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Impact of electrode geometry on force generation during functional electrical stimulation

Abstract: The goal of functional electrical stimulation is to restore lost movements by excitation of motor axons innervating the target muscle. For optimal electrode placement and geometry the distribution and spatial orientation of the desired motor axons has to be known. In this study, the response of motor axons with different orientations to electrical stimulation was simulated. Three electrode geometries with the same area were used. The simulated axon activation was compared to experimental force measurements and showed good agreements. It is now assumed that optimal electrode geometry does strongly depend on motor axon orientation, which can vary from one subject to the other. Lack of knowledge about the dominant motor axon orientation makes the use of square, round or multi-pad electrodes favorable.

Keywords: Functional electrical stimulation; electrodes; force; simulation

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1 Introduction

Functional electrical stimulation (FES) is a way to restore lost movements, e.g. grasping, and can be used to help people suffering from spinal cord injury or stroke [1, 2]. Multi-pad electrodes could be one way to solve several problems regarding FES. They could help reducing fatigue by excitation of different motor axons within one muscle as well as easing the process of finding the best spot and electrode shape for stimulation [3, 4].

Modeling and simulation studies can be a great assistance in developing and improving systems for FES, especially for future multi-pad systems, since they are not commercially available right now and need to be custom made for research activities. That is why it makes sense to spend time on simulation studies before expensive prototypes are developed.

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In this study, the goal was to determine the impact of electrode geometry on electrical stimulation. Therefore, a simulation study was performed to get insights on how axon activation is influenced by both axon alignment and electrode geometry. To validate these results, experiments with two subjects were performed to measure the force, generated by electrical stimulation of the finger flexor muscles.

2 Methods

2.1 Simulation

A two-step approach was used to simulate the outcome of FES. In COMSOL Multiphysics a 3D finite element (FE) model was created (see Figure 1). This simple model of the human forearm consisted of a skin and a fat layer, surrounding the muscle tissue. Inside the muscle tissue the ulnar and radial were placed. Besides the bones an elliptic cylinder was defined in which the motor axons, responsible for muscle activation, are located. This cylinder will from now on be referred to as the motor axon volume (MAV). It was located 1.5 mm under the fat layer, had a height of 16 mm, a width of 24 mm and was 30 mm long. The size of the MAV was estimated with regards to the results of Lieber et al. [5, 6] and El-Din Safwat et al. [7]. The idea behind the MAV was to represent the way of the motor axons from the nerve entry point in the muscle to the motor endplates and was inspired by Gomez-Tames et al.[8]. It was assumed that there is one dominant axon orientation. Three angles between the MAV and the longitudinal direction of the forearm were investigated (0°, 30° and 60°, see Figure 2b).

Two electrodes were placed on the surface of the skin. Thereby, the distal and bigger electrode was the indifferent and the electrode placed on top of the MAV was the active electrode. Three different active electrodes with the same area were considered in simulations and experiments: a longitudinal electrode (2 x 4 cm^2), a transversal electrode (4 x 2 cm^2) and a square electrode with an area of 8 cm^2 (see Figure 2a).

The electric potential caused by the electrical stimulation in the MAV was saved and exported to MATLAB to

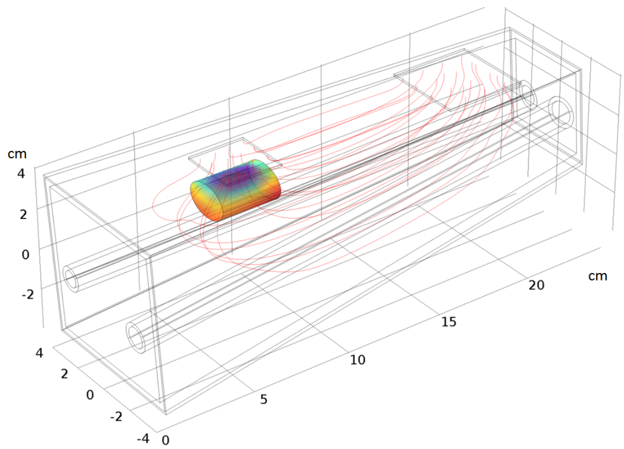

Figure 1: Simple 3D model of the human forearm. The red lines represent the current flow between the two electrodes, the multicolored volume illustrates the potential in the MAV.

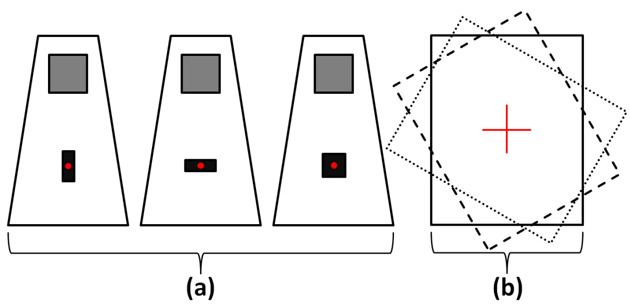

Figure 2: (a) Shows the three different electrode geometries used for both simulation and experiments. The grey square illustrates the indifferent electrode, the black rectangles/square the active electrode and the red dot the center of both, the electrode and the MAV lying underneath. (b) Shows the rotations of the MAV around the center of the stimulation electrode used for the simulation. The black line represents a rotation of 0°, the dashed line a rotation of 30° and the dotted line a rotation of 60°. The red cross illustrates the center of rotation under the active electrode.

calculate the response of the motor axons. For the simulation a current of 20 mA with a duration of 150 µs was used. The parameters used for the FE model can be seen in Table 1.

In MATLAB the electric potential was computed along homogeneously distributed parallel lines. Each line represented the extracellular potential along one axon. A random distribution of axon diameters, similar to [8] was associated to the potential lines of the MAV. The axon membrane potential was calculated according to McNeal [10] by solving

$$\frac{dV_n}{dt} = \frac{1}{C_m}[G_a(V_{n-1} - 2V_n + V_{n+1} + V_{e,n-1} - 2V_{e,n} + V_{e,n+1}) - G_m V_n]. \quad (1)$$

Table 1: Parameters used for the 3D FE model. The conductivity σ and permittivity ϵ_r are taken from Kuhn [9]. The geometry of the tissue was estimated.

Material	σ [S/m]	ϵ_r	Thickness [mm]
Electrode-skin interface	1/300	1	1
Skin	1/700	6000	1
Fat	1/33	25000	3
Muscle (longitudinal)	1/3	120000	240
Muscle (transvers)	1/9	40000	72-42
Cortical bone	1/50	3000	2
Bone marrow	2/25	10000	ca. 9

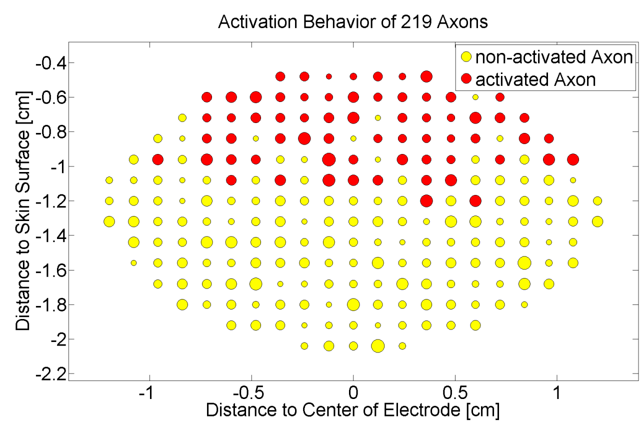

Figure 3: Cross section of the MAV. Red circles show activated axons, where the membrane potential surpassed the threshold potential. Yellow circles are non-activated axons. The diameter of the circles corresponds to the axon diameter. It can be seen that deep and small axons are less likely to be activated by FES compared to superficial and big axons.

If the membrane potential exceeded a certain threshold potential, activation of this particular axon was assumed. Figure 3 shows the cross section of the MAV with activated and non-activated axons. A passive calculation of the membrane potential was chosen since in this study the time depended behavior of specific ion channels was not of interest and the spatial behavior should not be affected by active membrane properties.

Since relatively short axons were investigated, particular attention had to be paid to the first and last node of Ranvier. The membrane potential of the first node of Ranvier was chosen to stay at resting potential. For the end of the axon, which is approaching the motor endplate, it was assumed that there is no myelin sheath between the last and the second last node of Ranvier. The parameters for the axon model are listed in Table 2.

Table 2: Overview of the used nerve parameters. With these values the axon conductance $G_a = \pi d^2/4\rho_i dx$, the membrane conductance $G_m = \pi dLg_L$ and the membrane capacitance $C_m = \pi dLc_m$ can be determined.

Parameter	Value	Reference
internodal distance Δx	$2\,mm$	-
node length L	$2.5\,\mu m$	[10]
axon diameter d	$7\text{-}17\,\mu m$	[8]
spezific axon resitance ρ_i	$0.7\,\Omega m$	[9]
membrane conductance/unit area g_L	$30.4\,mS/cm^2$	[10]
membrane capacitance/unit area c_m	$2\,\mu F/cm^2$	[10]
resting potential V_r	$-70\,mV$	[10]
threshold potential V_s	$-55\,mV$	-

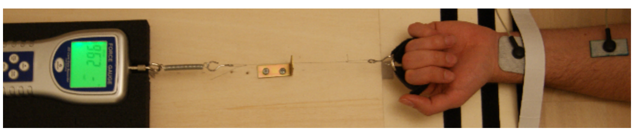

Figure 4: Experimental setup: The fingers are attached with a wire and a spring to the force gauge.

2.2 Experiments

The number of activated axons is supposed to correlate with the produced force. Therefore, force measurements were performed with two young and healthy subjects in order to validate the simulation results. Both subjects had been seated on a comfortable chair with the force measurement setup on a table in front of them. The ring, middle and index finger were attached to a wire, which was connected via a spring to a force gauge (PCE-FG 20SD, PCE Instruments, Germany). This way the tensile force caused by finger flexion could be measured (see Figure 4).

The electrical stimulation was delivered using the Motionstim8 (Medel, Germany). Electrodes were placed according to the simulations. The indifferent electrode was placed distal, close to the wrist, and the active electrode was placed on the motor point (the most sensible point for electrical stimulation) for finger flexion. The motor point had been searched carefully in advance with a pen electrode. The electrode dimensions were the same as in the simulation study.

For stimulation biphasic rectangular pulses with a frequency of 35 Hz and a pulse width of 150 µs were used. The amplitude was chosen to produce a strong contraction while not becoming uncomfortable (15 mA for subject 1 and 12 mA for subject 2).

For each of the three different electrode geometries the same procedure was performed: 5 s of stimulation followed by 20 s of rest until five stimulations were reached. Between changing electrodes there was a five minute break to avoid fatigue altering the results. The peak force value, which corresponds to the biggest magnitude of motion, for each stimulation phase was noted and out of all five stimulation phases the median force was determined.

3 Results

To compare the simulated with the experimental results the data had to be normalized. For subject 1 and subject 2 the achieved force level for each electrode geometry was normalized to the maximum force level. This way the electrode geometry which produced the highest force equals 100 %. For the simulation results the number of activated axons for each electrode geometry was normalized by the maximum achieved number of activated axons. As with the experimental results this way the electrode geometry which produced the highest number of activated axons equals 100 %. This had been done for all three MAV rotations. At the end the results of experiments with two subjects were compared to three different simulation outcomes.

Figure 5 shows the comparison of the results. It is obvious that there is a strong variation between the two subjects and also within the three different MAV orientations. Nevertheless, the experimental results coincide well with individual MAV orientation in simulation. The force generation behavior of subject 1 correlates to a MAV rotation between 0° and 30°. For subject 2 a 60° rotation shows good accordance between measured and simulated behavior.

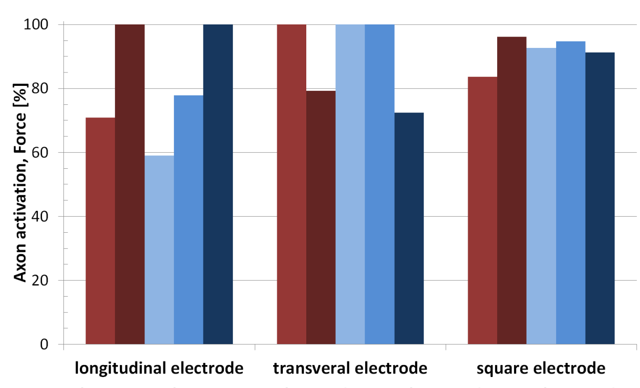

Figure 5: Comparison of the experimental with the simulated results. For subject 1 and 2 the normalized generated force is plotted, for the simulations the normalized number of activated axons.

4 Conclusion

In this study it could be shown that simulated axon activation correlates well with measured force. Thus the concept of a MAV seems to be promising for modeling force generation by electrical stimulation. Simulations as well as experiments showed that the optimal electrode geometry can vary from one subject to another and does probably depend on the dominant motor axon orientation. It could also be seen that square electrodes always performed well compared to rectangular electrodes. Gomez-Tames et al. [11] showed in a simulation study that there is no significant difference between square and round electrodes, which agrees with our experience. Therefore, using square or round electrodes is recommendable if the dominant axon orientation is unknown. The results of this study also show the potential of electrode arrays, where the stimulation electrode shape can be more or less changed freely.

In the future different movements, especially finger extension, should be investigated as well. It is also possible to simulate the impact of electrode misplacement and compare this to experimental results. This way it should be possible to characterize MAV size and orientation. It should also be considered that there may be more than one MAV for one movement due to multiple nerve entry points per muscle or co-contraction of neighboring muscles.

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Author's Statement

Conflict of interest: Authors state no conflict of interest. Material and Methods: Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use has been complied with all the relevant national regulations, institutional policies and in accordance the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

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