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A Grasping Forceps with a triaxial MEMS tactile sensor for quantification of stresses on organs

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Abstract— **This paper reports on a grasping forceps with a triaxial Micro Electro Mechanical Systems (MEMS) tactile sensor on a tip. The laparoscopic surgery is minimally invasive because the incisions are smaller than the open surgery. This results in fast recovery. However, it is a problem in the laparoscopic surgery to damage an organ by localized stress generated by grasping with a thin forceps. To avoid excessive stress applying to the organ, real time evaluation of the stress is important. However, there is no acceptable tool to measure the stress. We propose a grasping forceps with a triaxial MEMS tactile sensor on a tip for a measurement tool. We attached a triaxial MEMS tactile sensor which we have developed on a tip of a grasping forceps. The MEMS sensor can measure not only the pressure but also two directional shear stresses applied to the sensor surface. The sensor size is 7 mm × 7 mm × 2 mm. It is enough small to attach the sensor to the tip of a forceps 12 mm in diameter. In this paper, the characteristics of the forceps with the MEMS sensor during grasping, pushing and pulling actions were evaluated. In these experiments, output of each sensor for pressure and shear stress was proportional to the applied stresses, respectively. Moreover, as an in vivo experiment, we measured the shear stress applied to a pig liver block when it is lifted after being grasped with the forceps. We obtained that the shear stress applied to the liver block increased with the increase of the weight of the liver block.**

I. INTRODUCTION

The laparoscopic surgery is minimally invasive because the incisions are smaller than the open surgery. This results in fast recovery. However, it is a problem in the laparoscopic surgery to damage an organ by localized stress generated by grasping with a thin forceps. In the clinical situations, because of the insufficient assessment of the damage, procedures avoiding contact with weak organs are adopted. This is one of the reasons that make the laparoscopic surgery difficult.

To avoid excessive stress applying to the organ, monitoring the stress on organs is necessary. To figure out the stress becoming excessive, assessment of organ damage is also important. For the monitoring and the assessment, measuring tools of the stress are needed.

In the laparoscopic surgery, the main considerable actions for damage assessment are grasping, pushing and pulling. During such actions, pressure and shear stress are applied to organs. Especially in the case of a grasping forceps, it should be considered that the stress applied on organs by each of the two tips is different.

Moreover, because the qualification of the stress on organs is valuable not only for assessment of the organ damage but also for skill assessment and training, it is important to develop devices for qualification.

Some tools for measurement of the stresses are reported [1-4]. Tissue damage was assessed using motorized endoscopic grasper by De et al. [1]. In this study, applied stress on tissues was calculated from the output of a force sensor at the proximal end of the grasper. Trejos et al. developed a sensorized instrument attached strain gauges on the shaft [2]. In this case, the grasping force is calibrated by grasping a spring. The problem common in these two studies is that it is impossible to eliminate the influence of the external force generated by contacting other organs or the force transmission efficiency caused by the structure of the forceps. Tholey et al. embedded a resistive sensor and four piezoresistive sensors in the jaw of a forceps [3, 4]. Though the forceps had 3-D force measurement capability, the size of the jaw, which was nearly equal to the size of the sensor part, was 44 mm × 15mm × 13 mm.

In this study, we propose a grasping forceps with a triaxial Micro Electro Mechanical Systems (MEMS) tactile sensor. Because of the size of existing sensors, it was difficult to place the sensor to one of the two tips of a grasping forceps. However, the size of the MEMS sensor which we have developed is enough small, which is 7 mm × 7 mm × 2 mm, to attach the MEMS sensor to a tip of a grasping forceps 12 mm in diameter. The MEMS sensor can detect pressure and two directional shear stresses at the same time. Attaching such MEMS sensor to a tip of a forceps enables us to detect the grasping stress on organs at the actual point where the stress applied. By using two MEMS sensors, it is available that the stress applied by each of two tips can be detected individually. As demonstrated in this paper, because the MEMS sensor can be attached to existing devices, our method is expected to apply to device evaluation.

In this paper, we evaluated the characteristics of the forceps with the MEMS sensor during the general actions in the usage of a grasping forceps, which are grasping, pushing and pulling actions. Finally, we measured the shear stress during pulling action of pig liver blocks.

II. GRASPING FORCEPS WITH A MEMS SENSOR

We have developed the MEMS sensor whose size is 7 mm

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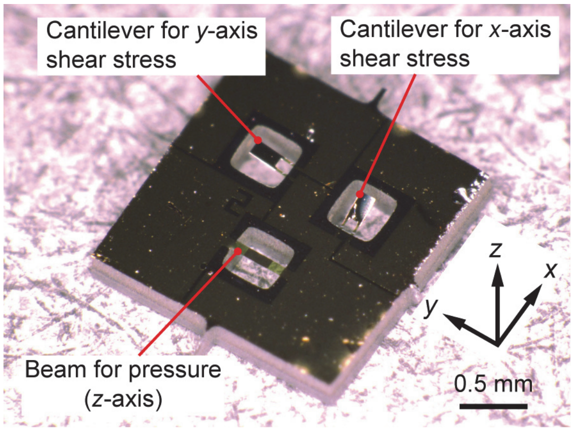

Figure 1. Photograph of a triaxial MEMS tactile sensor.

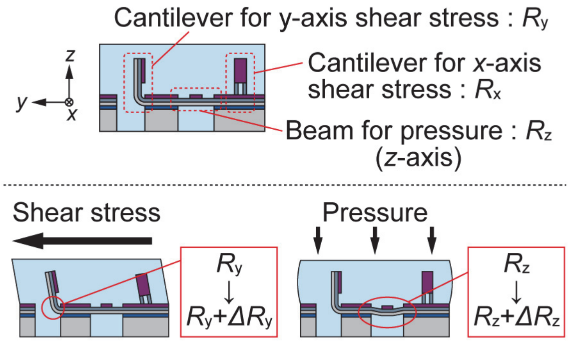

Figure 2. Measurement principle of the triaxial MEMS tactile sensor.

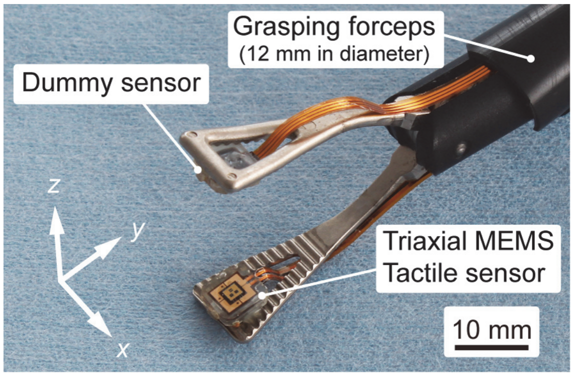

Figure 3. Photograph of the tip of the grasping forceps with a triaxial MEMS tactile sensor.

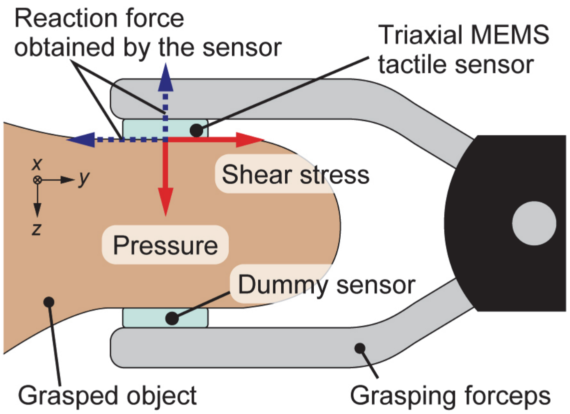

Figure 4. Schematic illustration of the force measurement when an object is grasped by the forceps with a triaxial MEMS tactile sensor.

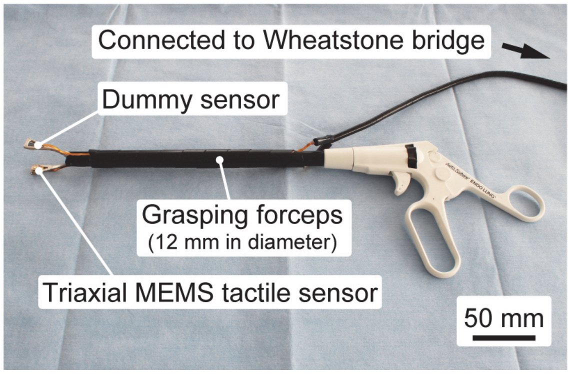

Figure 5. Photograph of the whole of the grasping forceps.

× 7 mm × 2 mm. The fabrication process is shown in [5]. Fig. 1 shows a photograph of a sensor chip buried in the developed MEMS sensor. The size is 2 mm × 2 mm × 0.3 mm. The sensor chip consists of a beam for pressure measurement and two cantilevers placed in orthogonal directions for measurement of two directional shear stresses. The MEMS sensor is formed by burying the chip in resin. A piezoresistive layer is formed at the surface of the beam and the cantilevers so that the resistances of the beam and the cantilevers change according to the stresses applied to them (Fig. 2). We can calculate the applied force from the resistance change [5, 6]. Because the cantilevers are placed in orthogonal directions, each piezoresistive cantilever independently detects the component of the shear stress in the cantilever's vertical axis. Therefore, the MEMS sensor can simultaneously detect pressure and two directional shear stresses. The resistance change is measured by being converted to voltage change using a Wheatstone bridge.

We placed the MEMS sensor on a tip of a grasping forceps (Covidien; ENDOLUNG) as shown in Fig. 3. The grasping forceps is 12 mm in diameter. To maintain the symmetry of the grasping part of the forceps, we placed a dummy sensor on the other hand of the tip (Fig. 3). The MEMS sensor and the dummy sensor were glued with the tip of the forceps using epoxy resin adhesive. By the forceps with the MEMS sensor, we quantify the stresses applied on an organ by a forceps. When the forceps grasps an organ, the forceps detects the reaction force generated by the applied stresses (Fig. 4). We estimate the stresses on the organ from the measured reaction force. A photograph of the whole grasping forceps with a MEMS sensor is shown in Fig. 5. The wire from the sensor to the handle is so thin that the grasping forceps can go through a trocar.

III. CHARACTERISTICS DURING GRASPING, PUSHING AND PULLING ACTIONS

Grasping, pushing and pulling actions are general actions in the usage of the grasping forceps. To evaluate the stresses on organs during such actions, we measured the relationships between the magnitude of applied pressure and shear stresses and the resistance change ratio of the MEMS sensor.

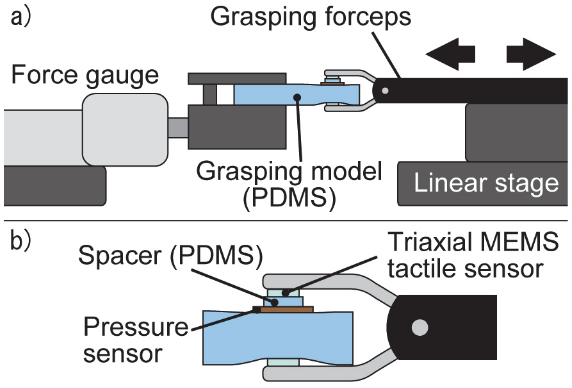

Figure 6. Measurement setup for pressure and shear stress.

A. Setup of the pressure and shear stress measurement

Measurement setup for pressure and shear stress is shown in Fig. 6. The setup consists of a grasping model as a grasping object including a pressure sensor (KYOWA; PS-05KC), a linear stage for moving the forceps in the axial direction of the forceps and a force gauge (IMADA; ZP-20N) for measurement of the shear force.

Grasping action is generated using a clamp fixed on the grip of the forceps. During the grasping action, the output of *z*-axis sensor of the MEMS sensor is compared with the output of the commercial pressure sensor. Pushing and pulling actions are generated using the linear stage. During the pushing and pulling actions, the output of *y*-axis sensor is compared with the shear stress calculated from the output of the force gauge.

The structure of the grasping model is that the commercial pressure sensor is sandwiched by a PDMS (polydimethylsiloxane) block and a PDMS spacer. The PDMS block deforms by the applied pressure and shear stress like an organ. The PDMS spacer is placed between the MEMS sensor and the commercial pressure sensor to adjust the contact area between the MEMS sensor and the grasping model and the thickness of the grasping model.

B. Grasping action

The relationship between the output of the commercial pressure sensor (p) and the resistance change ratio ($\Delta R_z/R_z$) of the *z*-axis sensor of the MEMS sensor is shown in Fig. 7. The resistance change ratio was proportional to the output of the pressure sensor. The proportional constant (k_{zz}) was 9.2×10^{-3} MPa^{-1}. This means that we can estimate the pressure on the grasping object from the *z*-axis sensor. The maximum grasping pressure using the grasping forceps was 0.15 MPa.

C. Pushing and pulling actions

The resistance change ratio ($\Delta R_y/R_y$) of *y*-axis sensor during pushing and pulling actions is shown in Fig. 8. The resistance change ratio and the output of the force gauge were measured every 100 μm displacement from 0 μm to ±500 μm. The shear stress (τ_y) is calculated from the following equation.

$$\tau_y = F_s \times u_t / A_s \tag{1}$$

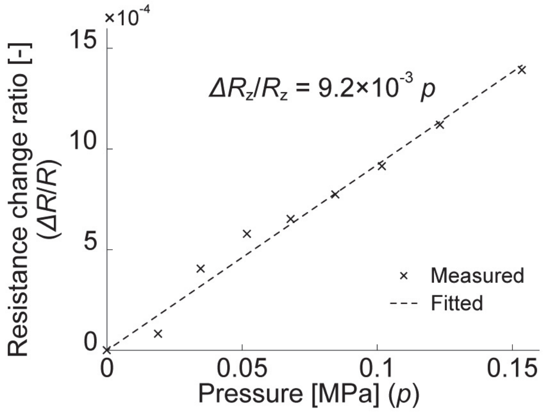

Figure 7. The relationship between the applied pressure and the resistance change ratio of the *z*-axis sensor.

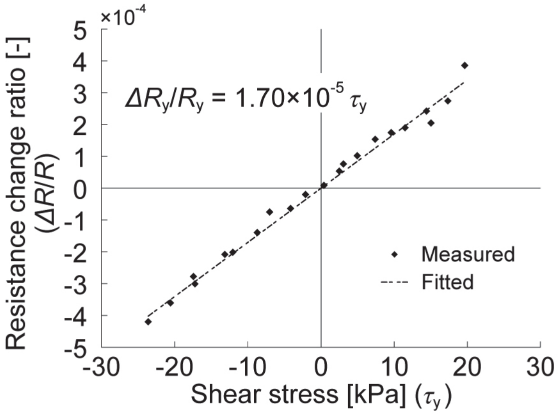

Figure 8. The relationship between the applied shear force and the resistance change ratio of *y*-axis sensor.

where F_s is the shear force measured by the force gauge, u_t is the ratio of the force on the MEMS sensor to F_s, and A_s is the area of the sensor surface. u_t is determined by the positional relationship between the tips of the forceps and the line of action of F_s. In this experiment, the distance between the line of action of F_s and the MEMS sensor is two-thirds of the thickness of the grasping model. Therefore, the calculated value of u_t is 1/3. $\tau_y > 0$ means the pushing action and $\tau_y < 0$ means the pulling action. The resistance change ratio of *y*-axis was proportional to the shear stress. The proportional constant (k_{yy}) was 1.70×10^{-5} kPa^{-1}.

IV. IN VITRO MEASUREMENT OF PULLING ACTION

We measured the shear stress on pig liver blocks during pulling action with grasping them by the forceps. We prepared 4 samples whose weights were 56.8 g, 117 g, 156 g and 208 g, respectively. As shown in Fig. 9, each sample was pulled up with being grasped. The grasping pressure was constant during each measurement. We compared the shear stress estimated from the weight of the liver blocks and the shear stress calculated from the data measured by the forceps. Each sample was pulled up 5 times. The means and the standard deviations are shown in Fig. 10. Estimated shear stress is calculated from the following equation.

$$\text{Estimated } \tau_o = w \times u_t / A_s \tag{2}$$

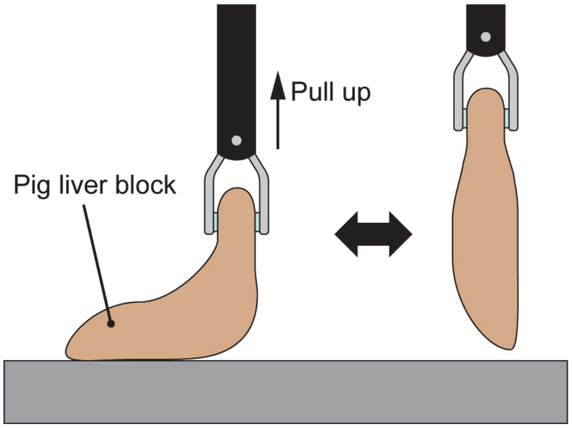

Figure 9. Pulling action of a pig liver block.

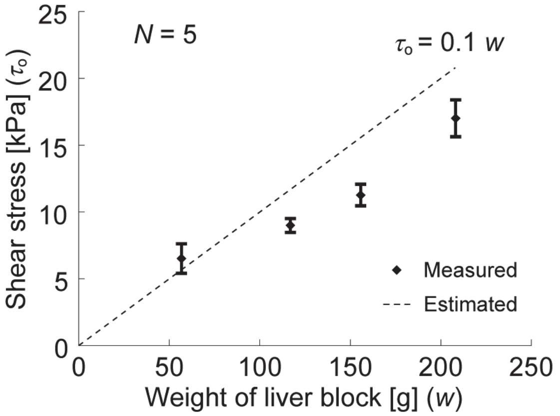

Figure 10. The relationship between the weight of the liver block and the shear stress.

where w is the weight of the liver block and u_t is the ratio of the force on the MEMS sensor to w. In this experiment, the value of u_t was 0.5 under the assumption that the load generated by the weight of the liver block was equally applied to the two tips of the forceps. Actually, the applied stresses on the tips were unequal because the liver blocks were asymmetric. Thus, the value of u_t was not always 0.5. Measured shear stress is calculated from the resistance change ratio of y-axis sensor using the following equation.

$$\text{Measured } \tau_o = (\Delta R_y/R_y)/k_{yy} \qquad (3)$$

The measured value increased with the increase of the weight of the liver block. Therefore, the grasping forceps with the MEMS sensor is applicable to the measurement of shear stress on organs. Moreover, the shear stress pulling up several hundred gram of liver block was several ten kPa. The maximum and the average differences between the estimated value and the measured value were 28% and 21% of the estimated value, respectively. The difference occurred because u_t is set to be 0.5 though the u_t varies with sample. The problem will be solved by measuring the shear force on each tip of a forceps attaching the sensors on the both tips of the forceps.

V. CONCLUSIONS

We attached a triaxial MEMS tactile sensor which we have developed to a commercial grasping forceps. The MEMS sensor can simultaneously detect pressure and two directional shear stresses. The sensor size, which is 7 mm × 7 mm × 2 mm, is enough small to attach to the tip of a grasping forceps 12 mm in diameter.

The characteristics of the forceps during grasping, pushing and pulling actions were evaluated. During grasping action, we compared the resistance change ratio of z-axis sensor of the MEMS sensor with the output of the commercial pressure sensor attached to the grasping model. The resistance change ratio was proportional to the output of the pressure sensor. The proportional constant (k_{zz}) was 9.2×10^{-3} MPa^{-1}. This means that we can estimate the pressure on the grasping object from the z-axis sensor. The maximum grasping pressure using the grasping forceps was 0.15 MPa. During pushing and pulling actions, we measured the resistance change ratio of y-axis sensor. Simultaneously, we measured the pushing and pulling force using a force gauge. Considering the relationship between the resistance change ratio and the shear stress calculated from the output of the force gauge, resistance change ratio of y-axis was proportional to the shear stress. The proportional constant (k_{yy}) was 1.70×10^{-5} kPa^{-1}.

An in vitro measurement using pig liver was done. Though the difference between the estimated value and the measured value was large, we confirmed that the measured value increased with the increase of the weight of the liver block. The measured shear stress was 21 % smaller than the estimated shear stress on average. This is not because the characteristics of the MEMS sensor, but because the inequality of the applied stress on the liver was ignored. This result shows that our system is applicable to the measurement of the stress applied on organs. Especially, the stress that the single tip of the forceps applies on organs was measured. The MEMS sensors have wide applications because it is available to attach them to various existing devices.

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