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# Analysis of Springback Displacement of dura mater Substitute for Precise Electrode Implantation*

Lei Cao[1,2], Jie li[3,1] and Chongyang Wang[1]

*1. State Key Laboratory of Robotics*
*Shenyang Institute of Automation, Chinese Academy of Sciences*
*Shenyang, Liaoning Province, China*

caolei@sia.cn, lijie_hit@163.com, wangchongyang@sia.cn

Cheng Zhang[1] and Hao Liu[1,*]

*2. University of the Chinese Academy of Sciences*
*Beijing, China*
*3. Shenyang Jianzhu University*
*Shenyang, Liaoning Province, China*

zhangcheng@sia.cn, liuhao@sia.cn

***Abstract* – Electrode implantation through the dura mater usually leads to inaccurate localization of the superficial of the brain. The springback displacement of dura mater along with the puncture is a major reason. In this paper, we establish an energy model which can be described from three parts to represent the mechanical properties of the electrode-dura interaction based on two phases of the electrode implantation. The puncture of dura mater is analyzed from the perspective of energy conservation. With the whole model of different phases in electrode implantation, the springback displacement can be calculated by the puncture force, the puncture displacement and the implantation velocity. A series of experiments in eight different velocities are implemented on the artificial tissue to validate the model and identify the character parameters for getting a relation with the implantation velocity. Finally the validation experiments in other two velocities show that the proposed model can well represent the whole process. The mean error of the springback displacement is 0.0703mm which can be accepted in electrode implantation.**

***Index Terms – Electrode-dura interaction. Energy model. Springback displacement. Implantation velocity. Parameter identification.***

## I. INTRODUCTION

Electrode implantation in brain has an important meaning to either exploring the function of different regions in brain or the treatment of serious diseases about human brain. The effectiveness of a treatment and the success or precision of a diagnosis is highly dependent on the accuracy of electrode implantation [1]. Among the different regions in brain, the cerebral cortex includes billions of cell bodies which are responsible for delivering important information for the human movement and language. In clinical routine methods, the operator implants electrodes through the dura mater to the cerebral cortex manually. When the operator feels the loss-of-resistance, he or she will stop implanting and then record the neural cells signal. Because of the elasticity of the dura mater, when the electrode punctures the dura mater, it will spring back a small displacement which can leads to the inaccurate localization of the target position. The prior knowledge of the dura mater deformation during the whole process in electrode implantation is the key to obtain the springback displacement. It can provide guidance for the electrode retreatment following the recovery of the dura mater to ensure accurate localization.

The problem of implanting the electrode through dura mater can be seen as the needle-tissue interaction problem. Roughly speaking, needle insertion models fall under two categories [2]. The first aspect focuses on the relation between the insertion force and the tissue deformation in different phases. Okamura et al. collected data from bovine livers and considered puncture of the capsule as a boundary to model the force in different parts [3]. They present the relation between needle depth and force during whole process of needle insertion. Mahvash et al. studied insertion forces prior to the puncture event and use a nonlinear viscoelastic Kelvin model to describe the process [4]. The model predicts it is a negative relation between tissue deformation and the insert velocity. The second aspect focuses on the mechanical reasons of the puncture formation. Azar and Hayward attempted to develop puncture mechanics approach to predict the puncture toughness by inserting the needle twice at precisely the same location, under the assumption that all phenomena are nearly identical except for the energy required to create the crack [2]. Heverly at el. investigated a puncture mechanics approach to show that the velocity dependence of tissue properties can reduce tissue motion with increased needle velocities [5]. From the researches we can see, neither the combined model nor the single model pays attention on the tissue recovery phase caused by puncture which is vital for electrodes implantation through dura mater. Meanwhile, the tissue deformation which caused by puncture is rarely discussed.

In our research, an energy model of the whole electrode implantation process is proposed to analyze the springback displacement of the dura mater when the puncture occurs. The model can be divided into three parts based on the phases of electrode-dura interaction. This paper is organized as follows. Section II describes the phases of electrodes implantation through the dura mater and establishes the model before and after the puncture. Section III presents a series of experiments based on different velocities to validate the proposed model and identify the parameters of the models. Experiments based on other velocities are aimed at verifying the accuracy of the

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springback displacement. Section IV and V make the discussion and the conclusion of this research.

## II. METHODS

### A. The Phases of the Electrode-Dura Interaction

According to the theory of [2]-[4] and synthesizing the purpose of our research, the process of electrode implantation through dura mater can be disassembled into two phases as Fig. 1. The specific expression of the phases can be seen as follow:

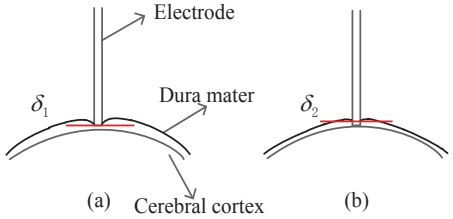



Fig. 1 The schematic diagram of two phases in electrodes implantation through dura mater. (a) The critical state of the puncture of the dura mater. (b) The moment of the puncture occurs and the dura mater springs back.

(a) Deformation Phase: The dura mater deforms with the electrode implants forward. It starts from the second that the electrode just contacts the dura mater. And it ends at the moment when the puncture occurs.

(b) Springback Phase: The dura mater is punctured by the electrode and it recoveries immediately. The springback displacement is $d\delta = \delta_1 - \delta_2$ and it is the main analysis object in this research.

With the two phases mentioned above, we establish an energy model which can be divided into three parts to describe the mechanical properties of the electrode-dura interaction to analyze the springback displacement.

### B. The Deformation Part Model

Dura mater is a thick membrane with two layers, the periosteal layer and the meningeal layer. According to Fung, most living tissues have viscoelastic behavior as long as small motions are considered [6] and viscoelasticity models are also widely used to represent the dura mater [7] [8]. The process we focus on is relative short-time and the mechanics of the two different layer tissues vary greatly. In terms of the research [9] [10], the Kelvin-Boltzmann model outperforms other possible viscoelastic models for this condition. We adapt the Kelvin-Boltzmann (KB) model to describe the deformation phase and calculate the energy stored by the interaction force worked from electrodes implantation before the puncture occurs. The schematic diagram of KB model can be illustrated in Fig. 2.

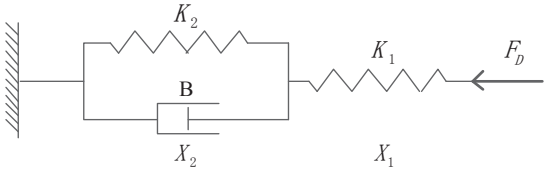



Fig. 2 The schematic diagram of Kelvin-Boltzmann model

According to the theory of damper and spring, the kinematic function of the KB model is given by:

$$F_D = K_1 X_1 \tag{1}$$

$$F_D = K_2 X_2 + B\dot{X}_2 \tag{2}$$

$$X_D = X_1 + X_2 \tag{3}$$

Where $F_D$ is the interaction force between the electrode and the dura in the deformation phase, $X_1$ is the shift of a spring element with elastic coefficient $K_1$, $X_2$ is the shift of a classic parallel Kelvin model with elastic coefficient $K_2$ and damping coefficient $B$. Besides, $X_D$ is the displacement of dura deformed by the implantation and it is the sum of two shifts. From (1) (2) (3) the interaction force can be solved as (4) by the convolution operation (the initial condition is $F_0 = 0$).

$$F_D = b_1 X_D + b_2 V_D (1 - \exp(-X_D / (\tau V_D))) \tag{4}$$

$$\text{Where } \begin{cases} b_1 = K_1 K_2 / (\mathrm{K}_1 + \mathrm{K}_2) \\ b_2 = B K_1^2 / (\mathrm{K}_1 + \mathrm{K}_2) \\ \tau = \mathrm{B}/(\mathrm{K}_1 + \mathrm{K}_2) \end{cases} \tag{5}$$

The parameters $K_1$, $K_2$ and $B$ are regarded as a constant in most of the researches about viscoelastic models for needle insertion, such as [10] [11]. When implanting the electrode into dura with different velocity, the surface of dura will present different characteristic. We assume that the parameters in the KB model in our research are dependent on the insertion velocity. The parameters will be identified through the experiments in Section III.

In the deformation phase, when the energy stored by the interaction force rises to a critical value, it can lead to puncture of the dura. With (4) the interaction force work before the puncture can be described as:

$$\begin{aligned} W_D &= \int_0^{X_P} F_D dx \\ &= b_2 V_D{}^2 \exp(-X_p / (\tau V_D)) / \tau + b_1 X_p{}^2 / 2 + b_2 V_D X_p \end{aligned} \tag{6}$$

Where $X_P$ is the critical displacement relative to dura before the puncture.

### C. The Internal Friction Part Model

On the basis of the principle of energy conservation, the electrode is taken as static at the moment that the electrode punctures through the dura. Hence the energy worked by the interaction force in the deformation phase transforms into two parts. One is the recoverable strain energy stored in dura which can lead to the springback of it and the other is the work of the friction inside of the dura and the area under the dura. This second part of work is usually called internal friction.

Internal friction represents the mechanical energy loss of viscoelastic polymer under the action of dynamic load. Hysteresis loop represents the energy loss between deformation and springback. The relation between the displacement and the interaction force can be expressed in Fig. 3. $X_P$, $F_P$ represent the displacement of dura and the interaction force when puncture occurs respectively. $X_R$, $F_R$ represent the springback displacement and force respectively. It can be seen that the hysteresis loop is not closed because when the electrode punctures into dura, the interaction

between electrode and cerebral cortex can produce counterforce. The force is too small which can be to ignored.

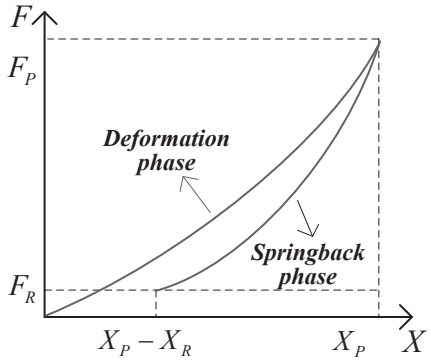



Fig. 3 The relation between displacement and force in two phases

The energy conservation function of the whole process in electrode implantation can be written as follows:

$$W_D = W_R + W_Q \tag{7}$$

$W_R$ means the energy stored in dura to produce the springback displacement. $W_Q$ represents the internal friction. The most common characteristic used to represent the internal friction is quality factor $Q^{-1}$. It can be calculated as follow [12]:

$$Q^{-1} = \frac{\Delta W}{2\pi W} = \frac{W_D - W_R}{2\pi W_D} \tag{8}$$

The deformation phase can be regarded as the process of energy storage. When it reaches the critical energy which the dura can afford, the puncture occurs. The puncture force can be seen as the amplitude of free attenuation curve. According to the characteristic of static hysteresis internal friction we can assume it is related to the puncture force.

*D. The Springback Part Model*

The model in the deformation phase is not adopted the springback phase because the duration of the puncture is nearly instantaneous. So we use an elastic model to represent the springback phase. The kinematic function of the elastic model is written as:

$$F_R = K_R X_R \tag{9}$$

Where $F_R$ is the springback force and $X_R$ is the springback displacement of dura. And the work $W_R$ produced by the springback force which is also the springback energy stored in the deformation phase is written as:

$$W_R = \int_0^{X_R} F_R dx = K_R X_R^2 / 2 \tag{10}$$

Substituting (6)(8)(10) into the energy conservation function (7), the springback displacement can be solved as:

$$X_R = \sqrt{\frac{4\pi Q^{-1}(b_2(V_D)V_D^2 \exp(-X_P/\tau V_D)/\tau + b_1 X_P^2/2 + b_2 V_D X_P)}{K_R}} \tag{11}$$

To sum up, the springback displacement $X_R$ is dependent on the implantation velocity $V_D$, the puncture force $F_P$ and the puncture displacement $X_P$ according to the model we proposed. The acquisition process of the springback displacement can be seen in Fig. 4. To validate the assumptions we proposed above, we set a series of experiments to simulate the process of electrodes implantation through dura mater.

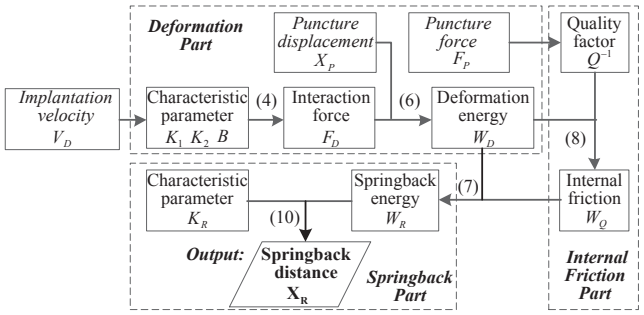



Fig. 4 The flow diagram of acquiring the springback displacement. The italic texts in the box represent the three elements which should be got to calculate the springback displacement based on the three models. The numbers on the connecting lines represent the equation number above.

## III. Experiments and Results

The model of the deformation part, the springback part model and the internal friction part which is proposed in this research will be validated through the implantation experiments. The experiment platform consists of a 6DOF robot arm, an electric sliding table with a force sensor, a syringe needle which is instead of the electrode and two-layer artificial tissue model which is made by gelatin solution and silicon sheet. The experiment platform is shown in Fig. 5.

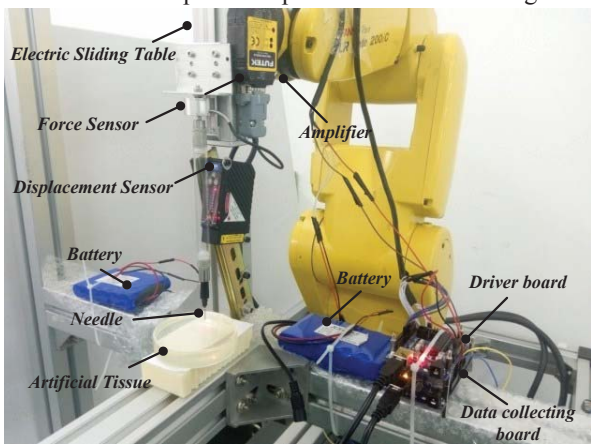
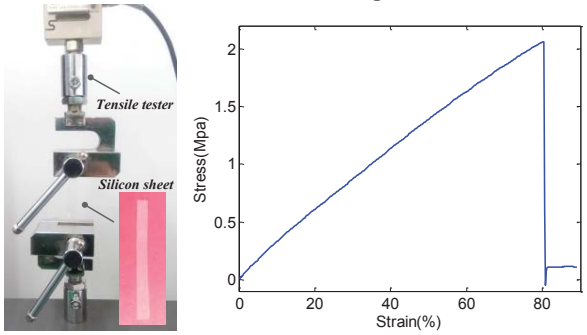



Fig. 5 The implantation experiment platform

*A. Experimental Setup and Procedure*

The artificial tissue offers many practical advantages over biological tissue, in terms of reproducibility, availability and visibility [13]. In our research, the artificial tissue phantom is set up to substitute the real brain tissue because it is convenient to acquire and not subject to the experiment environment. The real brain tissue simulation needs two layers which are the cerebral cortex and the dura mater. For the cerebral cortex layer, we fix the gelatin powder and water with the proportion 10:17.5 to get the gelatin solution and wait it to set. For the dura layer, silicon sheet is used to instead of the dura mater. For the size concern, the thickness of the silicon sheet is 0.3mm which is similar to the thickness of human dura according to [14]. For the mechanical properties concern, the puncture characteristic of the silicon sheet with a size 100 $\times$6.7$\times$0.3mm is measured through the tensile tester. The test

scenario and the stress-strain curve can be seen in Fig. 6. The tensile strength of the silicon sheet is calculated as 2.0624MPa. It is consistent with the tensile strength which is 2.49MPa of the dura mater from [15]. To sum up, a piece of silicon sheet (Ø7.3mm) is put on the solidified gelatin solution in a culture dish as the artificial tissue phantom.




(a) (b)

Fig. 6 (a) The tensile strength test platform of the silicon sheet, (b) The stress-strain curve of the tensile strength test

Considering the diameter of electrodes is usually less than 1mm, we choose a syringe needle with diameter 0.3mm to substitute. To simulate the process of the electrode implantation, we use an electric sliding table to hold the needle. And two arduino boards are regarded as the driver board and the data acquisition board respectively. The driver board actuates the electric sliding table carrying the needle. The data collecting board is used to collect the data from two sensors. A force sensor is used to record the interaction force during the implantation. A displacement sensor based on the infrared ray is used to measure the displacement of the surface of the artificial tissue. The power of both sensors is supplied by battery to avoid the electromagnetic interference. Both of the two sensor data are processed by mean filtering to reduce noise. The role of the robot is only to adjust the implantation degree of the needle to ensure the interaction force between needle and artificial tissue is vertical.

### *B. Validation and Parameter Identification of the Deformation Part*

In order to validate the model and identify the parameters proposed in Section II, the implantation experiments are set on the basis of the implantation velocities. Since the speed of electrodes implantation is very slow and constant to ensure the security, we chose 8 group velocities in the range of 0.4mm/s to 4mm/s. The detail velocities can be seen in TABLE I.

TABLE I
DIFFERENT GROUPS OF THE IMPLANTATION VELOCITY

| *No.* | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* |
|---|---|---|---|---|---|---|---|---|
| v(mm/s) | 0.4 | 0.8 | 1.25 | 1.5 | 2 | 2.5 | 3 | 4 |

The implantation processes of different velocities were recorded before and after puncture. The period before the puncture is extracted to validate the deformation part of the model. Therefore we use the model function (4) to fit the force data through least square method. We chose two velocities as examples which are 1.5mm/s and 4mm/s. The fitting results of the two velocities are shown in Fig. 7. It can be seen that the KB model gives a well-fitting result to the interaction force. The R-Square of the fitting result of each velocity is more than 0.95 either.

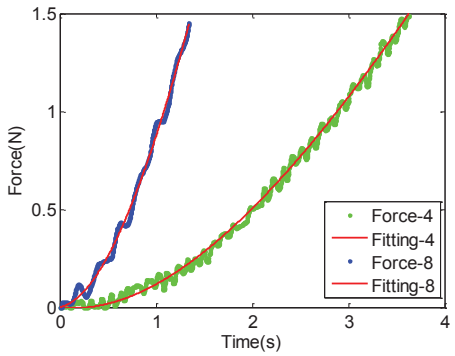



Fig. 7 The fitting results of the interaction force in the deformation phase. The numbers in the legend represent the velocity numbers in TABLE I

The characteristic parameters $K_1$, $K_2$ and $B$ in (4) of each velocity can be identified through the fitting results. To analyze how the implantation velocity effects on the tissue characteristic, we established the relation between the velocities and the characteristic parameters. The fitting results are shown in Fig. 8. It can be seen that $K_1$ and $K_2$ both are quadratic functions of the implantation velocity. The damping coefficient $B$ is an exponential function of the velocity and it can be regarded as constant when the implantation velocity is more than 1mm/s. It proves the deformation part of the model we proposed in this research can represent the tissue mechanism when implanting the electrode in different velocities. The identified parameter functions are shown as (12).

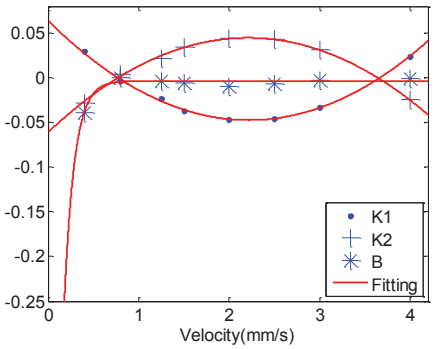



Fig. 8 The fitting results between KB model parameters and the velocity

$$\begin{cases} K_1(\mathrm{V}_D) = 0.0226\,\mathrm{V}_D^2 - 0.1005\,\mathrm{V}_D + 0.0644 \\ K_2(\mathrm{V}_D) = -0.0217\,\mathrm{V}_D^2 + 0.096\,\mathrm{V}_D - 0.0614 \quad (t < t_p) \\ B(\mathrm{V}_D) = -1.198\exp(-8.824\,\mathrm{V}_D) \end{cases} \tag{12}$$

Where $t_p$ means the puncture time. Substituting the fitting parameters into (6), the accumulated energy before the puncture $W_D$ can be calculated.

### *C. Validation and Parameter Identification of the Springback Part*

The positions of the surface of the artificial tissue were recorded by the displacement sensor during the whole period. The variation of the force and the position during the period between the puncture and the tissue springs back is shown in Fig. 9.

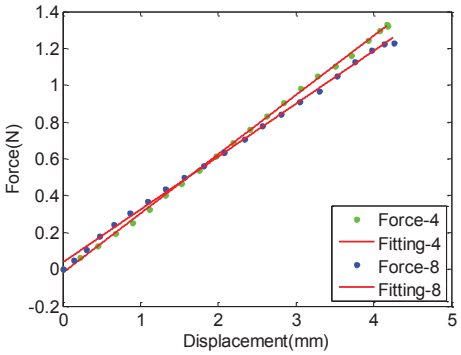


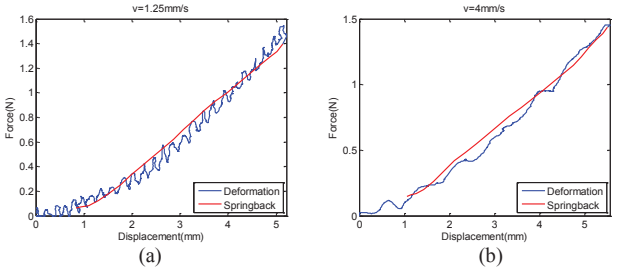

Fig. 9 The relation between the force and the displacement in the springback phase. The numbers in the legend represent the velocity numbers in TABLE I

The beginning of recovery is when the puncture event occurs and the end is when interaction force and displacement are stable. And the puncture time is regarded as the null point. The springback distance is the difference value of initial and terminated position. It can be validated from Fig. 9 that recovery force and displacement keep a linear relation and it conforms to the springback part model we proposed in Section II-D. Also, the elasticity coefficient $K_R$ was identified according to the fitting results. The results show $K_R$ is nearly a constant: $K_R = 0.3324 \pm 0.0110$ . Substituting mean $K_R$ and springback displacements into(10), the work which the artificial tissue does to the external environment $W_R$ can be calculated. It also represents the part which can provide the elastic energy accumulated before puncture.

### D. *Validation and Parameter Identification of the Internal Friction Part*

The difference of the variation of force and displacement in the deformation phase and the springback phase leads to the energy loss. The experiment data of this kind of variation is shown in Fig. 10. It can be seen that the force and displacement both cannot go back to the original state before the puncture. The unclosed hysteresis cycle confirmed the internal friction model in Section II-C. With $W_D$ and $W_R$ which are calculated above, it is easy to get the energy loss which represents the internal friction $W_Q$ of the artificial tissue through (7). Furthermore the common characteristic of the internal friction quality factor $Q^{-1}$ can be acquired from (8). The relation between $Q^{-1}$ and $F_P$ of all velocities is analyzed in Fig. 11. The quality factor is a logarithmic function of the puncture force. The numerical expression is shown as follow:

$$Q^{-1} = 4.4583 \ln(F_P - 1.391) + 46.1575 \qquad (13)$$




(a) (b)

Fig. 10 The variation of the force and the displacement in deformation phase and springback phase ((a) v=1.25mm/s, (b) v=4mm/s)

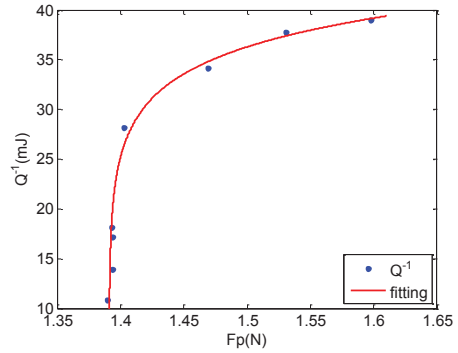
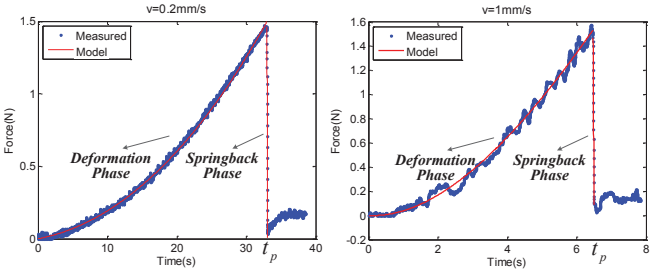



Fig. 11 The relation between the quality factor and the puncture force

### E. *Validation of the Springback Displacement*

With all parts of the model proposed in the research, the whole process of electrode implantation through the dura mater can be described. We chose two velocities to validate the model we proposed. The model force of two phases calculated according to the analysis above and the measured force are shown in Fig. 12.

From the figures we can see the model force can follow the measured force well. Meanwhile substituting the measured puncture force, displacement and the implantation velocity into (11), the springback displacement can be calculated according to the process in Fig. 4. In the validation experiments, the variation of the position of the artificial tissue is also recorded through the displacement sensor. Therefore the errors between the measured springback displacements and the displacements which are calculated based on the models are shown in TABLE II. The mean error of the springback displacement is 0.0703mm which can be accepted in electrode implantation.




(a) (b)

Fig. 12 The validation results of the models in two phases by two velocities ((a) v=0.2mm/s, (b) v=0.4mm/s)

TABLE II
THE VALIDATION RESULTS OF THE SPRINGBACK DISPLACEMENT

| *Velocity (mm/s)* | *Calculated $X_R$(mm)* | *Measured $X_R$(mm)* | *Error (mm)* |
|---|---|---|---|
| 0.2 | 4.2210 | 4.2515 | 0.0305 |
| 1 | 4.0648 | 4.1750 | 0.1102 |

## IV. DISCUSSION

Considering the traditional method of electrode implantation through dura mater easily leads to inaccurate localization to influence the analysis result of nerve electrophysiology, the springback displacement of dura when the puncture occurs is a major reason. In our research, we focus on the two phases of the electrode implantation through

dura mater which are the deformation phase and the springback phase. An energy model is proposed from three parts to represent the characteristic of the electrode-dura interaction base on the two phases. The whole process is explained from a perspective of energy conservation of the three parts. The relation of the puncture force and the tissue deformation is analyzed in some researches such as [4]. However it is the work of external force acted on the tissue reaches its critical puncture energy can lead the puncture occurs from the results of our research.

A series of implantation experiments in different velocities were implemented on the artificial tissue to validate the model we proposed. There are no obvious relations between the implantation velocities and the puncture force. It is different from the results in some researches such as [5] [10] which is the puncture force decreases with the velocity. Meanwhile we found that our model can represent the force variation in whole phases when implanting in very low speed while it is not very ideal in a relatively high velocity from the experiments. Therefore we consider it maybe because the velocity we focus on is far less than other researches.

One aspect of the further work is the control of the retreatment of electrode. The electric sliding table used in here cannot provide the rapid response time and the relatively large acceleration. According to the experiments data, the necessary velocity of the retreatment can be calculated. The springback time is $0.0334 \pm 0.0010$s and the springback velocities is $118.5236 \pm 9.7148$mm/s. The retreat mechanism needs to meet the two conditions. Another aspect of the further work is establishing the layered model of the whole brain. Because there are a lot of different regions in brain such as gray matter, white matter and corpus callosum, the adjacent two structures can be represented by the model we proposed above. Analyzing the puncture phenomenon between two adjacent regions can guide the precise control when implanting electrodes into whole brain.

## V. Conclusion

To acquire the intact neural signal in the cerebral cortex through electrode implantation, the springback displacement caused by the puncture of dura meter is essential. We focus on the two phases in the electrode-dura interaction and establish an energy model which is described from three parts to represent the mechanical properties of the implantation process. The deformation part is described through a modified KB viscoelastic model with variable characteristic parameters. The internal friction part reflects the energy loss which leads the tissue cannot recover to its initial position. The springback part is regarded as an elastic model because of the instantaneity.

A series of experiments on the artificial tissue based on the eight velocities is implemented to validate the proposed model and identify the parameters of the models. The results show that the force-time curve is well fitted by the proposed model and the character parameters of the deformation part are dependent on the implantation velocity. And the experiments based on other two velocities validate that the springback displacement of the tissue can be determined by the implantation velocity, the puncture force and displacement according to energy conservation. The mean error between the springback displacement which is calculated through the proposed model and the actual springback displacement measured by the displacement sensor is 0.0703mm.

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