FLEXIBLE TACTILE SENSOR ATTACHED TO LAPAROSCOPE FOR MECHANICAL CHARACTERISTICS OF SOFT MATERIALS AND TISSUES

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ABSTRACT

Detection of the mechanical characteristic of tissues is useful to distinguish the difference between a cancerous lump and healthy tissues for minimally invasive surgery (MIS). In this study, a novel miniaturized tactile sensor is designed to attach to laparoscope for differentiating soft tissues from animals. The flexible tactile sensor consists of two patterned flexible print circuit (FPC) sandwiching a polymer piezoelectric film (PVDF) and a small steel ball embedded in a soft material (PDMS) on the FPC surface. Due to the stiffness difference between steel ball and PDMS material, the uneven stress distribution on piezoelectric film can be induced and varied with contact objects. Therefore, the mechanical characteristics of contact object can be differentiated by the ratio of voltage outputs between the inner and outer electrodes on the piezoelectric film. As experimental results, the voltage ratio increases with the Young's Modulus for the commercial elastomeric materials. In addition, five soft tissues of animals also can be differentiated by the tactile sensor attached to a laparoscope.

KEYWORDS

Tactile sensor, Piezoelectric, PVDF, Minimally invasive surgery (MIS)

INTRODUCTION

In the minimally invasive surgery (MIS), the tactile feedback can provide additional information such as tissues compliance (reciprocal of stiffness), which can help the surgeon in decision making in MIS. Moreover, the mechanical characteristics of tissue could be useful for differentiating a cancerous lump between healthy tissues due to the hardness of cancerous lump is usually larger than healthy tissues for several times [1]. In general, endoscopy has been commonly employed for MIS because it not only provides an image for visual inspection but also enables biopsies and the retrieval of foreign objects. However, a visual inspection for an early diagnosis of a tumor is still often insufficient, for example, gastric submucosal tumors is used to define an intramural growth underneath the mucosa, the exact nature of which cannot be definitely determined either by standard luminal endoscopy or by barium contrast radiography [2]. Therefore, additional information of mechanical properties from direct contact with tissue could improve the accuracy of diagnosis by using miniaturized tactile sensor.

Recently, many researchers have presented different tactile sensors with the variety of designs and principles to measure the tactile information for MIS. Bonomo *et al.* [1] proposed a tactile probe consisted of two cantilever beams made of ionic polymer metal composites (IPMC), one cantilever beam was excited in a vibration mode, another cantilever beam was responded to contact with object and sensing output. However, the detectable range of soft tissue was limited by the small driven force of IPMC actuator. In 2005, Liu *et al.* [3] proposed a polymer micromachined multimodal tactile sensor for differentiation of object hardness. The structure of hardness sensor consisted of a bulk reference sensor and a membrane measurement sensor. Therefore, the pressure ratio of reference sensor and membrane sensor could reflect the stiffness of contact object based on spring model. In 2011, Liu [4] further employed similar two-spring model to fabricate a hardness sensor using two piezoresistive cantilevers with different stiffness. However, the contact angle between object and sensor could affect the sensor sensitivity which is difficult to apply for biological tissue of irregular shape. Recently, Based on similar concept of applying two springs with considerably different stiffnesses, Tabata *et al.* [5] and Rajamani *et al.* [6] developed a piezoresistive tactile sensor and a capacitive tactile for the detection of soft materials, respectively. Instead of piezoresistive tactile sensors, Drargahi et al. [7] proposed a piezoelectric tactile sensor for tissue characterization. In his work, three polymer piezoelectric films (polyvinylidene fluoride, PVDF) were attached to two stiff supporting structures and one compliable beam structure for acquiring the voltage output in terms of softness of contact object. However, the mechanical or electrical crosstalk still needs to improve as the object size is small than sensor.

In this study, in order to implement two-spring model with simple structure, we developed a soft piezoelectric tactile sensor with a hard steel ball embedded in a soft packaging material (Polydimethylsiloxane, PDMS). The simple structure can be fabricated by laminations of patterned flexible printed circuit (FPC) and PVDF film and packaged by molding technique. Due to the packaging material is biocompatible and waterproof; therefore, our tactile sensor can practically employ to endoscope or laparoscope of MIS.

SENSING MECHANISM

In order to describe the sensing mechanism a simplified structure of piezoelectric tactile sensor is illustrated in Fig. 1, a composite structure with two different Young's moduli are built on the surface of piezoelectric film (PVDF) such as the inner structure (E_1) and outer structure (E_2), respectively. When an elastomeric object contacts with the tactile sensor, the contact force acting on the sensor surface can be transferred to the piezoelectric film through the inner structure and outer structure, thus, two voltage outputs can be obtained from the piezoelectric film corresponding to inner structure and outer packaging layer as V_1 and V_2, respectively. As the Young's modulus of the inner structure is greater than outer packaging material i.e. $E_1 > E_2$, a non-uniform stress distribution will be occurred on the piezoelectric film, consequently, the induced voltages of V_1 and V_2 will be also different. For example, as the tactile sensor contacts a soft elastomer, the deformations of elastomer at the outer structure may be greater than the value at the inner structure. Therefore, the voltage ratio of V_1 to V_2 (V_1/V_2) will be relatively small, as shown in Fig. 1(a). Conversely, for contacting a hard elastomer, the majority of the normal force will be transferred by the inner structure; thus, the voltage ratio will be greater, as shown in Fig. 1(b). Therefore, the voltage ratio (V_1/V_2) could be taken as an index of mechanical characteristic of contact object.

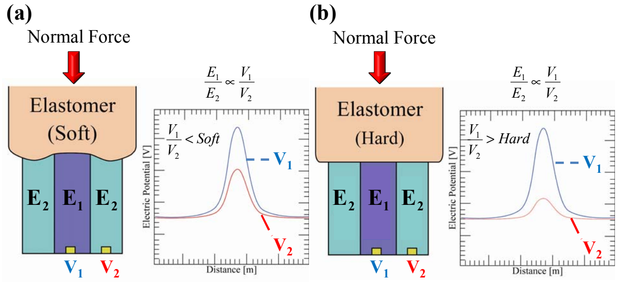

Figure 1: Mechanism of measuring the mechanical properties of elastomers: (a) as contact with a soft elastomer, the voltage ratio is small; (b) as contact with a hard elastomer, the voltage ratio is greater.

EXPERIMENTAL SETUP

Sensor fabrication

A PVDF-based tactile sensor with a steel ball and separated electrodes was fabricated, as shown in Fig. 2(a). A commercial 28µm-thickness PVDF thin film (Measurement Specialties, Inc.) was utilized as the sensing layer. First, we patterned the separated electrodes on the FPC substrates using standard photolithography and wet etching with a mask design. Then, we stripped both sides of electrode layers from the PVDF thin film by immersion in acetone. Later, the blank PVDF thin film was sandwiched with two patterned FPC's by a patterned adhesive film (Optical Clean Adhesive, OCA film). A steel ball with 0.8 mm in diameter was glued on the laminates of FPCs and PVDF corresponding to one of top electrodes. Finally, the tactile sensor was packaged with PDMS by molding technique as shown in Fig. 2(b). The specifications of the tactile sensor is given in Table 1.

Table 1：The specifications of tactile sensor.

Materials	Length (mm)	Width (mm)	Thickness (mm)
Steel Ball			0.8
Top PDMS	6.5	3.5	1
Bottom PDMS	6.5	3.5	0.02
PVDF Film	3.8	2	28×10^{-3}
Top FPC Film	5.5	2.5	38×10^{-3}
Bottom FPC Film	5.5	2.5	38×10^{-3}

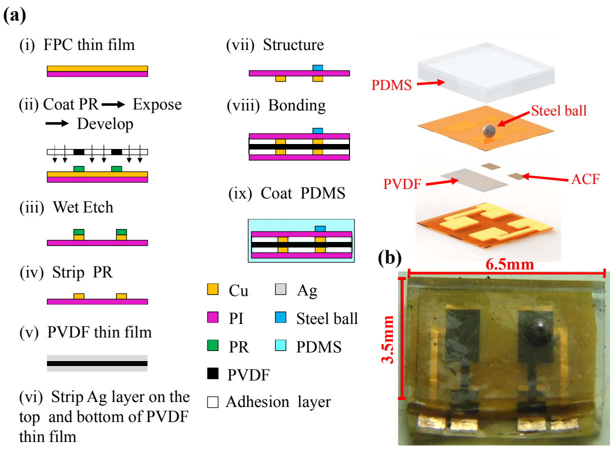

Figure 2：(a) The fabrication process of flexible tactile sensor; (b) The picture of finished tactile sensor.

Dynamic measurement setup

The piezoelectric tactile sensor cannot measure a static force because the induced electric charge dissipates rapidly. Therefore, a dynamic test system was built for measuring the mechanical properties of elastomers and tissues, as shown in Fig. 3. The signal generator (AFG3022, Tektronix Inc, USA) drove the shaker (GW-V4, Data Physics Co, USA) with 2 Hz and 500 mVp-p to contact the object. A force sensor (209C01, PCB Piezotronics Inc, USA) was installed on the shaker front to control the contact force between the tactile sensor and the object. Then, the force sensor output signals were passed through a signal converter to the oscilloscope (AFG3022, Tektronix Inc, USA) through Channel 1 (V_0) for monitoring of contact force. Basically, the magnitude of contact force was 1N at 2 Hz. The tactile sensor was attached on an acrylic plate and mounted to the shaker for vertically contacting with object. Additionally, two output signals of the tactile sensor were passed through a charge amplifier (B&K NEXUS2690A) to the oscilloscope through Channels 2 and 3 (V_1 and V_2). For example, two voltage outputs can be obtained as the sensor contacted samples of chicken gizzard, as shown in Fig. 4. As the results indicated in Fig. 4, two voltage outputs were in phase but different peak values were generated from the inner structure (steel ball) and outer structure (PDMS layer). Consequently, the voltage ratio can be calculated from these two peak values of sensor outputs i.e. V_1/V_2.

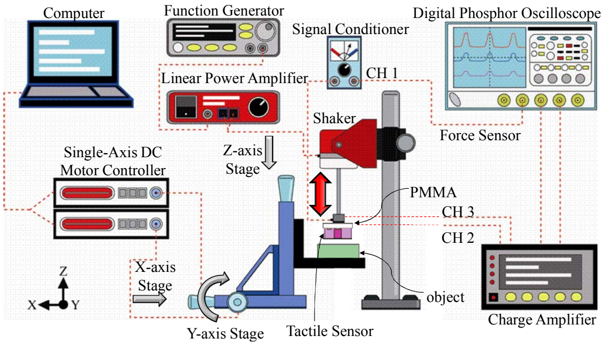

Figure 3: The dynamic measurement setup for the mechanical characteristics of elastomeric materials and soft tissues.

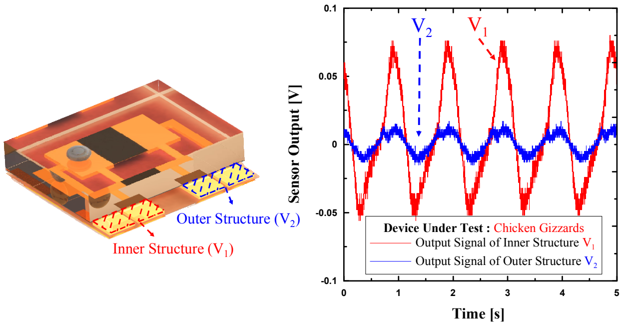

Figure 4: The voltage outputs from inner electrode (V_1) and outer electrode (V_2) as measuring chicken gizzards.

EXPERIMENTAL RESULTS

Characterization of Elastomers

Six kinds of elastomeric materials (Dow Corning Co., USA) with different Young's Modulus were used for evaluation of tactile sensor as shown in Fig. 5. Each elastomer were prepared according to the suggested mixture ratio of main agent and curing agent and solidified in a cubic mold (15 x 15 x 10 mm^3). In addition, the Young's Modulus of each elastomeric material was obtained by conventional tensile test as listed in Table 2. The voltage ratio for each elastomeric object was averaged from 10 times measurements and plotted in Fig. 6. As the measurement results, the voltage ratio proportionally increases with Young's Modulus, a harder object could induce a higher voltage ratio, which can verify the original concept, as described in Fig. 1. In addition, the voltage ratio varies more significant in the lower Young's Modulus region from 0.2 to 1.5 MPa. Therefore, the sensor sensitivity for soft elastomer is higher than for hard elastomer as the results in two different slops of linear fitting in Fig. 6.

Figure 5: The picture of elastomeric materials.

Table 2: Measurement of results of voltage ratio and Young's modulus for six kinds of elastomers.

Elastomeric Materials	Young's Modulus (MPa)	Voltage ratio (V_1/V_2)	Standard deviation
3120 RTV Rubber	3.51	1.94	±0.04
Sylgard 160	3.08	1.89	±0.03
Sylgard 184	1.40	1.73	±0.08
Sylgard 170	1.18	1.70	±0.06
Sylgard 186	1.01	1.64	±0.07
3-4207 Dielectric	0.26	1.37	±0.07

Tough Gel

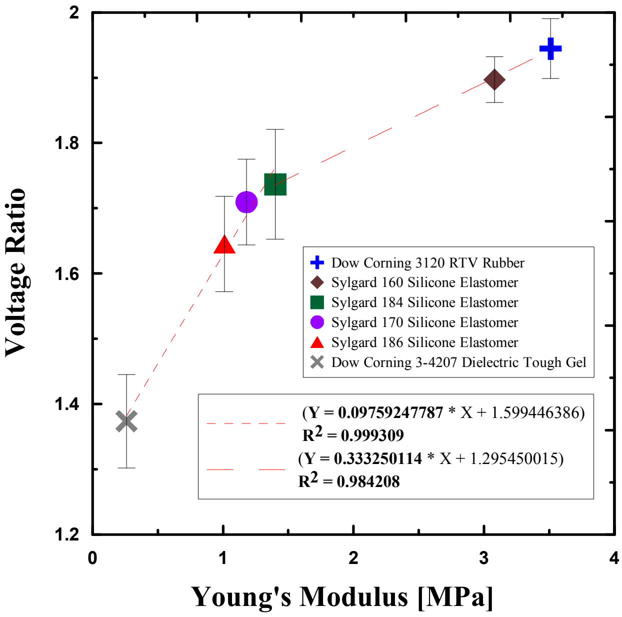

Figure 6: The voltage ratios of sensor output for six kinds of elastomeric materials.

Characterization of Animal Tissues

According to the dynamic measurement results of sensor output, the proposed tactile sensor possesses higher sensitivity for soft material. Therefore, we further attached the tactile sensor on the laparoscope and in vitro measured the animal tissues as shown in Fig. 7. Totally, five kinds of soft tissues: chicken gizzards, chicken hearts, chicken breasts, beef and pork were tested either by dynamic measurement or laparoscope operation. The voltage ratios for these animal tissues were obtained and plotted in Fig. 8. According to the results, the variations of voltage ratios between dynamic measurement and laparoscope operation is small, therefore, we can differentiate the hardness of animal tissue by the tactile sensor attached on a laparoscope without dynamic loading. However, the variations of sensor output from laparoscope operation are generally greater than from dynamic measurement. Consequently, a standard procedure is needed for laparoscope operation as grasping tissue in the future.

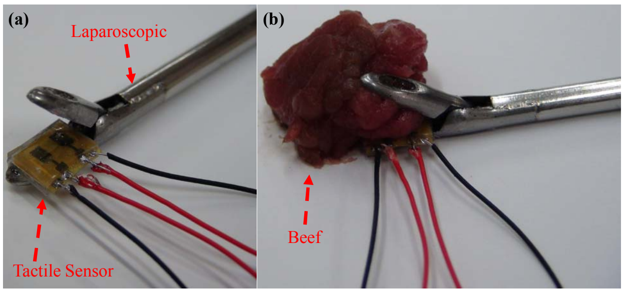

Figure 7: (a) The tactile sensor is attached to a laparoscope; (b) in vitro experiment for characterization of soft tissue (beef) by a laparoscope with tactile sensor.

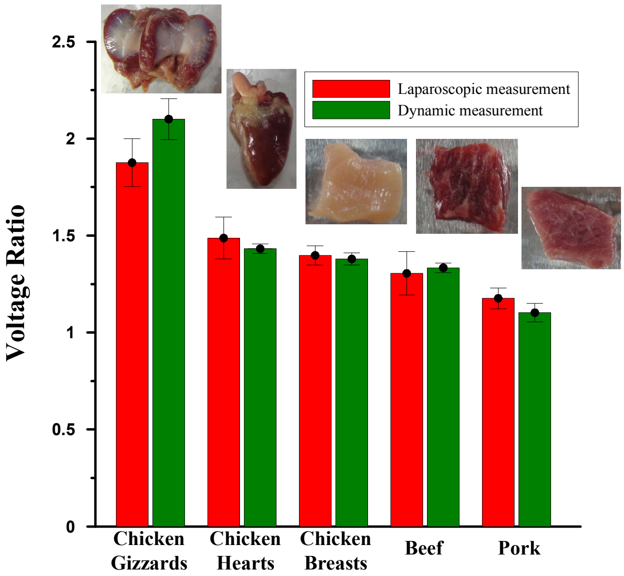

Figure 8: The voltage ratios of sensor output for five kinds of soft tissues.

CONCLUSIONS

We have proposed a simple and speedy measurement method for determining the hardness of elastomers based on a piezoelectric tactile sensor with a steel ball embedded in a soft packaging. With cycle loading, the voltage ratio obtained from hard inner structures and soft packaging layers can be regarded as an indicator of hardness of the contacted object. In general, the voltage ratio is proportional to Young's Modulus; furthermore, the tactile sensor possesses a higher sensitivity for low Young's Modulus materials. As the tactile sensor attached on a laparoscope, the hardness of animal tissues can be well characterized as well as in a dynamic measurement. Consequently, our tactile sensor is able to effectively provide information regarding hardness using in situ feedback control (grasping the object) and the in vivo measurement of specific tissues, allowing for minimally invasive surgery.

REFERENCES

[1] C. Bonomo, P. Brunetto, L. Fortuna, P. Giannone, S. Graziani, S. Strazzeri, "A tactile sensor for biomedical applications based on IPMCs," *IEEE SENS J*, vol. 8, pp. 1486–1493, 2008.

[2] L.G. Ponsaing, K. Kiss, A. Loft, L.I. Jensen, M.B. Hansen, "Diagnostic procedures for submucosal tumors in the gastrointestinal tract", World J Gastroenterol; 13: 3301-3310, 2007

[3] J. Engel, J. Chen, Z. Fan, C. Liu, " Polymer micromachined multimodal tactile sensors", *SENSOR ACTUAT A-PHYS*, vol 117, pp. 50-61, 2005.

[4] S. Zhao, D. Parks, C. Liu, "A Medical Tactile Sensor for Measuring Tissue Hardness in Robotic Surgical Tools", in *Digest Tech. Papers Transducers'11 Conference*, Beijing, China, June 5-9, 2011, pp. 2843 - 2846.

[5] A. M. R. Fath El Bab, K. Sugano, T. Tsuchiya, O. Tabata, M. E. H. Eltaib, M. M. Sallam, "Micromachined Tactile Sensor for Soft-Tissue Compliance Detection", *J. Microelectromech. Syst.*, vol. 21, pp. 635-645, 2012.

[6] P. Peng, R. Rajamani, "Capacitance Ratio Estimation on a Novel MEMS Tactile Sensor for Elasticity Measurement", *American Control Conference*, USA, June 29-July 01, 2011, pp. 3459-3464.

[7] S. Sokhanvar, M. Packirisamy, J. Dargahi, "MEMS Endoscopic Tactile Sensor: Toward In-Situ and In-Vivo Tissue Softness Characterization", *IEEE SENS J*, vol. 9, pp. 1679-1687, 2009.

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