not facilitate visualization of how the electrical potential is generated and are, therefore, not ideal for teaching. The electrostatic description of the IAP proposed in the present paper is simple and direct and enables students to understand how an electrical field develops in the extracellular medium. In addition, because it is based on electrostatic theory, it is of more general applicability, i.e., it is valid for any scenario involving a fiber and recording electrode.

Traditional models for calculating extracellular potentials consider the excitation source, (i.e., the IAP), exclusively in its temporal domain [15, 33, 34]. However, the amplitude and temporal characteristics of bioelectrical potentials are, in fact, also related to the spatial profile of the IAP [24, 25]. To avoid errors, then, the interpretation of an extracellular potential should take into account both the spatial and temporal profiles of the corresponding IAP. The dipole-based approach presented here encourages students to think in terms of both temporal and spatial profiles of the IAP and demonstrates how these, whether acting together or independently of each other, affect the extracellular potential.

8.2 Impact on teaching and learning

In the present paper we describe a way to explain and model bioelectrical signals in terms of electrostatic theory. This theory provides a suitable starting point for learning how the potential of a fiber membrane changes when the fiber is activated. From the authors' observations as teachers, students often encounter difficulties in establishing a mental picture of membrane polarization and the transmembrane voltage, concepts that students find easier to conceptualize when the voltage across a fiber membrane is represented as layers of electrostatic charges (as shown in Fig. 1).

An important objective in the teaching of bioelectricity is to provide students with the means to calculate extracellular potentials for a wide range of conditions. The electrostatic description of the IAP helps students in this respect by establishing direct relationships between the profiles of intra- and extra-cellular potentials. The approach is also valuable as a tool to validate and interpret potentials such as those obtained by use of simulation programs or those recorded experimentally and, therefore, constitute a solid foundation for the biomedical engineer.

9. Conclusions

An approach to modelling the electrical potentials produced by excitable cells based on the electro-

static theory has been presented. The approach responds to the needs of students of a Master Degree Program in Biomedical Engineering to understand and, in particular, to visualize the formation of the electrical potential around a muscle fiber. The electrostatic model of the intracellular potential has proved useful in showing students how the profile of the extracellular potential is progressively generated as the intracellular potential propagates along the excitable fiber. The model also enhanced the ability of students to predict and validate the shape of the extracellular potential as registered by an electrode at any possible location relative to the fiber.

The paper addresses an issue not frequently covered in post-graduate text books on Bioelectricity or in scientific papers: the necessity of considering both the temporal and spatial profiles of the intracellular action potential in order to interpret correctly the characteristics of extracellular potentials. Evaluation of students indicates that this electrostatic presentation of bioelectrical potentials has allowed them to gain insight into the formation of both intra- and extra-cellular potentials and has clearly heightened their interest in Bioelectricity.

Acknowledgement—The authors thank Prof. G. Dimitrov and Prof. N. Dimitrova for leading them into an understanding of the fundamental biophysical and electrostatic properties of excitable cells.

References

1. R. J. Johns, Current issues in biomedical engineering education, *IEEE Transactions Biomedical Engineering*, **22**(2), 1975, pp. 107–110.
2. A. R. Potvin, F. M. Long, J. G. Webster and R. J. Jendrucko, Biomedical engineering education: enrolment, courses, degrees, and employment, *IEEE Transactions Biomedical Engineering*, **28**(1), 1981, pp. 22–28.
3. T. C. Pilkington, F. M. Long, R. Plonsey, J. G. Webster and W. Welkowitz, Status and trends in biomedical engineering education, *IEEE Engineering in Medicine and Biology Magazine*, **8**(3), 1989, pp. 9–17.
4. J. G. Webster, Guest editorial, *International Journal of Engineering Education*, **15**(4), 1999, pp. 238–239.
5. P. King, Design and biomedical engineering, *International Journal of Engineering Education*, **15**(4), 1999, pp. 282–287.
6. J. Viik and J. Malmivuo, Biomedical engineering as a career resource: survey from Tampere University of Technology, *International Journal of Engineering Education*, **15**(4), 1999, pp. 308–320.
7. Z. O. Abu-Faraj, Bioengineering/Biomedical engineering education and career development: literature review, definitions, and constructive recommendations, *International Journal of Engineering Education*, **24**, 2008, pp. 990–1011.
8. Bologna Process. Bologna + 10 Ministerial Conference, http://www.ond.vlaanderen.be/hogeronderwijs/ bologna/ conference/, Accessed 15 February 2011.
9. J. Bronzino, Biomedical engineering: a historical perspective, in J. Enderle, S. Blanchard, and J. Bronzino *Introduction to Biomedical Engineering*, San Diego, CA, USA: Academic Press, 2005, pp. 1–29.
10. J. D. Bronzino, Editor-in-Chief, *The Biomedical Engineering Handbook*, Boca Raton, FL, USA: CRC Press, 1995.
11. R. Plonsey, The active fiber in a volume conductor, *IEEE Transactions Biomedical Engineering*, **21**, 1974, pp. 371–381.
12. J. Malmivuo and R. Plonsey, *Bioelectromagnetism: principles and applications of bioelectric and biomagnetic fields*, Oxford, United Kingdom: Oxford University Press, 1995.
13. R. Plonsey and R. C. Barr, *Bioelectricity. A quantitative approach*, New York, USA: Kluwer Academic, 2000.
14. S. Andreassen and P. Rosenfalck, Relationship of intracellular and extracellular action potentials of skeletal muscle fibers, *CRC Critical Reviews in Bioengineering*, **6**, 1981, pp. 267–306.
15. S. Nandedkar and E. Stålberg, Simulation of single muscle fiber action potentials, *Medical & Biological Engineering & Computing*, **21**, 1983, pp. 158–165.
16. A. Gydikov, Biophysics of the skeletal muscle extracellular potentials, *Bulgarian Academy of Sciences*, **132**, 1991, pp. 60–100.
17. G. V. Dimitrov and N. A. Dimitrova, Precise and fast calculation of the motor unit potentials detected by a point and rectangular plate electrode, *Medical Engineering & Physics*, **20**, 1998, pp. 374–381.
18. J. Rodriguez, J. Navallas and A. Malanda, Teaching a master student how to model the electrical potentials produced by the muscle, *International Journal of Engineering Education*, **26**(6), 2010, pp. 1–14.
19. E. Stålberg, Quantitative analysis of individual motor unit potentials: a proposition for standardized terminology and criteria for measurement, *Journal of Clinical Neurophysiology*, **3**(4), 1986, pp. 313–348.
20. J. R. Daube and D. I. Rubin, Needle electromyography, *Muscle & Nerve*, **39**, 2009, pp. 244–270.
21. R. Plonsey, Action potential sources and their volume conductor fields, *Proceedings of the IEEE*, **65**, 1977, pp. 601–611.
22. N. A. Dimitrova, Influence of the length of the depolarized zone on the extracellular potential field of a single unmyelinated nerve fiber, *Electromyography and clinical neurophysiology*, **13**, 1973, pp. 547–558.
23. G. V. Dimitrov and N. A. Dimitrova, Influence of the afterpotentials on the shape and magnitude of the extracellular potentials generated under activation of excitable fibers, *Electromyography and clinical neurophysiology*, **19**, 1979, pp. 249–267.
24. G. V. Dimitrov and N. A. Dimitrova, Extracellular potentials produced by a transition between an inactive an active regions of an excitable fiber, *Electromyography and clinical neurophysiology*, **29**, 1989, pp. 265–271.
25. N. A. Dimitrova and G. V. Dimitrov, Electromyography (EMG) modeling. In: Metin A, editor. *Wiley encyclopedia of biomedical engineering*, Hoboken, NJ, USA: John Wiley & Sons, 2006.
26. G. V. Dimitrov and N. A. Dimitrova, Changes in the extracellular potentials produced by unmyelinated nerve fiber resulting from alterations in the propagation velocity or the duration of the action potential, *Electromyography and clinical neurophysiology*, **27**, 1987, pp. 243–249.
27. F. N. Wilson, A. G. MacLeod and P. S. Barke, The distribution of the action currents produced by heart muscle and other excitable tissues immersed in extensive conducting media, *The Journal of General Physiology*, **16**, 1933, pp. 423–456.
28. T. Arabadzhiev, G. V. Dimitrov, V. Chakarov, A. Dimitrov, and N. A. Dimitrova, Effects of changes in intracellular action potential on potentials recorded by single-fiber, macro, and belly-tendon electrodes, *Muscle & Nerve*, **37**, 2008, pp. 700–712.
29. J. Rodríguez, A. Malanda, L. Gila, I. Rodríguez and J. Navallas, The peak-to-peak ratio of single-fiber potentials is little influenced by changes in the electrode positions close to the muscle fiber, *Journal of Electromyography & Kinesiology*, **21**, 2011, pp. 423–432.
30. J. Rodríguez, A. Malanda, L. Gila, I. Rodríguez and J. Navallas, A mathematical analysis of SFAP convolutional models, *IEEE Transactions Biomedical Engineering*, **52**(5), 2005, pp. 769–783.
31. R. L. Lieber, *Skeletal muscle structure, function, and plasticity*, Baltimore, MD: Lippincott Williams & Wilkins, 2010.
32. R. E. Burke, Motor units: anatomy, physiology and func-

tional organization. In: *Handbook of Physiology. The Nervous System. Motor Control*, Bethesda, MD: American Physiological Society, **2**, 1981, pp. 345–422.
33. F. Buchtal, The functional organization of the motor unit: a summary of results, *American Journal of Physical Medicine*, **38**, 1959, pp. 125–8.
34. Cellular Biophysics: Electrical Properties. Cambridge, MA: MIT Press, **2**, 1996.
35. J. Rodríguez, A. Malanda, L. Gila, I. Rodríguez, and J. Navallas, Estimating the duration of intracellular action potentials in muscle fibers from single-fiber extracellular potentials, *Journal of Neuroscience Methods*, **197**, 2011, pp. 221–230.
36. P. Rosenfalck, Intra- and extracellular fields of active nerve and muscle fibers. A physico-mathematical analysis of different models, *Acta Physiologica Scandinavica*, **321**, 1969, pp. 1–168.
37. S. M. Fleisher, Comparative analysis of modelled extracellular potentials, *Medical & Biological Engineering & Computing*, **22**, 1984, pp. 440–447.
38. K. C. McGill, Z. C. Lateva, A model of the muscle-fiber intracellular action potential waveform, including the slow repolarization phase, *IEEE Transactions Biomedical Engineering*, **48**, 2001, pp. 1480–1483.

Javier Rodríguez-Falces graduated from the Public University of Navarra, Spain in 2003. He obtained the PhD degree in 2007 from the Public University of Navarra, Telecommunication Engineering. 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 graduated from the Madrid Polytechnic University, Spain in 1992. He obtained the PhD degree in 1999 from the Carlos III University, Madrid, Telecommunication Engineering. 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. Since 1992, 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 graduated from the Public University of Navarra, Spain in 2002. He obtained the PhD degree in 2008 from the Public University of Navarra, Telecommunication Engineering. He has also worked as a software engineer. He is presently Assistant Professor in the Electrical and Electronics Engineering Department of this University. His research interests are modeling of biological systems and neurosciences.