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A Simulation Study: Effect of the Inter-Electrode Distance, Electrode Size and Shape in Transcutaneous Electrical Stimulation

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Abstract— **Transcutaneous Electrical Stimulation (TES) has been used widely to recover motor functions in neurologically impaired individuals by artificially activating skeletal muscles using superficial electrodes. Some simulation studies have investigated the percentage of fibers activated in denervated skeletal muscles, the comfort and selectivity, and the influence of fat thickness in the case of obese people, to optimize the inter-electrode distance and electrode size. However, the effect of the inter-electrode distance, electrode shape and electrode size might be further analyzed using the selectivity, activation depth and activation volume. In this regard, we developed a 3D multi-layer (skin, fat, muscle, and nerve) thigh model coupled with a mammalian nerve model using a finite element method for optimization of TES therapy. Different evaluation indices (motor threshold, activation depth, selectivity and activation volume) were inspected to compare different TES parameters in terms of nerve activation. The simulation results agreed with experimental data and new insights were obtained: selectivity is better in small electrodes; nevertheless, in high current stimulation, small electrodes and large electrodes have similar selectivity.**

I. Introduction

The effect of Transcutaneous Electrical Stimulation (TES) depends greatly on stimulation parameters, electrical and mechanical properties of the bio-tissues (which are subject-specific), daily physiological condition, morphological change due to muscle contraction and motion of the musculoskeletal system [1,2,3]. However, in clinical practice, the setting of TES, such as electrode positions, is empirically based on trial-and-error approaches.

The analysis of the TES parameters can be conducted by experimental or computational approaches. The former has the disadvantage in the assessment of geometric effect, selectivity and depth of the activation. Geometric effect refers to the influence of the shape and dimension of specific structures like fat thickness in the case of obese people [4]. Moreover, the measurement of selectivity and depth of the activation is difficult, invasive and exhausting for the subjects.

In past studies, the comfort and selectivity of TES has been used to calculate the optimal size of electrodes at different fat thickness [1]. In a similar approach the influence of fat thickness in the case of obese people was studied to optimize the inter-electrode distance and electrode size [4]. These computational models used a two-step method. The first step is the calculation of potentials within the tissues produced by the external stimulation. The second step is the prediction of an Action Potential (AP) for nerve or muscle fiber due to extracellular potentials generated by the stimulation. However, the effect of the inter-electrode distance and electrode size should be further analyzed using motor threshold, selectivity, activation depth and activation volume of the muscle.

Also, few studies have considered the effect of the electrode shape. Experimentally, Forrester and Petrofsky [2] studied the effect of three shapes (square, round, and serrated edge) with a similar area of 25.8 cm^2. They showed that the electrode shape did not significantly change electrical stimulation. Simulation studies have not examined the effect of electrode shape to the authors knowledge.

In this regard, we developed a 3D multi-layer (skin, fat, muscle, and nerve) model of the thigh using a finite element method (FEM) for optimization of TES therapy to study the effect of the inter-electrode distance, shape and size of the electrodes in the nerve activation.

II. Method

A two-step method [5] was adopted in a 3D multi-layer model of the thigh using a finite element method coupled with a mammalian nerve model. The model was implemented using COMSOL Multiphysics.

In the first step, computation of the voltage distribution within the tissues (*V*e) was performed, equation 1. The second step was calculated by employing a compartment model of a mammalian nerve [6] to predict nerve activity.

$$\nabla \cdot [\sigma \nabla V_e] - \nabla \cdot \left[\varepsilon \nabla \frac{\partial V_e}{\partial t}\right] = 0 \quad (1)$$

where conductivity σ and relative permittivity ε of the different tissues are presented in table I.

Compartment models help to explain the influences of applied electric or magnetic fields in representative target neurons. McNeal [5] developed a compartment model for myelinated nerve fiber and its sub-threshold response to external point source stimulation. He represented the myelinated nerve by an equivalent circuit for the Ranvier node and assumed that the myelin sheath was a perfect insulator. In this work, an electrical network for the myelinated nerve was employed, but the myelin sheath was modeled as a passive circuit, figure 1.

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The reduced membrane voltage $V_n = V_{i,n} - V_{e,n} - V_{rest}$ leads to the following system of differential equations for calculating the time-courses of V_n in every compartment

$$c_m \frac{\partial v_n}{\partial t} = -I_{ion,n} + \frac{v_{n-1} - 2v_n + v_{n+1}}{R} + \frac{v_{e,n-1} - 2v_{e,n} + v_{e,n+1}}{R} \quad (2)$$

where V_n is the membrane potential, i the internal location, e the extracellular location, n the compartment number, V_{res} the resting potential of the membrane, c_m the membrane capacitance, R the intra-axonal resistance between the centers of two adjacent compartments, and $I_{ion,n}$ the ionic current in the n-compartment.

In order to solve the membrane voltage, it is necessary to obtain $I_{ion,n}$. Consequently, the internodes are considered as passive membranes (constant membrane conductance, $G_{m,n}$). Also, CRRSS model (Chiu-Ritchie-Rogart-Stagg-Swenney) [6,7] was used to calculated $I_{ion,n}$ at the Ranvier nodes to describe the nonlinear gating mechanism of ion channels across the unmyelinated neuronal membrane. The model incorporates sodium and leakage currents but disregards potassium channels as they were found to be less important in the excitation process of myelinated mammalian nerves.

TABLE I. ELECTRICAL PARAMETERS OF THE TISSUES AND DIMENSIONS [8,9]

Layer	Conductivity (10^{-4}S/m)	Relative Permittivity (10^{4}S/m)	Dimension
Electrode	33.33	1.0X10^{-4}	Square and round (0.25-30.25) cm^2
Skin	2	0.1136	1.5 mm (radial)
Fat	406.40	15.15	5 mm (radial)
Muscle (Transversal)	760.00	932.9	50.6 mm (radial)
Muscle (Longitudinal)	2,667.00	932.9	50.6 mm (radial)
Bone Cortical	200.60	0.5853	6.0 mm (radial)
Bone Marrow	1013	7.246	7.6 mm (radial)

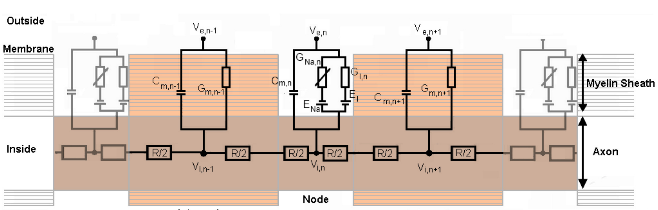

Figure 1. Compartment model of the myelinated fiber. Nodes are modeled as active membranes (CRRSS model). Internodes are modelled with constant membrane conductance, passive membrane [10].

A. Parameters

The effect of the inter-electrode distance was evaluated for a distance between electrodes from 1 mm and 12 mm using a cathodic square stimulus of 20 mA.

The area of the electrodes employed in the simulation were 0.25 cm^2 (0.5 cm x 0.5 cm), 2.25 cm^2 (1.5 cm x 1.5 cm), 6.25 cm^2 (2.5 cm x 2.5 cm), 12.25 cm^2 (3.5 cm x 3.5 cm), 20.25 cm^2 (4.5 cm x 4.5 cm), and 30.25 cm^2 (5.5 cm x 5.5 cm).

The effect of the shape of the electrode was inspected using a square and round electrode with two different areas (0.25 and 30.25) cm^2. The inter-electrode distance was 6 mm. Additionally, a nerve fiber located 4.2 mm below the muscle-fat interface was employed to study motor threshold.

B. Evaluation Indices

The evaluation methods to investigate the effect of different TES parameters in the nerve activation are activation volume (AV), activation depth (AD), selectivity and motor threshold.

The AV is defined as the region inside the muscle where the AP may occur [11]. It is useful to study how much portion could be activated using high intensity stimulation, where selectivity is not the main concern. The AV is limited by the activating function (AF) [12] over a threshold and the boundaries of the muscle domain, as shown in figure 2. The threshold value for activation depends on the fiber diameter and stimulation pulse duration [13]. The calculation of the activation volume is called, V_{AV}.

The activation depth (AD) is the distance between one point at the fat-muscle interface and the farther point to activate a fiber with a specific diameter. Both points are in a line normal to the center of the stimulation electrode. The AD is an index of the penetration within the muscle, and calculated for a specific fiber using the AF [1].

The selectivity of muscles indicates how focal is the activation, i.e., nerve activity without excitation of the surroundings. It considers the deeper penetration (AD) and the narrower volume under the electrode [1]. The estimation of the narrower volume is the inverse of the average of the transversal area of the volume, which is the quotient of V_{AV} and AD. The resulting expression is equation 3**.**

$$Selectivity = \frac{AD}{\frac{V_{AV}}{AD}} = \frac{AD^2}{V_{AV}} \quad (3)$$

Motor threshold is the nerve activation at the lowest stimulation intensity. One myelinated fiber is placed under the electrode to investigate its motor threshold. The cathodic stimulation current is increased until the trans-membrane potential exceeded a threshold of 80 mV and AP propagation is elicited using the CRRSS model.

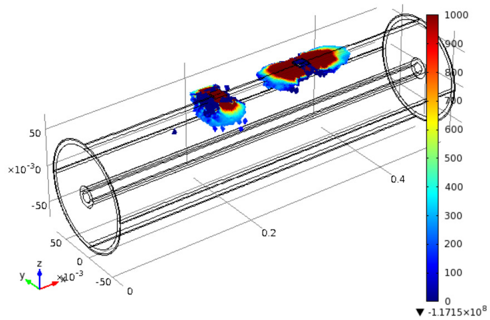

Figure 2. Activation volume in the cylindrical model of the skin, fat, muscle and bone layers using two superficial electrodes of area of 2.25 cm^2 with an inter-electrodes distance of 11 cm. The magnitude of the stimulation current is 20 mA.

III. SIMULATION

We investigated the effect of different parameter in the nerve activation, such as inter-electrode distance, electrode area and electrode shape.

A. Inter-electrode distance and electrode size

The figure 3-a illustrates the V_{AV} for different inter-electrode distances, where larger electrodes presented larger V_{AV}. Additionally, large electrodes had a maximum value of V_{AV} at small inter-electrode distance, and the location of the maximum V_{AV} shifted to larger inter-electrode distances when the size of the electrode decreased.

Figure 3-b depicts the AD. Smaller electrodes (0.25 cm^2, 2.25 cm^2, 6.25 cm^2) presented deeper activation. However, the AD of small electrodes decreased considerably for inter-electrode distance smaller than 3 cm, even lower than larger electrodes. For large electrodes (12.25 cm^2, 20.25 cm^2, 30.25 cm^2), its AD was improved for small inter-electrode distance. Selectivity is shown in figure 3-c. It is clear that selectivity was better for smaller electrodes.

B. Electrode shape

Motor threshold was calculated in a nerve fiber with a diameter of 14 µm and located 4.2 mm bellow the interface between the muscle and fat layer. According to table II, there was no significant difference between round and square electrodes in terms of motor threshold. Moreover, small electrode's selectivity was higher than large electrode but decreased with higher current; thus, large and small electrode had similar selectivity at high current stimulus, figure 4.

TABLE II. MOTOR THRESHOLD FOR SMALL AND LARGE ELECTRODE USING ROUND AND SQUARE ELECTRODES

Shape	Size	
	0.25 cm^2	*30.25 cm^2*
Round	8.865 mA	83.750 mA
Square	8.815 mA	82.750 mA
Percentage difference	0.57%	1.20%

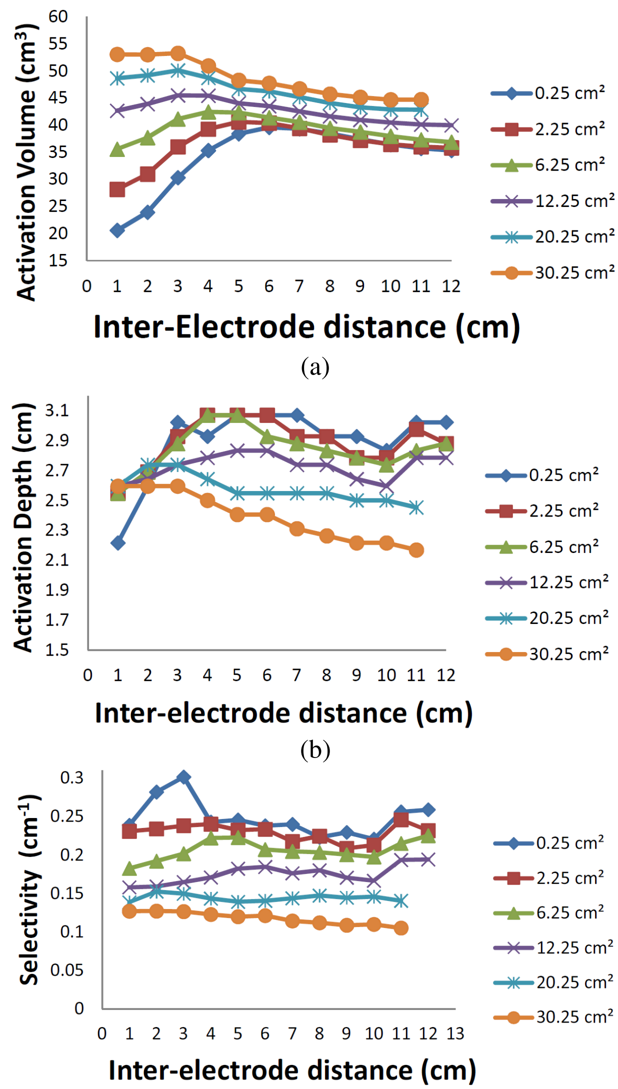

Figure 3. (a) Activation volume vs inter-electrode distance (b) Activation depth vs inter-electrode distance. (c) Selectivity vs inter-electrode distance.

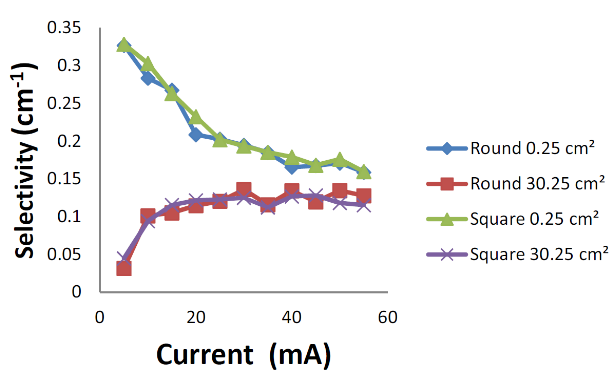

Figure 4. Selectivity vs current density for two electrode shapes (round and square) with different areas (0.25 cm^2 and 30.25 cm^2).

IV. Discussion

We argued that the main concern in achieving effective powerful muscle activation by TES is not the selectivity but is the number of activated fibers, which can be quantified by the volume of the activation volume (V_{AV}).

The results of inspecting the V_{AV} were the following: (1) large electrode presented larger V_{AV} compared to small electrode at the same inter-electrode distance and (2) the inter-electrode distance should be taken into consideration, as illustrated in figure 3-a. In case of large electrode, maximum V_{AV} occurred at small inter-electrode distance. On the other hand, maximum V_{AV} shifted to larger inter-electrode distance when the area of the electrode was decreased.

Experimentally, a large electrode produced more comfortable and stronger motor response than a small electrode, but more likely that the stimulation intensity will need to be increased [14]. The simulation result agreed because large electrodes presented greater V_{AV} than small electrodes. Furthermore, the optimal size of electrodes will depend on the size of muscle stimulated (selectivity) and location of stimulation (motor point) [15].

Doheny et al. [4] used the activating function to simulate the effect of inter-electrode distance for different electrode's area. They investigated the inter-electrode distance (4 cm, 5.5 cm, and 8.25 cm) using a square electrode of area 0.707 cm^2. The result was a decrease of the AF for larger inter-electrode distance, which are comparable to our results using the V_{AV}. Nevertheless, our results also showed that V_{AV} presents a maximum point (not only descendent) for the investigated inter-electrode distances, figure 3-a.

As expected, small electrode (0.25 cm^2, 2.25 cm^2, 6.25 cm^2) showed deeper activation, as reported in [14]. However, it was not reported before that small electrode's penetration is diminished and large electrodes experienced an increased in the activation depth over short inter-electrode distance, figure 3-b. Therefore, for deeper penetration, small electrodes should be used for inter-electrode distances over 3 cm and larger electrodes for smaller inter-electrode distance.

Moreover, selectivity is better for smaller electrodes, but inter-electrode distance should be considered for optimal selectivity. On the contrary, larger electrodes are not sensitive to inter-electrode distance. figure 3-c.

The effect of the shape of the electrode was considered. The mean current necessary to evoke an AP using round electrodes was slightly greater than square electrode. Nevertheless, there was no significant difference between round and square electrodes in the nerve activation, table II and figure 4, This result agreed with experimental data in [2].

Small electrodes presented better AD and selectivity. In contrast, selectivity was similar between large and small electrodes in the case of high current stimulation, as observed in figure 4. Therefore, larger electrodes are a better option for comfort and a major area of the muscle could be reached for activation in high current stimulation.

V. Conclusion

Firstly, large electrodes presented larger V_{AV} compared to small electrodes at the inter-electrode distances investigated. Secondly, the inter-electrode distance should be taken into consideration. Additionally, small electrodes presented deeper activation and better selectivity. Nevertheless, high current stimulation and small inter-electrode distance diminished the selectivity. Finally, there was no significant difference between round and square electrodes.

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