Electrical stimulation of the human median nerve: A comparison between anatomical and simplified simulation models

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Abstract— **Neuroprosthetic devices can be an innovative solution to support subjects suffering from a limb loss. The possibility of restoring tactile sensations by using sensory feedback represents a research area whose outcomes could significantly improve the quality of life of prosthesis users. One of the best techniques to restore close-to-natural and selective tactile sensations is the electrical current stimulation of nerves using neural electrodes. Their interaction with nerves is an important aspect to be studied. The aim of this work is to deepen, in the framework of computational modeling, the possibility of approximating a realistic 3D human median nerve model, based on anatomical imaging, to a simplified model using the hybrid FEM-Neuron approach. Often, a high computational simulation time is also related to the complexity of the model geometry; therefore using a geometrical simplified model can be an important aspect to be analyzed. The simplified model is built approximating inner fascicles shape to simple geometrical shapes, i.e. ellipses. The electrical current stimulation is studied in Comsol environment by using a ds-FILE electrode model implanted in the human median nerve. The results obtained from computational simulations using both anatomical and simplified models, allow concluding that the percentage activation ranges at different distances from the active site obtained by the two models are comparable.**

I. INTRODUCTION

With the aim of improving the quality of life of upper limb amputees, different innovative solutions are studied to allow the interaction between the nervous system and the prosthesis. Until now, amputees that use commercial myoelectric upper limb prosthesis cannot obtain information about the interaction between the prosthesis and the external environment [1], [2]. The user can in fact only control the prosthesis movement by means of electromyographic (EMG) sensors located on the stump able to decode signals from residual muscles. The lack of the afferent information, in these devices is one of the most important causes of myoelectric prostheses abandonment. Restoration of sensory feedback is one of the requirements of upper limb prosthesis users to improve their interaction with the environment, the embodiment of the robotic hand and the dexterity [2], [3]. One of the possible solutions to restore sensory feedback in upper limb amputees is the electrical stimulation of peripheral nerves by surface or neural electrodes [2]. Invasive electrodes can restore tactile sensations that are more natural and selective with respect to non invasive ones. Using neural interfaces to restore sensory feedback is an invasive solution that could be dangerous for the subjects. Therefore, it is fundamental to preliminarily study, in simulation, the interaction between the nerve and the electrode in order to maximize the safety and efficiency of the solution. Computational approach in the research field of neuroprosthetics is largely used to study the setting of stimulus parameters and the interaction between electrodes and nerves [4]. In recent studies the computational multiscale approach is used to gain more insights on nerve-electrode interaction. Finite element and computational axon models are considered [5]–[11]. In the work of Romeni et al. [5] a review study is presented, focusing the attention on the different steps followed to build a complete hybrid model, defined as the combined results obtained from Finite Element Methods (FEM) and Neuron models. One possibility related to the design of the nerve model is the simplification of the nerve section geometry to decrease the computational time related to the meshing and the solution computing. Starting from the segmentation of histological images fascicles of different shape can be found. The approximation of the inner fascicle to simpler geometrical shape of circles or ellipses can be a possible choice to reduce meshing and computational time. A comparison of the electric potential results into the nerve model, built using anatomical geometry of the inner fascicles and simplified geometry could be an interesting study to quantify the goodness of the approximation. In this paper, 3D models of human median nerve are developed. Two different geometries of inner fascicles shape are considered: anatomical geometry and simplified geometry. The anatomical geometry is developed starting from the segmentation of the histological image of a human median nerve section. The simplified geometry is obtained from the same image and approximating the shape of the inner fascicles to ellipses. The intraneural electrode model used is the ds-FILE electrode [12], already adopted in experimental studies on a human amputee [2].

The goal of this work is to compare the electric potential distributions into the median nerve subject to a current stimulus via FEM models, using anatomical and simplified geometry of inner fascicles. The advantage is that if the two distributions are similar, it is possible to approximate the anatomical geometry with a simplified one obtaining the reliability of results and less computational time to mesh and solve the FEM model. To gain more insight into the current intensity necessary to activate nerve fibers, the percentage of activation (PA) of the axons into the fascicles is also studied.

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II. METHODS

Two finite element 3D conductor models of the human median nerve are considered according to two different shape of the nerve section: a model with the nerve section that has fascicles according to the anatomical geometry and a model where the fascicles shape is approximated to simple geometrical shape like ellipses. To obtain elliptical shape approximations of anatomical fascicles a Matlab routine is used. Data related to anatomical fascicles are imported in Matlab and an ellipsis fitting is performed using fit_ellipse.m code by Ohad Gal [13]. Later, ellipses data are used in Comsol to build ellipses substituting the anatomical fascicles shape. The electrical potential distributions into the median nerve due to a current stimulus provided by an intraneural electrode is analyzed. These quantities are interpolated on the compartments of the axon models in Neuron [14] to study the percentage of activation.

Simulations are performed on a computer with an Intel Core i7-8750H CPU at 2.20 GHz, 16 Gb RAM.

A. Human median nerve and electrode FEM models

To obtain human median nerve models, data from an anatomical image are retrieved, as explained in [9]. Two sections with different fascicles shape are obtained from the anatomical image. We refer to anatomical geometry to identify the model whose fascicles section is a faithful reconstruction of the section shape of the histological image. We refer to simplified geometry to identify the model whose fascicles section is approximated using simple geometrical shapes like ellipses. Once the two geometries of the nerve section are built, they are imported in COMSOL Multiphysics ® v5.3 (COMSOL, Ltd, Cambridge UK) in order to obtain a 3D model of 10 mm length.

Different tissues properties are then assigned to each of the two obtained 3D models (the one with anatomical geometry and the other one with simplified geometry) of the median nerve according to the nerve anatomy. Three different tissues are considered, endoneurium, perineurium and epineurium. Each tissue has different electrical properties. Endoneurium has an anisotropic conductivity tensor with a transverse value of 0.00826 S/m and a longitudinal value of 0.571 S/m. Perineurium and Epineurium are considered as isotropic media with a conductivity values of 0.00088 S/m and 0.0826 S/m respectively [8]. The intraoperative environment were simulated by a medium with saline solution properties, with diameter of 76 mm. Finite element methods are used to solve Maxwell's equations in media, and Dirichlet boundary conditions are considered, at infinity V=0. Related to this, the diameter of saline solution is set larger than nerve dimensions.
To study the electric potential distribution into the nerve model a quasi static approximation of Maxwell's equations [15] is considered

$$\nabla \cdot (\sigma \nabla V) = 0 \tag{1}$$

V and σ are the electric potential and the conductivity of the medium, respectively.

The ds-FILE electrode model is built in Comsol ® (Fig.1) as a polymide body with 20 μm thickness and 360 μm height. The ds-FILE electrode has sixteen active sites as stated in [2]. Polymide and active sites have a conductivity of $6.7 \cdot 10^{-14}$ S/m and $8.9 \cdot 10^{6}$ S/m respectively. The ds-FILE is located in the middle of the nerve model and the current intensity is arbitrarily set to 20 μA: this value can be subsequently modified in the Neuron model.

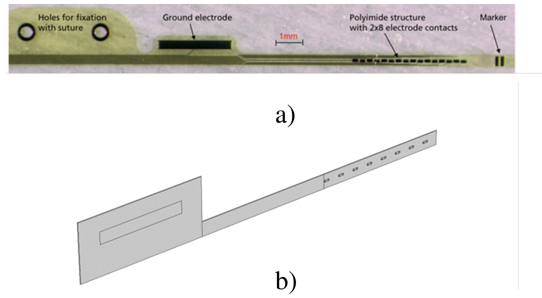

Fig. 1: ds-FILE electrode a) [12]; CAD model of the ds-FILE electrode b).

B. Axons mathematical models

To evaluate the fibers activation, a double cable model myelinated axon was developed. McIntyre Richardson Grill (MRG) channel mechanisms for the node of Ranvier [16] and imperfect insulation of other sections are considered. There are two myelin, two paranodal and ten internodal compartments between two nodes [4].

To define the electrical behaviour of the axon, linear and nonlinear properties of membrane dynamics are considered in the model. Linear leakage, non linear fast sodium, persistent sodium, slow potassium conductances and a membrane capacitance are used to describe the node of Ranvier behaviour, as cited in [16]. Other information about the definition of geometrical and electrical properties of the mathematical model of fiber can be found in [9].

Comsol Multiphysics is used to find electric potential along the nerve; data are processed in Matlab, exported in Neuron and used as extracellular potential. Stimulus waveform, defined in the extracellular potential, is a biphasic charge unbalanced waveform. Each pulse has a duration of 80 μs, the same duration is considered for the inter-pulse delay. This type of waveform is considered according to results obtained in previous studies [9] that demonstrated its safety and efficacy compared with other types of waveforms (i.e. biphasic charge balanced with inter-pulse delay and biphasic charge balanced without inter-pulse delay).

III. RESULTS

In this section data related to the electric potential distribution in the median nerve model subject to a current stimulus are shown. In Fig.2 the electric potential distribution reported in a color map can be observed. Two cases are distinguished according to the shape of inner fascicles. Fig.2a and Fig.2b show the results of the simulation on anatomical and simplified geometry, respectively. These color maps were obtained setting the arbitrary current value of 20μA.

The electric potential variation, normalized with respect to the absolute value of the electric potential maximum is shown in terms of percentage of variation as a function

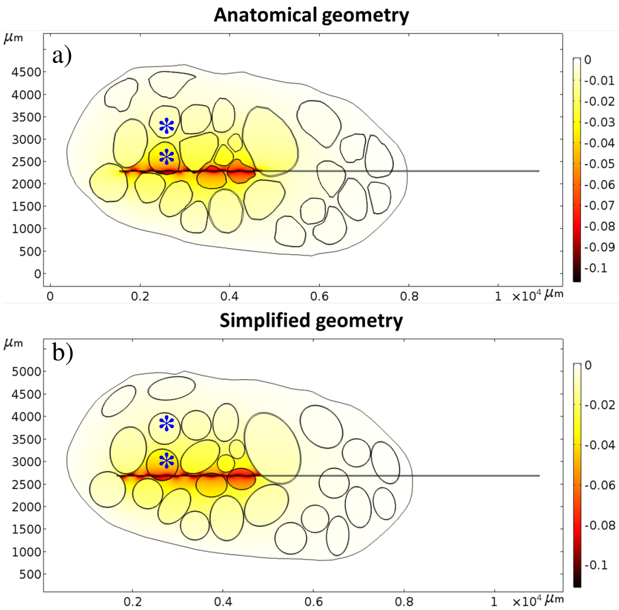

Fig. 2: Color map of electric potential distribution into the human median nerve model subject to a 20μA current stimulus. a) Anatomical and b) simplified geometries of inner fascicles are shown. Fascicles with blue symbols are considered for the study. Colorbar is in Volt.

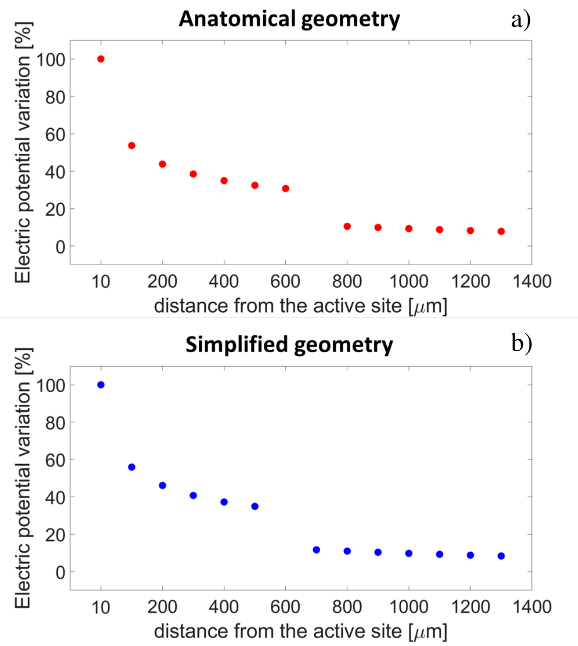

Fig. 3: Electric potential variation, expressed in percentage, along the y-axis in two fascicles. The variation is considered compared to the maximum value found close to the active site of the electrode, using anatomical a) and simplified b) geometries.

of distance from the active site. Different simulations were performed with the two models and the obtained results are shown in Fig.3. In particular, thirteen different distances from the active site are considered: they have a distance of 100μm from each other. This distance were chosen since it is considered as the minimum one to observe a significant potential variation. The first six distances in Fig.3b (seven in Fig.3a) are in a nerve fascicle where the active site is implanted in, the remaining ones are in the fascicle near to it, along the y axis. The stimulus waveform defined in the previous section is used to study fibers activation in Neuron MRG model. In Fig.4, results related to the minimum charge quantity necessary to obtain a 100% of fibers activation, according to the MRG model, at different distances from the active site are shown.

IV. DISCUSSION

Information about the stimulation parameters and activation of fibers can be estimated using hybrid FEM-Neuron computational models. More insight from these framework can be useful in the field of upper limb neuroprosthetics, in particular to provide guidelines about the restoring of sensory feedback. Electric potential distributions into the nerve can be studied when an electric current is delivered by an intraneural electrode. From FEM-Neuron computational models, the electric potential can be extracted from FEM simulations and used as extracellular potential in nerve fiber models in Neuron to evaluate the activation of fibers. The complexity of the FEM geometry can affect meshing and solution computational time, so results of simulations, performed using anatomical and simplified geometry are studied and compared. In particular, computational solution time related to simplified and anatomical models are 3 minutes 43 seconds and 8 minutes 30 seconds, respectively. Other time has to be considered for the anatomical model, including the time necessary to modify the mesh when the geometrical shape is more complex. From Fig.2 it is evident that the behaviour of the fascicles is the same when a current stimulus is delivered by an intraneural electrodes. The values of electric potential are in the range from -0.1 V to 0 V. From a quantitative analysis on electric potential obtained from the anatomical and simplified simulations, it is found that they follow the same trend with respect to the distance from an active site. The mean difference between the two trend is around 0.0039 V. In particular, the electric potential related to the simplified model is higher in absolute value than the anatomical one. Considering the fibers activation, it is also observed that the minimum current amplitude to obtain 100% of fibers activation using the simplified model is lower of 20μA than the anatomical one. From a geometrical point of view, it is noteworthy that the area of the fascicle sections and the volume of the fascicles of the simplified model are slightly lower than the anatomical one. Considering the same current intensity and the same distances from the active site for both the models, the high (absolute) value of the electric potential in simplified model could be related to a high (absolute) value of the electric potential density.In a similar way, it could also justify the lower current amplitude necessary to activate 100% of the fibers. Considering the same current amplitude for both the models, the electric potential in the simplified model is higher than the anatomical one, so a lower current amplitude value is needed to activate 100% of fibers. The behaviour of the different tissues is similar in both the pictures, high intensity is near to the active site and the

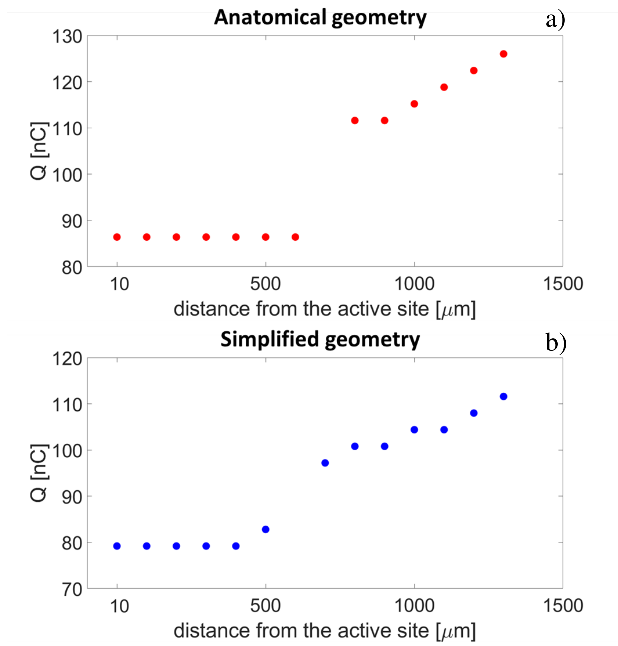

Fig. 4: Electric charge necessary to activate 100% of fibers at different distances from the active site, in two fascicles, for the anatomical a) and simplified b) geometries.

insulating properties of perineurium can be observed. From Fig.3, the percentage variation at different distances from the active site can be observed. 100% indicate the higher potential value found close to the active site, other values are the percentage variation compared to it. Observing the figure, it is possible to note that at 100μm of distance the electric potential decrease around 60% of the value close to the active site, for both the geometries. The points on the left of the plot are related to the fascicle where the active site is implanted in, the points on the right of the plot are related to another fascicle near to it. It is possible to observe that the trends related to both the simulations with different geometry are the same. Similar percentage variation are shown also in the right part of the plot, related to the second fascicle. In both the plots the variation is lower than the 20% of the value near to the active site. From Fig.4 it is possible to observe that the trend about the electrical charge quantity necessary to activate 100% of fibers is similar using data from anatomical and simplified geometry. From both the plots it is possible to note that lower values of electric charge are required to activate fibers in the first fascicle.

These results are in accordance with the ones shown in the colormaps, in terms of fibers activation. From Figs.4a, b is evident that electrical charge values, related to the simplified geometry, are lower than the values related to the anatomical geometry. In particular electrical charge values found from the simplified geometry are around tens nC lower than the results related to the simulation of anatomical geometry. Future works will analyze in more depth the obtained results and statistical analysis related to the fiber population will be improved.

V. CONCLUSIONS

In this paper, the electric potential generated by the direct electrical current stimulation provided by the intraneural electrode ds-FILE was studied through computation models. The results obtained with an anatomical nerve model and a simplified nerve model were compared to verify the possibility of considering the simplified model instead of the anatomical one. It could represent a great advantage in terms of computational time for meshing and solution finding. Results from the FEM simulations were processed in Matlab and exported in Neuron to study the fiber activation. The first results, comparing the electric potential distributions from Comsol simulations, indicated that the values from the anatomical and simplified geometrical model are comparable less than a value of 0.0039 V. A similar percentage of activation is observed in anatomical and simplified model with a displacement of 20μA one to the other.

From the minimum electric charge necessary to activate the 100% of fibers at different distance from the active site it is possible to observe that also in this case the trends are similar related to the anatomical and simplified models, but more insight will be performed to evaluate more statistical variability of nerve fibers dimension and location, introducing for instance different fibers populations spread in different fascicles. Future works will be devoted to analyze this aspect.

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