Force-based automatic classification of basic manipulations with grasping forceps

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***Abstract* –Haptic information is crucial for the execution of precise and dexterous manipulations. During minimally invasive surgery, doctors are required to indirectly sense force-related information from body organs and tissues via a surgical instrument because they cannot directly touch the tissue. Against such a background, skill evaluation based on force measurement is useful for judging whether a person has adequate manipulation skills. This paper addresses the challenge of automatically classifying basic manipulations performed with surgical grasping forceps. First, manipulations performed with forceps during laparoscopic surgery were categorized into four basic types from video observation. Grasping forceps with force-sensing capability were developed to support identification of these types, which were automatically classified by monitoring information on the force applied to the forceps. An experiment to investigate the efficacy of the proposed method produced manipulation logs showing that doctors are capable of conducting tasks with less force than novices. It was also confirmed that the prototype forceps are suitable for practical use in animal experiments.**

Keywords– Minimally Invasive Surgery; Forceps Manipulation; Automatic Classification

I. INTRODUCTION

Minimally invasive surgery has gained popularity due to the advantages it brings, including small incisions, rapid recovery and reduction of medical costs. However, surgery conducted with an endoscopic camera is challenging for surgeons because they typically cannot precisely determine the scale of internal organs or gauge the distance between organs and forceps due to the limitations of stereo visual perception. As a result, objective and quantitative evaluation of surgical skills remains challenging.

Simulation in minimally invasive surgery training environments is considered essential for doctors today, and is a required component of general surgery residency. Many surgical simulators have been developed to efficiently and safely hone surgical skills. Smith et al. developed a skill assessment device (SAD) based on the use of a laparoscopic simulator platform and computer-based skill assessment software that allows precise measurement of an instrument’s movement during timed laparoscopic manipulations for the quantification of speed and accuracy during laparoscopic operations [1]. Rosen et al. developed the Blue DRAGON system, which is used to determine the kinematics and dynamics of two endoscopic tools along with visual views of the surgical scene. The two mechanisms are equipped with a position sensor, a force/torque sensor and a contact sensor to measure the positions and orientations of the two tools along with the forces and torques applied by the surgeon's hands. Analysis of data from tasks performed on an animal model showed major differences between residents at different skill levels [2], [3], [4]. Ikuta et al. developed a surgery recorder system (SRS) as a comprehensive recording method to improve safety during minimally invasive surgery based on an objective clinical review process. The SRS can be used to record surgery information, including position/orientation and force/torque signals for surgical tools, endoscopic images and sounds as well as vital data from the patient in the operating theatre [5]. Scott et al. investigated the feasibility of implementing a proficiency-based Fundamentals of Laparoscopic Surgery (FLS) skill training curriculum and evaluated its effectiveness in preparing trainees for certification [6]. Hiroshima University’s research group has developed the endoscopic surgical assessment device (HUESAD) for the objective assessment of endoscopic surgical skills [7] and conducted scientific assessment [8], [9]. These systems have numerous sensors to collect data for the evaluation of manipulation skills, but the need for so many sensors is not cost-effective for a training setup. A variety of surgical simulators have also been developed for safe and efficient surgical skill training. These provide various levels of reality, including high-fidelity virtual reality [10], [11], [12]. According to the results of various studies [13], [14], [15], force feedback capability is also fundamental for improving skills in minimally invasive surgery. The primary issue in the development of VR simulators with force feedback capability is the extremely high cost of integrating the equipment with the simulator to provide users with natural and comfortable haptic sensation [16], [17].

With these points in mind, this study was conducted to analyze a laparoscopic surgery skill evaluation method with focus on the force applied to forceps. To support the realization of a cost-effective method of this kind, strain gauges were used for

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force measurement. As force information is critical in such operation, the force applied to the forceps is potentially a useful index in skill evaluation. This paper outlines the development of an assessment environment for forcep manipulation skill and an automatic real-time classification method for basic manipulations executed during minimally invasive surgery.

II. METHOD

A. Definition of Basic Manipulations

Basic manipulations were defined by observing laparoscopic surgery videos of cholecystectomy operations. The top part of Fig. 1 shows time-based classification of forcep manipulation during the operations. These observations revealed that the following four manual operations accounted for all contact time between the forceps and body tissue: pinching and grasping (grasping), opening and dissecting (dissection), holding and displacing (displacement) and tugging (traction). The basic manipulations defined are shown in Fig. 2. The bottom part of Fig. 1 shows the results of classification into the four basic manipulations, which covered 97% of the operation time.

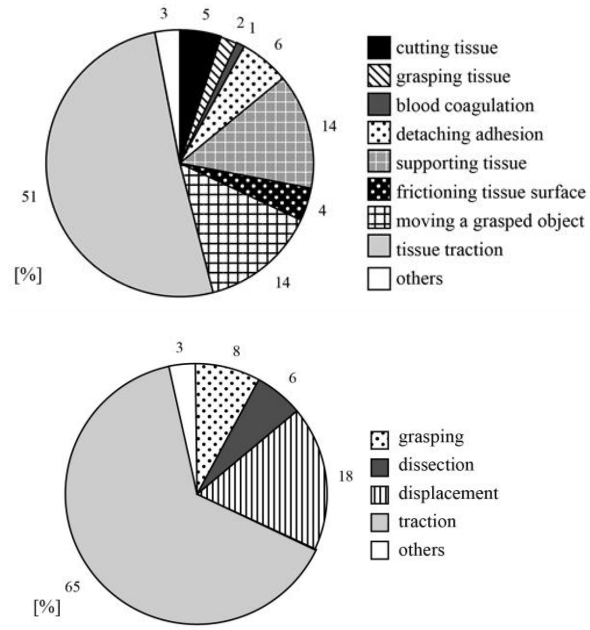

Fig. 1 Classification of forcep manipulations during cholecystectomy

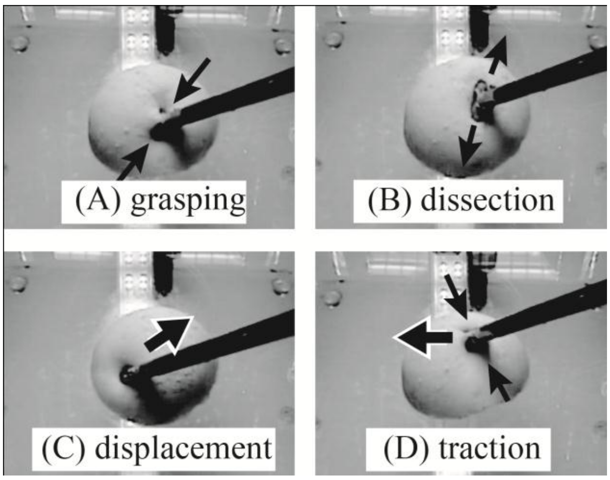

Fig. 2 Basic-manipulation snapshots

B. Prototype Grasping Forceps with Strain gauges

The basic manipulations can be distinguished by measuring the forces applied to the shaft and handle of the forceps. Fig. 3 shows the prototype force-sensing forceps, which were created using inexpensive strain gauges and commercially available forceps. Four strain gauges are attached at the CH1 – CH4 positions. Those at CH1 and CH2 primarily measure the force applied to the handle, while those at CH3 and CH4 primarily measure the force applied to the shaft. The strain gauges can be covered with rubber or silicon to support sterilization.

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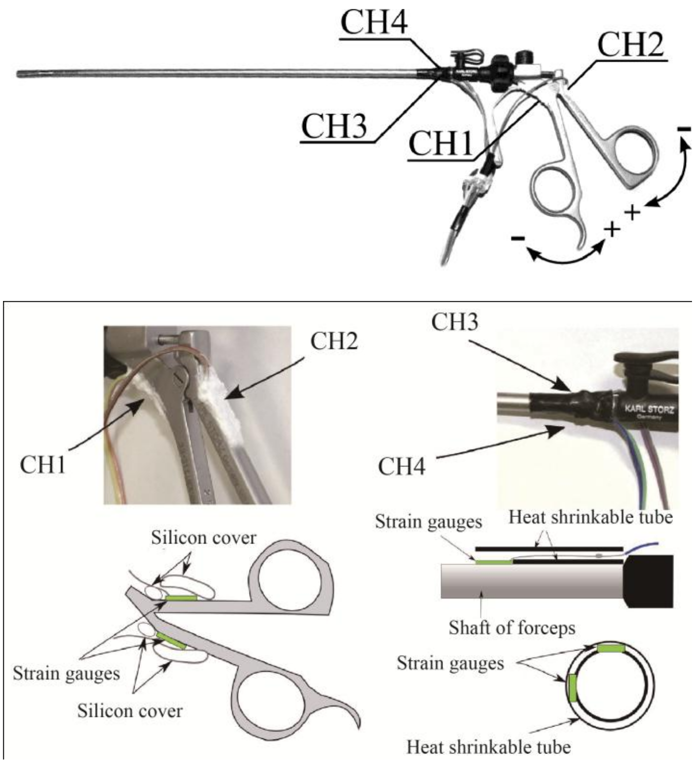

Fig. 3 Prototype force-sensing forceps

C. *Automatic Classification of Basic Manipulations*

The basic manipulations were automatically classified based on monitoring for the voltage of each strain gauge. Fig. 4 shows the voltage measured by the strain gauges during performance of the basic manipulations, each of which has a unique voltage profile. The gauges at CH1 and CH2 measured positive voltages in grasping manipulation and negative values in dissection manipulation. In both types, changes in voltage at CH3 and CH4 were relatively small. For displacement manipulation, the changes in voltage were relatively large according to the gauges at CH3 and CH4 and small for those at CH1 and CH2. In traction manipulation, all gauges measured large changes in voltage. Based on the monitoring of these voltages, which correspond to the forces applied to the gauges attached to the grip (CH1 and CH2) and the shaft (CH3 and CH4), basic manipulations can be automatically classified by comparing the measured values with predetermined thresholds. Table I shows the classification rules. In a subsequent experiment, thresholds of 0.015 [V] for CH1 and CH2, and 0.0025 [V] for CH3 and CH4 were set.

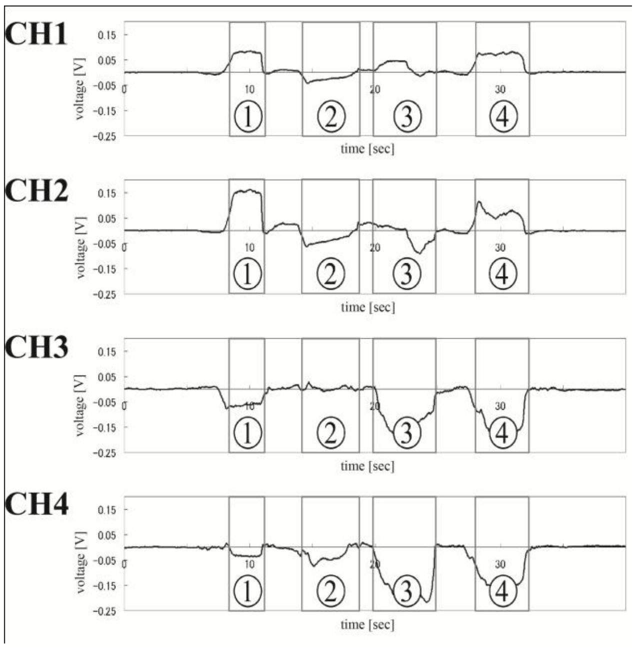

Fig. 4 Measured voltages for 1: grasping; 2: dissection; 3: displacement; and 4: traction manipulations

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TABLE I THRESHOLDS FOR AUTOMATIC CLASSIFICATION

	CH1	CH2	CH3	CH4
grasping	+	+	0	0
dissection	-	-	0	0
displacement	0	0	+/-	+/-
traction	+	+	+/-	+/-

+: detected when the measured value exceeded the positive threshold; -: detected when the value exceeded the negative threshold; 0: detected when the value did not exceed the positive/negative thresholds

Fig. 5 shows the results of automatic classification based on the proposed method for a subject conducting each basic manipulation once. The automatic classification is expected to be used for the evaluation of individual basic manipulations. The manipulation log obtained by the automatic classification also allows clear visualization of the manipulations performed during the operation.

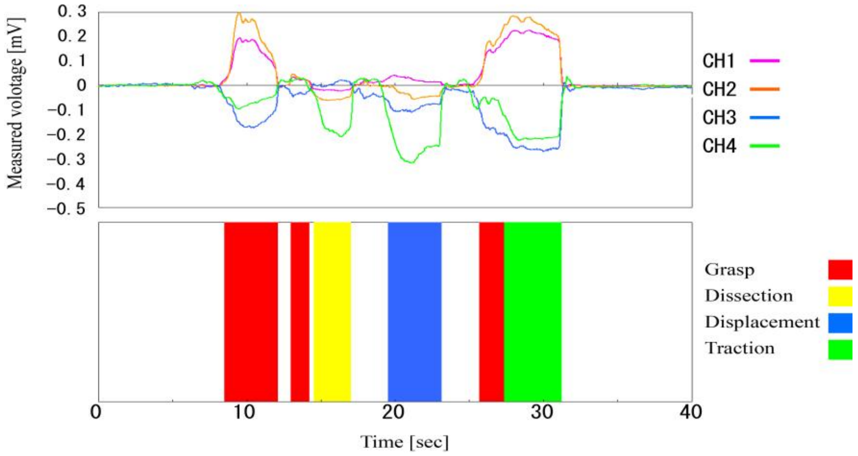

Fig. 5 Manipulation log obtained with the proposed threshold-based classification

III. EXPERIMENT AND RESULTS

A. Tape-peeling Experiment

To explore the application of the proposed method to medical skill training, a manipulation log was created in relation to a task requiring high precision, and the forces exerted during the task by experienced doctors and novices were compared.

The experiment involved six doctors with levels of laparoscopic surgery experience up to 40, 50, 80, 100, 200 and 800 procedures and six novices with no experience of using surgical forceps. All the subjects were right-handed. The task procedures of the training test are illustrated in Fig. 6. In the experiment, the subjects were asked to use the forceps with their dominant hand to peel a piece of vinyl tape from a sheet of paper. All visual information was provided by a monitor displaying camera images of the task area. The subjects were also asked to execute the task with a small range of force and with rapid movements. As the tape ripped easily with excessive force, the task required the subjects to use the forceps with delicacy and dexterity. If the tape ripped, the subjects were allowed to restart with no penalty. Five practice attempts were allowed before the experiment, and all participants gave informed consent.

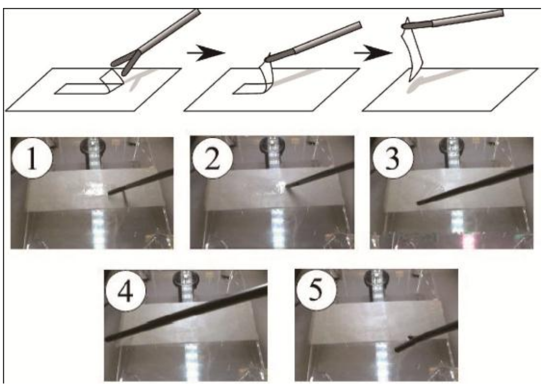

Fig. 6 Tape-peeling experiment

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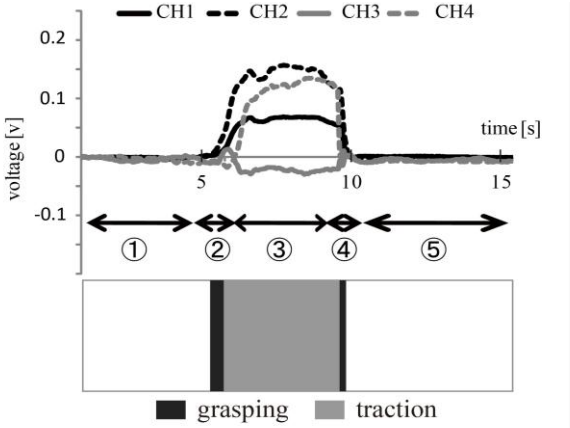
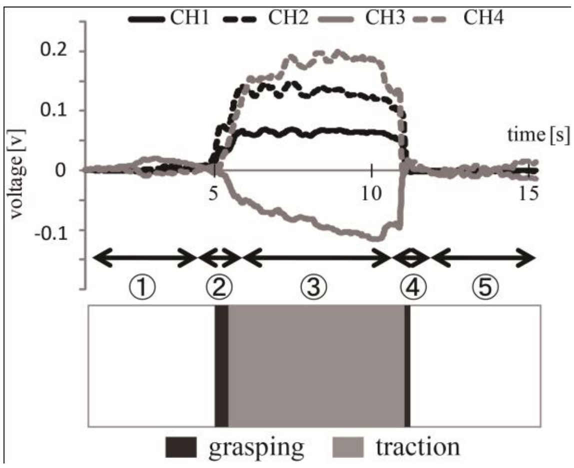
B. Automatic Classification Experiment Results

The voltages measured via the strain gauges and the manipulation log based on the proposed automatic classification are shown in Fig. 7. (a) shows the results for an experienced doctor, while (b) shows those for a novice. Manipulations observed during the tape-peeling task were classified into the two basic types of grasping and traction. Grasping is seen in Regions (2) and (4), and traction appears in Region (3). As traction was recorded when supra-threshold voltages were observed from all the strain gauges, traction manipulation is considered to require a relatively high level of force control. This also suggests that differences in traction manipulation skills between experienced doctors and novices should be large. To investigate such skill differences, focus was placed on force and time information during traction manipulation (Region (3) of Fig. 7).



(a) Experienced doctor



(b) Novice

Fig. 7 Measured voltages and manipulation log from the tape-peeling experiment. The numbers in the figure correspond to those in Fig. 6.

The average measured voltage and the average time elapsed during traction manipulation were computed using the manipulation log, and the results are shown in Fig. 8. The voltage for experienced doctors was clearly smaller than that for novices, and a statistically significant difference between the groups was determined in a t-test ($p = 0.042$). The manipulation duration for doctors was also shorter, but no statistically significant difference was observed ($p = 0.10$). This suggests that force-related information is useful for clarifying differences in forcep manipulation skills.

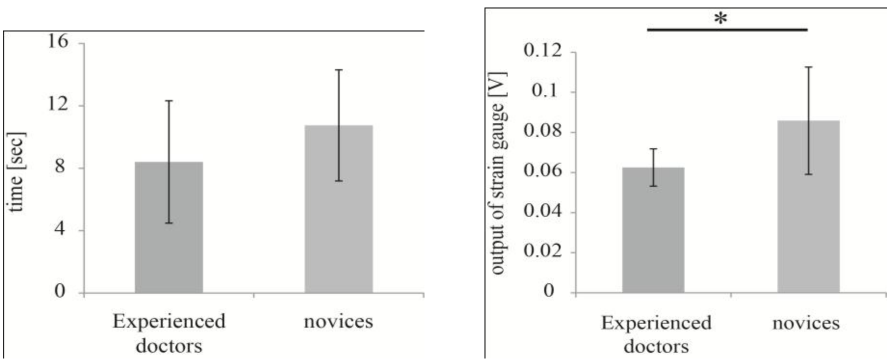


Fig. 8 Traction manipulation performance in the tape-peeling experiment (left: total time; right: mean voltage) (*: $p < 0.05$)

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C. Automatic Classification in an Animal Experiment

The proposed method was used in an animal experiment to support discussion of its applicability in a realistic situation. Fig. 9 shows a photo from the test, in which a medical doctor cut a piece of a tissue from the stomach of a living pig using resection forceps (A in the figure) with his dominant hand and grasping forceps with sensing capability (the study's prototype forceps; B in the figure) to hold the rest of the stomach with his non-dominant hand. The strain gauges were covered with rubber to eliminate any fluid-related influence. The experimental protocol was reviewed and approved in advance by the Hiroshima University Institutional Review Board.

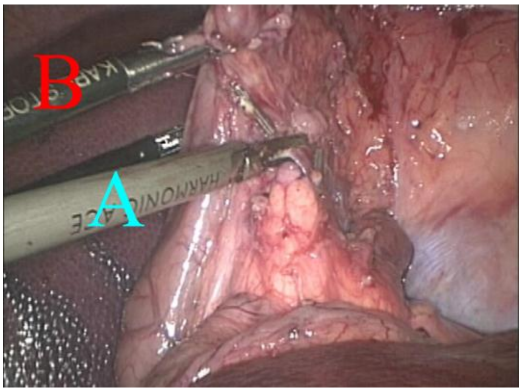

Fig. 9 Tissue cutting experiment

The voltage measured by the strain gauges and the manipulation log obtained are shown in Fig. 10. Grasping, traction and displacement manipulations were mainly observed during the task. It was noted that the grasping forceps were principally used for traction manipulation.

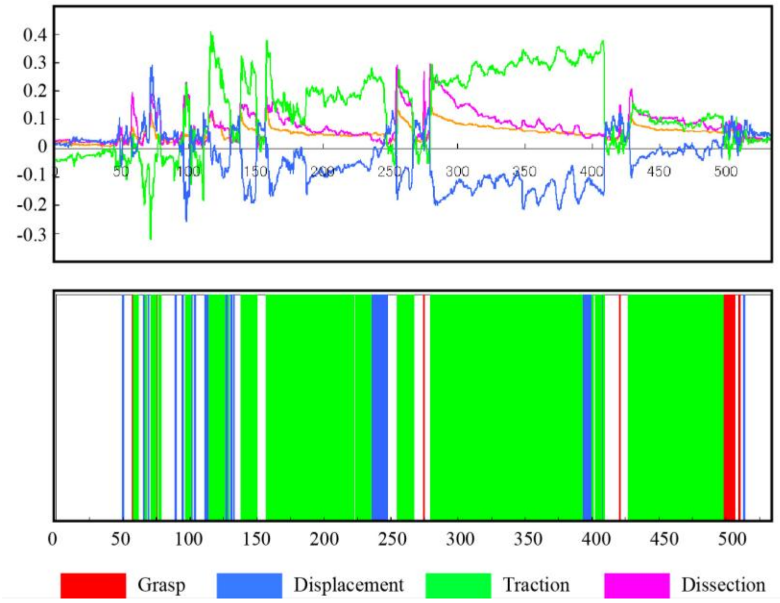

Fig. 10 Measured voltages and manipulation log from the tissue-cutting experiment

IV. CONCLUSION

In this study, basic manipulations were defined by observing laparoscopic surgery videos of cholecystectomy operations. The observations revealed that the four manipulation types of grasping, dissection, displacement and traction accounted for all contact time between the forceps and the body tissue. These manipulations were distinguished by analyzing the forces applied to the shaft and grip of the forceps. A manipulation log was automatically obtained based on monitoring to determine the strain gauge voltages corresponding to the forces applied. A tape-peeling task involving experienced doctors and novices was conducted using the prototype force-sensing forceps, and the manipulation log obtained was used to evaluate the manipulation skills seen during the task. The results showed that the experienced doctors were capable of using the forceps with much smaller levels of force than the novices. A further experiment conducted to obtain a manipulation log during a surgical operation on a pig confirmed the applicability of the proposed method in a practical situation.

The results detailed here indicate the importance of evaluating force information gathered during minimally invasive surgery. Investigation of more complex operations with two bilateral forceps is also included in our future study. Information

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to evaluate manipulation skills is different depending on the type of forceps used. The authors plan to gather information on forcep movement and enable overall evaluation of surgical performance by integrating force and position control skills for bilateral forceps manipulations.

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