Maneuverability Evaluation of a Surgical Robot for Single-Port Surgery

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***Abstract*—This study evaluates the operability of a surgical robot for single-port surgery (SPS) developed in our laboratory. The surgical robot operates under master–slave control implemented by the haptic interface Omega 7 and is reinforced with a force feedback mechanism. The maneuverability of the surgical robot system was assessed in a block transfer experiment and a ligation experiment. The completion times of forceps manipulation by robot operation were compared with those of manual operation. To assess the force feedback functionality of the surgical robot, we tested whether the robot could properly contact and avoid obstacles when using the forceps. The results verified the effectiveness of the surgical robot system for SPS.**

***Index Terms*—surgical robot, single-port surgery, maneuverability evaluation, force feedback**

I. INTRODUCTION

In recent years, minimally invasive surgery has become the preferred option in hospitals, but it requires accurate and delicate operation in a small workspace with a limited field of vision, demanding considerable skill of the surgeon. Single-port surgery (SPS) has been lately embraced by laparoscopic surgeons [1]. Various surgical robots controlled by a teleoperated master–slave system such as the da Vinci system have also been developed and used in conventional laparoscopic surgery [2]. Other surgical robots have been designed for SPS [3]-[8]. In addition, to perform minimally invasive surgery, only visual information is provided in the conventional robotic systems. Force feedback is particularly beneficial in surgical robot systems, as it improves the surgeon’s dexterity and enhances the operability of surgical robots in telesurvey execution [9], [10].

Our originally developed surgical robot for SPS is described in [11]. We analyzed the kinematics of the developed surgical robot and proposed a position control method based on inverse kinematics as an intuitive control.

The present study evaluates the maneuverability of the surgical robot for SPS. To this end, we assigned four tasks to the surgical robot and compared its performance against manual operation using commercially available forceps.

The first task is block transfer in which the robot grips and moves the block. The robot also performs the Task1 Peg transfer described in [12], [13]. The second task is a ligating operation using a surgical suture. The third and fourth tasks are contact detection of a soft tennis ball and obstacle avoidance, respectively.

These tasks are experimentally performed in manual and robot operations. The maneuverability of the surgical robot is evaluated by comparing these results.

II. SURGICAL ROBOT FOR SINGLE-PORT SURGERY

A. Single-port Surgery

In conventional laparoscopic surgery, the forceps and laparoscope are inserted through incision holes on the body surface. However, in SPS, they are inserted through a single-incision hole on the umbilicus. The scar is almost unnoticeable because the incision trace is indistinguishable from the umbilical wrinkle pattern [14]. Therefore, SPS yields a better aesthetic outcome than conventional laparoscopic surgery. In addition, SPS reduces the risk of adhesion-based postoperative complications because of its much lower invasiveness than the conventional method.

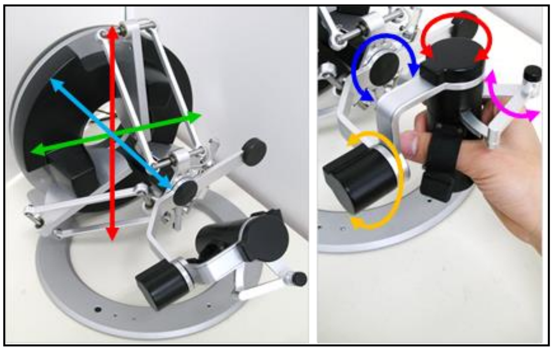

Figure 1. Haptic device Omega 7 and its manipulations (left panel indicates the yaw, pitch, and translational motions; right panel indicates the rotational motions (blue, red, yellow) and the grasping motion (pink).)

B. Experimental Devices

Fig. 1 shows the haptic device Omega 7 produced by Force Dimension, used as a master device for teleoperation control of the developed SPS surgical robot. Omega 7 can perform seven DOF operations: translational motions along three axes, rotary motions

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around these three axes, and a grasping motion around one axis. In addition, force feedback is available for the translational motions and the grasping motion.

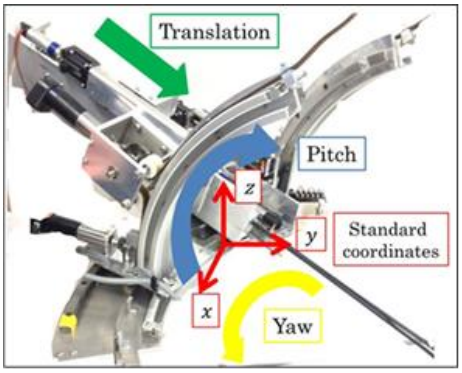

Figure 2. Overview of the SPS surgical robot.

Fig. 2 shows an overview of the SPS surgical robot. The surgical robot consists of two forceps manipulators and two robotic arms. The laparoscope is assumed to be operated manually by a laparoscopic camera assistant. As shown in Fig. 2, the surgical robot for SPS can perform yaw, pitch, and translational motions.

For this study, the surgical robot is also equipped with a force feedback function. A six-axis force sensor is attached in the root of the forceps shaft as shown in Fig. 3. Therefore, the system will detect loads applied to the shaft of the forceps. In tasks 3 and 4, the contact force was fed back to the operator through the Omega 7. The feedback force was based on the force measured by the sensor.

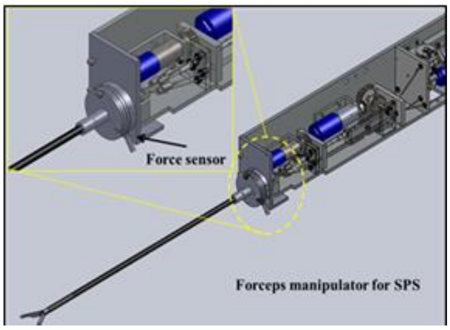

Figure 3. Forceps manipulator for SPS.

C. Kinematics

The standard coordinates (x, y, z) are set in the center of the curved guide of the surgical robot. Two Omega 7s and the SPS surgical robot are then placed as shown in Fig. 4.

This arrangement is called the home position. In the position tracking control, intuitive operation is realized so that the moving direction of the forceps tip coincides with the operating direction of Omega 7. An example is indicated by the blue arrow in Fig. 4, in which the right side surgical robot is controlled using the left side Omega 7. To achieve intuitive operation, we developed the following forward and inverse kinematics of the developed surgical robot.

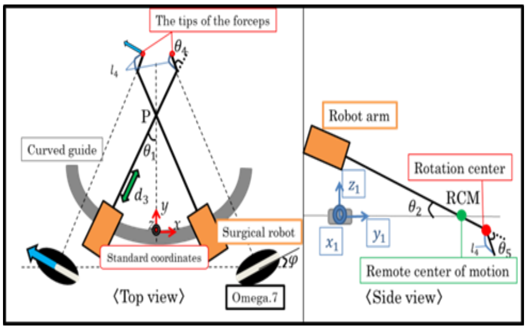

Figure 4. Placement of the surgical robot and Omega 7.

The forward kinematics are solved through a simultaneous transformation matrix, which converts the standard coordinates to the coordinates at the tip of the forceps, denoted as ${}^{L0}T_{L6}$.

$$ {}^{L0}T_{L6} = {}^{L0}T_{L1}\,{}^{L1}T_{L2}\,{}^{L2}T_{L3}\,{}^{L3}T_{L4}\,{}^{L4}T_{L5}\,{}^{L5}T_{L6} \tag{1} $$

The end position of the left-side robotic arm with forceps manipulator in the standard coordinates is obtained by multiplying the origin vector ${}^{L6}p = \begin{bmatrix} 0 & 0 & 0 & 1 \end{bmatrix}^T$ from the right side of (1).

In this study, we seek a numerical solution to the inverse kinematics using the Jacobian matrix.

Then, by Newton’s method, we obtain:

$$ \begin{aligned} \theta_{new} &= \theta_{old} + \Delta\theta \\ &= \theta_{old} + J^{-1}\Delta r \\ &= \theta_{old} + J^{-1}(r_{new} - r_{old}) . \end{aligned} \tag{2} $$

The previous angle of the robotic arm θ_{old} is measured by encoders mounted on the drive motors of the robotic arm, and r_{new} and r_{old} are detected by Omega 7. r_{new} and r_{old} represent a current tip position and the tip position from one step before. Thus, the updated angle of the robotic arm θ_{new} is obtained by numerically solving the inverse kinematics. Details are given in [11].

D. Control Methodology

The target angular displacement θ_{new} is provided to the surgical robot at each sampling time. As explained above, the target angle is found by numerically solving the inverse kinematics by Newton’s method. Tracking the target angular displacement provides a suitable position tracking control of the forceps tip.

The controller is a proportional-integral-derivative controller. The position of the forceps tip is tracked in the operating direction of the Omega 7. The control program was written in MATLAB/Simulink software. As the interface board, we used a digital controller (PCIA04; Inteco Co., Ltd.). The motor amplifier comprised a bipolar power supply (Metronix Inc.) and a VoltPAQ-X4 (Quanser Corp.)

III. OPERATING RANGE

In the first experiment, we evaluated the operating range of the forceps tip by robot operation using the surgical robot and by manual operation using the commercially available SPS forceps. The forceps used in the manual operation were commercially manufactured for SPS by Covidien Ltd.

A. *Operating Range Experiment*

In this experiment, two SPS forceps and an aluminum rod that mimics a laparoscope were inserted in crossover fashion into the single-incision laparoscopic surgery (SILS) port made by Covidien Ltd. Two of them were fixed to prevent their interference and another one was moved freely. The locus of the maximum movable range was traced onto a grid paper by a pen mounted at the tip of the rod and the forceps. The experiments were sequentially performed for the rod and the forceps. The SILS port was placed 15 cm from the grid paper as shown in Fig. 5. The experiment was carried out for robot operation using the surgical robot and for manual operation using the SPS forceps.

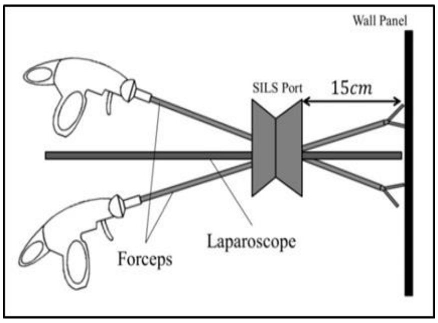

Figure 5. Schematic of the operating range experiment.

B. *Experimental Results*

The results of the operating range experiment are summarized in Table I.

TABLE I. RESULTS OF THE OPERATING RANGE EXPERIMENT

	Robot operation mm^2	Manual operation mm^2
Forceps A	8189	13000
Forceps B	5670	16375
Laparoscope	7419	11520
Total	21278	40895

For all the manipulated parts, manual operation of the SPS forceps far exceeded the maximum range of movement of the surgical robot's operation. This result is attributed to the limited operating area of the surgical robot, which narrows the movement range of the robot operation. However, it should be mentioned that the maximum movable range of the actual surgery is smaller than the movable range of measurement by manual operation.

IV. EVALUATION EXPERIMENT OF BLOCK TRANSFER

The maneuverability of the surgical robot was evaluated in block transfer tasks. The subject was a healthy 23-year-old male who is not a medical worker but is sufficiently familiar with forceps operation. The control program was created using MATLAB/Simulink software.

A. *Experimental Methodology*

The equipment of the evaluation experiment was set up as shown in Fig. 6.

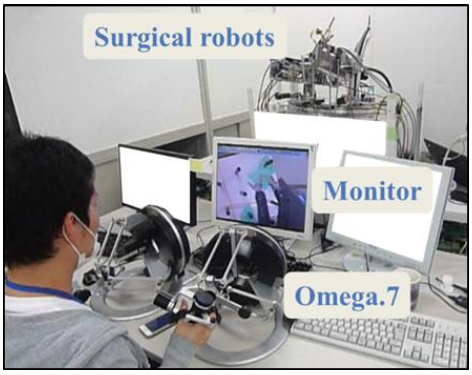

Figure 6. Setup of the block transfer experiment.

The block transfer tasks were performed with VTi medical Dexterity Blocks. In the block transfer experiments, three blocks were sequentially manipulated by the nondominant hand of the subject. The subject was required to transfer the object in midair to his dominant hand and then place the block on the opposite side of the board. The time to transfer three blocks was recorded.

10 block transfer tasks were conducted for the robot operation and the manual operation. The manual operations were performed in a cage, limiting the operations to the maximum movable range of the surgical robot. In this experiment, the bending angle of the forceps during the manual operation was fixed at approximately 30°. The bending angle of the right forceps (θ_4 in Fig. 4) of the robot operation was fixed at approximately 30°, and the bending angle of the left forceps was arbitrary changed depending on the hand operation.

The incident angle in the operating shaft relative to the operating face of the block board of the forceps was fixed at approximately 50°–60°. During this experiment, the surgical robot was operated without the force feedback function. The obtained results were analyzed to evaluate the maneuverability of the surgical robot for SPS.

B. *T-test*

The *t*-test evaluates the statistical significance of different results. Specifically, if the average values of two samples selected from a population appear to differ, the *t*-test determines whether the difference is likely to be real [15]. In our experiments, we evaluated whether the task completion time differed between the robot and manual operations.

The probability, called the *p*-value, actually measures the probability that differences among groups obtained during an experiment are chance occurrences. We considered that *p*-values were significant at the 0.05 level, because this means that the average completion times coincide between the manual and robot operations at a 5%.

C. Experimental Result

The results of the block transfer experiment are shown in Table II and Fig. 7. Fig. 8 plots the learning curve representing the time required for familiar operation. The blue and red bars in Fig. 7 represent the average task completion times of the manual operation and robot operation, respectively, and the thin black lines extend from the earliest to the latest completion time.

TABLE II. RESULTS OF THE BLOCK TRANSFER EXPERIMENT

		Robot operation	Manual operation
Count	1	1:33	2:08
	2	1:25	1:34
	3	1:08	1:56
	4	1:10	1:57
	5	1:23	1:10
	6	1:12	1:18
	7	0:52	1:02
	8	1:13	1:00
	9	0:52	1:14
	10	0:58	1:06
Average		1:10	1:26

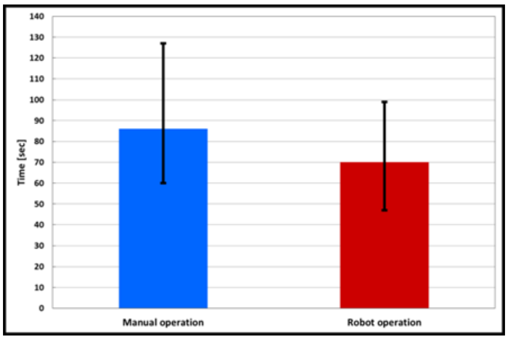

Figure 7. Time required for the block transfer task.

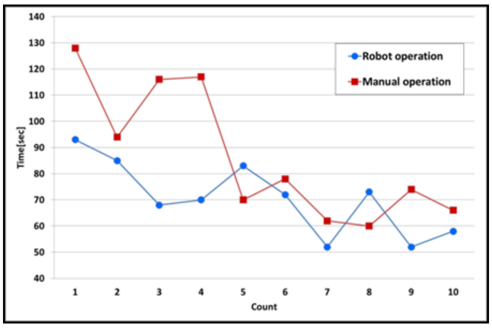

Figure 8. Learning curve in the block transfer experiment.

Clearly, the robot operation completed the task earlier than the manual operation, and the difference was statistically significant because $p = 0.0472$ was obtained. Therefore, the difference between the average task completion times was not due to accidental errors.

The learning curve demonstrates that by the 10th trial, the completion time of both manual and robot operations had reached its minimum. In the first few trials, the robot operation was accomplished faster than manual operation because the robot performs right and left operations with equal competency.

V. LIGATION OPERATION

To evaluate the surgical robot in a more practical setting, the robot performed ligation using a medical nylon suture, and its performance was compared with that of manual operation. The subject was a 23-year-old male who is not a medical worker but sufficiently accustomed to forceps operation.

A. Experimental Methodology

The manual operation was performed in no-cage and in cage situations, limiting the maximum movable range to that of the surgical robot. The ligation operation was performed four times by the manual operation and the robot operation, and the average completion time was calculated. The equipment of the ligation operation experiment is shown in Fig. 9. In this experiment, the surgical robot was operated without the force feedback function.

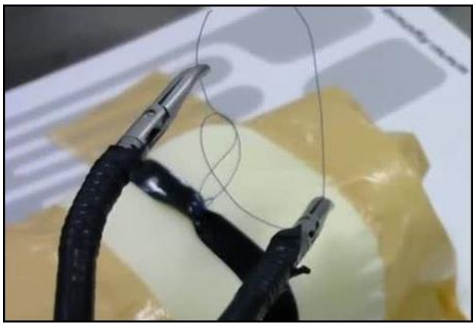

Figure 9. Appearance of the ligation experiment

B. Experimental Results

The robot operation required 28 s on average to complete the ligation procedure against 21 s by the manual operation in an unrestrained operating area and 24 s by the manual operation in the caged area.

The completion times of the manual operation were shorter than that of the robot operation. One of the reasons of this is considered as follows. Because the maximum movable range of the surgical robot is narrower than in the normal manual operation, large left and right movements for ligation operation are prevented under this condition.

VI. EVALUATION EXPERIMENT OF FORCE FEEDBACK

A. Experimental Methodology

During laparoscopic surgery, there is risk of organ damage when the surgical instruments contact the organ outside of the endoscope's field of view. Generally, the robots cannot detect contacted obstacles unless they elicit a tactile response.

Therefore, this experiment examined the judgment rate of the surgical robot when contacting obstacles outside the operation screen and compared the judgement performance with that of manual operation. For this purpose, the robot was equipped with the force feedback function.

After judging the contact obstacles from force feedback alone, the subject was required to avoid the obstacle. The force feedback function of the surgical robot was evaluated in two tasks. The human subjects were two students with sufficient knowledge of forceps operation.

As for the motion scaling of displacement, the forceps tip follows half of the movement of Omega 7, and as for the haptic feedback, doubled force was presented to the Omega 7.

1) *Contact judgement*

Fig. 10 shows the equipment of the contact judgment experiment. The subject moved the forceps tip to the left and the right without looking at the forceps tip. An obstacle was touched to the forceps tip by the experimental collaborator. The obstacle was a soft tennis ball mimicking the softness of an organ. The subjects were required to declare when they sensed contact with the tennis ball.

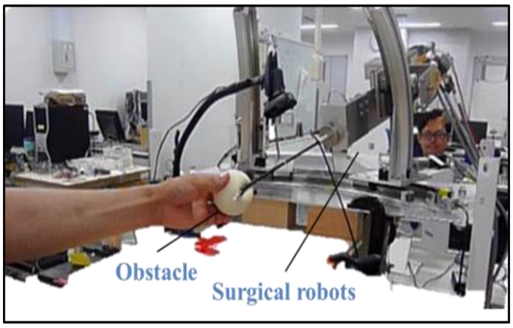

Figure 10. Experiment of obstacle contact judgment.

This task was conducted by the manual operation and the robot operation with the force feedback function. The case of “unsure contact” was considered a failure. The judgment rate of each subject was measured in 20 trials per subject.

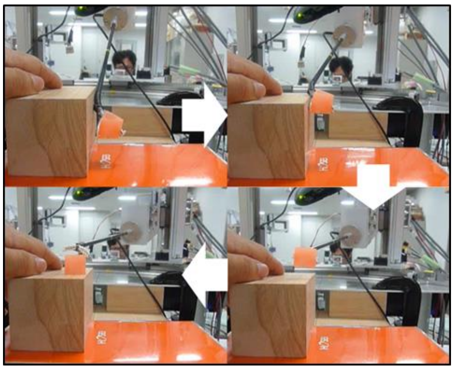

Figure 11. Snapshots of the obstacle avoidance task.

2) *Obstacle avoidance*

Snapshots of the obstacle avoidance task are presented in Fig. 11. The subjects started the experiment with grasping the block used in the block transfer experiment. Then, without looking at the forceps tip, the subject stacked it onto other specified building blocks by pushing the forceps tip to the sidewall of the building blocks, where the stack height was randomly selected. Since the subjects see only the shaft of the forceps on the operation screen, the forceps tip is completely hidden from the subjects.

This task was conducted by the robot operation with and without the force feedback function. If the position of the building blocks was not clearly identified or a block was not stacked onto other building blocks, the trial was considered a failure. The success rate was computed from 10 trials per subject.

B. *Experimental Results*

1) *Contact judgement*

The results of the contact judgement are summarized in Table III. In the robot operation, subject A successfully detected contact in 18 out of 20 trials (a success rate of 90%), whereas Subject B was successful in all trials. Therefore, both subjects clearly identified the contact with a soft tennis ball, verifying the functionality of the force feedback. The subject A failed in two trials. This is because when the tip of the forceps contacts the soft tennis ball, the force sensor attached in the root of the forceps cannot detect the contact due to the deflection of the forceps shaft.

TABLE III. RESULTS OF JUDGING CONTACT WITH AN OBSTACLE

	Subject:A		Subject:B	
	Count	Rate [%]	Count	Rate [%]
Robot Operation	18/20	90	20/20	100
Manual Operation	20/20	100	20/20	100

In the manual operation, the force was directly detected by the forceps; hence, the judgment rate was 100%.

2) *Obstacle avoidance*

The results of the obstacle avoidance task are summarized in Table IV. In the robot operation with force feedback function (Force FB ON), the avoidance success rate of both subjects was 100%, indicating proper contact with the obstacle. In the robot operation without force feedback function (Force FB OFF), the robot failed in all but one attempt. In the manual operation, the force was detected by the forceps, and the success rate was 100%.

TABLE IV. RESULTS OF THE OBSTACLE AVOIDANCE EXPERIMENT

	Subject:A		Subject:B	
	Count	Rate [%]	Count	Rate [%]
Robot Operation (ForceFB ON)	10/10	100	10/10	100
Robot Operation (ForceFB OFF)	1/10	10	0/10	0
Manual Operation	10/10	100	10/10	100

VII. DISCUSSION

In the block transfer experiment, the robot operation required an average of 70 s to complete the task, whereas manual operation required 86 s. The faster completion time in the robot operation was attributed to the equivalent left and right manipulation ability of the robot, and the intuitive tasking by the position tracking control.

In addition, in the right-hand robot arm, the subject was able to control the bending angle of the forceps tip arbitrarily during the experiment. Therefore, the robot's timing in the block transfer experiment might also have been shortened by the ability to grasp at a suitable angle.

The block transfer experiments demonstrated the usefulness of the surgical robot for SPS. However, in the ligation operation experiment, manual operation required less time than the robot operation. Furthermore, within the narrow operating space of the surgical robot, it is difficult to tie a tight knot in the suture. In further developments, we must adapt a proprietary ligation method to the surgical robot, adding the bending function of the forceps tip to both robot arms.

The force feedback function enables contact detection when the forceps tip touches an obstacle outside the operation screen. The experimental results verified the effectiveness of the force feedback function. However, when a small load was applied to the forceps tip, the small contact to the forceps tip was not easily detected by the force sensor attached in the root of the forceps.

VIII. CONCLUSION

This study investigated the performance of our developed SPS surgical robot and compared it with that of manual operation. The usability of the surgical robot was validated in a mock ligation operation and in block transfer experiments.

In addition, the force feedback function of the SPS surgical robot was verified in contact detection and obstacle avoidance experiments.

In future work, we will evaluate the maneuverability of our SPS surgical robot by adding a grasping force feedback function.

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