Theoretical Modelling of Microprobe Tips for Insertion into Peripheral Nerves

Martínez-Gómez J [1], Yoshida K [2], Kammer S [1], Koch KP [1], Hoffmann KP [1]

[1] Department of Medical Engineering and Neuroprostheses, Fraunhofer Institute for Biomedical Engineering, Ensheimer Str. 48, 66386 Sankt Ingbert, Germany
[2] Center for Sensory Motor Interaction, Aalborg University, DK-9220, Aalborg Øst, Denmark

E-Mail: juan.martinez@ibmt.fraunhofer.de

Abstract

Tungsten needles are frequently being used as microprobes for the implantation of thin-film electrodes into the peripheral nerves. Nevertheless, the effect of the tip geometric properties on the insertion performance has not been sufficiently characterized. We used theoretical models based on the finite element method (FEM) to calculate the buckling forces (Fb) that take place in the tip of a tungsten needle. Our design consists of a tip formed by two different angles and lengths, keeping the needle diameter constant. Moreover, the front tip geometry has also been analyzed. Our FEM simulation results showed that an increment in the angle between the shaft and the tip produces a slightly decrement of the Fb. This phenomenon suggests an improvement in the insertion behaviour during the penetration, reducing the exerted expected forces produced in this transition.

1. INTRODUCTION

Tungsten needles are frequently being used as microprobes for the implantation of thin-film electrodes into the peripheral nerves. A critical point during the implantation procedure of microprobes into live tissues is the insertion process. Tungsten needles must be strong enough to withstand the forces exerted during the insertion. At the same time, the dimensions of the microprobe must be as small as possible in order to not produce important lesions in the nerve tissue. The microprobe tip is also an important factor to take into account in the insertion forces. It is suggested that smooth and small tip angles produce lower forces, but make the buckling forces (*Fb*) decrease.

Different microprobes for implantation into live tissue have been developed. The mechanical designs are based on the use of different materials and geometries in order to obtain optimal strength and flexible properties [1]. Nevertheless, the tip geometries considered in the designs have not been based on thorough mechanical analysis. Therefore, there is lack in the study of the effect of the geometric properties on the *Fb* that take place in the microprobe tips.

In this paper, we present a theoretical model to study the *Fb* by analyzing different geometric parameters in a tungsten needle tip. Moreover, a manufacturing process to produce precise tungsten needle tips is also presented.

2. METHODS

2.1. Theoretical Modelling

During an implantation of a thin-film electrode inside the peripheral nerve, a tungsten needle is attached to the electrode to perform the insertion into the nerve [2]. The physical situation considers a cylindrical needle of 80 µm, ended in a conical tip, placed perpendicular on the tissue (figure 1(a)). A force is applied on the top of the needle to start the insertion process.

The *Fb* and the deformed shape of the microprobe tip were calculated using a numerical method based on the finite element method (FEM). To perform the computer simulations, the ANSYS mechanical package (Professional version 6.1, Ansys Inc., Canonsburg, USA) running on a Hewlett Packard-UNIX workstation with a 552 MHz was used. Due to the linear properties of the material (only Young's modulus and Poisson ratio were considered), the buckling strength was obtained by using a linearized model of elastic stability. Thus, the buckling analysis was formulated as an eigenvalue problem [3]:

$$\left([K]+\lambda_i[S]\right)\{\Psi\}_i=\{0\} \qquad (1)$$

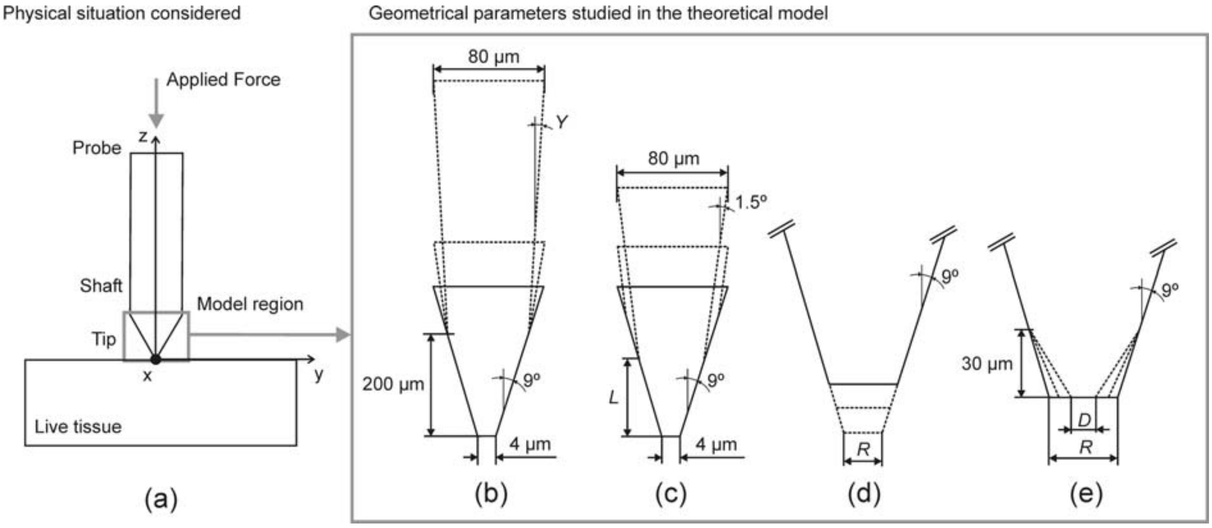

Figure 1*: Physical situation considered in the study of the tungsten needle insertion into peripheral nerves (a). Theoretical model proposed (out of scale) and geometrical parameters: Y, top tip angle (b); L, bottom tip length (c); R, bottom tip diameter (d); and D, bottom tip diameter keeping the length constant (in this case 30 μm) (e).*

Where $[K]$ is the stiffness matrix, $[S]$ the stress stiffness matrix, λ_i the *ith* eigenvalue (the solution), and Ψ_i the *ith* eigenvector of displacements. The buckling force is obtained by performing an iterative analysis. In this case, the applied load is increasing until the buckling is reached.

The model geometry consisted of a tungsten needle tip (Young's modulus of 361.83 GPa and Poisson ratio of 0.4378) with a conical shape and divided in two parts (top and bottom tip). The top tip has a top diameter of 80 μm and an angle value of *Y* (figure 1(b)). The bottom tip has a bottom length of *L* (figure 1(c)) and a diameter value of *R* (figure 1 (d)). In order to perform a thorough analysis of the bottom front tip, the parameter *D* has been included (figure 1(e)). The diameter value of *D* is modified by keeping a front tip length of 30 μm.

The theoretical model considered only the tip of the microprobe. No displacement constraints were applied at the top and bottom of the tip, allowing only an axial displacement of the applied force area from top to bottom. Due to the tip geometry, symmetry boundary conditions where applied in axis *x* (figure 1), considering only half of the structure. The discretization of the model has been done depending on the solution precision. We used the value of *Fb* as a control parameter in the sensitivity analysis. The chosen criteria in the discretization implied a more fine mesh at the bottom than at the top of the tip. A refining mesh was done until obtain an *Fb* within 1% of the value obtained from previous refinement steps.

2.2. Production Process Set Up

For the production of the tungsten needles an electrochemical etching setup with 2 Mol KNO_3 was used. A 12 VAC voltage was applied at a frequency of 15 Hz provided by a universal voltage source (3245A Universal Source, Hewlett Packard). Two centimetre tungsten wires with a diameter of 80 μm were fixed in a clamp and connected to the anode. The etching solution was filled in a metallised petri dish which was connected as cathode. To achieve a smooth change between the wire and a defined tip shape an ultrasonic sonotrode was used (UP 100H, Dr. Hielscher GmbH).

An amperemeter has measured the current via the dipped tungsten wire inside the etching solution. The current indicated the depth of the wire inside the solution as well as the status of the etching process.

RESULTS

The curves of the graphs in figure 2 show the results obtained from the simulations of the theoretical model. In this case, the *Fb* decrement is represented when the design parameters decrease (*Y, L, R, and D*). The curves with black dots represent the influence on *Fb* depending on the decrement of the design parameters related to its maximum values (9° (*Y*), 250 μm (*L*), and 8 μm (*R, D*)). On the other hand, the white dots represent the influence on *Fb* depending on the decrement of the design parameters related to its prior values.

The top graph in figure 2 shows that a decrement in the top tip angle *Y* (≈ 500 %) produce a slightly decrement in the *Fb* (< 4 %). The second graph shows that when the bottom tip length decreases the *Fb* suffers a significant decrement for values less than 100 µm (> 10 %). In the two bottom curves of the figure 2, it is possible to observe that the decrement of the diameter *R* makes the value of the *Fb* lower than reducing *D*. On the other hand, the white dot curves show that the differences in the decrement of the *Fb* become higher in every decrement of the design parameters. This phenomenon is especially outstanding in the variation of *L*.

During the production process, the current has reached a value of less than 1 mA after about 7 minutes which was the criteria to stop the process and achieving well defined tip shapes.

4. DISCUSSION AND CONCLUSIONS

The simulation results suggested that, the use of small angles in the top tip makes the transition between the shaft and the top tip smoother. This phenomenon suggests an improvement in the insertion behaviour during the penetration, reducing the expected exerted forces produced in this transition. On the other hand, reducing the angle of the top tip implies a decrement in the bottom tip length, which results in a thinner tip and a decrement in the exert forces produced by the needle.

The results also suggested that sharped tips with small values of *R* (e.g. less than 3 µm) results in a remarkable decrement in the *Fb*.

It is suggested that tungsten needles with top tips angles of 1.5°, bottom tip lengths of 150 µm, bottom tip diameters *R* more than 8 µm, and *D* values of nearly 4 µm, could result in an optimal microprobe design. The optimal parameters have been chosen taking into account a decrement in the *Fb* below 10 %. The optimal D value exceed this criteria, but it has been supposed that diameters more than 4 µm could result not efficient for piercing the tissue.

Finally, new investigations addressed to the improvement of the production techniques will be necessary in order to achieve this new microprobe tip designs.

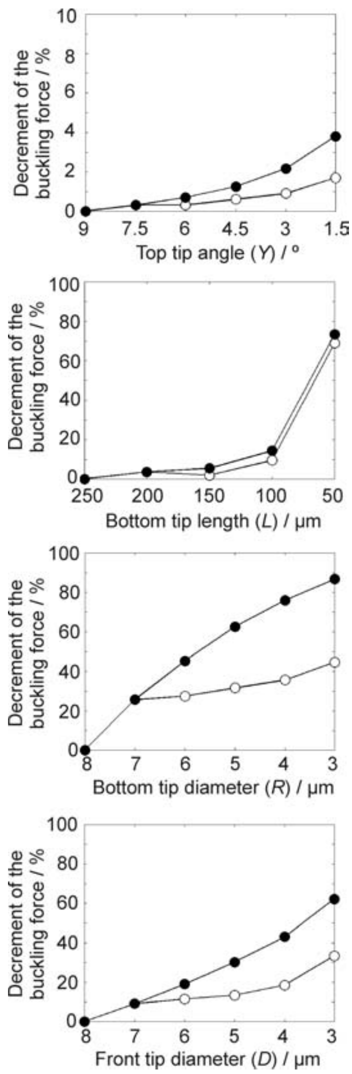

Figure 2: *Decrement of the buckling force for different values of the top tip angle (Y), bottom tip length (L), bottom tip diameter (R), and front tip diameter (D). Black dots represent the decrement related to maximum values of Y, L, R, D, and white dots the decrement related to the prior values.*

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