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CURRENT DISTRIBUTION AND MOTOR UNIT RECRUITMENT IN MULTIPLANE FES

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ABSTRACT
A multiplane 3-dimensional thigh model is considered. The current densities in various planes are obtained using Laplace equation. Electrodes are placed both in transverse and longitudinal direction. A method to have enough current densities over the entire thigh length using multiple electrodes has been suggested.

INTRODUCTION
In functional electrical stimulation (FES) for paraplegics one of the requirements is to selectively excite specific muscles or muscle groups. Also the total current delivered to the body must be minimized to avoid skin burns and pain. Limitations of two electrode excitation systems in this respect is well recognised. Earlier [1] it was shown that by employing more than two electrodes and multiple electrical sources in the same phase high current density in specific regions of the thigh can be obtained. A suitable choice of electrode configurations allows relatively more current to be delivered to some muscles such as the quadriceps than others [2]. Still two lacuna remain. Selectivity in respect of deeper seated muscles such as the adductor magnus is not satisfactory. Additionally a planar placement of electrodes delivers current to muscles in the transverse direction. Physiologically this mode of stimulation is not optimum because stimulation thresholds are lower with current flowing along the muscle longitudinal direction than the transverse direction.

To overcome these shortcomings it is appropriated to study current distributions in the thigh when the electrodes are placed at different axial levels so that currents take a preferential path longitudinally along the muscle. Further it needs to be investigated whether oblique directionality in the maximum current density areas in the axial direction can be obtained by placing the electrodes both displaced relative to each other axially and laterally. Study outlined is by theoretical electrical field distribution analysis since this approach offers considerable flexibility in the geometrical configurations.

THEORETICAL MODEL
A tomographic section of the thigh is shown in Fig(1). The curved boundaries of the structures were approximated by straight lines with a mesh size of 2.5 mm x 2.5 mm. However the present analysis uses a mesh size of 10 mm x 10 mm and 185 nodes per plane for optimizing on the computational time[1,2]. Conductivities of fat, muscle and bone tissue were taken in the ratio of 0.4, 1.7 and 0.5 respectively. The electrodes are placed as shown in Fig(2).

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Laplace equation is given as

\[
\text{del squared } V = 0 \quad \text{(1)}
\]

where \( V \) represents the potential at any given point. In non-homogeneous medium the potential at a point \( O \) having the coordinates \((i,j,k)\) can be represented as

\[
V(i,j,k) = V(i+1,j,k) + V(i,j+1,k) + V(i,j,k+1) + V(i,j,k-1) - \nabla \cdot V(i,j,k)
\]

where \( A \)'s represent the four different conductivities around the node.

**FIG. 2**

RESULTS AND DISCUSSION

Current distribution in various planes for the muscle adductor magnus for given electrode position are shown in Fig(3). It is clear that current density reduces progressively as one move from the second plane toward the 14th plane. The values of current density in planes 8th to 14th are less than 2 mA/sq cm with a given applied voltage of 100 volts. This part of the adductor magnus is not getting stimulation enough to cause contraction. In order to have effective stimulation over the entire length of the muscle, one may place the -ve electrode in planes 7th to 9th in position 'cc' of Fig(2). This electrode arrangement will obviously stimulate the muscle in the planes from 2 to 8 with an applied voltage of 75 volts. Stimulation of other regions of the thigh will remain at subthreshold value.

Therefore if the entire muscle is required to be stimulated then either the electrode length 'aa' and 'bb' is to be increased considerably (which has no practical use) or two sets of +ve electrodes are to be placed at the location 'aa'and'dd'and a -ve electrode at 'cc'. Such an arrangement would require a lower stimulation voltage and will stimulate all the planes between 10th to 14th. As more number of motor units are being stimulated more force can be achieved.

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