

A STUDY ON THE MODELING AND SIMULATION FOR THE MOTOR UNIT ACTION POTENTIAL

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ABSTRACT. Electromyography (EMG) is a technique that gives information about the neuromuscular pattern and function which is commonly-used in the practice of neurology. With this method, the signals obtained from the muscle cells using an amplifacore are enhanced to an amount enough to study on. The potentials monitored are called Motor Unit Action Potentials (MUAPs). In this study, the findings gathered by the simulation using the dipole model for the motor unit action potential (MUAP) have been evaluated. With the motor unit modeling and simulation, the effect of different anatomic characteristics of nerves and muscles on MUAP and EMG signals may be examined. It is not possible to perform such an action empirically. The modeling and simulation for MUAP and EMG also provides a good opportunity of practicing and studying for those who started recently and wish to learn EMG. In the simulation made using the dipole model, the variables such as the diameter and distribution of muscle fibers and the location of motor end-plate area have been studied; and the effect of these variables on the formation of MUAP has been analyzed. The result of the study has suggested that the MUAP simulation with the dipole and line source model was a proper tool to understand the physiology of MUAP and the pathological processes. Reliability and efficiency on diagnosing muscle and nerve disorders using electromyography (EMG) are essential points. We analyze the dipole and line-source model for modeling muscular action potential (AP).

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1. INTRODUCTION

A particular statement of an event, a process or a system in the real world is called model. The experiments made on the system, on the other hand, are called simulation. Since the real world is very complicated, models approach on the phenomena and the systems they are about to state in a simplifying way under particular assumptions. Models are not the realities but the incomplete statements of the reality no matter how perfect they are [1].

Electromyography (EMG) is a technique that gives information about the neuromuscular pattern and function which is commonly-used in the practice of neurology. With this method, the signals obtained from the muscle cells using an amplificatory are enhanced to an amount that is enough to study on. The potentials monitored are called Motor Unit Action Potentials (MUAPs). With the analysis on the potentials obtained, the information regarding nerves and muscles is gathered. MUAP represents the physiological features of the Motor Unit (MUAP) which is made of peripheral nerves, neuromuscular junction, and the muscles run by the nerves. The analysis of MUAP, which has a diagnostic value for the diseases, takes a major place in the investigation of EMG. Motor Unit Action Potential (MUAP) indicates the total amount of the action potentials generated by all of the muscle fibers in the motor unit. Variables reflecting the anatomic and physiological characteristics of MU in EMG are included in MUAP. The duration, the amplitude, and the space of MUAP are of those mostly used in the practice of EMG. The analysis of these variables helps deciding whether the disease is generally found in muscles or nerves. In muscular diseases, the potential obtained in accordance with the decrease in the number of the muscle fibers has lower amplitude and shorter duration compared to normal circumstances. On the other hand, the potentials observed in neural diseases have higher amplitude and longer duration. The distribution of muscle fibers in MU fluctuates especially in neural diseases. In this case, the muscle fibers are found in groups in MU.

In this study, findings obtained with a simulation of the action potential (MUAP) made by using two different models have been evaluated. With the motor unit modeling and simulation, the effect of different anatomic characteristics of nerves and muscles on MUAP and EMG signals may be examined. It is not possible to perform this empirically. The modeling and simulation for MUAP and EMG also provides a good opportunity of practicing and studying for those who started recently and wish to learn EMG. In the simulation made using the dipole model, the variables such as the diameter and distribution of muscle fibers and the location of motor end-plate area may be studied; and the effect of these variables on the formation of MUAP may be analyzed. According to the dipole model, dipole generator consists of the source and the sink those which have I current each and are $2b$ away from each other. The source and sink correspond to the motor unit end-plate area. MUAP is obtained by calculating the total potentials generated by the source and the sink in each muscle fiber. With the Line-Source model, some variables which are

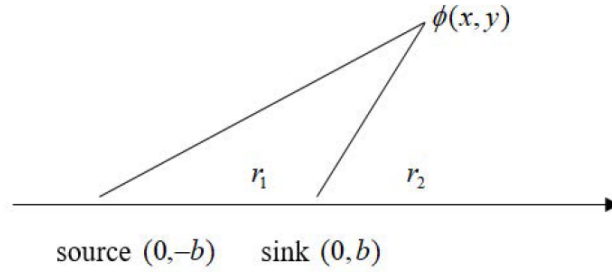


FIGURE 1. The Dipole generator

not included in the dipole model (such as the axial or radial position of recording electrode and the conductivity of the environment) and the effect of these variables on MUAP may be addressed. According to the Line-Source model, the action potential consists of the current passing through the cell membrane and the convolution of the weight function. Weight function is determined in accordance with the type of the recording electrode. Thereby, it is possible to develop simulation for the different recording methods (individual fiber EMG, concentric needle EMG, Macro EMG) using the Line-Source model. The result of the study has suggested that the MUAP simulation with the dipole and line source model was a proper tool to understand the physiology of MUAP and the pathological processes, and also that the Line-Source model was a realistic model to understand and evaluate the processes in question.

2. DIPOLE MODEL AND SIMULATION

2.1. The action potential generated by the individual muscle fiber. The dipole generator consists of the source and the sink those which have I current each and are $2b$ away from each other (Figure 1).

The source and sink correspond to the motor unit end-plate area. The I current which is a global potential area generated by the source is given by ϕ

$$\phi(r) = \frac{I}{4\pi r}. \quad (1)$$

Here, r stands for the distance from the source and v stands for the conductivity of the environment surrounding the muscle fiber. Consequently, the potential generated at (x, y) point by the dipole made of $(0, -b)$ source and $(0, b)$ sink is given by

$$\phi(x, y) = \frac{I}{4\pi v} \left(\frac{1}{r_1} - \frac{1}{r_2} \right). \quad (2)$$

If r_1 and r_2 distances in Figure 1 are calculated in accordance with the (x, y) coordinate system and written into the equation above, the result would be

$$\phi(x, y) = \frac{I}{4\pi v} \left(\frac{1}{\sqrt{(x+b)^2 + y^2}} - \frac{1}{\sqrt{(x-b)^2 + y^2}} \right). \quad (3)$$

According to the empirical studies, a motor unit in Biceps Brachii (BB) muscle is circular and its diameter is 5mm averagely. It is determined that each of these motor units contained 163 muscle fibers averagely. It is observed that the diameter of each muscle fiber was $50\mu m$. It is determined that the muscle fibers in motor unit field distributed normally in this circular area. The action potential generated by each muscle fiber in a motor unit in BB muscle disseminates $2bmm$ long on the muscle fiber. In the empirical studies made, the velocity of dissemination of the motor unit action potential in human BB muscle has been calculated as 4.1m/s at $36.5^\circ C$.

2.2. Motor Unit Action Potential (MUAP). The Motor Unit Action Potential (MUAP) indicates the total amount of the action potentials generated by all of the muscle fibers in the motor unit. Variables reflecting the anatomic and physiological characteristics of MU in EMG are included in MUAP.

2.3. MUAP Simulation. For the simulation study, the diameter of MU was taken as $5mm$, the velocity of dissemination of the action potential on the muscle fiber was taken as $v = 4.1m/s$, the length of motor end-plate was taken as $b = 0.1m$, and the length of the dissemination of action potential was taken as 10 mm [5]. Under the assumption that the muscle fibers in MU distributed normally [4] in this circular area (Figure 2), the MUAP that is made of the total amount of these values is shown in Figure 3 - Figure 4.

2.4. Results obtained from the Simulation for the Dipole Model. The change happened in MUAP that emerges on normal conditions of MU has been analyzed in accordance with the recording distance. In this analysis, it is observed that the amplitude decreased and the duration lengthened as the distance from the potential increased. The result of this study is a phenomenon observed in EMG. It is determined that the amplitude of the obtained MUAP decreased and the duration became shorter when the number of muscle fibers in MU is decreased [3]. This fact is interpreted as a finding which is in accordance with the short-time and low-amplitude *Myopathic* MUP image seen in muscular diseases. In cases when the muscle fibers in MU in the circular area are found not straightly but in groups, the effect of these groupings on MUAP has been examined.

3. LINE SOURCE MODEL AND SIMULATION

According to the Line-Source model, the action potential consists of the current passing through the cell membrane and the convolution of the weight function.

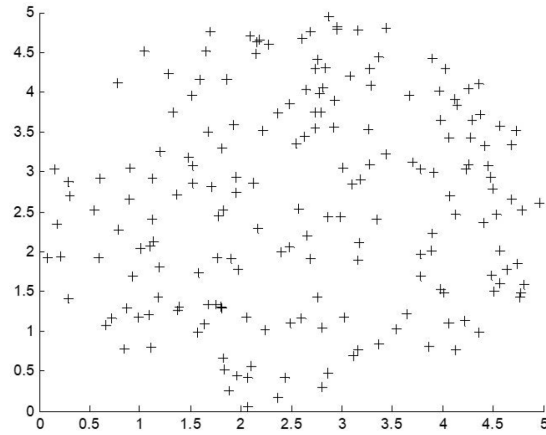


FIGURE 2. The muscle fibers in MU distributed.

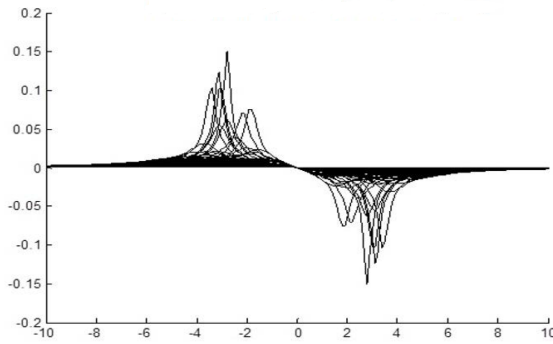


FIGURE 3. Potentials from each of the fibers.

The weight function is determined in accordance with the type of the recording electrode. Thereby, it is possible to develop simulation for the different recording methods (individual fiber EMG, concentric needle EMG, Macro EMG) using the Line-Source model.

3.1. The Model for the Intracellular and Trans-Membrane Action Potentials. Rosefalck [2] has given the mathematical expression for the intracellular action potential by

$$g(z) = 96z^3e^{-z} - 90 \quad (4)$$

On the other hand, the intensity of the trans-membrane current is in proportion with the 2nd derivative of the intracellular action potential as

$$g''(z) = 96z(6 - 6z + z^2)e^{-z} \quad (5)$$

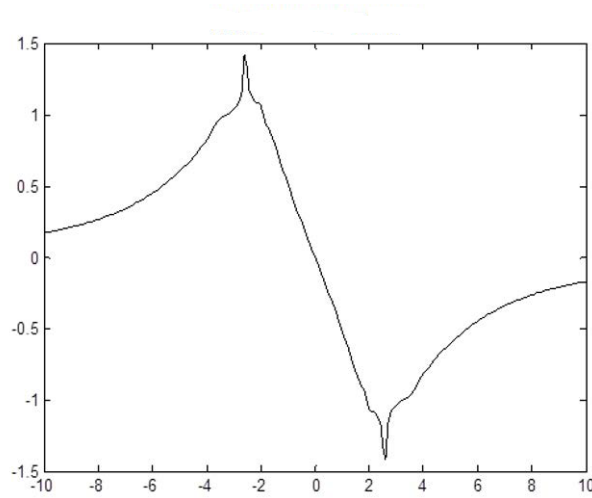


FIGURE 4. Total amount of potentials.

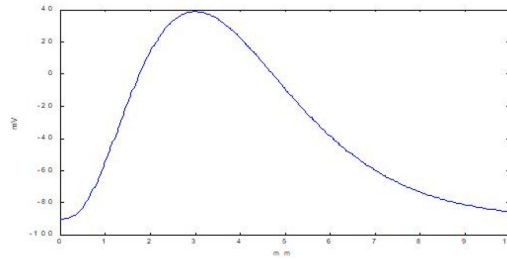


FIGURE 5. Intracellular action potential equation 4.

Thereby, the current passing through the membrane is calculated

$$\text{Im}(z) = \frac{\sigma_i \pi d^2}{4} g''(z) \tag{6}$$

Here, d stands for the diameter of the muscle fiber and σ_i stands for the intercellular conductivity. The graphics of potentials obtained from Equation 4 and Equation 5 are shown in Figure 5 and Figure 6.

To resolve the discordance between the findings obtained with the simulation and the empirical findings, Nandedkar and Stalberg [6] have taken the intracellular action potential as $e(z) = g(2z)$ and named this model as "Modified Line-Source Model". According to this model,

$$e''(z) = 4g''(2z) \tag{7}$$

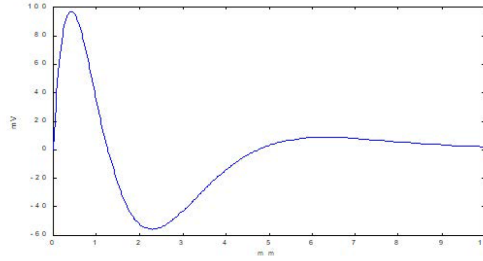


FIGURE 6. Intracellular action potential equation 5.

and the trans-membrane current is calculated as

$$\text{Im}(z) = \frac{\sigma_i \pi d^2}{4} g''(z) \quad (8)$$

Here

$$g(z) = 768z^3 e^{-2z} - 90 \quad (9)$$

Furthermore, as U stands for the velocity of dissemination, the velocity of dissemination of the action potential may be examined in time dimension with the $z = Ut$ transformation.

3.2. Weight Function Model. The weight function is calculated for the potential record on the assumption that the current potential disseminates from the end-plate area to the tendon area with a speed equal to the velocity of dissemination of the action potential. The potential generated by a source of unit current is given by

$$\Phi(r, z) = \frac{1}{4\sigma_r \pi \sqrt{Kr^2 + (z - z_0)^2}} g''(z) \quad (10)$$

Here, z_0 is the axial distance between the recording electrode and the potential $K = \frac{\sigma_z}{\sigma_r}$ is the division between the axial and radial conductivity, and r is the radial distance between the recording electrode and the potential. This function identifies the action potential as a point space. since the EMG electrode for individual fiber has a small recording surface, this potential function is used to model the action potential for the individual muscle fiber.

3.3. The Model and Simulation for the Action Potential of Individual Fiber Recorded by EMG Electrode for Individual Fiber. According to the Modified Line-Source model, the action potential is given by the

$$AP = \text{Im}(z) * \Phi(r, z) \quad (11)$$

convolution of the trans-membrane concurrent and the weight function. Taking the conductivity value as 0.0063 and the diameter of the muscle fiber as $55\mu\text{m}$ in

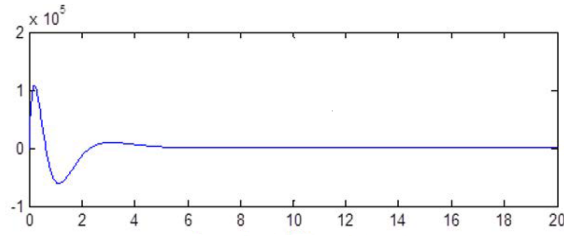


FIGURE 7. Trans-membrane concurrent-weight function of the electrode.

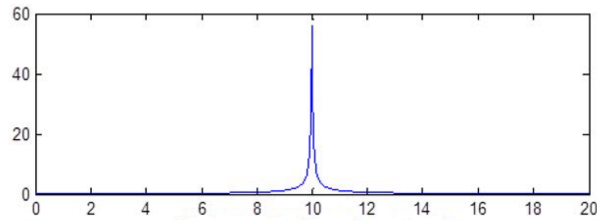


FIGURE 8. Trans-membrane concurrent-weight function of the electrode.

Equation 6, the axial distance between the recording electrode and the potential as 10mm, the division between the axial and radial conductivity as equal to 5, the radial distance between the recording electrode and the potential as 0.2mm in Equation 10; the potential calculated by 6 equality is given in Figure 7 the weight function calculated by Equation 10 is given in Figure 8 and consequently the potential calculated by Equation 11 is given in Figure 9 to develop a simulation on this model.

3.4. Results from the Line-Source Model and Simulation. According to the Line-Source model, the action potential consists of the current passing through the cell membrane and the convolution of the weight function. Weight function is determined in accordance with the type of the recording electrode. Therefore, the simulation for different recording methods has been developed with the Line-Source model. The potential changes in accordance with the diameters of the muscle fibers. The amplitude grows larger as the diameters of the muscle fibers do.

4. CONCLUSION

Reliability and efficiency on diagnosing muscle and nerve disorders using electromyography (EMG) are essential points. We analyze the dipole and line-source model for modeling muscular action potential (AP). In this work, important two

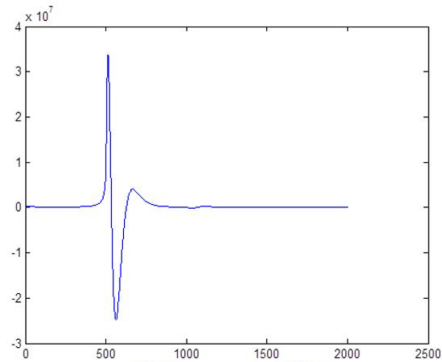


FIGURE 9. Consequently the potential.

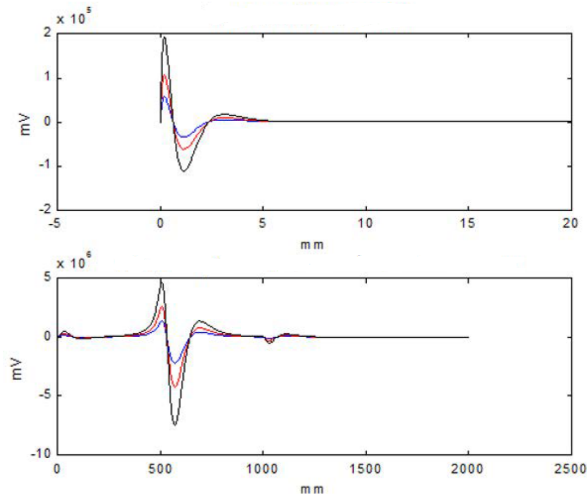


FIGURE 10. Trans-membrane current and the action potential for the individual muscle fiber.

basic potential (MUAP) have been evaluated. With the motor unit modeling and simulation, the effect of different anatomic characteristics of nerves and muscles on MUAP and EMG signals has been examined. The result of the study has suggested that the MUAP simulation with the dipole and line source model was a proper tool to understand the physiology of MUAP and the pathological processes. The modeling and simulation for MUAP and EMG also provides a good opportunity of practicing and studying for those who started recently and wish to learn EMG. The modeling and simulation may be provided to users as packaged software. The

result of the study has suggested that the MUAP simulation with the dipole and line source model was a proper tool to understand the physiology of MUAP and the pathological processes, and also that the Line-Source model was a realistic model to understand and evaluate the processes in question. Studies on MUAP modeling have been continuing [7]. The aim of our future work will be the modeling of MUAP of different muscles disorders such as myopathy and neuropathy.

Authors Contribution Statement The authors contributed equally to this work. All authors of the submitted research paper have directly participated in the planning, execution, or analysis of study. Finally, all authors of the paper have read and approved the final version submitted.

Declaration of Competing Interest The authors declare that there is no conflict of interest regarding the publication of this article. Besides, the contents of the manuscript have not been submitted, copyrighted or published elsewhere and the visual-graphical materials such as photograph, drawing, picture, and document within the article do not have any copyright issue.

REFERENCES

- [1] Oztürk, F., Ozbek, L., Matematiksel Modelleme ve Simulasyon, Pigeon Yayınları, 2016.
- [2] Rosenfalck P., Intra and extra-cellular potential fields of active nerve and muscle fibers, *Acta Physiol. Scand.*, Suppl.321, 1969.
- [3] George R. E., The summation of muscle fibre action potentials, *Med.and Biol.Eng.*, 8 (1970), 357-365.
- [4] Buchthal F. and Rosenfalck P., On the structure of motor units, *New Developments in Electromyography and Clinical Neurophysiology*, (1973), pp. 14-22.
- [5] Nandedkar, S.D., Stalberg, E, Simulation of single muscle fibre action potentials, *Med. Biol. Eng.*, 21 (1983), 158-165.
- [6] Hansson, B.J., Stalberg, E., Novel ideas for fast Muscle Action Potential simulations using the line source model, *IEEE Trans. Biomedical Eng.*, 51(11) (2004), 1888-1897.
- [7] Dridi A., Mtimet J., and Yscoub S., A model to simulate SEMG signals of different muscles, *2017 International Conference on Advanced Systems and Electric Technologies (ICASET)*, (2017), 30-33.