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A Finite Element Approach for Forearm Neuromodulation: *Impact of Electrode Size on the Current Density*

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Abstract. Electrical impedance myography is a transcutaneous neuromodulation method for assessing muscle conditions through the application of a high-frequency, low-intensity current to the muscle region of interest (ROI). It has been shown that the mechanisms underpinning these findings are controversial as studies showed that the current reaching the target structure may not be enough to activate tissue due to various factors. It has been shown that anatomical properties as well as non-anatomical factors including electrode shape and size, inter-electrode distance may affect the outcome. This study was conducted to investigate the impact of the different sizes of the electrodes on the current density of the ROI. It may not be feasible to investigate these parameters impact on the outcome using experimental procedures. Alternatively, the computational methos have been used as a tool to study electrical stimulation of bio-computational models. The neuromodulators can be designed and developed using such advanced methods. This study investigates the impact of the electrode size on the current distributions. The fundamental anatomical layers of the human forearm were generated based on standard dimensions using concentric shapes. A sinusoidal bipolar current pulse was applied on the different sizes of electrodes to simulate current distribution within the associated anatomical layers. It was shown that the electrode size has a significant impact on the induced current density of the target anatomical layer.

1. Introduction

Electrical impedance myography is a non-invasive technique that aims to measure impedance variation over the region of interest (ROI) of the target muscle. This method has been widely used for various health-related disorders as a primary diagnostic technique and as a biomarker to assess disease progression and response to therapy [1]. It has been shown that this method recently used for the hand motion interpretation and the promising results were obtained. The most used wearable hand motion interpretation is based on surface electromyography (sEMG), particularly for controlling myoelectric prostheses. The sEMG is commonly used to observe the motor neuronal activity within muscle fibers. However, decoding dexterous body movements from sEMG signals is still quite challenging [1], [2]. It has been indicated that the results based on this method rely on the flow of current from surface electrodes through multiple tissue layers. Thus, the technique is sensitive to both geometrical and electrical factors [3]. The electrical properties of the tissue layers and the anatomical features of the tissue around the ROI may have a considerable impact on the outcome. Also, the features of electrodes (e.g., size), and the position of the muscle fibers (e.g., parallel, or perpendicular to the muscle fibers)

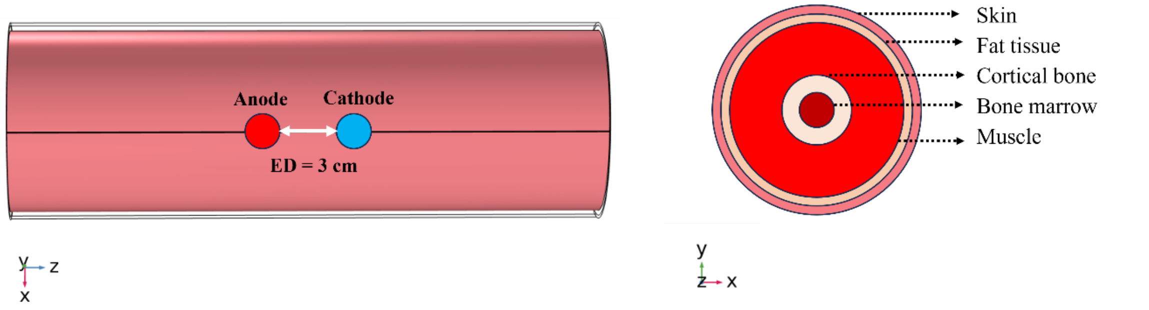

Figure 1. The 3D model of the human arm is based on the fundamental tissue layers including skin, subcutaneous fatty tissue, muscle, cortical bone, and bone marrow. The simulation electrode pairs are merged with the model to analyze the results. The polarity of the electrodes and electrode distance (ED) are highlighted.

may have an impact on the measured impedance. It is not feasible to investigate the impact of these parameters on the results using conventional experimental tests.

It has been proved that finite-element analysis (FEA) is an effective tool to study biophysical phenomena to design and develop neuromodulators for biomedical applications [4]– [7]. In this study, the impact of the electrode size was investigated on the current density of the human arm muscle using such computational modeling systems. Also, the induced electrical potential on the electrodes was recorded to analyze the results based on different electrode sizes. The previous studies suggested the smooth geometrical representation of the tissue layer for the upper arm can be used to generate a computational model of the human arm. Thus, the volume conductor of the human arm was developed based on concentric geometric shapes in COMSOL Multiphysics shown in Fig. 1.

2. Methods

2.1. Finite element analysis

The finite element analysis (FEA) was performed using AD/DC and Design Modules in COMSOL Multiphysics based on Electrical Current Physics. The human arm model was generated based on existing studies by considering their average anatomical variations [3]. The human arm computational models were generated based on fundamental tissues including skin, subcutaneous fat, muscle, cortical bone, and bone marrow as shown in Fig. 1. The electrode arrangement was merged with the model. A large layer was defined around the model to imitate the infinite.
The sinusoidal charge-balanced current pulse was generated in COMSOL to apply the surface of the electrode contacts. The boundary conditions were applied to complete the volume conductor. By this, it was ensured that the current density and the electrical potential continued between the tissue layers, electrode-tissue interfaces, and electrodes. It was noted that the electrodes were set as '*Terminal*' in COMSOL.

2.2. Electrode design procedures

The electrode arrangements are a promising technology that is widely used for transcutaneous electrical stimulation (TES). It has been approved that the dynamic adaptation of electrode size and position helps to simplify the use of electrical stimulation systems and to increase their clinical efficacy [8]– [10]. However, it is still unclear how the electrode size affects the current distribution of the target muscle. Thus, four different electrodes were generated based on different sizes to analyze the current distribution on the RIO and the electrical potential variation on the electrode terminals as shown in Fig. 2.
It is vital to make sure that the electrode pair has full contact with the skin layer. To confirm this, the skin layer was constructed from the electrode using Boolean operation in COMSOL. In this way, the

electrode volume that is the inside of the skin was removed. Then, the skin layer should be re-generated to complete the volume conductor. This step was repeated for all electrode arrangements. It is noted that electrode distance (ED) was kept constant for a fair comparison.

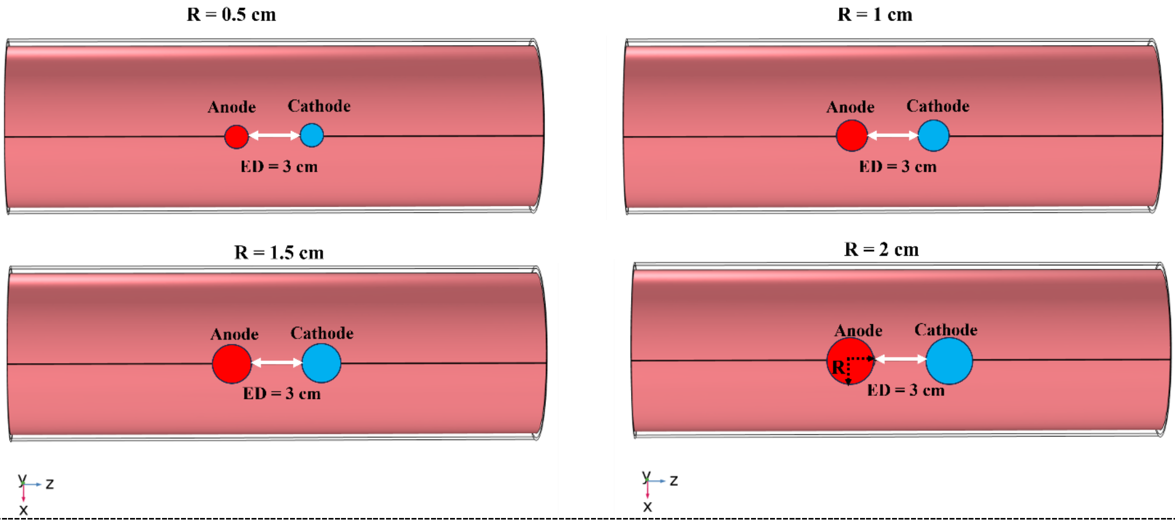

Figure 2. Shows four different electrode models. **R** shows the radius of the electrode and **ED** represent electrode distance between two contacts. The polarity of each electrode is highlighted.

2.3. Computational simulation

It has been shown that the capacitive simulation has a significant impact on the results [11]. Thus, the simulation was designed based on transient simulation by considering the capacitive factor of the tissue layers using (1).

$$\nabla \cdot \left(\sigma \nabla V - \varepsilon_0 \varepsilon_r \nabla \frac{\partial V}{\partial t} \right) \tag{1}$$

where σ shows each tissue conductivity, the electrical potential in the representative geometry is represents with V, Each tissue has different relative permittivity, and it is shown with ε_r .

After attaining the dielectric properties of the associated tissue layers in COMSOL based on 10 MHz using [12] , the current magnitude (e.g., 1 mA) was defined based on the sinusoidal waveform in the Electrics Current section in COMSOL. Also, the outer boundary surfaces of the large sphere were set as electrically insulated as ground to complete the electric circuit. To obtain the simulation results, each domain of the volume conductor was discretized using tetrahedral finite element methods in the Mesh model in COMSOL. It is vital to classify each domain based on their region of interest. Since electrodes, skin and muscle are the RIO of this study, they need to be finely meshed compared to the remaining layers. Thus, the regions of interest (mainly electrode pairs) were more finely meshed using *Finer* settings, while the rest of the region was relatively coarsely meshed using *Normal* mesh settings. This resulted in 0.25 million tetrahedral elements and about 0.3 million degrees of freedom. It is noted that the same procedures were repeated for all four electrode models.

3. Results and Discussion

The current density variation based on different electrode sizes is shown in Fig. 3. The current density distributions are visualized using color-based contour levels in COMSOL. The current density range is arranged between 100 mA/m^2 to 500 100 mA/m^2 to identify which electrode size has better variation.

It is shown that when the electrode size (radius, R) increased, the current density spread wide area of the muscle. Also, the distribution of the current density is proportional to electrode size when the magnitude of the current density through the inner layer is considered. This can be associated with the definition of the electrode as they have equipotential distribution over the whole area. Thus, the larger electrode can cover more territory of the muscle. However, this may not always desired due to stimulation of the neighbouring muscle fibers if a specific muscle fiber is targeted.

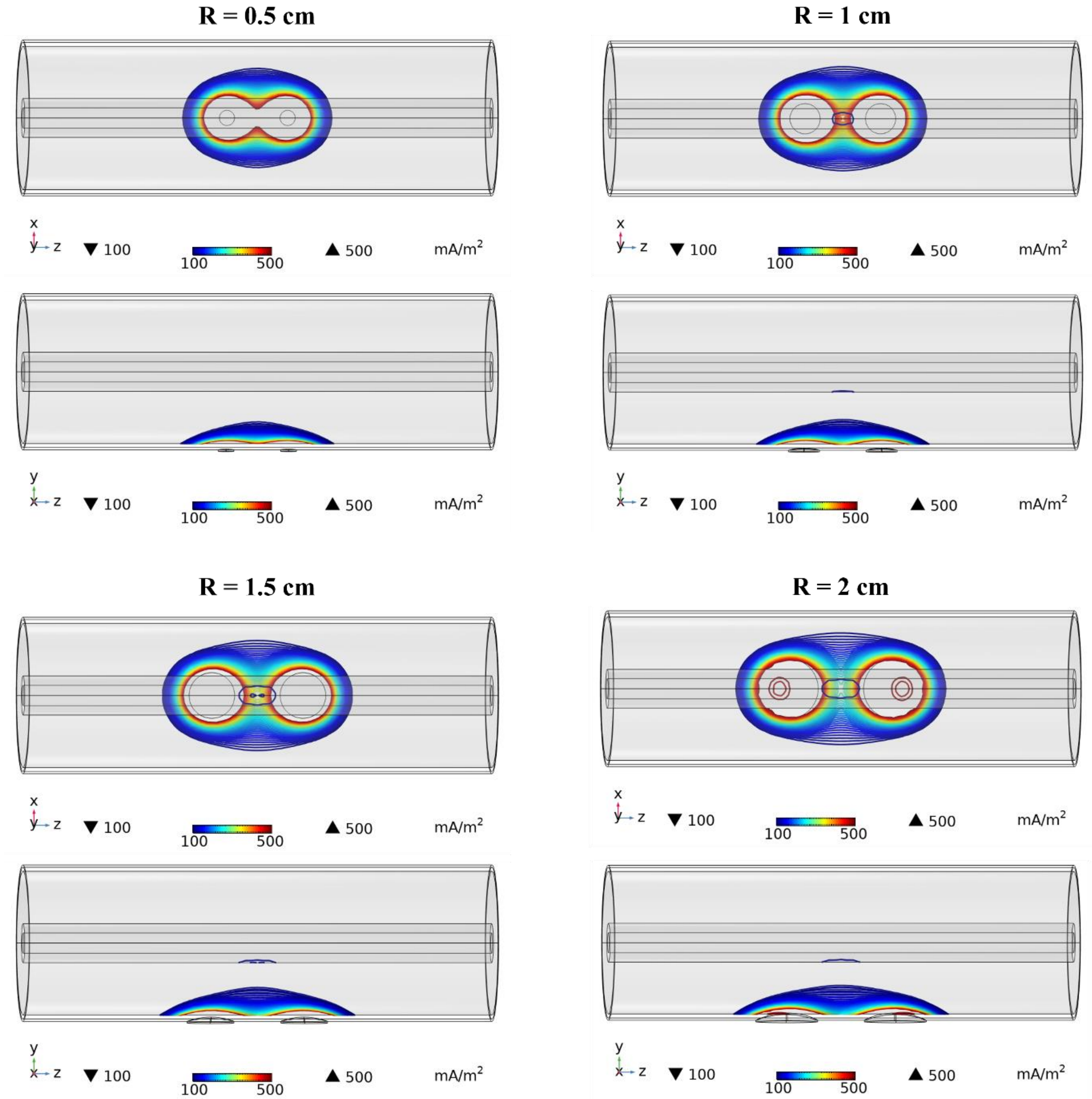

Figure 3. Shows current density variation using different sizes of the electrode pairs. The current density range is arranged between 100 mA/m^2 to 500 100 mA/m^2 to identify which electrode size has better variation.

The electrical potential variation on each electrode pair is calculated and shown in Fig. 4. The induced electrical potential variation for each electrode size is recorded for both anode and cathode polarities. It is shown that the induced electrical potential variation on the electrode surface is inversely proportional to the electrode size. This valid for both anodic and cathodic polarities. When the electrode size is doubled, the induced electrical potential variation drops in half, and this is valid for all electrode sizes. Although the results showed that the current density is proportional with electrode size in this study, different electrode shapes and size of the electrodes should be considered to conclude the outcomes. The results for different electrode shapes may show different variation although circular electrode is mostly used for the TES systems.

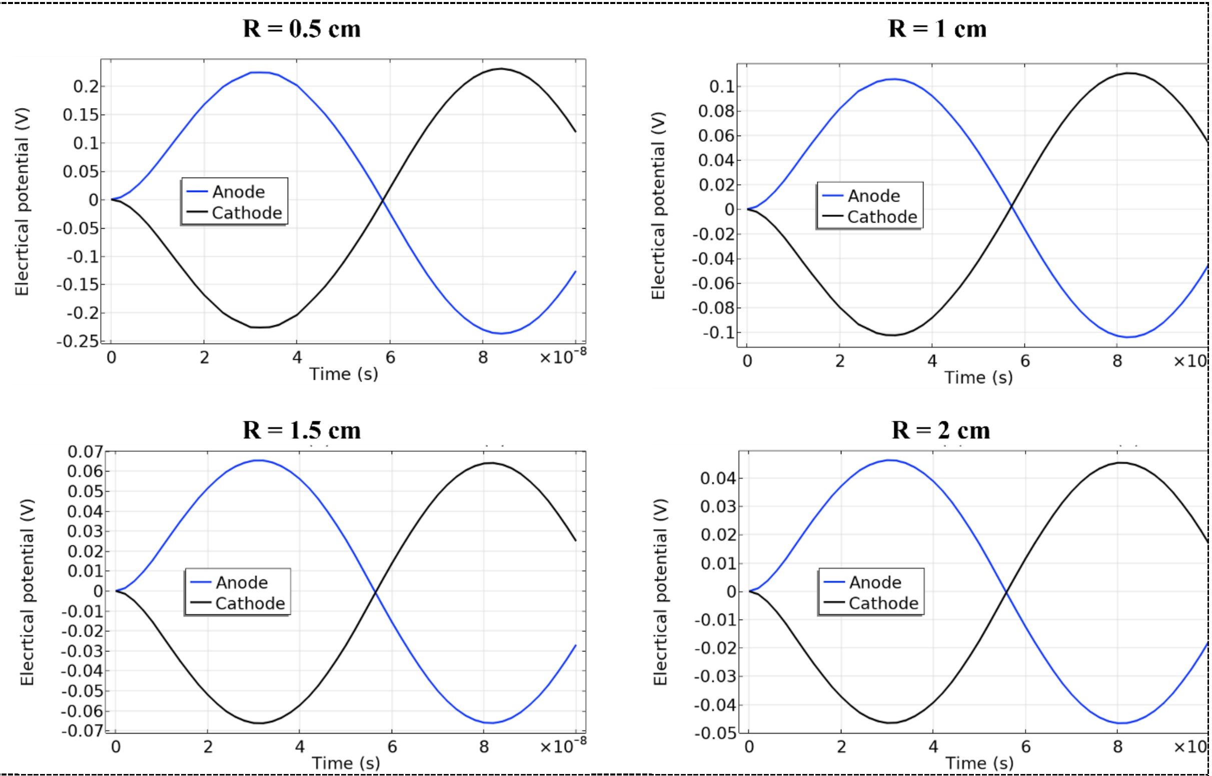

Figure 4. The electrical potential variation for different electrode sizes. The induced electrical potential variation is recorded for both anode and cathode polarities. The results for anode and cathode are highlighted in blue and black, respectively. The electrode sizes are highlighted.

4. Conclusion

The FEM model of the human arm was generated based on smooth geometric shapes using the average size of the fundamental tissue layers including skin, fatty tissue, muscle, and bony layers. After defining the boundary conditions and attaining the dielectric properties of the tissue layers, the transient response of the current pulse was calculated using biphasic sinusoidal waveform based on 10 MHz. The impact of the electrode size on the current density and induced electrical potential variations was investigated. Thus, different size of the electrode was generated, and each model was simulated, and the results were recorded based on the transient simulation by considering the capacitance factor. It was shown that the electrode size has a significant impact on the current density variation and electric potential variation.

Acknowledgments

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