Silicone retractor with embedded force-sensing function for attachment to surgical suction pipes

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Abstract—A silicone retractor that can be attached to suction pipes was developed in order to enhance the usability [1]. The measurement of the retracting force is desired in order to avoid damage to brain tissue due to an unexpected large force. This paper presents a force-sensing embedded silicone retractor that can be attached to suction pipes. The developed silicone retractor can provide three functions at the same time: suction, retracting, and retracting force measurement. The force-sensing system is based on a visualization mechanism that displays the force as a colored pole motion. The surgeon can then roughly estimate the retracting force. With a fiberscope, the retracting force can be measured with a resolution of 0.05–0.3 N. The retractor is made of silicone and has the advantages of disposability, low cost, and easy sterilization/disinfection. The system was validated through finite element method analysis and experiments.

I. INTRODUCTION

Recently, many medical devices for surgical operations have become popular. For example, medical devices for neurosurgery include the electrical scalpel, forceps, retractor, bipolar forceps, endoscope, and suction. These devices are very convenient for the surgery itself, but surgeons are required to change medical devices many times. This decreases the usability for complex surgical procedures and increases the surgery time, which places a burden on the patient. Devices with more functions are desired. A key resolution is for a single medical device to provide more than two functions.

In neurosurgery, some of the most frequently used devices are suctions and retractors. Retractors pull back tissues to produce a visible field and space for surgery. Suctions suction blood and soft tissues. Very frequent changes are usually required, and surgeons sometimes use suctions as a retractor. Based on this situation, the neurosurgeons among the authors previously developed a silicone retractor that can be attached to the tip of suction devices [1] (see Fig. 1). By providing an area for retracting to the suction tip, surgeons can not only suction but also retract tissues at the same time. However, the force applied by this device to the tissue is unknown. In neurosurgery, tissues are very soft and fragile, and damage to normal tissues has to be avoided. Therefore, a force-sensing system should be provided for the hybrid retraction/suction device. The present paper presents a force-sensing function embedded in a silicone retractor that can be attached to suction devices. The main features are as follows.

Force visualization: A mechanism to visualize the force is utilized so that surgeons can understand the magnitude of the load on tissues just by looking. If an endoscope or camera is used, the force can be quantified with high resolution.

Easy setup: The sensor system itself is constructed from only silicone parts and does not need any electric components. It is easy to attach to the suction pipe and has the advantages of disposability, low cost, and easy sterilization/disinfection.

Multiple functions: Similar to [1], functions for suction, retraction, and retracting force-sensing are provided at the same time.

The remaining parts of this paper are organized as follows. Related works are described below. The developed force-sensing systems are described in Section II, and the experimental results for validation are presented in Section III. Section IV summarizes the results.

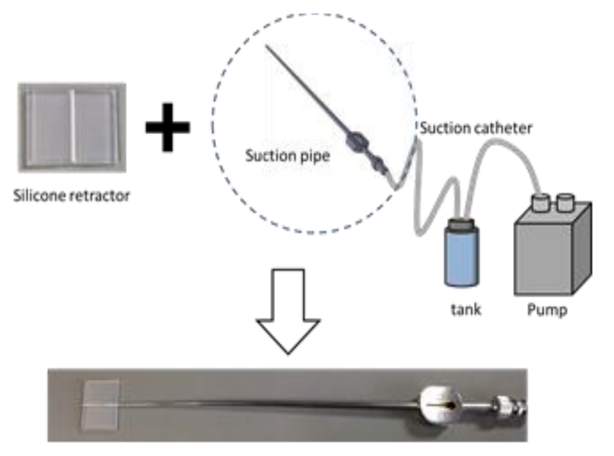

Figure 1. Suction pipe/device and silicone retractor for suction pipe

A. Related works

Many studies have focused on developing force-sensing systems. One approach has been developing force and tactile sensors for medical surgeries [2–7]. The objective of this approach is to provide haptic feedback to surgeons so that they can easily manipulate the devices and find the tumor. One of the most commonly used force-sensing systems is based on strain gauges [8–10]. Electrical components have a significant role in transferring the force information. However, medical

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devices need sterilization or disinfection, which is difficult to do with electrical components. In addition, extra parts such as an amplifier are required, and the overall system is usually large and expensive. Noise in the wiring for signal transfer is another problem. Thus, several research groups have developed force-sensing systems that are free of electrical components. Takaki et al. [11] developed a forceps that includes a force-sensing function based on force visualization using moiré fringe patterns. Tadano and Kawashima [12] developed force sensation feedback system with a pneumatic servo system. Kawahara et al. [13] developed an organ stiffness measurement system that utilizes an air jet and endoscope. Peirs et al. [14] developed a forceps with an embedded force sensor based on a mechanism for detecting the deformation of flexible optical fibers. Tada et al. [15] developed a force sensor based on detecting the change in illumination of a light source attached to an elastic frame. Watanabe et al. [16, 17] developed a force-sensing system that can be attached to a fiberscope using a highly elastic fabric. However there has been no system aimed at providing the suction, retracting, and force-sensing functions at the same time.

With regard to force visualization-based sensors in other fields, Ohka et al. [18] developed a three-axis force sensor where the force is estimated from the poses of conical feelers. Kamiyama et al. [19] developed a force distribution sensor where forces are detected from the poses of two-layer spherical markers. However, the target ranges for the force and size differ from those of the force sensors for neurosurgery. Miniaturization is an important issue, as noted in [6, 7].

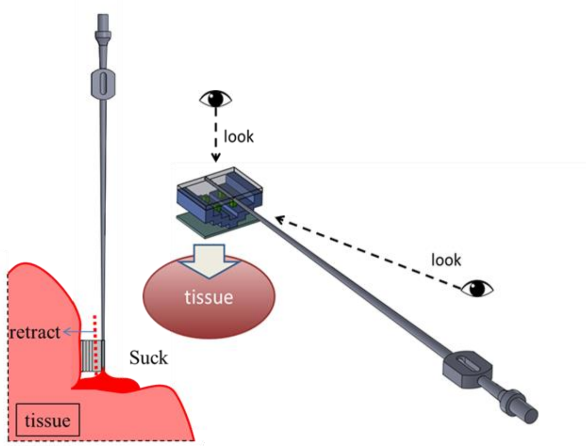


Figure 2. Target situation I: surgeon evaluates force visually

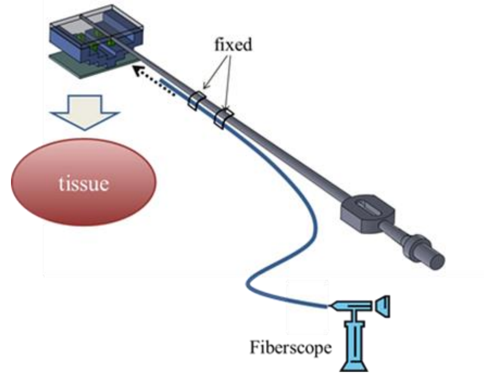


Figure 3. Target situation II: retracting force is captured with fiberscope

II. FORCE-SENSING SYSTEM

A. Target situation

This study focused on the suction and retraction in neurosurgery. As shown in Fig. 2, the proposed silicone retractor with the embedded force-sensing function works by attaching the silicone retractor to the tip area of the suction pipe. The suction pipe suctions not only tumors but also blood and soft tissues to clear the visible area. The silicone retractor extends the visible area by retracting brain tissue that disturbs the viewing area of the surgeons. Embedding a force-sensing and visualization mechanism into the silicone retractor allows surgeons to control the retracting force based on the received information and avoid unexpected fracture or breaking of normal brain tissues because of unexpected large forces.

In the situation shown in Fig.2, whether surgeon can get the visualized force information depends on the viewing angle of the surgeon. Then a fiberscope or endoscope is used if quantitative force information is needed. This was another situation considered in this study, as shown in Fig. 3. The visualized force information is captured by the camera in the fiberscope or endoscope, and the force values are calculated. The obtained force value provides feedback to the surgeons. In this case, the surgeons can understand the force information with higher resolution and accuracy.

B. Design requirements

The design requirements for the proposed retractor are as follows.

1. The force can be visualized.
2. Retraction and retracting force measurement can be performed at the same time.
3. The device can be attached to suction pipes.
4. There should be no electric components.
5. The dimensions should have a width of less than 30 mm, length of less than 20 mm, and thickness of less than 15 mm.
6. The force range is 0–0.3 N with a resolution of 0.05 N.

In order to consider the above two situations, a force visualization-based mechanism is required. To enhance usability, the device should be able to provide the suction, retracting, and retraction force measurement functions at the same time. If the silicone retractor can be attached to the suction pipe, suction can be provided by the suction system. The silicone retractor itself is then required to provide the retraction and retracting force measurement functions. In order to facilitate easy setup and usage, a disposable and low-cost silicone retractor is preferred. A disposable retractor means easy sterilization and disinfection. For this purpose, the silicone retractor should not have any electrical components. The nominal dimensions of the original silicone retractor are a width of 23 mm, length of 18 mm, and thickness of 2 mm. Realizing the same dimensions is difficult. As a preliminary step, the target size was set to be a width of less than 30 mm, length of less than 20 mm, and thickness of less than 15 mm. The required force range and resolution were determined based on the experimental results of conventional studies [8]–[10], where the typical force magnitude was around 0.1 [N]. The force information obtained by the silicone retractor is not for force control but for display to surgeons. The resolution of 0.05 N was thus considered to provide sufficient accuracy.

C. Principle of force sensing

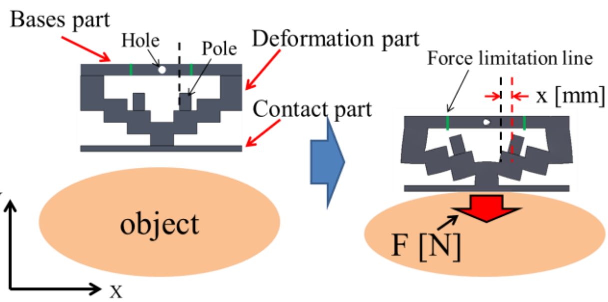


Figure 4. Principle of force sensing

The developed force-sensing system is based on a force visualization mechanism. Fig. 4 shows a schematic view of the principle of the force-sensing system. The X- and Y-axes are defined in Fig. 4. F [N] denotes the force in the Y direction and corresponds to the magnitude of the retracting force. x [mm] denotes the moving distance of the tip of the poles (markers) in the X direction from the initial position. The silicone retractor mainly comprises a base, deformation part, pole, and contact part. The base is the reference for deformation and is made of a relatively hard material. There is a hole at the center of the base so that the silicone retractor can be attached to the tip of the suction pipes. The contact part adds the function of retracting a wide area and is made of a relatively hard material. The force-sensing is available at roughed or curved surfaces because force is detected at the center area of the contact part. Note that we don’t consider the case when retracting tissue with a part of contact part because retractor is for extending viewing area and the entire part of the contact area is needed for the extending. The stair-like structure for the deformation part enlarges and shows the deformation resulting from the retracting force. When retracting tissues, the stair-like structure deforms. The joint part for each step is thin, and stress concentrations occur. Because of the stress concentrations, large deformations can be expected. The pole is attached to the stair as a marker that displays the enlarged deformation as force information to the operators. The pole position is on the (second) stair so that the pole can enlarge and show the deformation while tilting/moving without contacting any other areas/walls. The maximum moving point is the tip of the pole: x [mm]. The moving distance depends on the magnitude of the retracting force. Thus, when calibrating the relationship between the retracting force F [N] and moving distance of the pole tip x [mm], the magnitude of the retracting force can be derived from x [mm]. Therefore, the moving distance of the tip of the pole can be used to visualize the force information.

D. Structure of silicone retractor with embedded force-sensing function

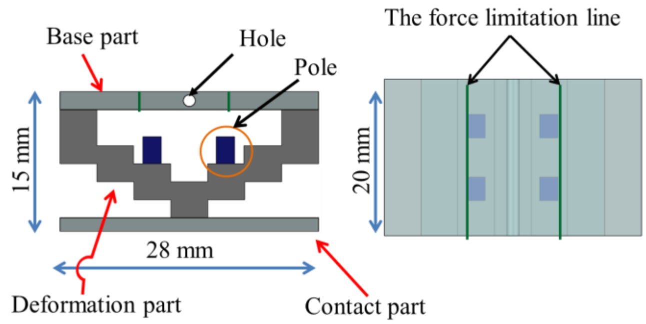


Figure 5. Schematic top and side views for structure of silicone retractor with an embedded force-sensing function

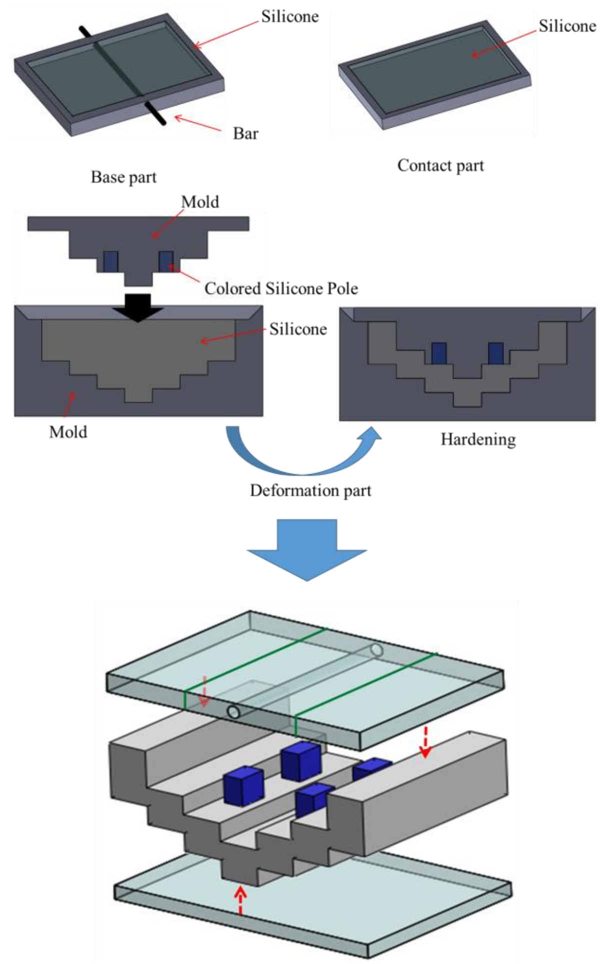


Figure 6. Overview of manufacture and assembly processes for silicone retractor with embedded force-sensing function

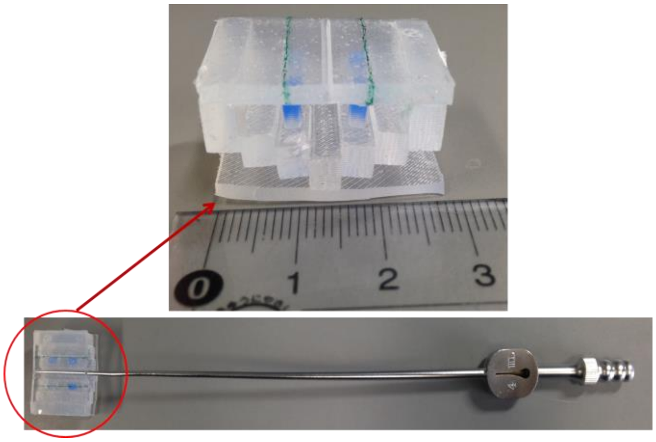


Figure 7. Manufactured silicone retractor with embedded force-sensing function

Fig. 5 shows a schematic view for the structure of the silicone retractor with an embedded force-sensing function. The silicone retractor consists of a base, deformation part, contact part, and poles. All parts are made of silicone so that the retractor is disposable, low-cost, and easy to sterilize or disinfect. The base and contact parts are made from hard silicone, and the other parts are made from soft silicone. All parts were made from base materials and hardeners produced by Shin-etsu Silicone Company. The base part is transparent so that the movement of the pole can be viewed from the top. The pole was colored with K-COLOR-BL-70 produced by Shin-Etsu Chemical Co., Ltd. Colored lines are drawn on the base so that the operators can visualize the force limits. The lines were drawn by colored pen harmless to human tissue. If the tip of the pole goes over the line of the force limit, this means that the retracting force is over the allowable maximum value (in this case, 0.3 N). By checking whether the tip of the pole is over the line or not, the operator can maintain the retracting force under the allowable maximum value in order to avoid damage to brain tissues. The top view is intended for observation by surgeons, while the side view should be captured with a camera. The dimensions of the silicone retractor are a width of 28 mm, length of 20 mm, and thickness of 15 mm. The poles have a width of 2 mm, length of 3 mm, and thickness of 3 mm.

Fig. 6 shows an overview of the manufacturing and assembly processes. First, the poles are manufactured with a mold. After the poles are placed into the holes in the mold for the deformation part, liquid silicone is poured into the molds, and the deformation part is manufactured. The base is manufactured by utilizing the mold with a bar. The contact part is also manufactured with a mold. For the manufacture of the base, the base and deformation parts can be joined. Similarly, the contact can be joined with other parts during its manufacture. For easy manufacture of the prototype, bonds were used for jointing. The manufactured retractor is shown in Fig. 7.

E. FEM analysis on relationship between retracting force and moving distance of pole tip

TABLE I. MATERIAL PROPERTIES IN FEM ANALYSIS

	Young's modulus [MPa]	Poisson's ratio
Base part	0.5	0.3
Deformation part	0.2	0.3
Contact part	0.5	0.3

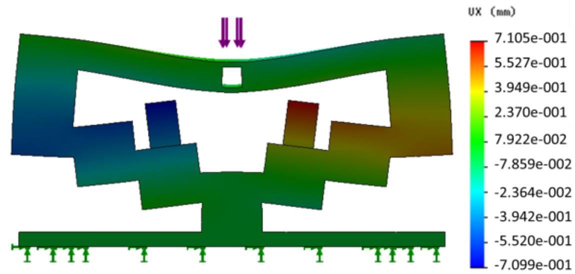


Figure 8. Results of FEM analysis with applied load of 0.1 N

Finite element method (FEM) analysis was performed in order to determine the relationship between the retracting force *F* [N] and moving distance of the pole tip in the *X* direction *x* [mm]. SolidWorks Simulation (SolidWorks) was used for the analysis. The undersurface of the contact part was fixed, and a load was applied at the hole in the base part in the negative Y direction (see the coordinates in Fig. 4). The load was changed from 0 N to 0.3 N in increments of 0.05 N. Table I lists the material properties of each part. Note that the material properties were determined based on the stress–strain diagram derived from experimental results. Fig. 8 shows the result when the applied load was 0.1 N. The largest moving distance was obtained at the top left and right points of the right and left poles. Therefore, by checking the moving distances of the pole tips, the force information can be obtained with high resolution and accuracy. In order to estimate the force value, the relationship between the load *F* [N] and moving distance of the pole tip *x* [mm] had to be calibrated. The moving distance of the pole tip *x* [mm] for every *F* [N] was calculated, and the results are plotted in Fig. 13. The derivation of the relationship is described in the next section with the experimental results.

III. EXPERIMENTAL EVALUATION

Experiments were conducted in order to validate the developed silicone retractor with an embedded force-sensing function and determine the relationship between the retracting force *F* [N] and moving distance of the pole tip (in the *X* direction) *x* [mm]. Fig. 9 shows a schematic overview of the experimental setup, and Fig. 10 shows a photo of the actual setup. A suction pipe equipped with the developed silicone retractor was attached to the automatic positioning stage (IMADA MX2-500N), which precisely controlled the magnitude of the load by moving the suction pipe in the vertical direction. The silicone retractor was placed on the stage of the electronic weighing instrument (SHIMADZU TW223N) to measure the load applied to the silicone retractor. A digital camera (CANON PSS120BK) was used to capture the movement of the poles in the silicone retractor. Table 2 presents the related specifications of the experimental devices.

TABLE II. RELATED SPECIFICATIONS OF EXPERIMENTAL DEVICES

Camera	Resolution: 2816 × 2112 pixels
Electronic weighing instrument	Resolution: 0.001 [g]
Automatic positioning stage	Resolution: 0.01 [mm]
	Speed: 10 [mm/min]

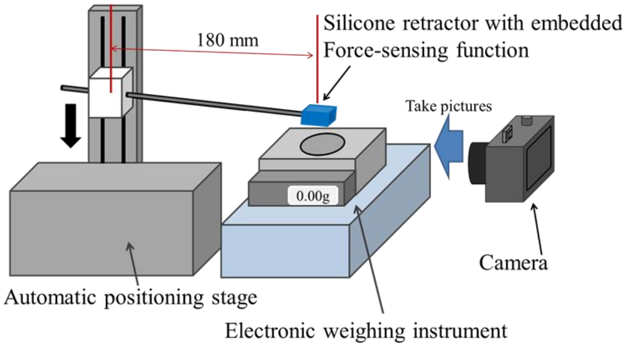


Figure 9. Schematic view of experimental setup

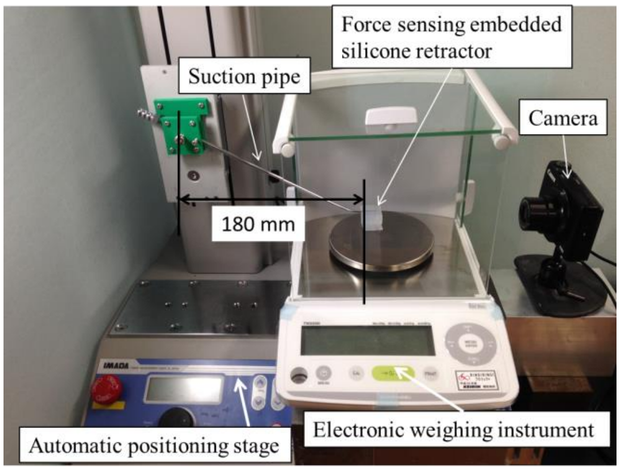
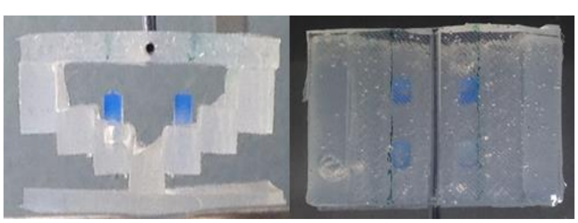


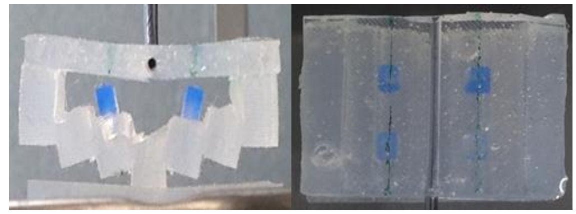
Figure 10. Photo of experimental setup

A. Procedure

First, the automatic positioning stage was moved so that the silicone retractor was in contact with the stage of the electronic weighing instrument while the latter read 0.000 g (0.00 N). Then, the automatic positioning stage was controlled to increase the magnitude of the load by 0.05 N. After the control, a photo was taken with the camera in order to measure the moving distance of the pole tip *x* [mm]. This procedure was repeated for loads of 0.00 N to 0.30 N at increments of 0.05 N. The entire procedure was repeated five times. In total, 35 photos were obtained. Fig. 11 shows the photos when the load was 0.00 and 0.02 N as representative results.



(a) Load of 0.00 N



(b) Load of 0.20 N

Figure 11. Photos of silicone retractor

B. Procedure to derive moving distance of pole tip in silicone retractor

The image processing toolbox of MATLAB (MathWorks) was used to derive the moving distance of the pole tips. Imtool of MATLAB was used to obtain the pole positions and the information for unit conversion. As shown in Fig. 12, $\boldsymbol{p}(F)$ was the position of the top left point of the right pole, where F was the applied load. Imtool was used to derive $\boldsymbol{p}(F)$ for every load F. For the unit conversion, a ruler was also captured, as shown in Fig. 12. The pixel value corresponding to 10 mm was derived, and the unit conversion from pixels to millimeters was conducted. The moving distance of the pole tip in the *X* direction was derived with $|p_X(F) - p_X(0.00)|$, where $p_X(F)$ denotes the *X* coordinate of $\boldsymbol{p}(F)$. Note that the movement of the *X* coordinate was significant, as shown in Fig. 4.

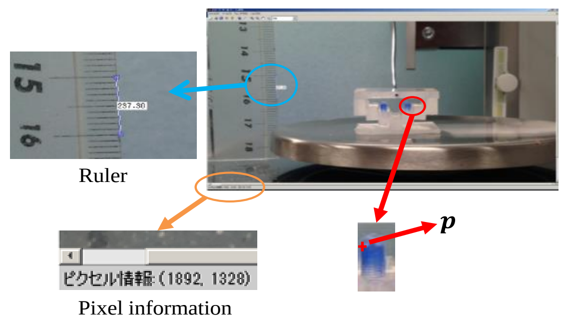


Figure 12. Photo to derive moving distance of pole tip with Imtool

C. Experimental relationship between retracting force and moving distance of pole tip

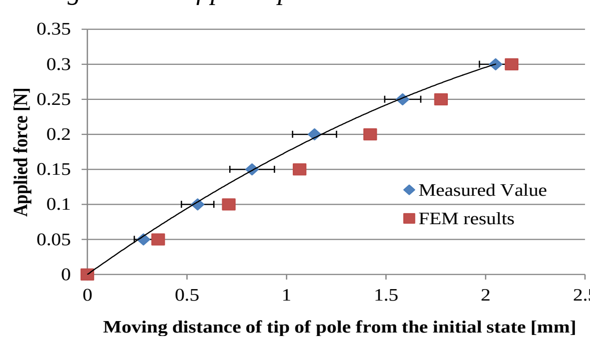


Figure 13. Relationship between retracting force and moving distance of tip of pole

Fig. 13 shows the results of the experiment (blue diamonds) and FEM analysis (red squares). Mean values with error bar expressing standard deviation are given for the experimental results. The regression curve for the experimental results is given by

$$F = -0.029\,x^2 + 0.21\,x. \quad (1)$$

Note that we don't consider a force over 0.3[N] because it is over-load.

Table 3 presents the obtained coefficient of determination and RMSE. The calculation was performed with the curve fitting toolbox of MATLAB.

TABLE III. PROPERTIES OF REGRESSION CURVE

Dimension of polynomial function	Coefficient of determination: R^2	RMSE (Root Mean Squared Error)
2	0.99	0.013

D. Discussion

The results of the experiments and FEM analysis showed a small difference. This may be because it was difficult to make the silicone retractors from the exact same materials as those used for the FEM analysis. The shapes of the manufactured silicone retractors were also not exactly the same as those used in the FEM analysis. However, the obtained values were close to each other. Thus, the results of the experiments and FEM analysis were validated. The moving distance of the pole tips monotonically increased with the applied load. The regression results (Table 3) showed that a quadratic function can express the relation very well. Therefore, the retracting force can be estimated from the moving distance of the pole tips with a high degree accuracy. The resolution of the force-sensing system was less than 0.05 N, and the sensor has a measurement range of 0–0.3 N. Fig. 11 (right) shows that the relation between the blue pole position and line expressing the force limit can provide a rough estimate of the force. Even if there is no camera or fiberscope, a surgeon can estimate the retracting force using the developed silicone retractor with an embedded force-sensing function.

IV. Conclusion

In this paper, a silicone retractor with an embedded force-sensing function that can be attached to a suction pipe was presented. Suctions and retractors are the most frequently used medical devices in neurosurgery. Recently, a device combining the two functions was developed [1]. However, a force-sensing function was not included. This paper presented devices that can provide the three functions of suction, retraction, and force measurement at the same time. The force-sensing system is embedded into the silicone retractor, which can be attached to the tip of a suction pipe. The force is sensed through a force visualization mechanism. The embedded color pole moves/tilts if a retracting force is applied. The moving distance of the pole is associated with the magnitude of the retracting force. The moving distance of the pole can be used to estimate the retracting force. The force can be visualized, and the surgeon can then roughly estimate the force. If a camera or fiberscope is used, the force can be measured with a resolution of 0.05 N up to a maximum value of 0.3 N. Because the developed retractor is made of silicone, it is disposable and low-cost, and sterilization and disinfection are easy. The developed silicone retractor is expected to not only reduce the number of times tools need to be switched but also provide safer retraction. However, for practical application, further miniaturization and evaluation in real situations are needed. These issues will be considered in future works.

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