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Sensing Elasticity from the Phase Difference of the Stepper Motor *

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Abstract— **We have developed a made-to-order surgical support manipulator with a function that senses the mechanical characteristics of internal organs, and which can be customized based on the maximum grasping force of the patient. The purpose of this study is to establish an elasticity-sensing model that uses the phase difference of the stepper motor based on material strength and to apply it to *in vitro* organs. In this study, we propose a measurement model and develop a prototype that is used in experiments on silicon rubber and *in vitro* organs in a dog. Young's modulus *E* and spring constant *K* are measured by the prototype and a material testing machine. The results of the prototype showed good agreement with those of the material testing machine, and that the proposed model will be a great help in the development of surgical support manipulators.**

I. Introduction

Tactile sense is a necessary element in determining an organ's condition during surgery. Knowing the mechanical characteristics of the organ ensures effective diagnosis and treatment. A surgeon's hand can sense the characteristics in open abdominal or chest surgery. However, the sensing ability is reduced in endoscopic surgery and is completely lacking in robotic-assisted surgery. Many methods have been developed to sense the grip force or the mechanical characteristics of the organ such as [1-5]. For a surgical manipulator with a sensing function, it is important for the mechanism to be simple and autoclavable. Strain gauges are simple sensing devices and they are easy to use, and pneumatic actuators are free of the possibility of electric shock. However, these technologies are not compatible with autoclave sterilization because of their electrical components or system indivisibility. A bilateral master-slave manipulator has a mechanism that can be divided into autoclavable mechanical parts and electrical parts; however, it is difficult to construct simple master mechanisms because of the motor and the encoder. In our design concept, we considered that it is necessary for the simple surgical manipulator to have an autoclavable tool mechanism, a unilateral control system, and a separate function of sensing and grasping as needed. In addition, the grasping force should be able to be set based on the sensing characteristics. Our goal is to develop a made-to-order surgery support manipulator with a sensing function for the mechanical characteristics of internal organs that can be customized based on the maximum grasping force for each patient. To this end, we propose an elasticity-sensing gripper that uses the phase difference of the stepper motor that can sense and grasp objects. When the applied force from the motor and the reaction force from the object are the same, the motor loses synchronism between rotor speed and stator excitation speed; which is known as the step-out phenomenon. The elasticity can be calculated by the maximum torque of the motor and the displacement of the object until step-out. We developed a measurement model based on Newton's equation, constructed a prototype and calibrated it by means of an extension coil spring, and applied it to *in vivo* organs in [6-7]. The purpose of this study is to establish an elasticity-sensing model based on material strength, build prototypes, and apply them to silicon rubber and *in vitro* organs.

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II. Principle of Sensing Elasticity

A. Measurement model

The elasticity of an object measured by this proposal model is defined as Young's modulus *E*, which was calculated as shown below. A model to measure the stress and the strain for a test piece is shown in Fig. 1. Although shearing force was generated in the test piece, it could be ignored becaue of the minute angle displacement. When the applied force from the stepper motor and the reaction force from the test piece were the same, they were in a state of static equilibrium. At this time, the tangential force F applied from the motor to the test piece was calculated from the motor torque T and the arm length L as follows: $F = T / L$. The compressive force in the vertical direction P was calculated from the angle displacement of the rotaed arm $d\theta$ as follows: $P = F \cos d\theta$. The compressive stress σ was finally measured from a cross-section area of the test piece A as:

$$\sigma = P/A = T \cos d\theta / LA \tag{1}$$

The tangential displacement of the test piece dx until step-out approached the angle displacement multiplied by the arm length as: $dx = L \sin d\theta \fallingdotseq Ld\theta$. The linear displacement in the vertical

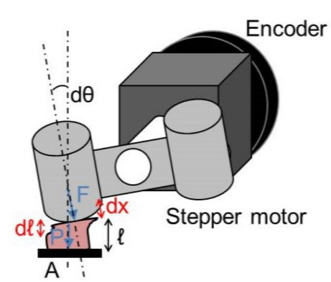

Figure 1. Method of measuring the stress and the strain for a test piece using the phase difference of the stepper motor.

direction dl was calcurated as: $dl = dx \cos d\theta$. The compressive strain ε was finally measured from the height of the test piece l as:

$$\varepsilon = d\ell/\ell \fallingdotseq L\, d\theta \cos d\theta / l \quad (2)$$

From these steps, the model-based Young's modulus (Em) was measured from the stress σ and the strain ε at the step-out phenomenon as:

$$Em = \sigma / \varepsilon = T\, l / L^2 A\, d\theta \quad (3)$$

The elasticity of the organ measured by the proposed model was redefined as spring constant K because the organ was a mass. The model-based spring constant (Km) was measured from the compressive force in the vertical direction P and the linear displacement in the vertical direction dl at the step-out phenomenon as:

$$Km = P / dl = T / L^2\, d\theta \quad (4)$$

B. *Prototype for verifying proposed model*

We constructed a prototype to verify the measurement model for the object as shown in Fig. 2. The applied force was about 1 N because the gripping force for the organ was about 5 N as described in [8]. The prototype consisted of a stepper motor (maximum torque: 0.033 Nm, mechanical step angle: 0.72 deg/step, CFK523BP2, Oriental Motor Co., Ltd.), an arm (length: 15 mm), and a rotary encoder (resolution obtained by multiplication by four: 1.125×10^{-3} deg/pulse, MES-30-5000PST16, Microtech Laboratory Inc.). The mechanical step angle of the motor is further divided into 2.88×10^{-3} deg/step by multi-phase excitation for some stator coils.The size of the prototype was 136×55×59 mm, and it had a mass of 490 g. It had a resolution of 0.8 μm at the tip of the arm.

C. *Experimental method*

To evaluate the measurement model for Em, the model was used in an experiment for homogeneous elastic bodies as described below. The experimental device is shown in Fig. 3.

i) The objects in the experiment were seven silicon rubber test pieces with hardness degrees of 5, 10, 20, 30, 40, 50, and 60. The size of each test piece was 8 mm in diameter and 3 mm in height, and the test pieces were cut out by a sampler.

ii) A test piece was set on the Z axis stage. The distance at the top of the test piece was measured by an LED sensor (resolution: 20μm, LH-512, Panasonic Industrial Devices SUNX Co., Ltd.). The arm was positioned above the top of the test piece. The distance at the top of the arm was measured by the LED sensor. The arm was brought into contact with the test piece by adjusting the Z axis stage about the calculated air gap.

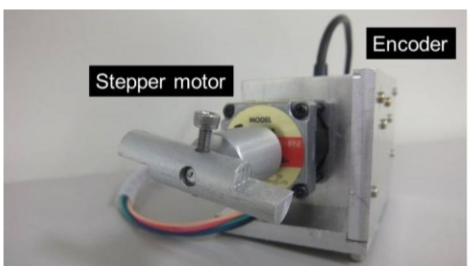

Figure 2. Prototype of the measuring device.

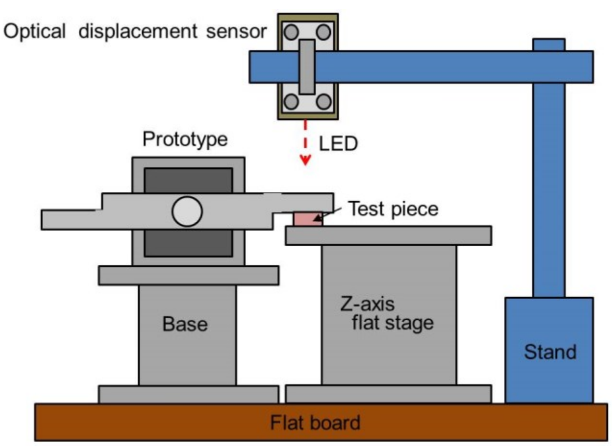

Figure 3. Experiment device for measuring the stress and the strain of a test piece using the prototype.

Table 1. Results of Young's modulus for 7 silicon rubber test pieces measured by the material testing machine *Et*, and the prototype *Em*.

Hardness of silicon rubber [degree]	**Young's modulus [N/m^2]**	
	Et	***Em***
5	0.52	0.38
10	0.67	0.42
20	1.31	0.54
30	1.32	0.59
40	1.60	0.87
50	2.95	2.50
60	3.36	2.62

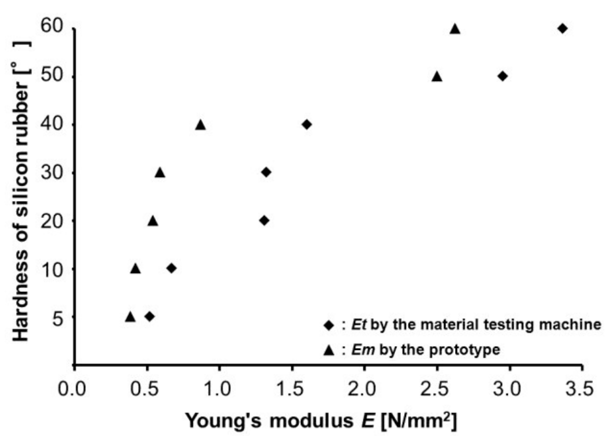

Figure 4. Comparison of measured Young's modulus *Et* by the material testing machine and *Em* by the prototype.

iii) The motor was driven at maximum torque and a frequency of 4 kHz. The tangential applied force was 2.3 N and the speed was 3 mm/s. The encoder gave the rotational angle.

iv) The *Em* was measured finally from (3).

v) For a comparison of the *Em* measured by the prototype, the true compressive stress and strain curve of the test piece was measured using a material testing machine (resolution: 0.08 N, EZ-Test, Shimadzu Corp.). The applied speed of the cross head was 0.1 mm/s. The true Young's modulus (*Et*) was calculated by the differential value of the stress and strain curve.

D. Results

The *Em* measured by the prototype and the *Et* measured by the material testing machine are shown in Table 1 and Fig. 4.

III. Measurement of *In Vitro* Organs

A. Prototype of Bevel-geared Gripper

We constructed a prototype of a gripper to verify the measurement model for the organ as shown in Fig. 5. The prototype consisted of a stepper motor (maximum torque: 0.023 Nm, mechanical step angle: 0.72 deg/step, CFK513BP2, Oriental Motor Co., Ltd.), a bevel-geared jaw (length: 20 mm) and a rotary encoder (the same as above). The mechanical step angle of the motor was further divided into 2.88×10^{-3} deg/step. The gripper had a capacitance sensor to detect contact with the organs. The size of the prototype was 150×56×60 mm, and it had a mass of 425 g. It had a resolution of 1 μm at the tip of the arm.

B. Experimental method

To evaluate the measurement model for *Km*, the model was used in an experiment using organs by as follows. An organ has inhomogeneous elasticity and viscosity depending on the structure, even if it is the same organ.

i) The objects in the experiment were five fresh *in vitro* organs enucleated from a dog within 12 hours. The organs were the liver, small intestine, colon, urinary bladder, and greater omentum. The small intestine and colon were emptied of contents. The organs were misted directly with a humidifier. The environmental conditions were maintained at a temperature of 25 to 30 °C and a humidity of 70 to 80%.

ii) The jaw of the gripper was brought into contact with the organ as detected by the capacitance sensor.

iii) The motor was driven at maximum torque and a frequency of 5 kHz. The tangential applied force was 1.2 N and the speed was 5 mm/s. The encoder gave the rotational angle.

iv) The *Km* was measured from (4).

v) For the comparison of the *Km* measured by the prototype, the true force and displacement curve of the organ was measured using the testing machine. The applied speed of the cross head and environmental conditions were the same as the prototype. The true spring constant (*Kt*) was calculated by the differential value of the force and the displacement curve. The above steps were repeated five times. The average and the standard deviation (SD) were then calculated.

C. Results

The *Km* measured by the prototype and the *Kt* measured by the material testing machine are shown in Table 2 and Fig. 6.

Table 2. Results of spring constant for five fresh *in vitro* organs from a dog measured by the material testing machine *Kt*, and the prototype of bevel-geared gripper *Km*

Organs	**Spring constant [N/m] ± SD**	
	Kt	***Km***
Colon	488±3.1	487.1±70.2
Bladder	382±6.7	378.2±42.1
Omentum	228±3.3	193.5±8.0
Liver	204±5.4	173.5±3.7
Small intestine	163±3.6	151.0±4.9

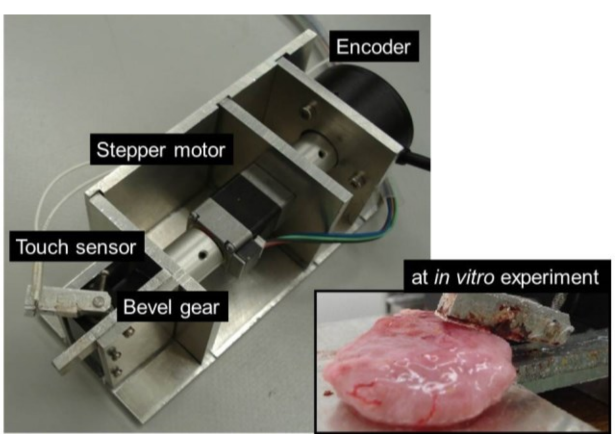

Figure 5. Prototype of bevel-geared gripper with a single jaw.

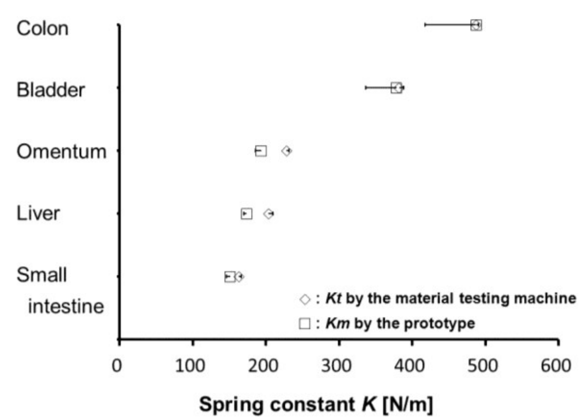

Figure 6. Comparison of measured spring constant *Kt* by the material testing machine and *Km* by the prototype of bevel-geared gripper.

IV. DISCUSSION

The true Young's modulus or spring constants measured by the masterial testing machine were calculated from tangent stiffness under precompression. The values measured by the prototype were calculated by linear displacement from the point of arm contact to the point of step-out of the motor. The *Em* or *Km* was obviously smaller than the *Et* or *Kt*, and the trends in the differences were readily identifiable. Comparing the trends of the data as shown in Fig. 4 and Fig. 6, the *Em* was similar to the *Et*, and the *Km* was similar to the *Kt*. Based on the result, it was confirmed that the proposed model was good enough to measure the trends of difference of Young's modulus for silicon rubber and the spring constant for *in vitro* organs. Furthermore, a specialist in gastroenterological surgery confirmed that the results showed the same differences in surgery. This paper demonstrates the possibility of replacing a force sensor by using the proposed method with a stepper motor for measuring organ properties.

For the measurement of *in vivo* organs in an endoscopic view, it is necessary for the mechanism to have a long axial shape and a low-friction transfer mechanism. To detect the touch of the organ, an autoclavable sensor such as air pressure is needed for the jaw of the gripper. To apply the design to hard organs, a convertible mechanism is needed to change the mode of grip and sense. For clinical use, it is important to sense and display the elasticity of an organ automatically. Therefore, a new prototype has been developed as shown in Fig. 7. *In vivo* experiments will be performed in the near future. The *in vivo* elasticity of hollow viscera such as small intestine and colon are expected to change because these are expanded by air or are full of contents, in addition the bowel wall of the colon is thin. To know the true spring constant of organ, the viscoelasticity needs to be calculated based on a dynamics model such as the Maxwell model or the Kelvin-Voigt model as described in [9]. These measuring properties of organs will lead to the development of a surgical simulator and training system.

V. CONCLUSION

We established a new elasticity-sensing model using the phase difference of the stepper motor based on material strength to build prototypes to sense elasticity, and applied it to *in vitro* organs. Based on the experimental results, it is concluded that the proposed model will be a great help in the development of a made-to-order surgery support manipulator with a sensing function for the mechanical characteristics of internal organs that can be customized based on the maximum grasping force for each patient. Future work includes an *in vivo* experiment for laparoscopic surgery using a new prototype and constructing a measurement method for the viscoelasticity of organs using the prototype.

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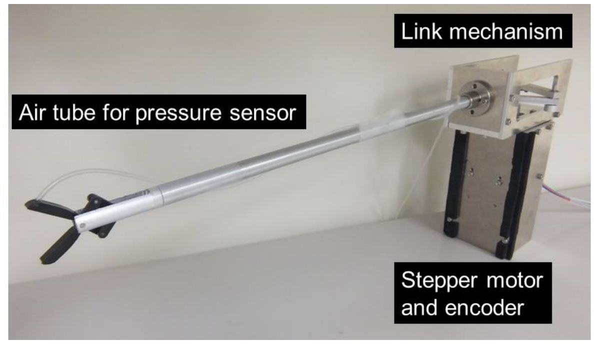

Figure 7. Prototype of long axis shape with air pressure sensor.

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