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Pilot Study on Effectiveness of Simulation for Surgical Robot Design Using Manipulability

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***Abstract*—Medical technology has advanced with the introduction of robot technology, which facilitates some traditional medical treatments that previously were very difficult. However, at present, surgical robots are used in limited medical domains because these robots are designed using only data obtained from adult patients and are not suitable for targets having different properties, such as children. Therefore, surgical robots are required to perform specific functions for each clinical case. In addition, the robots must exhibit sufficiently high movability and operability for each case. In the present study, we focused on evaluation of the mechanism and configuration of a surgical robot by a simulation based on movability and operability during an operation. We previously proposed the development of a simulator system that reproduces the conditions of a robot and a target in a virtual patient body to evaluate the operability of the surgeon during an operation. In the present paper, we describe a simple experiment to verify the condition of the surgical assisting robot during an operation. In this experiment, the operation imitating suturing motion was carried out in a virtual workspace, and the surgical robot was evaluated based on manipulability as an indicator of movability. As the result, it was confirmed that the robot was controlled with low manipulability of the left side manipulator during the suturing. This simulation system can verify the less movable condition of a robot before developing an actual robot. Our results show the effectiveness of this proposed simulation system.**

I. Introduction

ROBOTS have been introduced into the medical domain to make operations more precise and to reduce the burden on patients and surgeons. In clinical cases, the latest medical technologies, such as da Vinci® (Intuitive Surgical Inc.) and Zeus® (Intuitive Surgical Inc.), have been indispensable [1]-[2]. Applying these surgical robots in the medical domain has allowed surgeons to solve problems, especially in endoscopic surgery. For example, motion scaling of the surgical instrumentation and hand-eye coordination during an operation can be enhanced to achieve high operability for a surgeon in clinical cases. In addition, surgical robots can allow the surgeon to reduce his or her mental workload during surgery and yet provide the patient with advanced medical treatment [3]–[4]. Therefore, medical technology has advanced with the introduction of robot technology, which makes it possible to perform previously difficult or impossible medical treatments. Nevertheless, the surgical robot has been developed only to reproduce popular surgical techniques on the body size of adult patients.

However, symptoms always vary according to the patient, even for the same type of surgical procedure because of the significant individual differences among patients. Patients who must undergo surgery include not only adults, but also children and elderly individuals. Consequently, surgical robots can only be used in a limited number of clinical cases. To realize robotic surgery as a common method of medical care, the development of surgical robots must suit a variety of individual clinical cases. Also, the environment of surgical robot development and a method of evaluating the effectiveness must be established to allow mechanical design and control techniques to be verified during a surgical procedure.

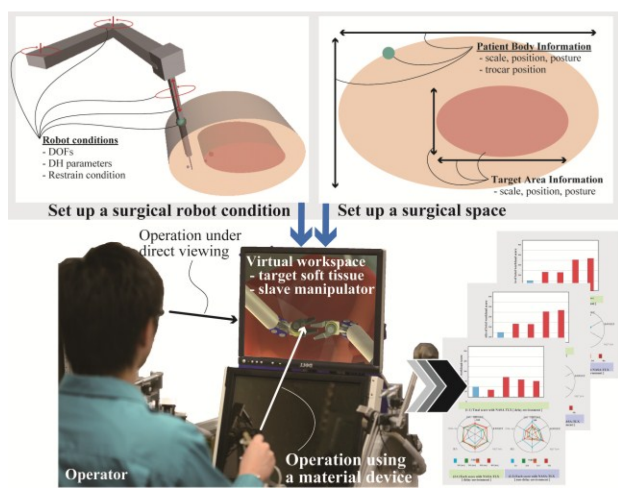

Fig. 1. System concept overview. The proposed surgical simulation attempts to verify the configuration of a surgical robot before robot development. The proposed system also attempts to evaluate the movability and operability of the designed robot using a real master controller.

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II. Motivation

In the development of surgical robots, it is common to adopt a process to verify the effectiveness by using a prototype robot after the actual robot has been manufactured. However, animal experiments for evaluations of a robot have become more restrictive because of ethical issues. Also, in spite of the requirements for complicated surgical conditions, a surgical robot does not have clear design guidelines and techniques suitable for each patient. Additionally, to more quickly promote clinical applications, the mechanical design of a surgical robot in the development stage must already apply to a clinical case. Recently, modeling and geometrical validation of surgical assisting tools [5] and the workspace based on the trocar point on the human body for a surgical robot has been studied [6]–[7]. From the viewpoint of assisting a surgical procedure, automating a surgical task by using a robot has been developed [8]. In a previous study, assuming a tele-robotic surgery environment using a communication network, we performed an operability evaluation under a virtual delay environment [9].

In our current research, we focused on a simulation reproducing surgical conditions that change according to the target organs and the surgical procedures in order to take advantage of the design and development of a surgical robot (Fig. 1). We assumed that this simulator enables robots to be developed in a systematic manner based on the surgery itself. This paper shows that the simulator can change the mechanical parameters of the robot easily and describes an experiment performed for verification of the movability of robot motion.

In Section III, we present an overview of our simulation system. In Section IV, we show the experiment verifying the effectiveness of our simulation system. Section V concludes our paper.

III. Simulation System Overview

In this study, we constructed a simulation to evaluate a surgical robot using a surgeon's operability and the robot's movability during an operation (Fig. 2). For the proposed system, we integrated the developed numerical simulator and a real master controller.

It is important for the development of a surgical robot to consider the viewpoints of patients and surgeons in a clinical application. From the viewpoint of the patient, the significant factors of the design of surgical robots are the size and shape of the surgical workspace in the patient's body. The simulator is required to respond to intra-operative changes in the surgical workspace caused by the deformation of organs when using the surgical assisting robots. In previous work, we constructed the simulator by using diagnostic information to reproduce the expected surgical space and the robot control method using real-time information from intra-operative medical ultrasound equipment [10]. From the viewpoint of the surgeon, it is difficult to perform actions such as suturing using the surgical equipment inserted into the body through a trocar in a very limited workspace during minimally invasive surgery. The trocar point of the surgical equipment and the mechanism of the surgical assisting robot (configuration flexibility, length of each arm, and range of robot motion) are verified in advance and are set properly to perform the action efficiently in the limited space. Thus, the simulator must evaluate the design of the robot with consideration of the surgeons' operability.

In this research, the proposed system using a real master controller is constructed to verify both the operability of the surgeon and the mechanism of the surgical robot. Therefore, the simulator could change the parameters of a surgical assisting robot easily and verify the task space involving the mechanism of the robot and the trocar point in each configuration. Also, the quality of the mechanism and the trocar point on the patient's body can be quantified by using this simulation. Consequently, optimization of the parameters of the robot configuration, such as the length of the links, can be carried out.

IV. Experiment

A. Experimental method

A simple evaluation of the movability of a surgical assisting robot was performed as a pilot study to confirm the effectiveness of the proposed simulation system. In this experiment, we performed an operation using a surgical instrument that reproduces two forceps manipulators and two SCARA-type support manipulators in a virtual workspace (Fig. 3). We carried out a simple task imitating suturing motion in this virtual workspace. In this experiment, we used an actual passive master controller having 6 DOFs in each

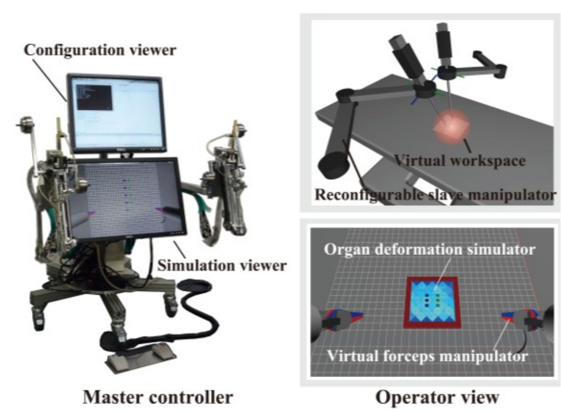


Fig. 2 Proposed simulation system overview. This simulation system consists of a virtual slave manipulator, an organ deformation calculator [11] and a real master controller.

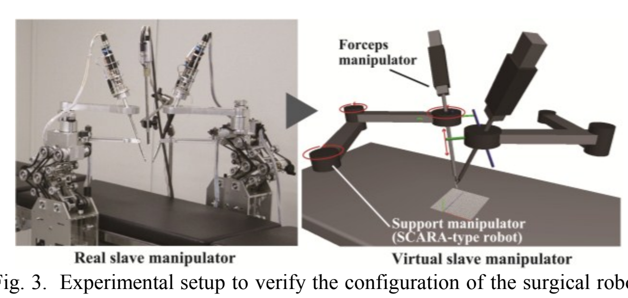


Fig. 3. Experimental setup to verify the configuration of the surgical robot. We simulated a master-slave type surgical robot [12].

arm and a virtual slave manipulator having 7 DOFs (forcep: 3 DOFs, support: 3DOFs, gripper: 1 DOF). In the suturing, the right side manipulator has a curved suture needle and the left side manipulator is supported the suturing motion. The mechanical parameters of the robot using Denavit-Hartenberg (DH) method are listed in TABLE I, and the experimental setup is given in TABLE II. We evaluated the movability of this robot by using its manipulability. The manipulability is calculated using Equation (1). The higher manipulability indicates the higher movability of the manipulator, whereas the lower manipulability indicates the lower movability of the manipulator at a position.
where **J** is Jacobian Matrix of each slave manipulator which is determined by the mechanical parameters of the slave manipulator and **θ** is rotational angle of each joint[13].

$$w = \sqrt{\det(\mathbf{J}(\boldsymbol{\theta})\mathbf{J}^T(\boldsymbol{\theta}))} \qquad (1)$$

B. Results

In this experiment, the mean manipulability of the right side manipulator was 1715±670.7 and the mean manipulability of the left side manipulator was 1684±803.7. The maximum value of the left side manipulator was 318% of the manipulability at the initial position and the minimum value was 17%. The maximum value of the right side

TABLE I
DH parameters of the experimental devices

#	a [mm]	α [deg]	d [mm]	θ [deg]
1	0.0/0.0	0.0/0.0	0.0/0.0	46.2/46.2
2	250.0/250.0	0.0/0.0	0.0/0.0	−106.1/106.1
3	250.0/250.0	180.0/180.0	0.0/0.0	0.0/0.0
4	0.0/0.0	0.0/0.0	200.0/200.0	90.0/90.0
5	0.0/0.0	90.0/90.0	0.0/0.0	−190.0/−190.0
6	10.0/10.0	90.0/90.0	0.0/0.0	90.0/90.0
7	10.0/10.0	0.0/0.0	0.0/0.0	0.0/0.0

In this table, the right and left parameters are separated by a slash, and the first column indicates the joint number, as shown in Fig. 4.

TABLE II
Experimental conditions

Condition	Parameter
Master controller	6 DOFs
Slave manipulator	6+1 DOFs
No. of Subject	2
Task	suturing

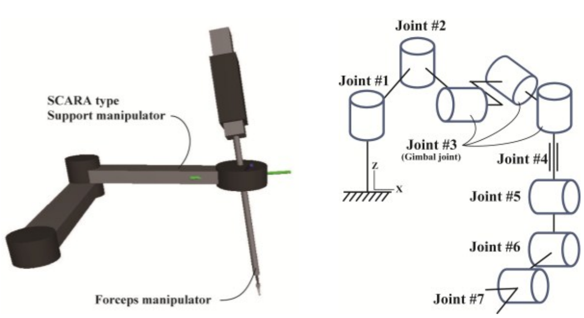
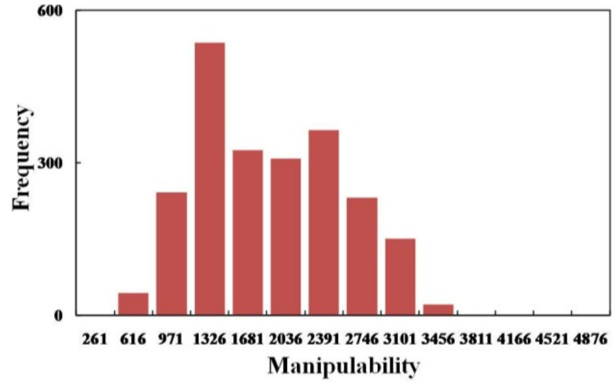
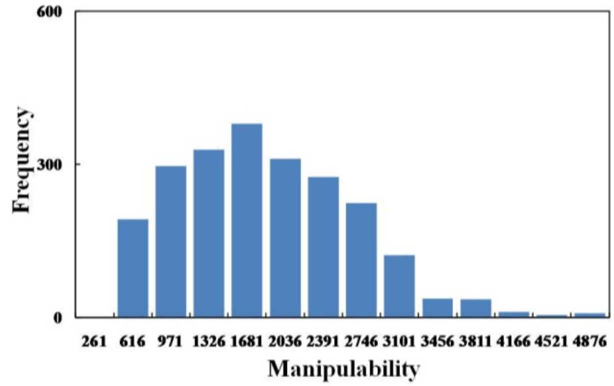


Fig. 4. Joint ID number for DH parameters in TABLE I. This figure shows the joint ID number of each manipulator to set up the initial DH parameters.

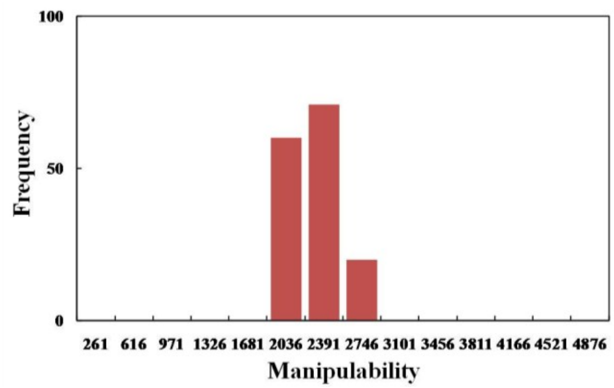


(a) Manipulability of the right side manipulator

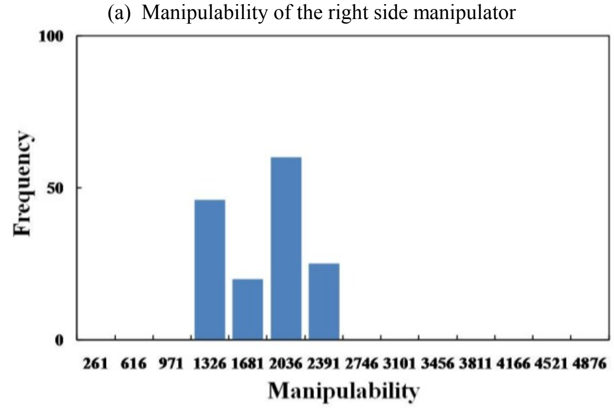


(b) Manipulability of the left side manipulator.

Fig. 5. Experimental result (all tasks). This figure shows the frequency of the manipulability during the experiment.



(a) Manipulability of the right side manipulator



(b) Manipulability of the left side manipulator

Fig. 6. Experimental result (suturing). This figure shows the frequency of the manipulability during suturing task.

manipulator was 238% and the minimum value was 20%. Fig. 5 shows the manipulability frequency of the right and left side manipulators during all tasks. Fig. 6 shows the frequency of the manipulability during suturing.

C. Discussion

In these results, the manipulability during the task, shown by the robot movability, has varied greatly across the virtual workspace and the differences depended on the task undertaken by each manipulator. In these results, we suggest that manipulability is useful as one of the indicators for designing a suitable robot. In Fig. 5, it was confirmed that the frequency of the manipulability has a wide range and the distribution of the manipulability is different for each manipulator. In Fig. 6, the manipulability of the right side manipulator during suturing has some low frequencies, whereas the manipulability of the left side manipulability has some high frequencies.

When the suturing is performed, the right side manipulator has a curved suture needle and inserts it into the target. The left side manipulator is supported the motion of the right side manipulator. During this motion, the right side manipulator is rotated simply about a longitudinal direction axis of the forceps manipulator. The left side manipulator has complex motion to be supported the other side manipulator. Therefore, it seems that the manipulability of the right side manipulator is higher than the manipulability of the left side manipulator.

Because we carried out suturing, which are important techniques in surgery, this experiment suggests that this robot system has a less movable mechanism for the surgeon's control when suturing is performed using the robot. Therefore, we suggest that verification using this simulation system is effective for designing the surgical assisting robot before developing the actual surgical assisting robot.

V. Conclusion

We presented a simple experiment to verify the condition of the surgical robot during the task including the suturing motion. The manipulability of the robot was evaluated using the proposed simulation system of the robot motion of an actual robot. In this experiment, the simulation system consisted of the virtual slave manipulator, organ deformation calculator and real master controller. As the result, it was confirmed that this robot is controlled with low manipulability during suturing, whereas it has high manipulability in reference to the initial position. This simulation system verified the less movable condition of the robot before development of the actual robot, and so we verified the effectiveness of the proposed simulation system. The next research step is to focus on how to indicate a suitable robot design using both operability and movability for various types of surgeries.

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