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# Development of a Sensor System with Syringe Based on Tactile Sensing Using Balloon Expansion

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*Abstract*— **The aim of this study is the development of a human-friendly tactile sensor for measuring softness, sliminess, smoothness, and so on. We have proposed active tactile sensing method using balloon expansion. A balloon is contacted with an object and expanded by using fluid. Tactile information is evaluated by measuring the expansion process. In this paper, we developed a sensor system using syringe. It is a compact system and can ensure enough safety for human body tissues in safe contact, using no electric power, and sterilization. Pressure changes and volume changes of the balloon can be measured together in the balloon expansion. First, overview of the developed sensor system is presented. Next, composition of the sensor system and the sensing process are presented. Then, experiments using the developed sensor are conducted on samples with different stiffness and surface conditions. Features extracted from sensor outputs indicate that the sensor can know the difference both the stiffness and surface condition. The results show the validity of the proposed sensor system.**

## I. Introduction

Tactile sensing techniques have been desired in medical field. Surgeons perceive various information of body tissue such as stiffness and smoothness through active touch during usual surgery. Tactile information plays an important role for tumor diagnosis, area cognition, and so on. Currently, such tactile information is evaluated subjectively. Furthermore, it is hoped that minimally invasive surgery (MIS) such as endoscopic surgery is widely used. MIS is the technique of operating on the internal organs of the body without damaging a much greater amount of surrounding healthy tissue. It benefits the patient through the reduction of trauma, postoperative complications, disruption of life-style, and so on. However, MIS needs highly trained skill and is available to limited procedures. One of the limitations of the present MIS is the lack of tactile sensitivity. It seems that tactile sensing techniques are effective to MIS.

Recently, medical tactile sensors have been proposed [1][2]. These studies have focused on measurement of contact force, pressure distribution, and stiffness of objects. Stiffness is an important factor for diagnosis. However, surface conditions such as sliminess are also important as well as stiffness. Concerning human tactile perception, it is described that feeling of surface conditions is an independent factor from the feeling of stiffness [3]. Therefore, medical tactile sensors that can measure stiffness and surface conditions are expected to evaluate like human touch. Medical tactile sensors that can measure stiffness and surface conditions are more effective.

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Tactile sensors for measuring various tactile information have been proposed except medical application [3][4]. However, these sensors can not be usable as medical sensors. They must provide enough safety for human. Safe contact to body tissue (non-damage and biocompatible material) and sterilization is necessary. In addition, sensors must keep prevention of leakage current to the body. Sensors should not use electric power in the body. Additionally, sensors are required to be applicable to endoscope or catheter in size and shape for MIS. Generally, devices used in MIS have small and linear shape.

Recently, some tactile sensors considering enough safety for body tissue have been proposed. The force sensor using a balloon [5], stiffness sensor using a air cushion [6], and the non-contact impedance sensor using air bursts and a laser displacement sensor [7] have been proposed. However, they are not available for measuring surface conditions.

The aim of this study is the development of a human-friendly tactile sensor for measuring softness, sliminess, smoothness, and so on. We have proposed active tactile sensing method using balloon expansion [8][9]. A balloon is contacted with an object and expanded by using fluid. We developed the sensor probe with the balloon and assembled the sensor system with the pump. Pressure changes were measured in the balloon expansion and stiffness and sliminess were evaluated by using them. We confirmed a potential of the sensing method through fundamental analysis and experiments. The sensor system is human-friendly in safe contact and using no electric power. However, it has some issues to address for clinical application. It is composed of many equipments, a regulator, pressure sensors, tank, etc. The time for sensing is long. Furthermore, it can not ensure sterilization of the fluid in balloon. By using the pump, the fluid is contacted with the pump, the pressure sensor, the solenoid valve, and others. It is necessary to sterilize all of them for the sterilization of the fluid. It is very difficult and impractical.

Therefore, we propose a sensor system with a syringe in this paper. It is compact and can ensure the sterilization the fluid as well as safe contact and using no electric power. Furthermore, in this system, pressure changes and volume changes of the balloon can be measured together in the balloon expansion and the time for sensing is short. More effective valuation of tactile information is expected.

First, overview of the developed sensor system is presented. Next, composition of the sensor system and the sensing process are presented. Then, experiments using the developed sensor are conducted on samples with different

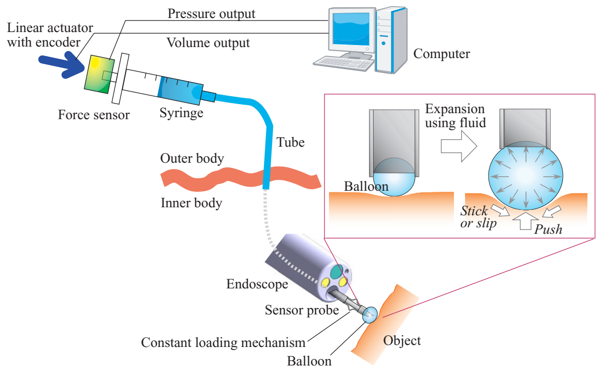



Fig. 1. Conceptual schematic illustration of proposed sensor.

stiffness and surface conditions. Features extracted from sensor outputs indicate that the sensor can know the difference both the stiffness and surface condition. The results show the validity of the proposed sensor system.

## II. Tactile Sensor with Balloon Expansion

### A. Overview

*1) Basic Idea:* In our proposed sensing, a balloon is contacted with an object and expanded by using fluid. In the process of the expansion, the balloon pushes the object and the contact surface of the balloon slips or sticks. These phenomena depend on stiffness and surface conditions such as friction of the object. Therefore, by evaluating the expansion of the balloon, it is expected that various tactile information can be measured.

In this paper, we developed the sensor system with a syringe. Fig. 1 shows the conceptual schematic illustration of the sensor system. The sensor probe has a balloon at the top terminal and a constant loading mechanism. It is filled up in water and is connected to a syringe through a tube. The balloon is expanded by pushing the syringe with a linear actuator. The pressure of the balloon can be measured by a force sensor set on the syringe and the volume of the balloon can be measure by the pushing distance of the syringe. Tactile information is evaluated by using pressure changes and volume changes in expansion.

*2) Safety for Human:* The proposed sensor is highly human-friendly. The balloon is soft and flexible and load given to the object is mechanically kept to be constant. When the sensor is applied to the inner body, sensor output signals, which are pressure and volume of the balloon, are measured in the outer body. The sensor does not need electric power in the body. Furthermore, the sensor probe, the tube, and the syringe, which we call "sensor probe unit" in set, can ensure sterilization including the fluid in the balloon by fabricating them by the set under sterile condition. Actually, balloons, tubes, and syringes are already used in clinical application. Therefore the sensor probe unit can fabricate under sterile condition. Additionally, in this case, it is required to make the sensor probe unit disposable. It is realistic because the sensor probe, tube, and syringe are not expensive. Here, device for pushing syringe and measurement system such a force sensor are not required to be sterilized since they does not contact with the body tissue.

Furthermore, the sensor probe has a potential to have compatibility with the endoscope since it has a linear shape. And, tools with balloons such as balloon catheters and double balloon endoscope have been already used as clinical application. So it is expected that it is not difficult to minimize the size of the proposed sensor.

*3) Locally Active Sensing:* The proposed sensing has another advantage for human body. It is generally to slide a sensor over an object for measuring surface conditions of the object [3]. However, it is very difficult to steadily slide a sensor over body tissues since they are soft and their surface geometries are not flat but usually various. Our proposed sensor does not need to be slid over an object. The sensor touches an object locally through the balloon expansion. Partial slippage occurs between the contact surface of the balloon and the object. Here, detection of surface conditions such as friction is necessary for us to lift an object by an adequate grasping force. It is known that partial slippage between fingers and an object is important [10]. The soft finger in which tactile sensors for measuring friction were embedded was developed [11][12] and it was confirmed that the friction can be detected the moment the finger contacts with the object. In the proposed sensing, due to using partial slippage between the balloon and an object, the physical phenomenon is similar to human case. Therefore, obtained output signals might include similar features to tactile information that human obtains.

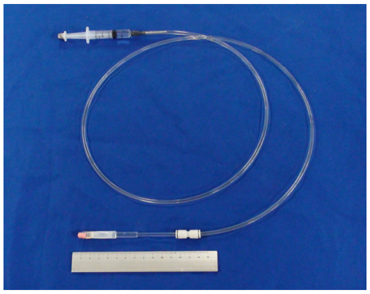
### B. Sensor System

*1) Sensor Probe Unit:* Photograph of a sensor probe unit is shown in Fig. 2 (a). It is composed of a sensor probe, a flexible polyurethane tube which is 4 [mm] in outer diameter, 2 [mm] in inner diameter, and 1.1 [m] in length, and a syringe which is 2.5 [ml] in volume.

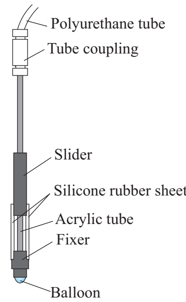
Geometry of the sensor probe is shown in Fig. 2 (b). A latex balloon is fixed at the top terminal of an acrylic tube which is 4 [mm] in outer diameter and 2 [mm] in inner diameter. The balloon is 4 [mm] in diameter and 0.15 [mm] in thickness before expansion. The other terminal of the acrylic tube is connected to the polyurethane tube by a coupling.

In addition, the sensor probe has a constant loading mechanism [9]. It is composed of two larger tubes, which are a fixer made of a light curing resin tube and a slider made of an acrylic tube with inner diameter of 4 [mm], and four silicone rubber sheets, which are 1 [mm] in thickness, 20 [mm] in length, and 45 [deg] in arc of cross section. As shown in Fig. 2 (b), the acrylic tube with the balloon is inserted in the fixer and the slider. The fixer is attached on the terminal of the acrylic tube. The slider is set on the acrylic tube. The silicone rubber sheets are set between the fixer and the slider by bonding their edges.

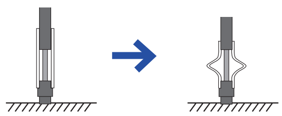
The constant loading mechanism keeps a load given to the object constant. It is difficult that electric instruments such a force sensor are applied to the probe to keep a load constant as mentioned above. The developed sensor probe mechanically keeps a load constant. In order to contact the



(a) Photograph




(b) Geometry of probe



(c) Constant Loading by buckling

Fig. 2. Sensor probe unit.

sensor probe with an object, the slider of the constant loading mechanism is held and moved to the object.

Fig. 2 (c) shows schematic illustration of the contact by the probe. When the probe is contacted with the object, the silicone rubber sheets are compressed and buckled. After buckled, they are deformed largely and the load is almost constant. The load does not largely change according to moving distance of the slider. This range is enough long to see by sight. Therefore, operators are easy to keep a load constant. The developed sensor prove gives a constant load of 0.59 [N] Here, a constant load can be adjusted by changing physical properties of the silicone sheets such as Young's modulus, thickness, etc.

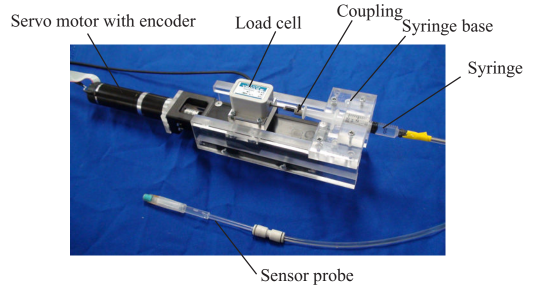
*2) Syringe Driver and Measurement Unit:* Fig. 3 (a) presents the syringe driver. The syringe driver is composed of a linear actuator which is driven by a servo motor with an encoder, a load cell, and a base to set the syringe. By moving the load cell with the linear actuator, the syringe is pushed. There is a coupling on the bottom of the syringe and the syringe is connected with the rod of the load cell. Pressure and volume of the balloon are measured by the load cell and the encoder, respectively.

Fig. 3 (b) presents the measurement setup. The system is compact and it is easy to move. The measurement setup is composed of a strain gauge amplifier, a controller box, and a PC for display of sensing result. The controller box have a SH4A microcomputer. It receives output signals from the load cell and the encoder by A/D converter and counter and sends a control voltage to the motor by D/A converter. The output from the load cell is sent to the controller box via the amplifier. The sensing results, which are output signals, rating value, status of the sensor system, and so on, are displayed in the PC by sending the data from the controller box through TCP/IP connection. The start or stop of sensing is conducted by using a foot switch.

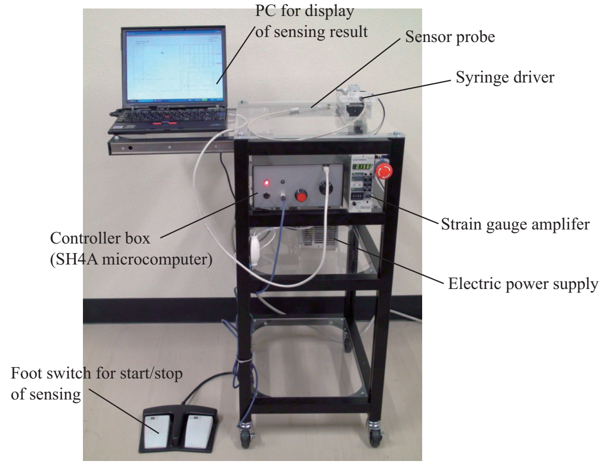
## III. Sensing Process

### *A. Pressure Changes and Volume Changes in Balloon Expansion*

Typical output which is obtained by expanding the balloon under free condition, in case of no object, is shown in Fig. 4.




(a) Syringe driver




(b) Measurement setup

Fig. 3. Syringe driver and measurement unit.

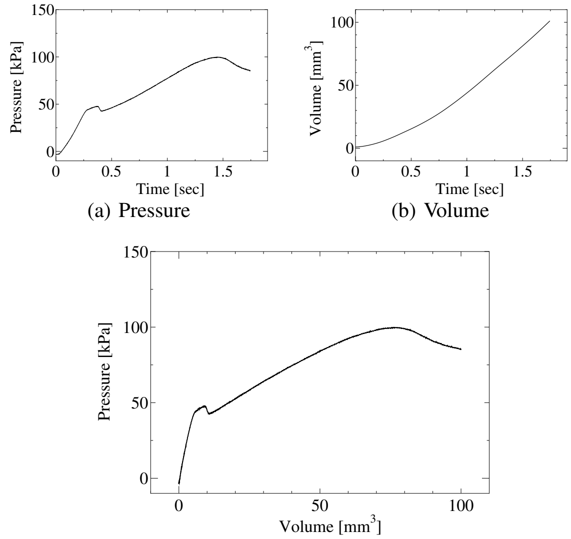
The syringe was pushed by driving the motor at a constant torque. Pressure changes and volume changes are presented in Fig. 4 (a) and (b). Furthermore, we can obtain the relation between pressure and volume of the balloon from these data. The result is shown in Fig. 4 (c).

The volume monotonically increases since the syringe is pushed continuously, while pressure has a peak and then decreases. This result is well known as the characteristic of the balloon [13].

### *B. Initialization and Measurement Method*

As shown above, pressure changes in the expansion have a peak. To ensure the repeatability of the sensing, the volume of the balloon at the sensing start is required to be constant. Consequently, we have focused on the peak point in the relation between the pressure and volume in the expansion in case of no object. Preliminarily after setting up the sensor system, the volume at the peak point in the expansion in case of no object is found and recorded by pushing the syringe with the motor. Then, the syringe is pulled back from the peak point at the set volume ($75\,[\mathrm{mm}^3]$). Therefore, the sensing is always conducted under the same condition where the volume of the balloon is absolutely same. The volume of the balloon is let to be 0 at this start position for the sensing.

In the sensing, the motor is driven at a constant torque and is stopped when the volume reaches to $100\,[\mathrm{mm}^3]$ from the start position. Then, the syringe goes back to the start position for next sensing. In this position recovery, the precise position control is necessary for the accurate sensing. We use the proxy-based sliding mode control, which is a



(a) Pressure (b) Volume

(c) Pressure vs. volume.

Fig. 4. Sensor outputs under free condition (in case of no object).

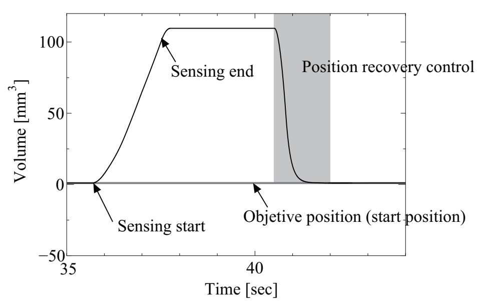


Fig. 5. Position recovery control after sensing.

novel control method proposed by Kikuuwe and Fujimoto [14]. It is an extension of PID control scheme to achieve safer overdamped recovery from large positional errors without sacrificing tracking accuracy during normal operation. Fig. 5 shows an example of volume changes in the position recovery control after the sensing. It is found that the position goes back to the start position precisely.

Additionally, the sensing time is about 2 [sec] in the developed sensor system. In the previous sensor system with the pump, the sensing was conducted up to 15[sec] [9]. The sensor system was largely improved in the sensing time from the previous sensor system.

### C. Processing of Sensor Output Signals

We calculate the outer pressure of the balloon by using the obtained output signals, pressure and volume of the balloon. The expansion of the balloon proceeds with receiving force from the object and the load by the sensor probe. Therefore, the outer pressure means the force given to the balloon from the object and constant loading mechanism of the probe. For rating of the tactile information of the object, it is useful to extract the outer pressure.

The pressure of the balloon is equal to sum of force based on the membrane stress of the balloon and outer pressure as follows:

$$p = \frac{2h}{r}\sigma + p_{out}, \tag{1}$$

where $p$, $r$, and $h$ are the pressure, radius, and thickness of the balloon, respectively, and $\sigma$ and $p_{out}$ are the membrane stress of the balloon and outer pressure given to the balloon, respectively. Here, when the expansion in case of no object, $p_{out} = 0$. Therefore, $p_{out}$ can be obtained by subtracting the pressure obtained in case of no object, which is shown in Fig. 4, from the pressure obtained in the sensing on the basis of the volume.

This processing has the other effect. Pressure changes and volume changes are influenced by changes of physical characteristics of the balloon and tube depending on temperature and other environmental conditions. Pressure output signals include friction due to pushing the syringe. However, the processing as mentioned above can cancel these influences since the subtraction of the pressure is conducted between the result under the condition with the object and the result under the condition without the object. It seems that the environmental conditions except the object are not changed if the condition at the initialization of the sensor system is the same as the condition at the sensing. We calculated the outer pressure by using this processing in the following experiments.

## IV. Experiments

### A. Samples and Method

Body tissues are soft and have surface conditions like sliminess. As shown in Fig. 6, soft gels with liquid membrane on the surface were prepared as samples like body tissues. They are composed of a soft urethane gel and embrocation. Two kinds of urethane gels, A and B, and three kinds of embrocations, water, water laced with yam, which we call "yam water ", and milky lotion, were prepared. Six samples were used in the experiment. Here, the embrocations were applied to each gel at the same volume of 2 [ml]. Young's modulus of the gel A is 0.14 [MPa] and the gel B 0.44 [MPa]. The embrocations give urethane gels different surface conditions. The milky lotion is smooth. The yam water is slimy. The water is not smooth compared with the others. Static friction coefficient of water is 2.07, yam water 0.86, and milky lotion 0.08. The friction was measured by sliding a rigid hemisphere covered with the balloon over the gel B with each embrocation. Viscosity of water, yam water, and milky lotion are 0.90, 2.44, and 118 [mPa·S], respectively. In future work, we will investigate the relationship between tactile sensation like sliminess and physical properties like friction coefficient, viscosity, and so on.

In the experiments, the sensor probe was held on a hand and moved to be contacted with the object Here, the probe was contacted at right angle to the object by sight and the balloon was shortly cleaned with water before the measurement on the sample with different embrocation to avoid mixing in the surface condition.

### B. Results and Discussions

Fig. 7 presents typical outputs obtained on each sample and outer pressure calculated by using the processing mentioned in section III-C. It is found that output signals are

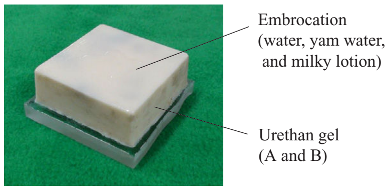



Fig. 6. Sample used in experiments.

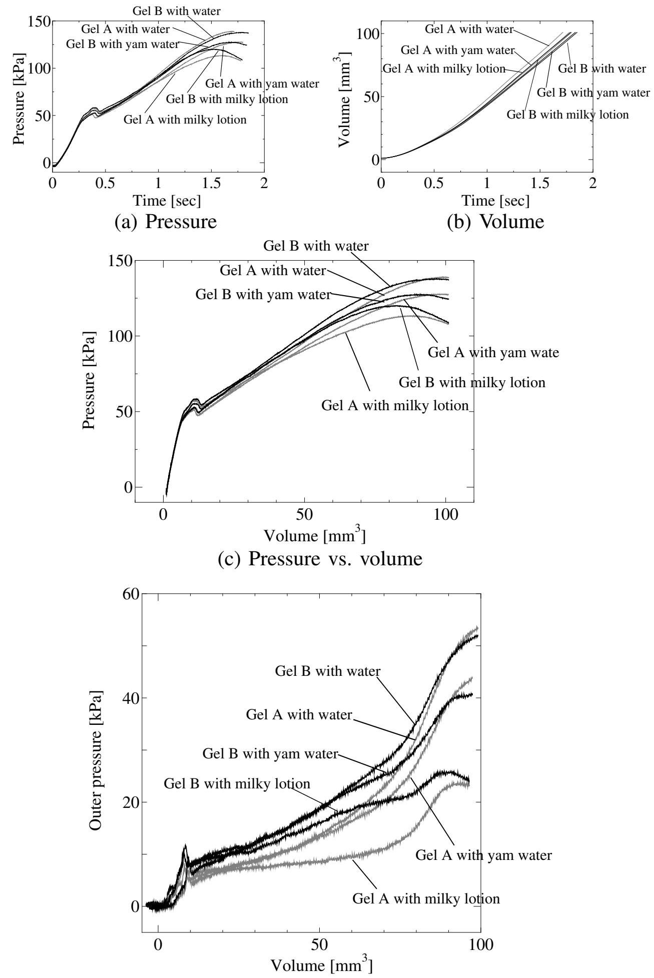
largely different in pressure between samples. Concerning volume changes in time, it seems that increasing gradients on gel A are larger than those on gel B, but large differences are not seen. We focus on the obtained outer pressure as shown in Fig. 7 (d). It can be seen that characteristics of outer pressure largely change around the volume of $60\,[\mathrm{mm}^3]$. Outer pressure is mainly dependent on stiffness until the volume reaches to about $60\,[\mathrm{mm}^3]$ and is mainly dependent on surface conditions after that.

Concerning stiffness, the pressure around the volume of $50\,[\mathrm{mm}^3]$ on sample with large stiffness (gel B) is larger than that with small stiffness (gel A). Concerning embrocations, increasing gradient of the pressure around the volume of $80\,[\mathrm{mm}^3]$ is clearly different between embrocations. Gradient on samples with milky lotion is smaller than that with other embrocations. Gradient on samples with water is large.

Here, under the condition that the sensor probe gives a constant load to an object, the balloon pushes the object at the beginning of the expansion and the balloon expands without pushing in the latter term. This means that the state of the force applied to the balloon by the object and the probe changes with the expansion. Fig. 8 shows the state change of the force applied to the balloon. Let $F_n$ be the load by the sensor probe, $F_s$ be the force applied to the balloon by the object, $F_{sn}$ be the normal component of $F_s$, and $p$ be the pressure of the balloon.

At the beginning, the part except the balloon in the sensor probe also contacts with the object due to the small pressure of the balloon and form of the sensor probe (Fig. 8 (a)). $F_n$ is applied not only to the contact surface of the balloon but also to a part of the sensor probe. Here, the load applied to the balloon by the sensor probe is equal to $F_{sn}$. Then, $F_s$ increases according to the balloon expansion and only the part of the balloon in the sensor probe is contacted with the object (Fig. 8 (b)). Here, $F_{sn}$ is equal to $F_n$. After that, the balloon continues to expand keeping $F_{sn} = F_n$. Therefore, the contribution by the stiffness of the object is dominantly generated on the beginning of the expansion. It seems that the softer the object, the smaller the pressure is. The contribution by the surface conditions of the object is dominantly generated on the latter term of the expansion since pushing phenomenon by the balloon does not occur. Here, friction force and viscous force are given to the balloon according to surface conditions. Therefore, it seems that the smoother the object, the smaller the pressure is. The experimental results are corresponding to these discussions.

Here, we conducted the same experiments by using the sensor probe which has a smaller constant loading mechanism (0.15 [N]). The result is shown in Fig. 9. It is found that

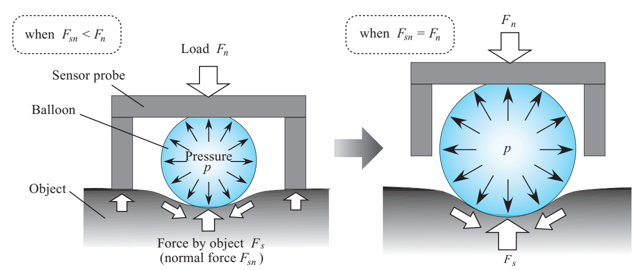



(a) Pressure (b) Volume

(c) Pressure vs. volume

(d) Outer pressure vs. volume

Fig. 7. Experimental results on samples.




(a) When $F_{sn} < F_n$ (b) When $F_{sn} = F_n$

Fig. 8. State change of force applied to balloon.

differences of the pressure are small in stiffness. Concerning embrocations, differences between milky lotion and others are large around the volume of $80\,[\mathrm{mm}^3]$. When the load is small, the state as shown in Fig. 8 (a) is not long and the force applied to the balloon becomes state as shown in Fig. 8 (b) soon. Therefore, the pushing phenomenon is not enough to obtain pressure changes with differences in stiffness. It is found that the load condition must be adequately set.

### *C. Discrimination of Samples with Different Stiffness and Surface Conditions*

On the basis of the results and discussions as mentioned above, we focused on the pressure changes around the

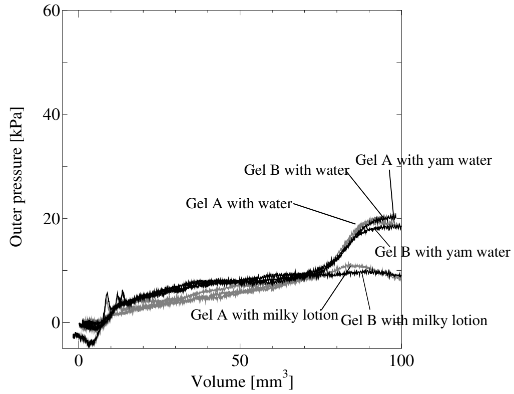



Fig. 9. Experimental results in case of small loading (0.15 [N]).

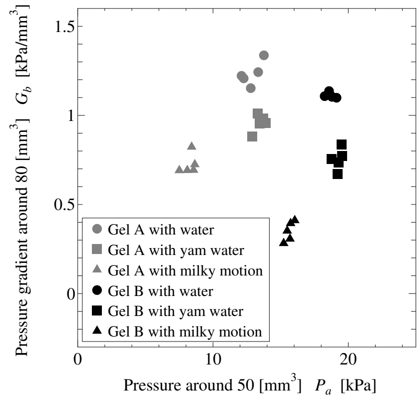



Fig. 10. Sensor output distributions.

volume of $50\,[\mathrm{mm}^3]$ and $80\,[\mathrm{mm}^3]$. The average of pressure values from 45 to 55 $[\mathrm{mm}^3]$ in volume was extracted as $P_a$. The pressure gradient from 75 to 85 $[\mathrm{mm}^3]$ in volume was extracted as $G_b$ by least-square method.

The measurement was carried out five times on each sample under the same experimental condition as shown in Fig. 7. Distribution of $P_a$ and $G_b$ calculated from each obtained outer pressure is shown in Fig. 10. Each plot indicates the output in a single measurement. It is found that outputs on each sample are located in different area. $P_a$ is small on soft samples and $G_b$ is small on slippery samples.

Therefore, it can be described that the proposed sensing has a potential to measure stiffness and surface conditions. By analyzing more detail about relation between the output signals and characteristics of the object, evaluation of other tactile information and improvement of the sensing accuracy might be conducted.

## V. Conclusions

We developed the compact sensor system with the syringe based on tactile sensing using balloon expansion. It can ensure the safety for human in safe contact, using no electric power, and sterilization, which are necessary to apply the sensor in the human body. Furthermore, in this system, pressure changes and volume changes of the balloon can be measured together in the balloon expansion and the time for sensing is very short. Experiments using the developed sensor were conducted on samples with different stiffness and surface conditions. Features from sensor outputs were extracted on the basis of experimental results and discussions. The results showed that the sensor can discriminate the samples and supported a potential to measure stiffness and surface conditions. It can be described that the proposed tactile sensor is available as medical sensor for measuring tactile information like stiffness and surface conditions.

In future works, theoretical analysis will be investigated on the basis of the analysis of the previous system [8]. The sensor output might be influenced by boundary condition of the object like the size of the object, the stiffness around the object and so on. We will investigate the capability of the sensor in region and resolution through the theoretical analysis and experiments. And recently, we have discussed the application of the sensor into neurosurgery. We will try the sensor on real tissue (animal) in the near future.

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