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Microsurgical Skill Assessment: Toward Skill-Based Surgical Robotic Control

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Abstract— **A surgical skill assessment system was developed to quantify microsurgical skills. Infrared optical makers, an inertial measurement unit, and strain gauges were mounted on tweezers to record surgical tasks. In preliminary experiments, the tool tip trajectory, acceleration, and applied force were measured and microsurgery videos were evaluated by three expert surgeons. The preliminary results indicated the feasibility of the system by showing the significant difference between unskilled and skilled surgeons.**

I. INTRODUCTION

COMPUER-assisted surgery has been developed to increase the dexterity and manipulation accuracy of surgeons. In the field of microsurgery, which requires very high precision, many microsurgical robotic devices and systems have been proposed. Although these microsurgical robotic systems have shown great potential to improve clinical outcomes, there is still room for further use of robotic technology to go far beyond human ability.

Image guidance, which has already been implemented in many surgical robotic systems, is a good example of the accuracy that can only be achieved with robotic aid. The autonomous or semi-autonomous execution of a surgical task is another example of the advantages of robotic technology. For example, autonomous knot tying has been investigated [1-3] to enable rapid completion of the repetitive task. These studies have targeted laparoscopic surgery because shorter operation time is one of the most important factors, especially for robotic surgery. On the other hand, in microsurgery, the quality of the surgical task is far more important than the operation time, and this factor directly affects the clinical outcome. According to neurosurgeons, needle placement is the most important surgical task related to microvascular anastomosis, and this task requires robotic assistance. In neurosurgery, blood vessels with a diameter of 1 mm or smaller are anastomosed using 0.02-mm surgical sutures, as shown in Fig.1. This task requires very precise maneuvering of surgical tweezers. Moreover, it is crucial to apply adequate force to the blood vessels and surgical sutures for successful anastomoses.

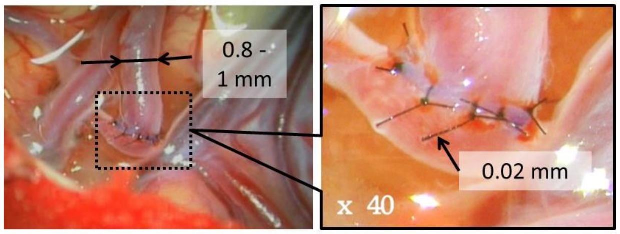

Fig. 1. Anastomosis of small blood vessels in microsurgery

There have been several attempts to assess microsurgical skills, but most of these have been rather subjective. As a result, the knowledge obtained has not been sufficiently quantified; thus, it is difficult to implement expert surgeons' skills on surgical robotic control or training systems. If data quantifying microsurgical skills is available, microsurgical training systems focusing on the training of certain skills can be easily developed. In addition, surgical robotic parameters such as the force required to hold a surgical needle can be autonomously controlled. Force feedback to robotic master arms, which has been widely studied, would not be useful for controlling the force to hold a needle because the adequate force is unknown. Another possible example is autonomous needle positioning. The proper angle and position of the surgical needle can be suggested by a system and executed after approval by the surgeons.

In this paper, a new microsurgical skill assessment system is presented. The first step toward development of this system is creating an assessment system that can collect as much data as possible. These data are then analyzed to determine the parameters that represent high microsurgical skills. By extracting motion elements that can be executed only by skilled surgeons, new criteria for microsurgical skill assessment and training systems and advanced surgical robotic control can be developed.

II. MICROSURGICAL SKILL ASSESSMENT

A. *Microsurgical skill assessment methods*

In the microsurgical field, trainee surgeons do not benefit from advanced training systems, which are often used in the field of laparoscopic surgery [4]. Instead, the surgeons have to learn surgical skills by carefully observing an expert's work in the operating room and later trying to imitate it using artificial

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phantoms or animal models. There are several clinical-based microsurgical skill assessment methods [5, 6], but these require expert surgeons to evaluate the trainees' skill by direct observation or by watching microsurgical videos; therefore, there are not many opportunities for trainees to assess their skill level.

Owing to the recent development of miniaturized or wireless sensors, devices dedicated to microsurgical skill assessment are now being studied. McBeth, et al. measured the tool tip trajectory, excursion, and velocity using an optical motion tracking system to evaluate microvascular anastomosis in animal models, but they evaluated only one experienced surgeon [7]. Lin, et al. placed inertial measurement units on tweezers to evaluate the tool tip acceleration and angular velocity, but only one out of 14 subjects was a medical doctor, and the task was not based on actual surgical tasks [8]. Park, et al. validated the difference between an expert surgeon and a trainee surgeon in coronary artery bypass grafting using artificial vessels and found that vessels anastomosed by the expert surgeon showed smaller energy loss [9]. These devices are promising, but parameters representing high microsurgical skills are yet to be identified. In addition, experiments involving both expert surgeons and non-experienced surgeons need to be conducted to quantify the skills. Therefore, an integrated measurement system needs to be developed to collect as many parameters as possible, and experiments involving many medical doctors with a wide range of clinical experience must be conducted to select adequate parameters for skill assessment.

III. SYSTEM DESIGN

A. Overall System Design

Based on the aforementioned considerations, a microsurgical skill assessment system with motion-measuring and force-sensing capabilities was designed.

The developed system was designed to be portable. This is because it is difficult to find many expert surgeons to participate in the experiments, but a portable experimental setup provides opportunities to conduct experiments. For example, experiments can be conducted at conference sites, which would be useful to increase the number of subjects and the diversity of their clinical experience. Although this type of on-site measurement might be influenced by the doctor's physical condition and feelings of tension, we assumed that the difference between experts and non-experts would still be evident. To develop a portable setup, the microscope was separated from the arm of an OCS-500 stereo microscopic system (Olympus Medical Systems Corp, Japan) and fixed to a custom-made stand that could be placed on a writing desk (Fig.2). A Polaris Spectra™ optical tracking system (Northern Digital Inc., Canada) was then placed at a distance of approximately 1300 mm from the microscope and a height of 1600 mm with a downward inclined angle of 30°. Other devices used in the setup include a Windows PC (CPU: Pentium D 2.80 GHz, Memory: 2.0 GB), two displays (one for the user interface and the other to show the experimental tasks to other participants), a CLH-SC light source and OTV-S6 camera controller (Olympus Medical Systems Corp, Japan), and a strain amplifier AC STRAIN AMPLIFIER AS1302 (NEC Avio Infrared Technologies Co., Ltd.) for use in the force measurement. This system enables experiments to be conducted any place where a desk, a height-adjustable chair, and an area measuring 2 m × 3 m are available.

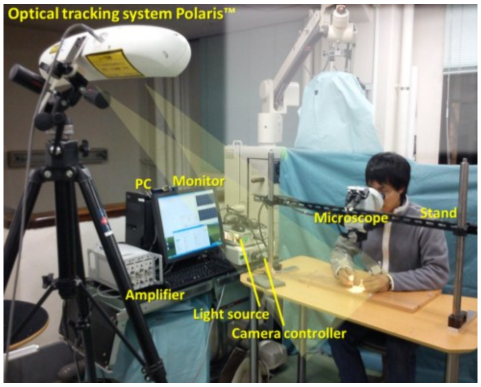

Fig. 2. Setup of microsurgical skill assessment system

B. Sensorized Tweezers

Watch-makers' tweezers (K-1AA130m/m, KFI, Japan) commonly used by neurosurgeons for suturing practice were employed in the developed system. An e-nuvo IMU-Z IMU unit (ZMP Inc., Japan) and infrared markers for optical tracking were mounted on the tweezers, as shown in Fig.3 (a). The sampling frequency of optical tracking was 60 Hz, and the theoretical RMS error was 0.30 mm. The sampling frequency of IMU was 100 Hz, and the theoretical resolution was 0.0096 m/s^2 for acceleration and 0.24 °/s for angular velocity.

The weight of the sensorized tweezers was 38 g. This weight is greater than that of surgical tweezers (18 g), but we assumed that some differences between experts and non-experts could still be detected under the same conditions. This assumption was supported by medical doctors.

C. Force Sensors for Tweezers

To measure the gripping force applied by the tweezers, a pair of strain gauges (KFR-02N-120-C1-11 N10C2; Kyowa Electronic Instruments Co., Ltd., Japan) was attached as shown in Fig.3 (b) and Fig.3 (c), and a tool for force calibration was designed.

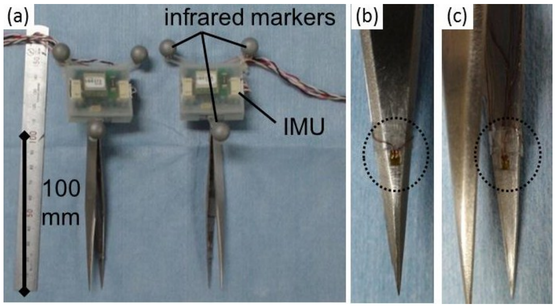

Fig. 3. Sensorized tweezers (a) tweezers equipped with sensors, (b) strain gauge on outer surface, (c) strain gauge on inner surface

IV. PRELIMINARY EXPERIMENTS

A. Experimental objective

The main objective of the preliminary experiments was to identify tendencies of surgical manipulation among the surgeons to enable selection of key parameters representing high skills in microsurgery. The sensors were selected based on the requirements and advice of medical doctors; however, it was also necessary to confirm that their measuring ranges covered the individual differences among the surgeons.

B. Registration of subjects

A registration form to be filled in by each subject was designed, and the items to register included gender, age, handedness, clinical specialty, years of clinical experience, years of microsurgical experience, volume of bypass surgery, and surgical volume per year. The experimental protocol and data disclosure policy were approved by the ethics committee of the School of Engineering at the University of Tokyo.

C. Tasks designed to assess microsurgical skills

We designed three tasks for the experiments, and the preliminary results of two of the tasks are reported herein. Specifically, the results of anastomosis of artificial blood vessels and a task designed to measure hand tremor are presented herein. In the anastomosis task, each subject was asked to conduct an end-to-end anastomosis of 0.7-mm artificial blood vessels (Material: silicone; Microvascular Practice Card, Muranaka Medical Instruments Co. Ltd., Japan) with three stitches using a 10-0 surgical suture (10V43-10R, Muranaka Medical Instruments Co. Ltd., Japan). Each suture was secured with three knots. In the hand tremor measurement, the subject was asked to place the tip of the tweezers at the cut end of an artificial blood vessel and keep them at that position for 60 s. During the experiment, the hand was supported by the desk.

D. Evaluation of surgical skills by medical doctors

The original idea for the evaluation of the anastomosed vessels was to measure specific dimensions representing the quality of the final product (i.e., anastomosed artificial vessels) so that the measurement was objective and quantitative. However, this turned out to be very difficult because the artificial blood vessels made of silicone were very fragile and easily damaged. Most surgeons could anastomose them, but the locations of the needle insertion points differed from those in clinical cases according to their comments. Therefore, we asked expert medical doctors to assess the skill level by watching videos recorded during the anastomosis task. The maximum score, newly defined as the medical assessment score, was 30 points. This score was the sum of 10 points for the needle placement task, 10 points for the suture handling task (after needle placement and before knot tying), and 10 points for the knot-tying task.

V. EXPERIMENTAL RESULTS

A. Subjects

In this paper, the preliminary results of 13 neurosurgeons are described. The clinical experience of the subjects ranged from 3 to 28 years (mean: 20, SD: 9.9). All subjects were male and right-handed, and their ages ranged from 26 to 53 years (mean: 46, SD: 10.3). The specialty of seven neurosurgeons was cerebral vascular disorder. The subjects' experience in microsurgery ranged from 1 to 28 years (mean: 15, SD: 9.7), their volume of bypass surgery ranged from 0 to 300 (mean: 30, SD: 91), and their surgical volume per year was 1 to 300 (mean: 71, SD: 102).

After the experiment, three expert surgeons watched microscopic videos and provided medical assessment scores for each stitch. The scores were normalized to eliminate the individual differences of the evaluators.

B. Trajectory

Figure 4 shows the tool tip trajectories of the tweezers recorded during the first stitch performed by two subjects. Subject A was a novice surgeon with six years of clinical experience who obtained the tenth highest score from all the evaluators. Subject B was an expert with 22 years of clinical experience who obtained the highest score from all the evaluators. Although the excursion distance, which can be easily quantified, was not strongly correlated with any of the registered parameters or scores (data not shown), surgeons with a higher medical assessment scores appeared to move the tweezers more efficiently and their performance was stable for all stiches. The parameters that can appropriately quantify this difference should be derived by further analysis of the data.

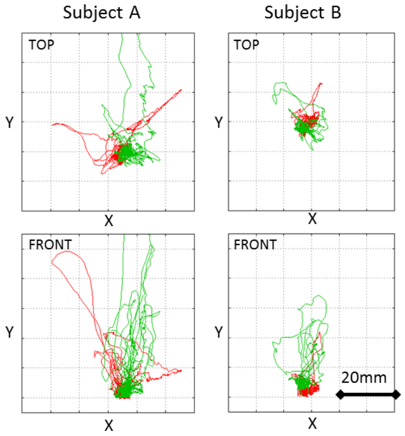

Fig. 4. Trajectory of tweezers during first stitch. Subject A obtained the tenth highest score from all the evaluators, and Subject B obtained the best score from all the evaluators. (Red line: right hand, Green line: left hand.)

C. Force

Figure 5 shows the maximum gripping force applied at the tool tip during each phase of the needle placement task. The results show that surgeons with higher medical assessment scores applied less force when they pushed and pulled the needle (Fig.5 (b), Fig.5(c)). This tendency was not observed when the data was sorted by clinical experience or other registered parameters. In previous studies, novice and expert surgeons were distinguished only by clinical experience, but these results suggest that skills are less related to clinical experience in microsurgery. Thus, a combination of technical analysis and medical assessment would be necessary to extract skilled motion elements. Estimation of the force applied by skilled surgeons would be useful for designing automated control by microsurgical robots.

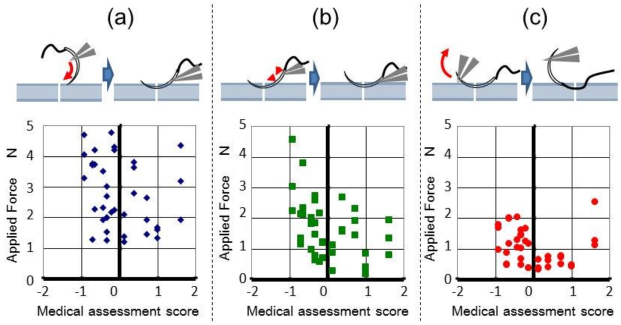

Fig. 5. Force applied during needle placement task: (a) inserting, (b) pushing, and (c) pulling out needle.

D. Hand tremor

Figure 6 shows the amplitude spectrum of the right-hand acceleration calculated by a fast Fourier transform (FFT) analysis. The subjects were the same as those shown in Fig.4. These findings indicate that the skilled experts have less hand tremor or they know a specific technique to suppress the tremor.

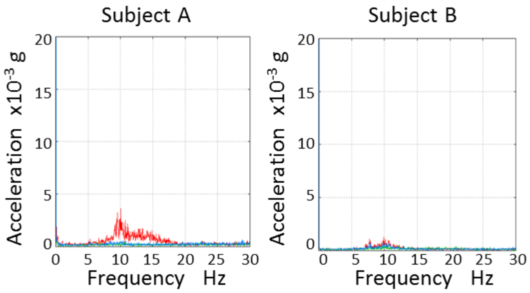

Fig. 6. FFT of right-hand acceleration. Subject A received the tenth highest scores from all the evaluators, and Subject B received the best scores.

VI. DISCUSSION AND CONCLUSION

Preliminary results clearly demonstrate the potential contribution of our system to microsurgical skill assessment. In particular, the gripping force and hand tremor, which have not been measured in other studies on microsurgical skill assessment, are useful parameters to assess these skills. We are currently collecting data from trainee surgeons to distinguish skills learned in a short time (i.e., during the training period), which doesn't need technical assistance, from skills learned in a long time (i.e., after the training period), for which an intensive training or robotic control is required.

Surgical robotic control, which can replicate the motion of expert surgeons, would enable young inexperienced surgeons to conduct surgery with high precision. An investigation of quantification methods will be conducted after our data collection is complete.

The measured values showed a stronger correlation to the medical assessment scores than clinical experience or other parameters. These findings suggest that the skills are not entirely related to clinical experience in microsurgery, probably because inherent physical abilities are important. Accordingly, the criteria for microsurgical skill assessment must be different from those for other surgical techniques.

In conclusion, we developed a microsurgical skill assessment system capable of measuring many parameters, including the tool tip trajectory, acceleration, and applied gripping force, and the results of preliminary experiments demonstrate the feasibility of the developed system. Further analysis of the data will be conducted to extract motion elements that are only seen in skilled surgeons. This should lead to the development of efficient training systems and skill-based control methods for surgical robots.

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