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Force Visualization Mechanism Using a Moiré Fringe Applied to Endoscopic Surgical Instruments

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Abstract— **This paper presents a force visualization mechanism for endoscopic surgical instruments using a Moiré fringe. This mechanism can display fringes or characters that correspond to the magnitude of a force between the surgical instruments and internal organs without the use of electronic elements, such as amplifiers and strain gauges. As this mechanism is simply attached to the surgical instruments, there is no need for additional devices in the operating room or wires to connect these devices. The structure is simple, and its fabrication is inexpensive. An example is shown with the mechanism mounted on a 10-mm forceps. We experimentally verified in vivo, using a pig, that it can display characters corresponding to the magnitude of the force, thus visually displaying the force even in endoscopic image.**

I. Introduction

One of the problems in endoscopic surgery is the difficulty in estimating the magnitude of force to be applied to organs, as surgery is performed using instruments inserted through small incision openings. The instruments must be small and their parts shaped such that they can be inserted through these small openings. This makes it structurally difficult to attach sensors that can measure the applied force, and the issue of sensing of force applied is still being studied [1]-[5]. Most studies have used electronic sensors, such as strain gauges, which require wiring for devices, such as an amplifier to amplify the electronic signals from the sensor, and special devices or modified monitors to display the sensed force. This tends to make the overall systems larger and more expensive.

In this study, we propose a mechanism that can display fringes or characters that correspond to the magnitude of the force without the use of electronic devices. We focus on the small displacement produced by the application of the force, and visually magnify and display its displacement with a Moiré fringe. As this mechanism is simply attached to the surgical instrument, there is no need to place additional devices in the operating room or for wires to connect these devices. Therefore, the proposed approach does not occupy space in the operating room or interfere with the movements of the surgeon. A further advantage is that the structure is simple and its fabrication is inexpensive.

Visual presentation of the magnitude of the force is significant. As this mechanism shows the force visually, the force cannot be monitored if the display unit is hidden behind an organ or some other structure, or if it is outside the visualization field of the endoscope. However, when the display unit can be located properly, it provides important information for surgical judgment, and information on the applied force can be shared by all the people looking at the endoscopic image. In addition, the force applied can be recalled from the recorded images. This mechanism would also be useful when, for example, an experienced surgeon wants to convey to young surgeons or engineers how much force is to be applied to forceps. In such cases, the experienced surgeon can conveniently move the display unit to a position where it can be seen. In addition, because more force information can be provided than with conventional instruments, this mechanism should be useful when training young surgeons; skill levels can be evaluated by referring to the recorded images, when identifying the cause of an unexpected occurrence during or after surgery, and when gathering information on newly-developed instruments.

This paper is organized as follows. Section II presents the principle of the force visualization mechanism. Section III describes a new Moiré fringe pattern that achieves both high magnification and clarity, without using expensive printing technology. Section IV describes a method for mounting this device on endoscopic instruments, and Section V gives an example of this mechanism mounted on a commercial 10-mm forceps. Section VI demonstrates experimentally that characters that correspond to the magnitude of the force can be displayed, and verifies that the display on this mechanism is visible on an endoscopic image in vivo using a pig. Section VII concludes the paper.

II. Force Visualization Mechanism

As shown in Figs. 1 (i) and (ii), when applying a force to an elastic element, a slight displacement x occurs. The magnitude of the force is visualized by magnifying this displacement x with a Moiré fringe. Let us first explain Moiré fringes. As shown in Fig. 2 (i), by superimposing line grating 1 of pitch p on line grating 2 with pitch $p+\Delta p$ ($\Delta p \ll p$), a fringe known as a Moiré fringe appears at pitch W. Pitch W is larger than pitch of line gratings 1 and 2. Their relationship is given by

$$W = \frac{p+\Delta p}{\Delta p}\, p. \tag{1}$$

As shown in Fig. 2 (ii), when line grating 1 is moved in direction (A) at pitch p, the Moiré fringe moves in direction (A) at pitch W. Therefore, the displacement x can

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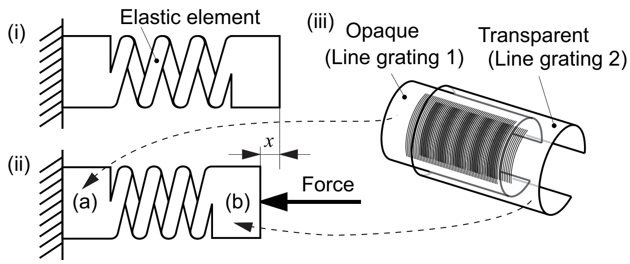

Fig. 1. An elastic element with a Moiré fringe.

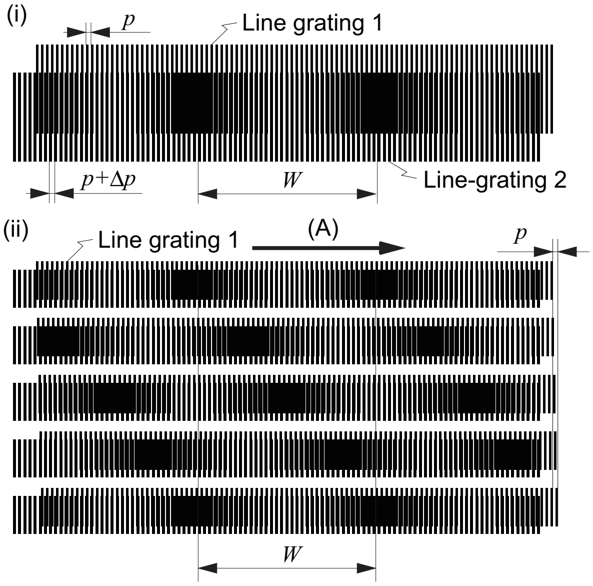

Fig. 2. A Moiré fringe.

be displayed visually at a magnification of $(p + \Delta p)/\Delta p$. This magnification is defined as M.

As shown in Fig. 1 (iii), line gratings 1 and 2 are printed on opaque and transparent film, respectively, and fixed at locations (a) and (b). A slight displacement x produced by the application of force is displayed by the Moiré fringe at a magnification of M. Therefore, the magnitude of the force can be confirmed visually. Hereafter, these force visualization elements together are referred as the force visualization mechanism.

III. Improving Visibility of the Moire Fringe

A. Displaying characters with the Moiré fringe

The Moiré fringe shown in Fig. 2 is a simple fringe pattern, and its visibility is not necessarily adequate. To improve the visibility, in this section, a method is proposed to display characters with the Moiré fringe. The movement of the Moiré fringe is shown on the left in Fig. 3. Similar to Fig. 2, if line gratings 1 and 2 are superimposed and line grating 1 is moved in direction (A), the Moiré fringe moves, as in Figs. 3 (i)-(iii).

We propose a method to display characters with a Moiré fringe, as shown in the right in Fig. 3. In place of line grating

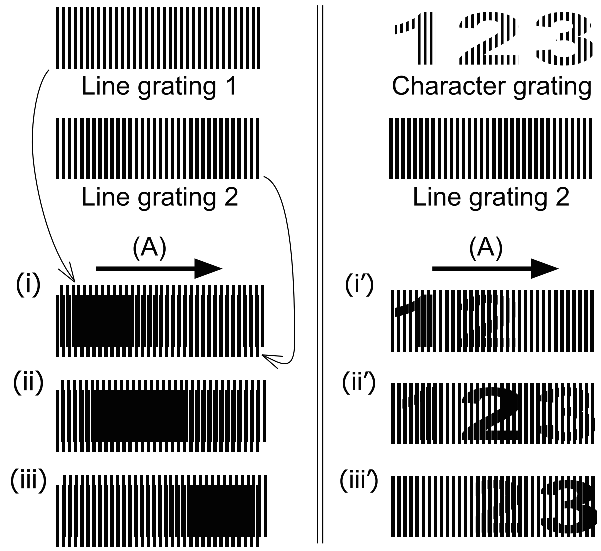

Fig. 3. A moiré fringe with characters.

1, we propose using gratings in the shape of characters, which we refer to as character gratings. If this character grating and line grating 2 are superimposed and the character grating is moved in direction (A), characters are displayed in the order shown in Figs. 3 (i')-(iii').

B. Highly magnified, legible Moiré fringe and printing technology

The Moiré fringe in this mechanism needs to have high magnification and be sufficiently legible. Moreover, for this method to be practical, fabrication should be possible with inexpensive printing technology so as not to increase medical expenses. In this section, a method is presented to show a highly magnified, clear Moiré fringe, even with a grating fabricated using inexpensive printing technology. First, we describe printing technology and magnification, and then the clarity of the Moiré fringe. Afterward, we propose a grating pattern that produces a clear Moiré fringe, using inexpensive printing technology.

Printing technology and magnification: Assuming the fabrication of a fringe using a printer, we discuss the resolution of the printer at magnification M. For example, if a printer has a resolution of 600 dpi, the finest lines that can be printed are $1/600$th of an inch. A unit of the finest lines that can be printed is defined as u. From Eq. (1), to obtain a high magnification M, the Δp against pitch p should be small. However, considering the printing technology, the minimum Δp is u. In the following, Δp is defined as u. For example, to obtain a magnification M of $\times 10$, pitch p and $p + \Delta p$ must be $9u$ and $10u$, respectively, for line gratings 1 and 2 according to Eq. (1). To obtain magnification M of $\times 28$, they need to be $27u$ and $28u$, respectively. These Moiré fringes are shown in Figs. 4 (i) and (ii).

Clarity of Moiré fringes: The Moiré fringes produced with this mechanism should be clear. When the grating lines are

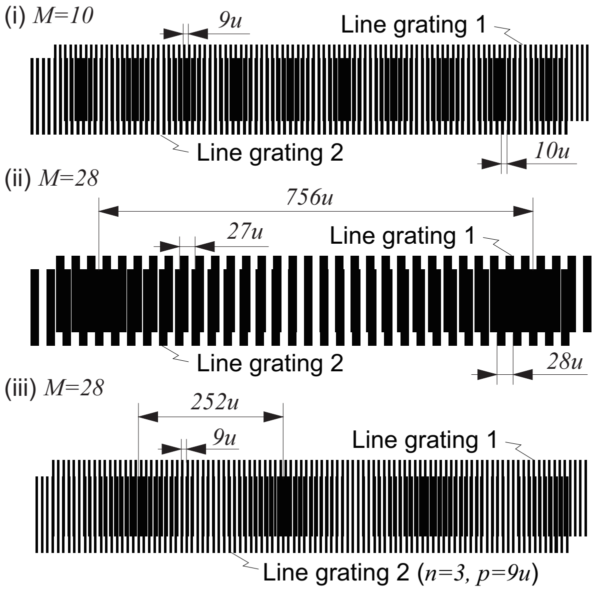

Fig. 4. Moiré fringe and magnification M.

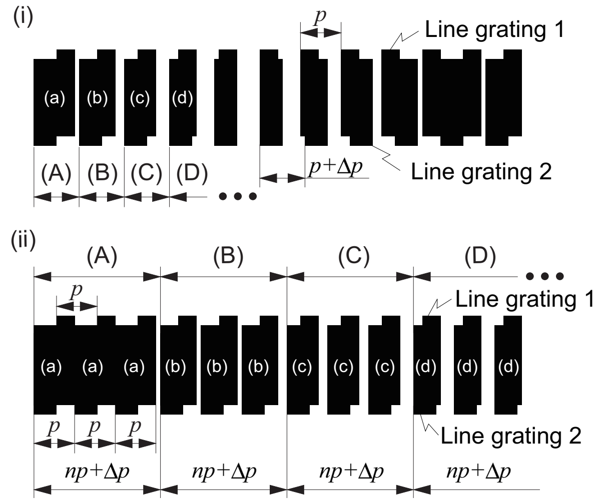

Fig. 5. Fine Moiré fringe with inexpensive printing techniques.

too fine to see, the Moiré fringe can be clearly observed. Conversely, when the grating lines are thick, the grating stands out more than the Moiré fringe, and the fringe cannot be clearly observed. Thus, the Moiré fringe in Fig. 4 (i) is clear because the line grating is fine, and the Moiré fringe in Fig. 4 (ii) is less clear, because the grating is thicker.

Magnification and clarity: The magnification M of the Moiré fringe in Fig. 4 (i), which is clear, is small at $\times 10$. M in Fig. 4 (ii), which is not clear, is large at $\times 28$. Thus, there is a tradeoff between clarity and magnification in Moiré fringes. In this grating pattern, to achieve both a high magnification M and clarity, u must be small. However, to make u small, a more expensive printing technology that can print very fine lines is necessary, which is undesirable because it leads to higher medical costs.

Proposed grating pattern: To obtain clear and highly magnified Moiré fringes without the use of expensive printing technology, we propose a new line grating pattern. Figure 5 (i) shows a magnified figure of one pitch of the Moiré fringe in Fig. 4 (i). The dark areas where the lines of gratings 1 and 2 are superimposed are defined as (a), (b), (c), and (d), in that order. We propose a configuration of line grating 2 in which the dark areas are repeated as (a)(a)(a)..., (b)(b)(b)..., (c)(c)(c)..., and (d)(d)(d)..., as shown in Fig. 5 (ii). In this pattern, the fringe of pitch p repeated n times (in the figure, $n = 3$) is placed every $np+\Delta p$. Pitch W of the Moiré fringe in Fig. 5 (ii) is

$$W = \frac{np + \Delta p}{\Delta p}\, p, \tag{2}$$

and the magnification M is $(np+\Delta p)/\Delta p$. The Moiré fringe, when $p = 9u$, $n = 3$, is shown in Fig. 4 (iii). From Eq. (2), its magnification M is $\times 28$ and the magnification M in Fig. 4 (ii) is also $\times 28$. However, the pitch of the line grating is finer in Fig. 4 (iii). Therefore the Moiré fringe in Fig. 4 (iii) is clearer than that in Fig. 4 (ii). If line gratings are configured in this way, expensive printing technology, which can print small u, is not necessary; a clear Moiré fringe with high magnification M can be obtained with inexpensive printing technology.

Here we explain why the pitch W of the Moiré fringe differs while the magnification is the same ($\times 28$) in Figs. 4 (ii) and (iii). The relationship between the pitch p of line grating 1, pitch W of the Moiré fringe, and the magnification M is $W = Mp$ from Eqs. (1) and (2). Therefore, even with the same magnification M, when the pitch p of line grating 1 differs, pitch W of the Moiré fringe also differs correspondingly. In the case of Figs. 4 (ii) and (iii), the pitch p of line grating 1 is $27u$ and $9u$, respectively; therefore, the pitch W of the Moiré fringe is $756u$ and $252u$.

IV. Structure of Endoscopic Instruments and Mounting Methods

A. Structure of endoscopic instruments

The general structure of instruments used in endoscopic surgery (for example, forceps, stapler, or scissors) is shown in Fig. 6. Most of these instruments have an outer cylinder, and a shaft internally to transmit a force from an operating portion to an end effector. If the magnitude of the force F_s, which is applied to the shaft, is visualized, the magnitude of the force f_{end} produced in the end effector can be indirectly visualized. We focus on the magnitude of an internal force on the outer cylinder F_o in the direction of the shaft that is produced in response to the shaft force F_s.

Relationship between forces: Figure 7 shows the relationship between the shaft force F_s and the internal force on the outer cylinder F_o. This figure uses the example of forceps; however the relationships described below are the same for all instruments structured as shown in Fig. 6, with a shaft passing through an outer cylinder. When there is no external force on the outer structure, based on the principle of action

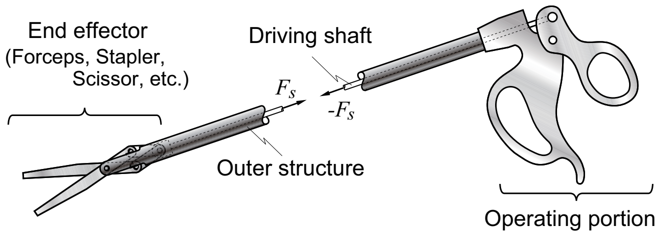

Fig. 6. Structure of endoscopic surgical instruments.

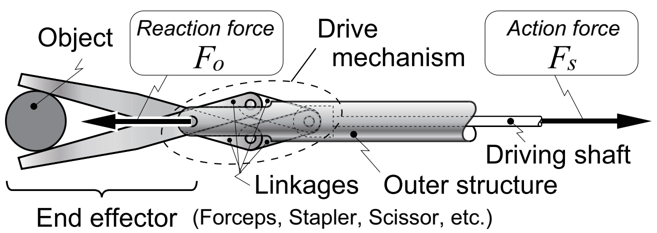

Fig. 7. Action-reaction forces.

and reaction, the relationship between shaft force F_s and internal force on the outer cylinder F_o is

$$F_o = F_s. \tag{3}$$

Let us consider the external forces that act on the instrument from the weight or elasticity of the organ being grasped, for example, as shown in Fig. 8. Let f_a and f_r be the magnitude of the external force in the axial and radial directions to the shaft, respectively. The internal force on the outer cylinder F_o is that from the shaft force F_s plus the external force f_a on the same axis as the shaft. Therefore, F_o is

$$F_o = F_s + f_a. \tag{4}$$

Influence of external forces f_a: Let us consider the relationship between the shaft force F_s and the force of the end effector f_{end}. When the shaft is moved dx, the end effector correspondingly moves by dy. From the principle of virtual work, this relationship is

$$F_s = \frac{dy}{dx} f_{end}. \tag{5}$$

An example with forceps is shown in Fig. 9.

With an internal force on the outer cylinder F_o, the influence of the external force F_{ext} on the force of the end effector f_{end} is considered from the following equation, obtained by substituting Eq. (5) in Eq. (4):

$$F_o = \frac{dy}{dx} f_{end} + f_a. \tag{6}$$

From Eq. (6), the influence of f_{end} on F_o is magnified dy/dx times, whereas the influence of f_a is of the same magnitude. For example, even when f_{end} and f_a are the same size, if $dy/dx = 10$, the external force f_a acts on the internal force on the outer cylinder F_o with only $1/10$th the amount of force of the end effector f_{end}. In other words,

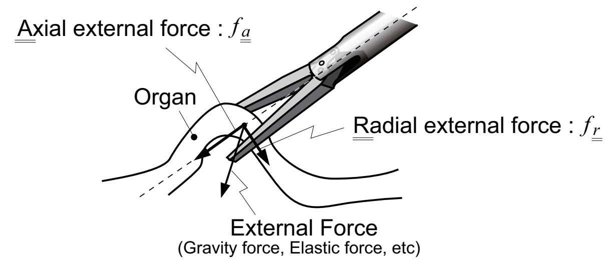

Fig. 8. External forces.

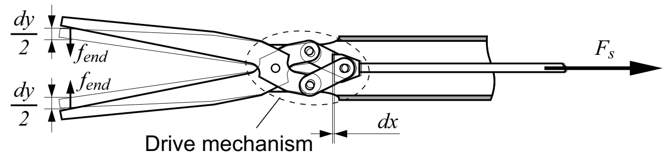

Fig. 9. Virtual work of the drive mechanism.

as dy/dx increases, the influence of the external force f_a on the internal force on the outer cylinder F_o decreases. If dy/dx is large, the relationship between F_o and f_{end} is given approximately by

$$F_o \simeq \frac{dy}{dx} f_{end}. \tag{7}$$

Note that dy/dx is dependent not only on the drive mechanism (Fig. 9), but also on the contact point between an organ and forceps, and on an open width of forceps; therefore, dy/dx is dependent on how to grasp an organ.

Mounting method: To obtain a displacement corresponding to the internal force on the outer cylinder F_o, an elastic element is installed in the outer cylinder, as in Fig. 10. When this displacement is displayed in magnification with the Moiré fringe, the internal force on the outer cylinder F_o can be visualized. Therefore, from Eq. (7), the force of the end effector f_{end} can be visualized.

Influence of external forces f_r: When an external force f_r is applied to forceps including the elastic element, the forceps deform undesirably, as shown in Fig. 11. However, the display of the Moiré fringe is desired to indicate the magnitude of the grasping force f_{end} without the influence of external force f_r. To satisfy this need, the neutral axis of the film printed with the line grating and of the outer structure must be designed on the same axis. Therefore, the shape of the film must be designed as a circular cylinder, same as that of outer structure.

V. Mounting Examples

Figure 12 shows an example of mounting this mechanism with forceps. A commercial 10-mm forceps is modified to use this mechanism.

Display portion: The display portion is located near the tip of the forceps. An enlarged photo is shown in Fig. 12 (ii). The size is 19×7.5 mm, and the numbers 1, 2, and 3 can be displayed. The line grating was produced by printing on film

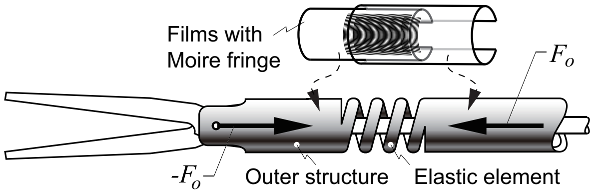

Fig. 10. Force visualization mechanism applied to endoscopic surgical instrument.

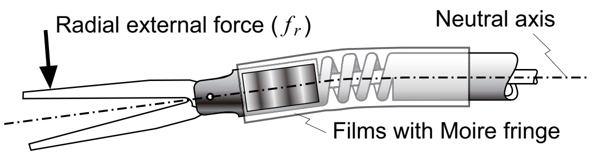

Fig. 11. Radial external force and neutral axis.

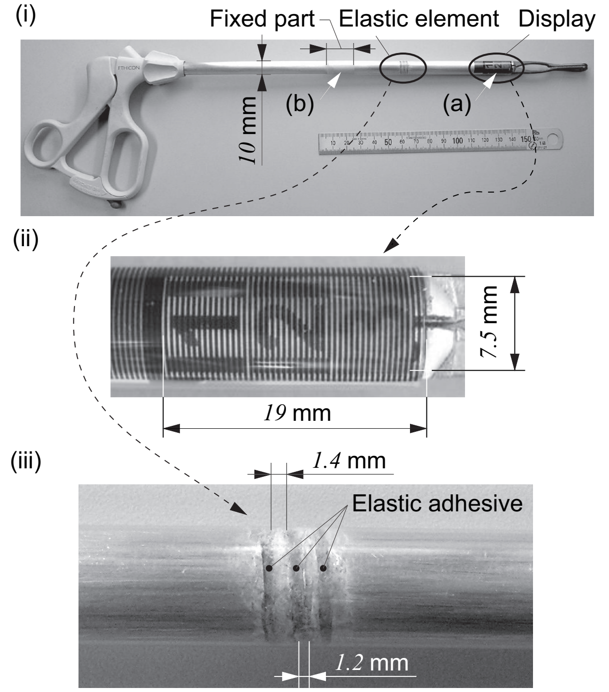

Fig. 12. The developed forceps.

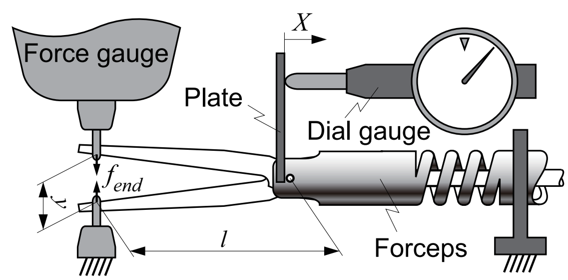

Fig. 13. The method of measuring f_{end} and x.

using a general laser printer (OKI Microline 5100) with 600 dpi resolution. The finest line that can be printed using film is $1/300$th of an inch, and so a pattern for the line grating is designed with $\Delta p = 0.085$ mm ($= u = 1/300$th of an inch).

The line grating pattern proposed in Section III-B is used, with $p = 0.42$ mm and $n = 15$. From Eq. (2), the pitch W of the Moiré fringe is 45.6 mm and the magnification M is $\times 76$. Film printed with a character grating is attached at (a) in Fig. 12 (i). Film printed with a line grating is attached at (b). These two gratings are superimposed at (a) to produce a Moiré fringe.

Elastic element: To make an elastic element, the forceps is cut in a helix, as in Fig. 12 (iii). The gap in this helix is fixed with an elastic adhesive to stiffen the elastic element (ingredients: ethylene vinyl acetate copolymer ($50 - 60\%$) and hydrocarbon resin ($40 - 50\%$)). When the user tightly grips the forceps, the grasping force at the tip of the forceps (=the force of the end effector f_{end}) is about 6 N. Therefore, assuming the maximum grasping force f_{end} of 6 N, we set specifications so that the number 3 is shown on the display at this time. To display the numbers 1, 2, and 3, the necessary displacement of the elastic element is about 0.3 mm. Through trial and error we determined that the thickness and the gap of the helix are 1.4 and 1.2 mm, respectively, and there are two twists in the helix.

VI. Experiments

A. Experiment to investigate the relationship between force and displacement

The generation of displacement x corresponding to the grasping force f_{end} is demonstrated experimentally. As shown in Fig. 13, one end of the forceps is fixed open at $h = 15$ mm, and using the other end, the grasping force f_{end} is measured with a force gauge (M1P-50NIM, Shiro Industry) at a point $l = 50$ mm from the rotation axis. The displacement x is measured using a dial gauge (NF1200, Noga, Japan) with an attached plate (Fig. 13). The grasping force f_{end} is measured five times for each 0.05 mm displacement x. The experimental results are shown in Fig. 14. The error is shown with the standard deviation using error bars. In the figure, (a) is when the grasping force f_{end} is increased, and (b) when it is decreased. The displacement x is produced in accordance with the grasping force f_{end}; however, hysteresis occurs when the grasping force f_{end} is increased and decreased. This is considered to be due to the friction that occurred in the drive mechanism (Fig. 9).

B. Experiment to visualize the grasping force

We verify that displays corresponding to the grasping force f_{end} are produced with this mechanism. The grasping force f_{end} is measured by the same methods as in section VI-A, with $l = 50$ mm and $h = 8$ mm. The experimental results are shown in Fig. 15. On the left are photos of the display taken at every 1 N while the grasping force f_{end} is increased from 0 to 6 N. It is confirmed that the numbers are displayed in the order 1, 2 ,and 3, according to the grasping force f_{end}.

We also verify the influence of the external force f_a. To apply an external force f_a, and measure its magnitude, the

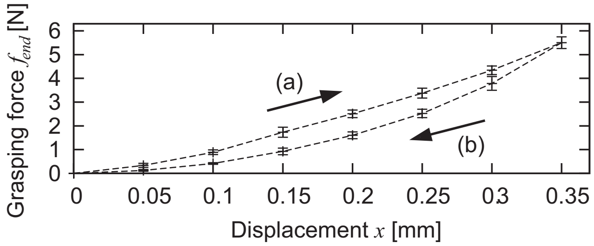

Fig. 14. The grasping force f_{end} versus the displacement x.

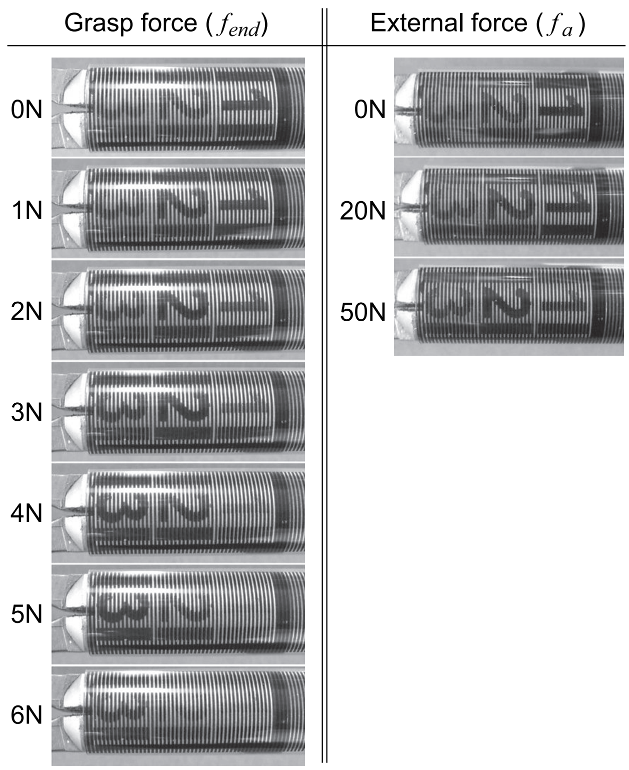

Fig. 15. The display of the force visualization mechanism.

force gauge is pressed on the forceps as in Fig. 16. The right of Fig. 15 shows photos of the display at 0, 20, and 50 N as the external force f_a was increased from 0 to 50 N. When the large external force f_a is applied, the display changed slightly, producing error. However, with the external force f_a about the same size as the grasping force f_{end}, there is almost no change in the display. In other words, the grasping force f_{end} can be displayed with almost no influence from the external force f_a. In this case, dy/dx is about 20; therefore, the influence of the external force f_a is only about $1/20$th of the grasping force f_{end}.

C. Use in endoscopy

Using a pig, it was demonstrated that the display of this mechanism can be read in endoscopic images in vivo. The forceps is manipulated by surgeons and engineers, as shown in Fig. 17 and thus confirming that the display can be read even in endoscopic images.

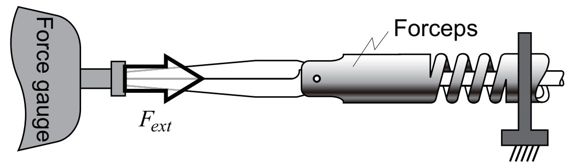

Fig. 16. The method of measuring f_a.

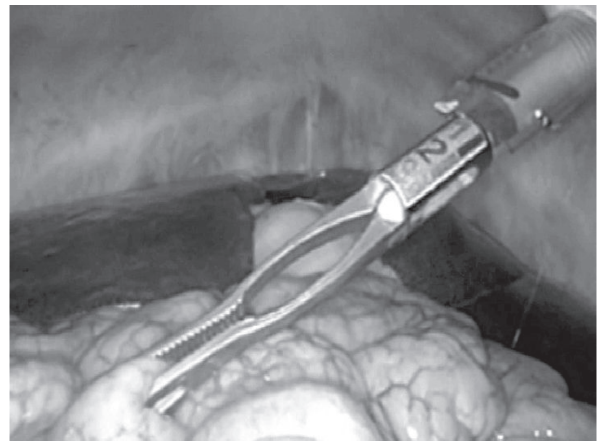

Fig. 17. Photograph of in vivo pig experiment.

VII. Conclusion

A method was proposed to display fringes or characters that correspond to a force by applying Moiré fringes without the use of electronic elements. In addition, a line grating pattern was proposed that enables highly magnified, clear Moiré fringes to be obtained, even with inexpensive printing technology. An example was shown with the mechanism mounted on a 10-mm forceps, and it was confirmed experimentally that numbers corresponding to the grasping force could be visualized. It was also confirmed in vivo experiment that the display of this force visualization mechanism could be seen in endoscopic images. In the future, we plan to develop a more sensitive force visualization mechanism and investigate the application of this mechanism to other surgical instruments.

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