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Biomechanical Strain Analysis at the Interface of Brain and Nanowire Electrodes on a Neural Probe

The viability of neural probes with microelectrodes for neural recording and stimulation in the brain is important for the development of neuroprosthetic devices. Vertically aligned nanowire microelectrode arrays can significantly enhance the capabilities of neuroprosthetic devices. However, when they are implanted into the brain, micromotion and mechanical stress around the neural probe may cause tissue damage and reactive immune response, which may degrade recording signals from neurons. In this research, a finite-element model of the nanowire microelectrode and brain tissue was developed. A rigid body method was provided, and the simulation efficiency was significantly increased. The interface between the microelectrode and brain tissue was modeled by contact elements. Brain micromotion was mimicked by applying a displacement load to the electrode and fixing the boundaries of the brain region. It was observed that the vertically aligned nanostructures on the electrode of the neural probe do increase the cellular sheath area. The strain field distributions under various physical coupling cases at the interface were analyzed along with different loading effects on the neural electrode. [DOI: 10.1115/1.4005484]

1 Introduction

The use of neural sensing devices is essential for longitudinally and sensitively monitoring neuronal activities in mechanistic studies of neurological and behavioral disorders, understanding neuronal network circuitry, as well as developing quantifiable indicators in preclinical studies of disease progression and treatment efficacy [1–3]. Ideal neural electrodes should have high charging capacity and charge injection efficiency together with long-term reliability for chronic implantation in brain tissue [4,5]. In previous research, we have developed nanotechnology-enabled neural electrodes, which are small enough to sense localized unit cell spikes and dopamine concentration levels [6,7]. Even with increased sensing efficiency, the function and longevity of neural electrodes is limited by adverse tissue reaction and immune response upon implantation and micromotion in the brain [8]. In particular, the brain micromotion can induce strain in the area around neural probes, which in turn induces cellular sheath formation. As shown in Fig. 1, brain motion ranging from a few tens to few hundreds of microns arises from many different sources such as physiological internal motion (respiration and cardiac pulses) and external motion (spontaneous head movements and external impact) [9,10]. The relative motion and mechanical disturbances by rigid neural probes could generate mechanical stresses and

strains on the brain tissue adjacent to the electrode [11]. It is believed that compression, expansion, and even tearing of the neural cells trigger immune response and form compact sheath layers, eventually isolating the probe function from neural cells around it [12].

Due to limited methods in which to analyze the microenvironment, little research has been done on the mechanical analysis on the neural probe and brain tissue interface. Previous studies on localized strain around the probe tip and electrodes induced by deformation of brain or static force on the probe have been limited for the conventional Michigan probe electrode type designs, as well [13,14]. In this study, a finite-element model analysis is extended to the nanowire electrode–brain tissue interface in order to understand the effects from vertically aligned nanostructures. It is anticipated that the analysis of the strain field distribution under nanoscale interface conditions and different loading effects applied on the neural electrode may provide useful information, which can enhance the biocompatibility and longevity of neural sensing in the brain.

2 Methods

2.1 Model. In this study, we assume that the neural probe is implanted in the brain. Because of the small dimensions of the implanted microelectrode, the brain tissue around the microelectrode is considered to be homogeneous. In the simulation, the model consists of two regions representing the brain tissue and the electrode. The brain tissue can be modeled as a soft isotropic

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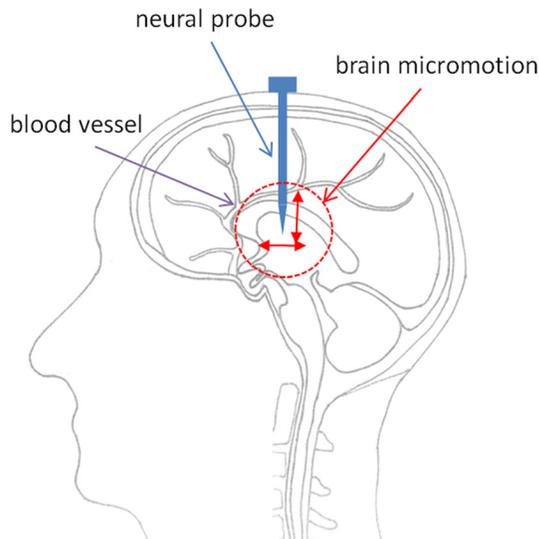
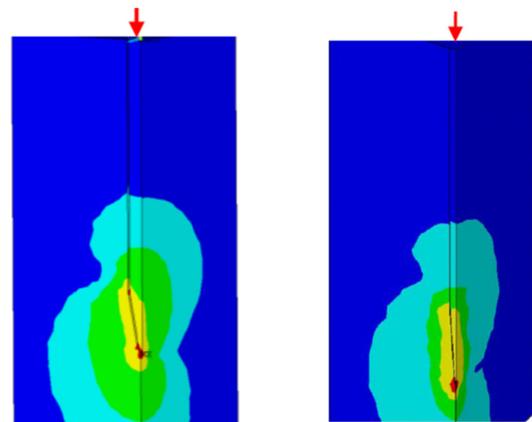


Fig. 1 Schematic diagram of brain micromotion around a neural probe

elastic material [15–17]. The Young’s modulus and Poisson’s ratio used for the brain tissue are 15 kPa and 0.499, respectively [18,19]. Because the strain effects are expected to be localized near the electrode, the geometric representation of the brain is limited to the region surrounding the electrode. The boundaries of the brain model are defined to have sufficient distances from the microelectrode to avoid the disruption of the strain field. For conventional neural probe electrodes, such as the Michigan electrode, the neural probe electrode is modeled as an elastic material with very high bulk modulus in comparison with the brain tissue. The neural probe shank, which is the component inserted into the tissue, has a thickness around 10 μm , a width around 100 μm , and a length within a few millimeters in our simulation. Due to the sharpened region near the tip of the neural probe shank, the mesh density in that region needs to be refined, and a huge number of elements will be generated. In this study, vertically aligned nanowires are integrated into the neural probe design developed in our previous research [6,20,21]. Due to the tiny diameter of the nanowire (~ 100 nm), the required mesh density in the nanowire area will generate too many elements to run the simulation effectively in a university research lab environment. In order to overcome the problem, a rigid body method is developed to dramatically reduce the number of elements in the simulation. Since the elastic



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(a) (b)

Fig. 2 Von Mises strain fields of the brain tissue for Michigan electrode under longitudinal loading: (a) using rigid body method; (b) results of Lee, H. et al. [13], applying elastic properties for both electrode and brain tissue

modulus of both nanowires and neural probe are very high compared to that of the brain tissue, they can be considered as rigid bodies, and the deformations within the nanowire area and neural probe can be ignored during the brain micromotion.

2.2 Elements and Meshing. The brain tissue area is meshed using 3D 10-node tetrahedral structural solid element-SOLID92 (ANASYS v11.0). Manual mesh is used to better control the mesh density, which varies in different parts of the brain tissue area, in order to increase the simulation efficiency. Low mesh density is applied to the brain tissue area that is far away from the electrode, and the mesh density around the microelectrode is refined to focus the simulation on the interface between the brain and the electrode. To precisely simulate the possible large deformation at the regions around the tip of the neural probe shank and the nanowire areas, further refinements to the mesh densities at those regions are conducted.

2.3 Interface Conditions. In order to simulate various degrees of physical coupling at the interface between the neural probe shank and the brain tissue as well as the interface between

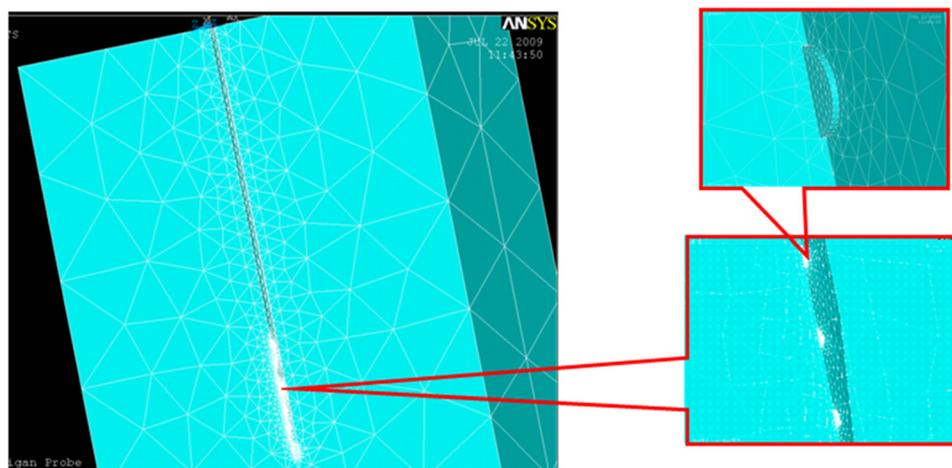


Fig. 3 Meshed half symmetry model of microelectrode with nanowire areas implanted in the brain tissue

the nanowire area and the brain tissue, the friction coefficients vary in the contact finite element model. Friction coefficients of 0, 0.5, 1, and 5 were used to simulate different degrees of physical coupling at the interface. The zero friction case represents no adhesion, which means the surface of the brain tissue and the electrodes can move freely without interrupting each other along the tangent direction at the interface. Friction coefficients of 0.5 and 1 represent the “slip” case in which the physical coupling between the electrodes and the brain increases as a higher friction coefficient is applied to the interface. A friction coefficient of 5 is used to simulate the nearly “bonded” case. The results will be discussed in Sec. 3.

2.4 Load Application. In actuality, one end of the neural probe is fixed at the skull, and the brain moves, due to intracranial pressure changes. For modeling convenience, a reverse loading condition is applied. The equivalent loading mode in this modeling can be chosen as micromotion, which is mimicked by applying a displacement load to the electrodes and fixing the

boundaries of the brain region. In this study, “micromotion” is defined as the movement of electrodes. The load was applied along different directions to simulate longitudinal and transverse brain micromotions.

3 Results

3.1 Michigan Electrode. In order to validate our rigid body assumption and evaluate the efficiency of the new method compared with the conventional one, a classic Michigan electrode under longitudinal loading is first studied using the rigid body method. The result is compared with that of previous researchers’ work as shown in Fig. 2 (zero friction case).

As shown in the Fig. 2, a quarter symmetric model is used for the simulation based on the simple geometry of the Michigan electrode. Von Mises strain field obtained by rigid body method [Fig. 2(a)] is very close to that simulated by the conventional method [Fig. 2(b)]. However, due to the assumption that the

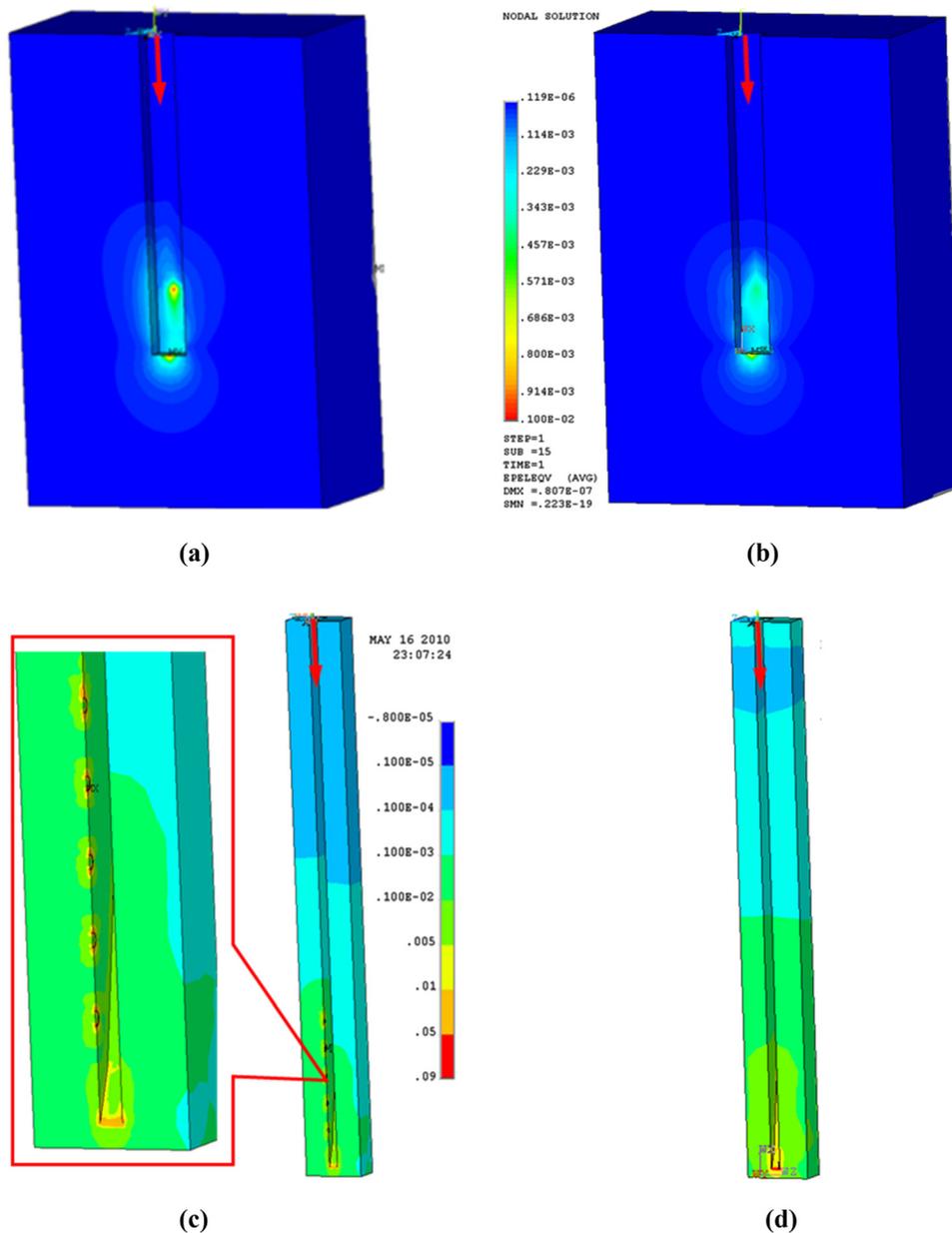


Fig. 4 The comparison of the Von Mises strain fields under longitudinal loading: (a) globe strain field for microelectrode with nanowire; (b) global strain field for Michigan electrode; (c) local strain field for microelectrode with nanowire; and (d) local strain field for Michigan electrode

neural probe shank is rigid, no elastic element is generated in the probe region, which significantly reduces the total number of elements used in the simulation, hence saving computing time. One thing to be noted is that the new method also brings faster convergence in comparison with the conventional method, which creates a large material property mismatch at the interface between the probe and the brain tissue by using elastic elements for both regions.

3.2 Microelectrode with Vertically Aligned Nanowires. Since the diameter of each nanowire is around 100 nm and the distance between two nanowires is less than 1 μm , the number of nanowires is too huge to model them individually. Moreover, due to the high Young's modulus of the material used for the nanowire (Au), once the neural probe is implanted into the brain tissue, there are little deformations for both the nanowire and the tissue inside the nanowire area. Based on that, the nanowire areas are modeled as five rigid cylinders at one side of the neural probe

shank. Each cylinder is 30 μm in diameter, 2 μm in height, and the distance between the centers of two cylinders is 150 μm . The distance between the tip of the probe and the center of the nearest cylinder is 200 μm . Because the five rigid cylinders are at one side of the neural probe, a half symmetry model is used instead of quarter symmetry as shown in Fig. 3.

3.2.1 Effect of Longitudinal Loading. The comparison between Von Mises strain fields of the neural probe electrode with vertically aligned nanowires and the Michigan electrode under longitudinal loading (friction coefficient of 0.05 for both electrodes) is shown in Fig. 4. For the purpose of clear demonstration, the results are divided into two parts—the global strain field of the brain tissue, which is comparably far away from the electrode [Figs. 4(a) and 4(b)] and the local strain field of the brain tissue which is close to the electrode [Figs. 4(c) and 4(d)]. First, comparing the global strain fields, it can be found that unlike the symmetric strain field around the Michigan electrode the five vertically aligned nanowire areas do increase the strain field along the

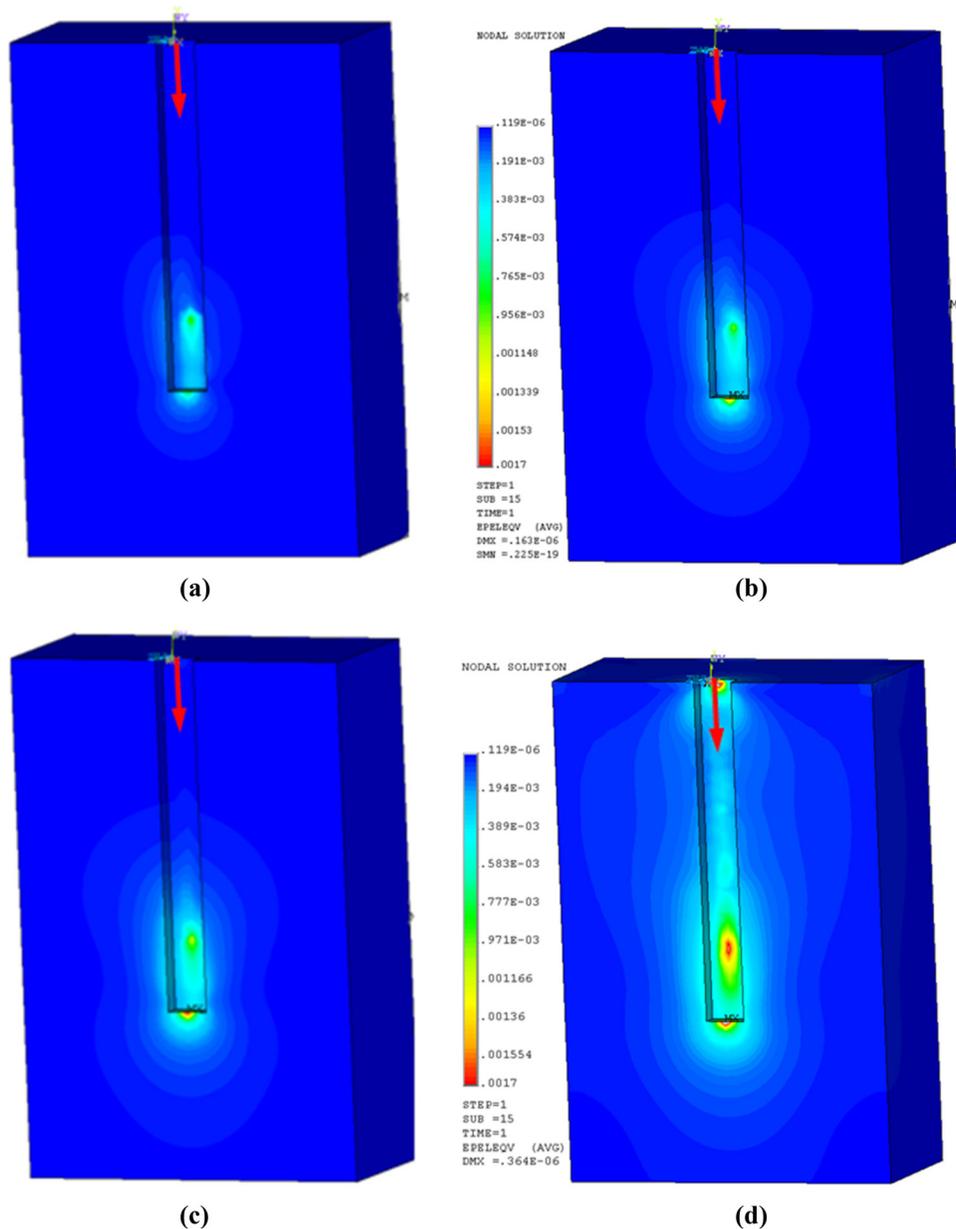


Fig. 5 Global strain fields of nanowire microelectrode with varied friction coefficients: (a) friction coefficient = 0; (b) friction coefficient = 0.5; (c) friction coefficient = 1; and (d) friction coefficient = 5

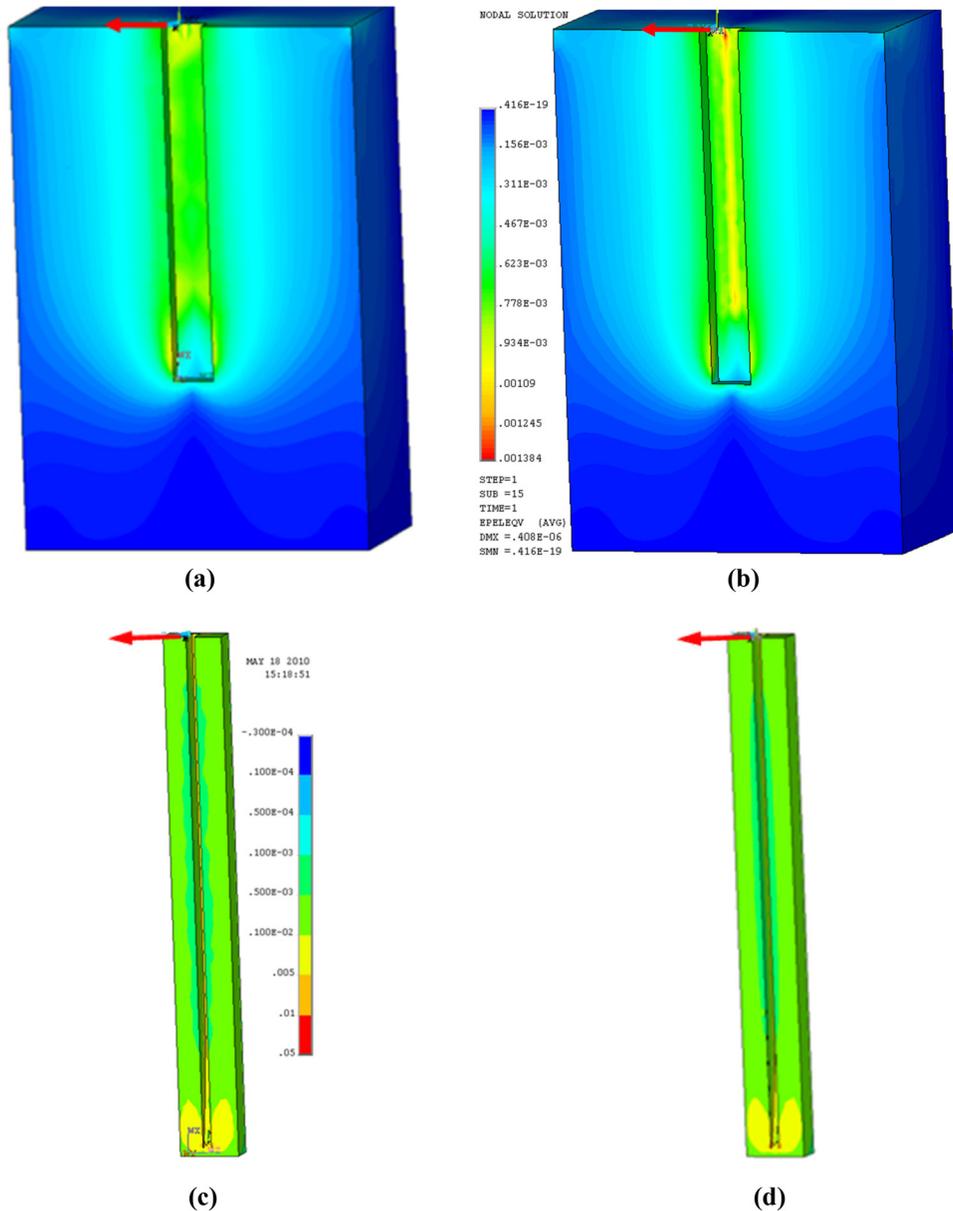


Fig. 6 The comparison of the Von Mises strain fields under transverse loading: (a) global strain field for microelectrode with nanowire; (b) global strain field for Michigan electrode; (c) local strain field for microelectrode with nanowire; and (d) local strain field for Michigan electrode

corresponding side of the probe electrode and generate an unsymmetric strain field as expected. Second, by comparing the local strain fields, it can be found that the maximum strain is at the circular interface between the nanowire area and the brain tissue for neural probe electrode with nanowires. However, for the Michigan electrode, the tip of the electrode has the maximum strain.

In order to study the effects of different physical coupling conditions at the interface between the neural probe shank and the brain tissue, and also the interface between the nanowire area and the brain tissue, global strain fields are plotted for a variety of friction coefficients of 0, 0.5, 1, and 5, as shown in Fig. 5. Comparing the results, it can be found that the Von Mises strain field increases as the friction coefficient becomes larger.

3.2.2 Effect of Transverse Loading. The transverse loading is applied at the bottom of the neural probe electrode parallel to the width of the symmetric plane as shown in Fig. 6. Comparing the globe Von Mises strain fields of both the microelectrode with nanowires and the Michigan electrode, little difference can be

found in the results. Although there are five nanowire areas at one side of the probe shank, the globe strain field still keeps symmetry around the probe. Also, it should be noticed that the amplitude of the deformation induced by the transverse loading is larger than that generated by the longitudinal loading.

4 Conclusion

A rigid body method for mechanical analysis of nanowire microelectrode-induced deformation has been developed. Comparing with the conventional method, the simulation efficiency is significantly increased. Based on the simulation using the rigid body method, it is shown that the vertically aligned nanowires on the electrode of the neural probe do increase the Von Mises strain field, hence increase the cellular sheath area. By changing the friction coefficients at the interface between the neural probe shank and the brain tissue and the interface between the nanowire areas and brain tissue, strain field distributions under different physical coupling conditions are analyzed. Finally, the effects of different loading directions are discussed.

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