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Feasibility Analysis of a Pressure Sensitive Rubber - based Tactile Sensor

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***Abstract* – In order to ensure the safety of the MIS (minimally invasive surgery), the pressure sensitive rubber has been proposed to be used in robotic catheter system as the tactile sensor. The contact force between the catheter and the blood vessel wall can be obtained precisely in this way. However, the structure of the blood vessel wall is thin film. Whether the vascular wall will be damaged or not is related to the contact force and the contact area. In this paper, the research of the piezoresistive characteristics of the carbon black filled pressure-sensitive conductive composite material have been carried out, and the relationship between the resistance and the contact area is deduced. Then experiments are designed to draw the relationship curve of the resistance and the contact area. A two-dimensional calibration curve is obtained utilizing the calibration system. Meanwhile, the experimental results indicate that the pressure sensitive rubber can be effectively used as the tactile sensor in robotic catheter system.**

Index Terms – Pressure sensitive rubber, Contact area, Piezoresistive characteristics, Tactile sensor.

I. Introduction

Nowadays, cardiovascular and cerebrovascular diseases are serious threats to human health. The minimally invasive surgery has become an increasing popular method to cure these diseases for its less incision and less recovery time. However, it requires the surgeon to have enough skills and experiences. During the process of the operation, the doctor will be exposed to X-ray. Then the robot-assisted catheter system has been developed, which solves the above problems effectively. Many researchers at home and abroad are devoted to the development of the master-slave system. In recent years, a novel catheter operating system with force feedback has been proposed [1]. Tele-Operation Master-Slave System for Minimal Invasive Brain Surgery has been reported [2]. Then A Novel Robotic Catheter System with Force and Visual Feedback for Vascular Interventional Surgery has been reported [3]. The master-slave catheterization system for positioning the steerable catheter has been reported [4]. Utilizing this system the doctor can operate the insertion mechanism for positioning the distal end of catheter with the assistance of 3D guiding image. In recent researches, many teleoperation systems [5] - [8] have been developed at home and abroad.

During the process of minimally invasive surgery applying the robotic catheter system, the doctor operates the master manipulator to insert and rotate the catheter, and the control commands will be transmitted to the slave computer, then the controller of the slave side will control the slave manipulator to insert and rotate the catheter as if the doctor is just beside the patient. Some force sensors are fixed on the catheter. Through this method the force feedback information can be obtained and transmitted to the surgeon precisely. In order to realize this function, many researches have been carried out, which are about the realization of the tactile sensors based on the resister, capacitor, piezoelectric, conductive rubber, MEMS and PVDF materials [9]. A novel tactile sensor using pressure conductive rubber has been proposed [10]. Compared with the other sensors, the tactile sensor based on pressure sensitive rubber has higher precision and simpler control circuit. As is shown in Fig.1, the tactile sensors based on pressure sensitive rubber are pasted on the front and side wall of the catheter, then the contact force can be measured [11].

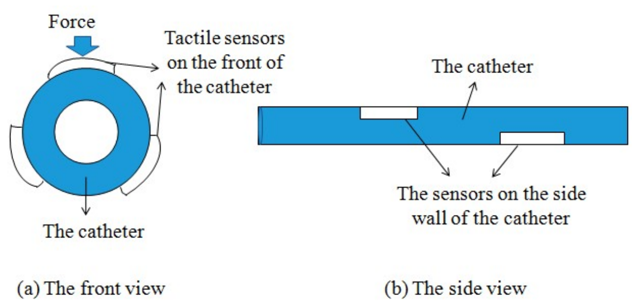

Fig. 1 The location of the sensors on the catheter

However, the sensor can only measure the value and the position of the contact force. The contact area can not be obtained. As far as we know, whether the vascular wall will be damaged or not is related to the contact force and the contact area. If we want to ensure the safety of the surgery more accurately, the contact area should be measured. However, the researches about the pressure sensor are rarely involved in the contact area. In this paper, the relationship equation between the resistance and the contact area is deduced based on the pressure sensitive rubber. Then, a simple calibration system has been designed. A series of experiments are carried out to obtain a relationship curve of the resistance and the contact area. Moreover, a two-dimensional curve of the resistance and the contact area is achieved. The experimental results indicate that the pressure sensitive rubber can be used feasibly as the tactile sensor in the robotic catheter system.

II. The Robotic Catheter System

During the process of the minimally invasive surgery, the doctor is exposed to X-ray. In order to protect the surgeon from X-ray, the master-slave robotic catheter system has been developed. The conceptual diagram of this system is shown in Fig.2. There are two sides in the whole system. On the master side, the doctor operates the master manipulator to move along axial and radial directions [12]. The control commands will be transmitted from the master side to the computer of the slave side. Then the slave manipulator will insert and rotate the catheter according to the control commands. As if the doctor is just beside the patient. Through this method, teleoperation can be realized. The insertion force of the doctor on the master side should be transmitted to the slave side, at the same time, the insertion force of the slave side must be returned to the doctor.

Besides the control information, the force feedback information also plays an important role in the surgery. The contact force between the catheter and the vascular wall, when the catheter is being inserted, must be measured precisely utilizing a proper tactile sensor. Therefore, on the slave side, a force sensing system is added into the robotic catheter system. The force feedback information will be transmitted to the master side, and the surgeon could feel the force actually. Visual feedback is added to this system. It helps the surgeon to know the situation of the surgical site.

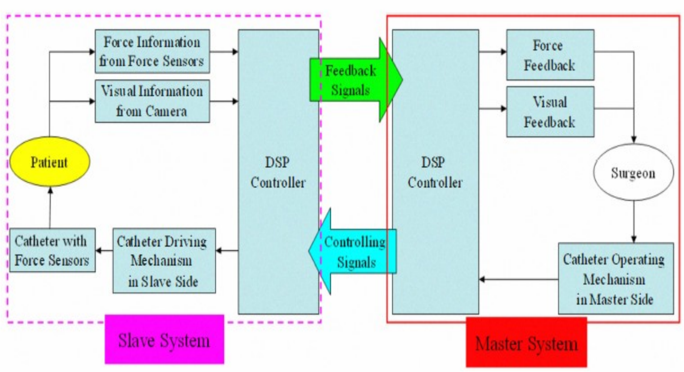

Fig. 2 Conceptual diagram of the novel robotic catheter operating system

When the catheter contacts the blood vessel wall, the value of the contact force can be measured precisely utilizing a proper tactile sensor. In our robotic catheter system, the pressure sensitive rubber is used as the tactile sensor to measure the contact force. However, the structure of the blood vessel wall is thin film. Whether it will be damaged or not is related to the contact force and the contact area. However, in the previous calibration of the tactile sensor, we did not take the influence of the contact area into consideration. The contact area cannot be achieved precisely. As is shown in Fig.3, the shape of the blood vessel is twist, and there are many branches. All these problems make the contact area difficult to be measured. In the view of the present case, we can just imagine there are three situations when the tactile sensor contacts the vascular wall, and they are one point, part of the surface and the entire surface. This paper is just a research about the influence of the contact area on the output of the tactile sensor when the catheter in the blood vessel.

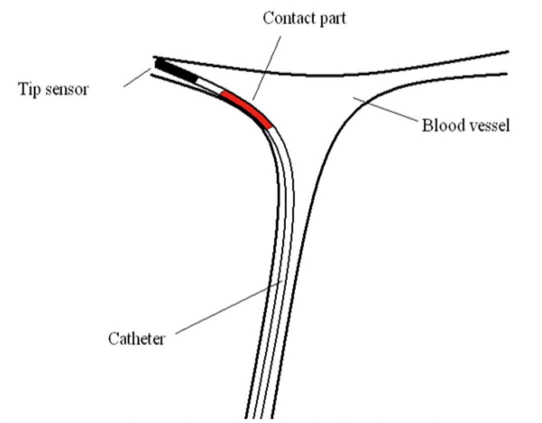

Fig. 3 The catheter in the blood vessel

III. The Analysis of Piezoresistive Characteristics

The pressure sensitive conductive rubber is a kind of complex hybrid material. It is made from natural rubber or synthetic rubber. The rubber itself is not conductive, however, after vulcanized by mixed with conductive particle, the material become conductive and sensitive to pressure. The conductive particles can be carbon black [13], [14], metal particles, graphite, fibrous conductive filler, etc. The conductivity differs as the adding conductive fillers change. The pressure sensitive rubber researched in this paper is a sensitive material with piezoresistive effect. That is to say, the resistance value of the pressure sensitive rubber can change regularly according to the change of the external force.

In the previous research, the piezoresistive characteristics model of the pressure-sensitive composite material was established based on quantum tunnel effect theory [15]. Quantum tunnel effect theory has been used to explain the conductivity of the pressure sensitive rubber from the micro electronic movement. Supposing the statistic average value of the conductive particle space is ω [16], the macro current density can be expressed as follows:

$$J_{(\varepsilon)} = J_0 \exp[-(\pi\chi\omega/2)(\varepsilon/\varepsilon_0 - 1)^2] \tag{1}$$

where $J_{(\varepsilon)}$ is the macro current and ε is the electric field between spaces when external force is applied, J_0 is the macro current and ε_0 is the field between spaces when external force is not applied, the mathematical formula of χ is shown in equation (2).

$$\chi = \sqrt{2mV_0/\hbar^2} \tag{2}$$

where m is the electric mass, V_0 is the barrier height, $\hbar$ is the reduced Planck constant.

Supposing F is the external pressure force applied on the pressure-sensitive composite material, there is:

$$F = k_1(h_0 - h) \quad (3)$$

where k_1 is the elastic coefficient, h_0 is the initial thickness of the conductive composite material, h is the thickness when the external force is applied.

Assuming that ω is directly proportional to the thickness of the pressure sensitive material, h is the thickness, k_2 is the proportion coefficient, then there is:

$$\omega = k_2 \cdot h \quad (4)$$

The ratio of ε and ε_0 can be shown as follows:

$$\varepsilon / \varepsilon_0 = \omega_0 / \omega = h_0 / h \quad (5)$$

According to the law of Ohm, then, bringing the equation (1) and (3)-(5) to the above equation, we can get the relationship equation of the external force F and the resistance $R_{(F)}$:

$$R_{(F)} = h/\sigma S = Jh/ES$$

$$R_{(F)} = R_0 - \frac{R_0}{k_1 h_0} \cdot F + \frac{\pi \chi k_2 R_0}{2k_1^2 h_0} \cdot F^2 + \frac{\pi^2 \chi^2 k_2^2 R_0}{8k_1^3 h_0 (k_1 h_0 - F)} \cdot F^4 + \cdots \quad (6)$$

Under general situation, it is considered as quadratic equation [17]:

$$R_{(F)} = R_0 - AF + BF^2 \quad (7)$$

where R_0 is the resistance without external force, A and B are both constant.

The resistance is related to the area of the material, According to the law of Ohm. The equation (6) is deduced under the condition that the change of the area is ignored. That is to say, the effect to the resistance from the loading area is ignored. The volume of the material is invariable, the thickness changes, so the area changes. In general situation, the change is very small, it can be ignored. However, in the robotic catheter system, the pressure sensitive rubber is used as tactile sensor. The contact force which will be measured is very small, it is not larger than 0.5N. The change of the thickness is micro, so the change of the area should be considered.

We considered the contact area as a variable, the volume V as a constant value. There is an equation about the volume:

$$V = S_0 \cdot h_0 = S \cdot h \quad (8)$$

where S_0 is the initial area, S is the area with external pressure force.

Then we bring the equation (1), (3)-(5) and (8) to the resistance equation, the relationship of the resistance and external force is as follows:

$$R_{(F)} = S_0[\frac{Vk_1}{h_0 k_1 - F} \cdot R_0 - \frac{VR_0}{(h_0 k_1 - F)h_0} \cdot F + \frac{V\pi\chi k_2 R_0}{2(h_0 k_1 - F)k_1 h_0} \cdot F^2 + \frac{V\pi^2 \chi^2 k_2 R_0}{8k_1^2 h_0 (k_1 h_0 - F)^2} \cdot F^4 + \cdots]$$

$$= S_0^2[\frac{h_0 k_1}{h_0 k_1 - F} \cdot R_0 - \frac{R_0}{(h_0 k_1 - F)} \cdot F + \frac{\pi\chi k_2 R_0}{2(h_0 k_1 - F)k_1} \cdot F^2 + \frac{\pi^2 \chi^2 k_2 R_0}{8k_1^2 (k_1 h_0 - F)^2} \cdot F^4 + \cdots] \quad (9)$$

The result shown in equation (9) declares that, if we consider the external force as a constant value, the resistance is proportional to the square of the area. Then, the relationship of the resistance and the contact area can be deduced utilizing this equation.

Reviewing the equation (9), we can get the general relationship between the resistance and the contact area, as the following equation shows:

$$R_{(S)} = A \cdot S^2 \quad (10)$$

where $R_{(S)}$ is the resistance which will change along with the change of the contact area, A is a constant, S is the contact area. A simple mathematical model has been established.

IV. Experimental Results And Analysis

From the equation deduced in part three we can know that as the contact area changes the resistance of the pressure sensitive rubber changes. In order to analyze the feasibility that the pressure sensitive rubber can be used as the tactile sensor in the robotic catheter system, some experiments are carried out. The experiments are divided into two kinds, one is finite element analysis using ANSYS software, the other kind is to design a calibration system and achieve a data curve.

Utilizing ANSYS software, we build a simple solid model, all the parameters are set as the reference [18] introduces. Then mash the model in a proper method. We keep the external force as a constant value, and change the loading area. Because of the limitation of the ANSYS technology, we can just change the number of the loading nodes, the more nodes are loaded, the larger the contact area is. The data achieved are shown in Table. I.

TABLE. I

The Increasing Strain With The Increase of The Contact Area

The number of the nodes	534	1595	2430	3953	5062
Strain	0.532713 E-08	0.121972 E-07	0.168839 E-07	0.235888 E-07	0.27357 3E-07

From the data which have been shown in Table. I, we can easily learn that the contact area affects the strain. The strain is the proportion of the deformation and initial shape along the Z-axis direction. So the deformation in Z-axis is affected by the contact area. From the equation (3), we can know that the deformation in Z-axis is proportional to the external force, then it affects the resistance of the pressure sensitive rubber. The result that the contact area affects the resistance of the pressure sensitive rubber is obtained.

In the experiments using ANSYS software, we can just get a general qualitative analysis result. In order to provide a more powerful proof, we design a calibration system [19]. We keep the external pressure force as a constant value but change the contact area linearly to get a new calibration curve. The Fig.4 shows the calibration system. The circuit we design in this system is simple, as is shown in Fig.5. The sensor and a fixed value resistance are connected in series, a DC power of 5V is applied in this circuit.

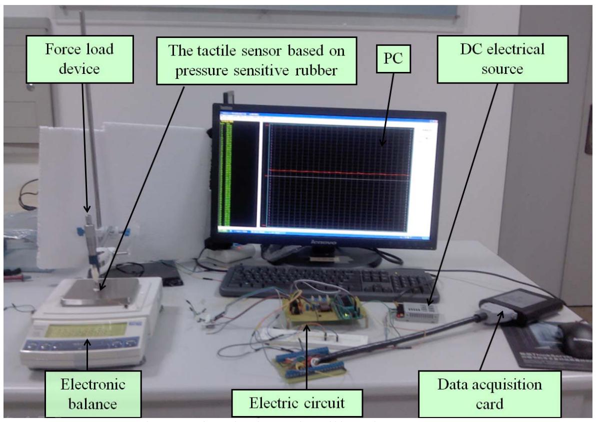

Fig. 4 The designed calibration system

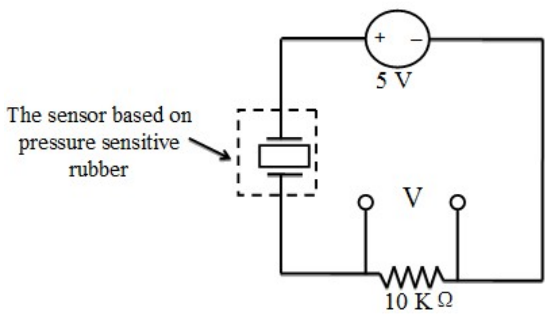

Fig. 5 The control circuit of the tactile sensor

As is shown in Fig.6 and Fig.7, a tactile sensor based on pressure sensitive conductive rubber is designed. On the upside and downside of the pressure sensitive rubber is the copper electrode, and the pressure sensitive rubber is in the middle. The force we apply on the pressure sensor based on pressure sensitive rubber is 0.5N, as is shown in Fig.8, the reading of the electronic balance is around 50.00g, and the error is in a reasonable range. Each time the force applied on the sensor is the same, and the variable is the value of the contact area. The size of the tactile sensor we design is 5mm ×5mm.

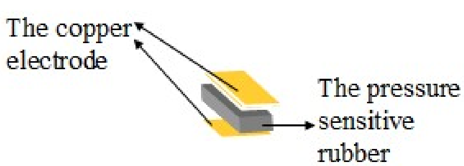

Fig. 6 The structure of the sensor

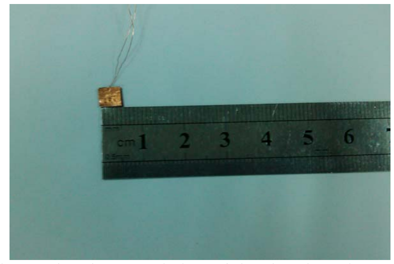

Fig. 7 The shape and size of the developed sensor

Fig. 8 The display of the electronic balance

In minimally invasive surgery, the catheter will be inserted into the blood vessel of a patient. The contact area should be very small, so in this research, the variation range of the contact area is from 2 mm^2 to 20 mm^2. Ten groups of data are obtained. The output voltage V we achieved is the voltage of the fixed value resistance in the control circuit. According to the law of Ohm, the voltage of the tactile sensor based pressure sensitive rubber $V_{(S)}$=5-V. We connect the ten data points with a smooth curve. The Fig.9 shows the curve of the data.

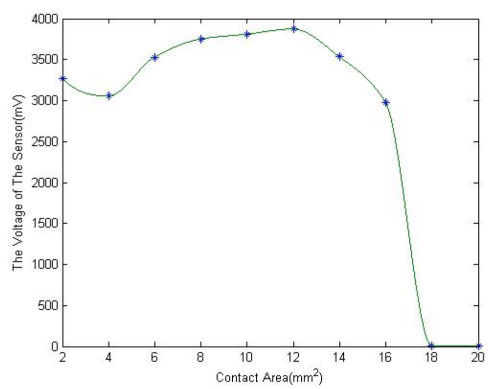

Fig.9 The data curve of the contact area and voltage of the sensor

From the mathematical model proposed in part three, the equation (10). We fit the data curve into a quadratic curve utilizing MATLAB software, the curve is shown in Fig.10. We can see the points of data can not fit the curve completely. They are distributed on both sides of the curve, the distribution is generally uniform. This result indicates that the quadratic fitting curve and the data are consistent.

The relationship curve of the resistance of the pressure sensitive rubber and the contact area value is more intuitive. Then, on the basis of the law of Ohm, the resistance of the sensor $R_{(S)}$ is as follows:

$$R_{(S)} = \frac{5-V}{V/R_0} = \frac{R_0 \cdot (5-V)}{V} \quad (11)$$

where V is the voltage of the fixed value resistance, R_0 is the resistance value of the fixed value resistance. Then, the relationship curve of the resistance of the sensor and the contact area is shown in Fig.11.

We can obtain a relationship equation from the achievement process of Fig.11.

$$R_{(S)} = -0.3048\, S^2 + 5.6666\, S + 4.0044 \quad (12)$$

where $R_{(S)}$ is the resistance of the sensor, S is the contact area.

Comparing the equation (10) and the equation (12), difference exists between them. In the deduced equation, the term of the first degree and the constant term do not exist. That is because there are interruptions in our experiments. The design of the calibration is rough. As the limitation of our technology, we only achieve ten groups of data, more experiments should be carried out to gain more data.

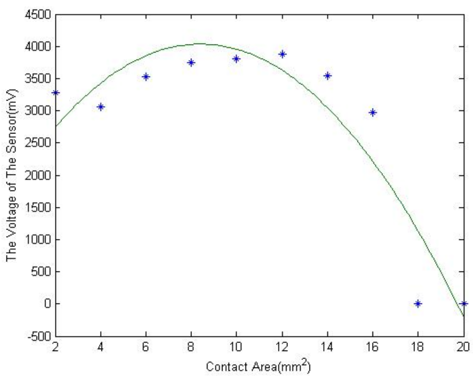

Fig. 10 The quadratic fitting curve

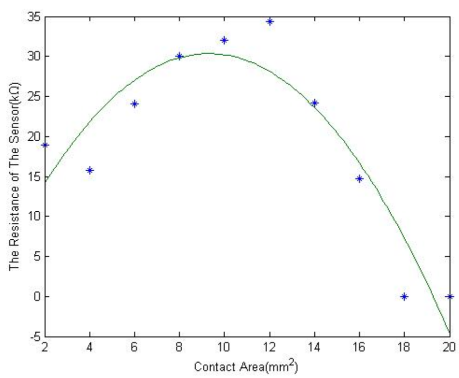

Fig. 11 The relationship curve of the resistance and the contact area

V Conclusion And Future Work

In minimally invasive surgery, the force feedback information was important to improve the safety of the surgery. The pressure sensitive rubber had been proposed to be used in the robotic catheter system as the tactile sensor. The contact force and the contact area determined whether the blood vessel would be damaged or not. In this paper, the influence of the contact area was considered during the calibration process of the tactile sensor. We analyzed the characteristics of the pressure sensitive rubber-based tactile sensor, the following conclusions can be drawn：

1) The pressure sensitive rubber was proposed to be used as tactile sensor in the robotic catheter system.
2) The relationship equation of the resistance and the contact area was deduced. In general situation, it was a quadratic relationship when the external force was constant.
3) Finite element analysis was carried out to indicate that the contact area affected the strain.
4) A simple calibration system was designed and a two dimensional calibration curve of the resistance and the contact area was obtained using this system.
5) The experimental results proved that the pressure sensitive rubber could be used effectively as the tactile sensor in the catheter system.

During the process of the research, we have found out some problems. The calibration system designed in this paper is rough and disturbances are unavoidable. Because of the limitation of technique, the range of the contact area is not enough, more data should be measured. The accuracy of the calibration curve needs to be improved. Furtherly, as we know, whether the vascular wall will be damaged or not is related to the contact force and contact area. The resistance of the pressure sensitive rubber is related to the pressure and the loading area. In the future, a three dimensional calibration curve of the resistance, contact area and external force can be developed. Utilizing the three-dimensional calibration curve, we can judge out whether the vascular wall will be damaged accurately.

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