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# Pilot Study of Design Method for Surgical Robot using Workspace Reproduction System

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*Abstract*—**Recent development methods for surgical robots have an inherent problem. The user-friendliness of operating robot cannot be revealed until completion of the robot. To assist the design of a surgical robot that is user-friendly in terms of surgeon's operation, we propose a system that considers the operation manner of surgeon during the design phase of the robot. This system includes the following functionality: 1) a master manipulator that measures the operation manner of the surgeon (operator), and 2) a slave simulator in which the mechanical parameters can be configured freely. The operator can use the master manipulator to operate the slave simulator. Using this system, we investigate the necessity of considering the operator's manner when developing a surgical robot. In the experiment, we used three instruments with mechanisms that differed with respect to the length between bending joints and measured the trajectory of each instrument tip position during the surgical task. The results show that there are differences in the trajectories of each mechanism. Based on the results, changes in the mechanism of the surgical robot influenced the operator's manner. Therefore, when designing the mechanism for a surgical robot, there is a need to consider how this influences the operator's manner.**

## I. Introduction

### A. Background

MINIMALLY invasive surgical techniques are continually being developed to reduce the invasiveness of various surgical procedures. Beginning in the 1990s, the development of new technologies, including advanced laparoscopes, clip appliers, and energy sources for laparoscopy, provided a period of rapid development in minimally invasive surgery [1]. In recent years, research and development of the technology, such as surgical robots and navigation systems, has been undertaken. The expectation of surgery performed by minimally invasive surgical robots has increased, and research and development of surgical robot systems has advanced in many fields [2]-[3].

Laparoscopy and other minimally invasive surgeries have successfully reduced patients' postoperative pain, complications, and hospitalization time, and have improved cosmetics. Most existing robotic surgical systems are designed for minimally invasive laparoscopic procedures [4]. For example, Intuitive Surgical Inc. provides the da Vinci system commercially [5]-[6]. Ikuta developed a surgical robot with a wide moving range [7]. Minor developed a surgical robot that has excellent stiffness by using gear-links [8].

### B. Problems

In recent years, many kinds of surgical robots have been developed to improve performance, including accuracy, moving range, and stiffness, through changes in the mechanisms. On the other hand, there is a problem that surgeons cannot judge how easy or hard it is to operate the robot until the robot has been completed. As such, we may develop a surgical robot that is not user-friendly for the surgeon to operate. This is a major problem in the development of a high performance surgical robot.

In today's development methods for surgical robots, the problem exists that the user-friendliness of the surgeon's operation manner cannot be revealed until completion of the robot. To solve this problem, there is a need to reveal the surgeon's manner of operation before actually designing the robot. If we consider the surgeon's manner of operation during the design phase of the robot, there is a greater possibility of being able to design a robot that is user-friendly in terms of the surgeon's operation.

### C. Objectives

In this research, to efficiently develop a surgical robot that is user-friendly in terms of the surgeon's operation, a system that can reveal the manner to operate the surgical robot during the design phase of the robot is developed. The system implements two functions: 1) a master manipulator that measures the operation manner of the surgeon (operator), and 2) a slave simulator whose mechanism can be freely set. The operator can use the master manipulator to operate the slave simulator and the operation manner can be measured. This paper reports on the necessity to reveal the operator's manner during the design phase.

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The rest of the paper is organized as follows. Section II presents the system details. Section III presents the experimental method and results, while Section IV discusses the result. Finally, Section V provides a summary and alludes to future work.

## II. System Overview

In this section, we give an overview of the system. The system has been established in such a way that the operator can operate the robot without the need to develop a robot actually. Therefore, the basic requirements of the system capabilities are as follows: 1) ability to change the settings of the instruments mechanism freely, and 2) ability of the operator to actually operate the mechanism that is set.

Based on these specifications, the developed system consists of the following 2 functions. 1) A master manipulator with 6 DOFs for position and posture and 1 DOF for grip and the ability to measure the operator's manner. 2) A slave simulator with the ability to change the mechanism setting of the instrument freely. A schematic illustration of the developed system is shown in Fig. 1 and the specifications are listed in Table 1. By using this system, the operator can actually operate the assembled mechanism of the instrument through the simulator and also obtain the information of the instrument tip and each joint such as the position, the posture and the joint angle.

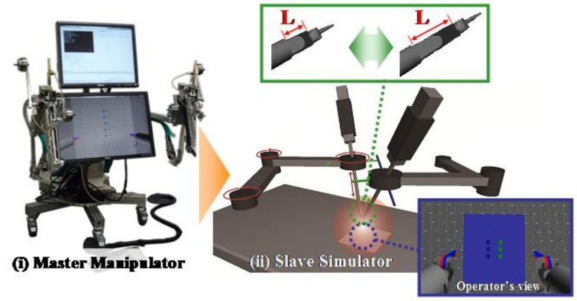


Fig. 1. System to reproduce the workspace

TABLE I
Specifications of the proposed system

| | Master manipulator | Slave simulator |
|---|---|---|
| OS | QNX | Windows |
| CPU | 3.0 GHz | 2.8GHz |
| GPU | N/A | nVidia GeForce |
| Memory | 512MB | 16GB |

### A. *Master manipulator*

The master manipulator, consisting of left and right manipulators both with 7 DOFs, measures the operation manner. A more detailed explanation of the DOF of the master manipulator is 6 DOFs for the position and posture and 1 DOF for grip. Of the 6 DOFs the master manipulator has 3 DOFs for the position and 3 DOFs for posture, so the operator will not get any restraint from the DOFs when determining the position and posture of the slave simulator. Sensors to detect the angle of the joint are included and these are designed to move completely passively without the use of an actuator. We have already reported this master manipulator in our previous article [9].

### B. *Slave simulator*

#### 1) *Overview*

In this system, the slave manipulator is replicated on the simulator. Parameters such as DOF, joint type, and length of the instrument parts transformations can be freely set. The slave simulator is activated in action with the master manipulator and the tip of the slave simulator moves with the same position and posture as the tip of the master manipulator. The calculation period is set to 30 Hz so that the instrument is able to operate in real-time with the operator. Instrument settings, position, posture, and the operator's viewpoint, can be freely changed. Thus, the surgical environment can also be freely changed.

#### 2) *Kinematics*

The tip of the slave simulator moves with the same position and posture as the tip of the master manipulator. Consequently, there is a need to calculate the displacement of each joint of the slave simulator according to the movement of the master manipulator. The displacement of each joint is calculated through the use of inverse kinematics.

The mechanism of the slave simulator (instrument) can be freely changed so that the calculation of the inverse kinematics should be solvable for any freely set mechanism. Thus, the inverse kinematics needs to be shown as a general equation. Based on this need, a method for solving the inverse kinematics is considered as follows.

In ordinary inverse kinematics, there are 3 solution methods: a) transforming the equation into an algebraic solution, b) using the characteristics of the function in a geometric solution, and c) using the Jacobian matrix and solving this by a numerical calculation method. We investigated the calculation method of this system with respect to these solution methods. Method a) needs to be applied to nonlinear highly ordered simultaneous equations, the outcome of which may be too complex or unable to be solved. The calculation of the inverse kinematics in method b) cannot be written as a general formula, because the characteristics of the function cannot be obtained without setting the mechanism. The calculation of the inverse kinematics in method c) can be written as a general formula. The calculation becomes easier by comparing this method with method a). Therefore, method c), using a Jacobian matrix is employed as the calculation method of this system.

In method c), the displacement of each joint is calculated using Equation (1).

$$\dot{\theta}_{slave} = J^{-1} \cdot \dot{q}_{master} \tag{1}$$

where $J$ denotes Jacobian matrix of the slave simulator, $\dot{q}_{master}$ denotes the velocity vector of the master manipulator's tip, and $\dot{\theta}_{slave}$ denotes the joint angular velocity vector for the slave simulator. In the Jacobian matrix calculation method, the equation needs to be solved for every calculation period.

## III. Experiment

In this section, we explain the experimental method of a system to investigate the relation between the operation manner and changes in the instrument. In the experiment, three types of instruments were used to perform a surgical task. These instruments differed in terms of the length between bending joints on the instrument. We measured the trajectory of each instrument tip during performing a surgical task. And we considered the necessity of revealing the operation manner during the design phase based on the result.

### A. Methods

In the experiment, instruments with three different mechanisms were used. A surgical task was carried out using each mechanism. Given below are the detailed experimental conditions.

#### 1) Characteristics of the instruments

The basic mechanism of the slave simulator used in the experiment has 6 DOFs for the position and posture and 1 DOF for the grip. This is because the most basic surgical robots have a slave manipulator with such DOF.

As shown in Fig. 2, instruments with three types of mechanism were used for the surgical task. These instruments differed in the length L, that is, the length between the bending joints located on the instrument. For mechanism I, L = 0 mm, for II, L = 5 mm, and for III, L = 10 mm. All other parameters, except length L were fixed at the equal values.

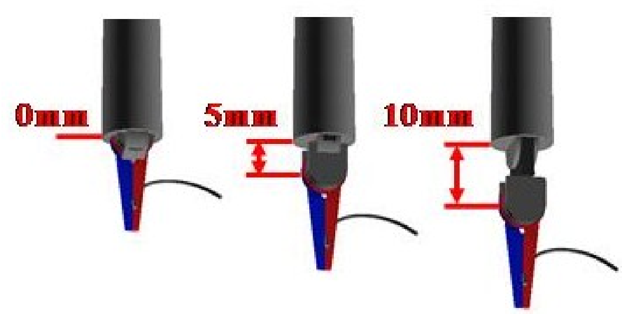


Fig. 2. Target mechanism of the instrument

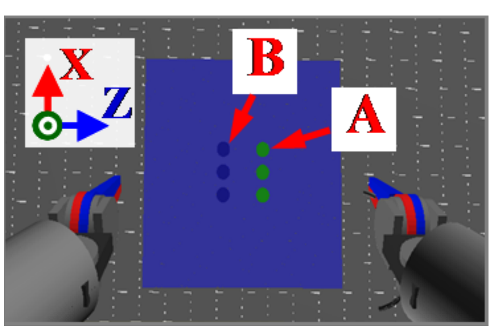


Fig. 3. Operator's view

#### 2) Experimental task

For the surgical task, needle-retaining motion was chosen because it is considered to be the most basic surgical task. In the set task, the needle gripped by the slave simulator is inserted at point A in Fig. 3 and pulled out from point B.

#### 3) Other experimental conditions

A healthy subject (operator) with plenty of experience using the system was chosen. The initial position and posture settings of the instrument were the same at the beginning of each experiment, while the image viewed by the operator was set up to display a picture from immediately above the organs (Fig. 3).

### B. Results

Fig. 4 shows the trajectory of each instrument tip as the needle-retaining movement is carried out using the three different mechanisms. The dark orange, light orange, and yellow lines in the figure show the trajectories of the instruments with length L=0 mm, L=5 mm, and L=10 mm, respectively. The trajectory is taken from the start of the experiment until the tip of the needle reaches point A. In Fig. 4, the horizontal axis is shown as the Z-axis, and the vertical axis as the X-axis. These coordinate systems are taken from Fig. 3. The green and blue points in the figure depict points A and B, respectively.

Fig. 4 shows that there are differences in the trajectories of each mechanism. Mechanism I with L=0 mm (Dark Orange Line) largely deviated in the positive direction of the X-axis before point A. Mechanism II with L=5 mm (Light Orange Line) deviated a little in the negative direction of the X-axis before point A. Mechanism III with L=10 mm (Yellow Line) moved in a fairly straight line to point A.

When carrying out the needle-retaining motion as shown in Fig. 4, the operator displayed the following manner of operation. In the experiment with mechanisms I and II, the

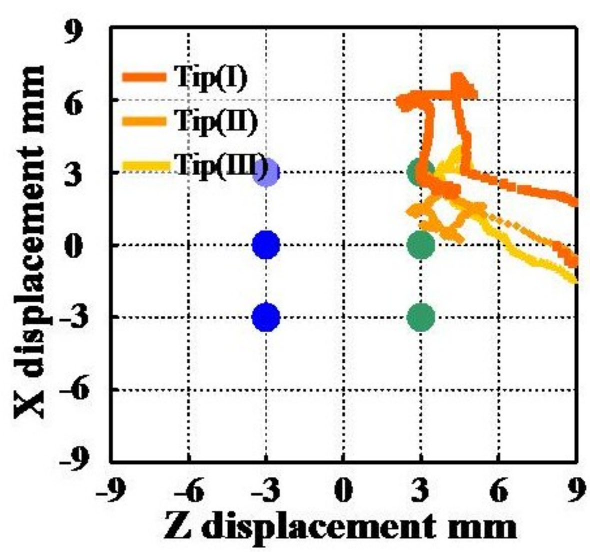


Fig. 4. Experimental results

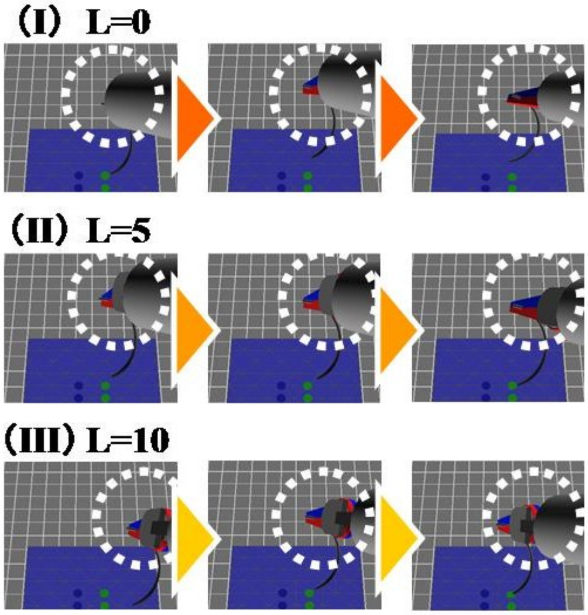

Fig. 5. Operator's manner of needle-retention

operator had to operate the instrument in a manner that checked instrument tip for the needle-retention before point A, whereas in the experiment with mechanism III, the operator did not need to apply this operation manner before point A.

The operator's visual information of the needle-retaining motion of Fig. 4 is shown in Fig. 5. This figure shows the operator's manner of operation in the three experiments for each of the mechanisms I, II, and III before reaching point A.

## IV. Discussion

This section discusses possible reasons for the differences in the trajectories of the instrument tip. The variations in the trajectory of the instrument tip for each mechanism may be due to the difference in the operator's visual information. Mechanism I and II in Fig. 5 shows that as the length L becomes shorter, it becomes more difficult to identify the tip of the instrument and the needle-retaining motion becomes more difficult for the operator. Thus, for mechanisms I and II with a shorter L, the operator needs to operate the instrument in such a way as to be able to identify the instrument tip. So the trajectories of mechanism I and II deviated before point A. On the other hand, it is not difficult for the operator to identify the tip of the instrument and operate the needle. Therefore the trajectory of mechanism III is fairly straight line to point A.

From the results of the experiment, it is clear that the operator changes the manner of operation depending on the visual information available. As a result, if the mechanism of the instrument changes, the operator's manner also changes, even though the surgical task remains the same.

This shows that the change in the mechanism of the surgical robot influences the operator's manner. Therefore, when designing the mechanism for the surgical robot, there is a need to consider how this influences the operation manner.

## V. Conclusion

In this paper, we investigated the need to consider the operator's manner when developing a surgical robot. To achieve this, we proposed a system that can freely change the instrument mechanisms of the surgical robot and can also be operated. Using this system, an experiment based on a surgical task using instruments with three types of mechanism was carried out by the simulator. The three instruments differed in the length L between bending joints on the instrument, that is, 0, 5, and 10 mm. The results show that the trajectory of each instrument tip differs. Mechanism I with L=0 mm largely deviated in the positive direction of the X-axis before inserting the point of the needle. Mechanism II with L=5 mm deviated a little in the negative direction of the X-axis before inserting the needle point. Mechanism III, on the other hand, with L=10 mm moved in a fairly straight line to the insertion point. From the results of the experiment, it is clear that the operator changes the manner of operation according to the visual information available.

Change in the mechanism of the instrument could be a factor in the change of the operator's visual information. Therefore, change in the mechanism of the instrument can influence the operator's manner. In conclusion, when designing the mechanism for a surgical robot, there is a need to consider not only the accuracy, moving range, and stiffness, but also how the differences in the instruments influence the operation manner.

In the future, the effectiveness of considering the operator's manner when developing surgical robots will be evaluated.

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