Study on Master Manipulator Design Parameters for Robotic Microsurgery

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Abstract—The design of master manipulators for master-slave surgical robotic systems is important because it may influence slave manipulator performance as well as the operator’s workload. However, no design strategy has been presented thus far for optimizing the master manipulator design parameters. A master manipulator prototype and an experimental setup were developed for investigating design parameter influence using our master-slave microsurgical robotic system. The preliminary results showed that the relative position of the holding point, the corresponding point for the slave manipulator’s working point, and the center of the gimbals are important for master manipulator design, especially for tasks requiring large or frequent posture changes. The experimental results also suggested that the optimized parameters would contribute to enhancing task efficiency and decreasing the workload, rather than increasing task accuracy.

I. INTRODUCTION

M ASTER–slave robotic systems have been employed in surgical robotics for enhancing surgeons’ dexterity as well as enabling motion scaling. The most famous surgical robotic system, the “da Vinci Surgical System,” has its own master manipulator design, facilitating intuitive manipulation of the slave robotic arms. Many research groups have also tried to design their original master manipulators or use available haptic devices [1]; however, to the best of the present authors’ knowledge, there is no design strategy for surgical master manipulators. Master manipulator design affects system usability, the slave manipulators’ motion accuracy, and operator workload. Further, it is obvious that better master manipulator design facilitates the introduction of surgical robots to clinical cases. Moreover, master manipulator design may depend on the target clinical applications or tasks, and thus, a design theory is required. The research focus in laparoscopy has been on the enhancement of dexterity and usability as well as the implementation of haptics, rather than the enhancement of accuracy, and thus, many research groups use commercial haptic devices such as the PHANTOM series (SensAble, USA) (for example, in [2], as shown in Fig. 1(a)) and the Delta/Omega/Sigma series (Force Dimension, Switzerland) (for example, in [3], as shown in Fig. 1(b)). There are also several original designs using the Delta structure [1, 4]. Meanwhile, accuracy and precision are of the utmost importance in microsurgery. For example, microsurgical robots for neurosurgery need to perform very fine and complex tasks such as the anastomosis of 0.7 mm blood vessels. Although there are several neurosurgical robotic systems [5-8], their target applications are limited to simple tasks such as needle insertion and tumor removal. Hence, the usability of master manipulators for complicated tasks remains to be established. Microsurgical robots include eye surgery robots (for example, the eye surgery robot reported in [9]). However, no complex tasks require to be performed in an eye surgery. Consequently, we have focused on the usability of a master manipulator, especially for micro neurosurgical robots having six degrees of freedom (DoFs), with the three positioning DoFs decoupled from the three orientational DoFs.

In this work, the design parameters of surgical master manipulators were investigated using a microsurgical robotic system in order to clarify the unique microsurgery features that need to be considered in the design of master-slave surgical robots. Master manipulator prototypes were designed by attaching a mechanism to a commercial haptic device in order to vary the design parameters. Experiments were conducted in order to quantify the effects of design parameters on the robot performance and workload.

The paper is organized as follows. The prototype design is described in Section II, and Section III details the experimental setup and method. Section IV reports the experimental results, and the paper is concluded in Section V.

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Fig. 1. Master manipulators for surgical robotic systems. (a) Raven [2], (b) DLR MiroSurge [3], (c) NeuroArm [5], and (d) Brain Tumor Removal Robot System [6].
II. PROTOTYPING

A. Master-Slave Robotic System for Microsurgery

Master manipulator designs were investigated using our master-slave microsurgical robotic system [10]. This system was designed for both neurosurgery and eye surgery. The anastomosis of 0.3 mm artificial blood vessels [11], which is a very difficult manual operation, was demonstrated with the system.

Figure 2 shows the master-slave microsurgical robotic system overview. The operator (i.e., the surgeon) manipulates two master arms while looking at the microscopic stereo view provided on the 3D monitor. The slave robotic system is composed of two robotic arms, each with six DoFs, and a surgical tool unit with one gripping DoF mounted onto each arm. The surgical unit can be interchanged with another unit based on the target clinical application or task. The translational motion of the master manipulator is scaled down and transmitted to the slave robot.

![Fig. 2. Master-slave microsurgical robotic system.](image)

Human arm motion was previously quantified and the master manipulators shown in Fig. 2 were designed [12]. The master manipulator employed a pen-like gripper because the manner in which a pen is held, called a tripod grip, is similar to the manner in which a pair of surgical tweezers is held in microsurgery. Figure 3 (a) shows the manner in which a pair of tweezers is held, where C is the working point, H is the holding point, and O is the approximate center of rotation. The gripper of the master manipulator (Fig. 3(b)) was designed to replicate these relative positions; the hand grasping point, H, was approximately 30 mm from the gimbal center, O, whereas the point, C, to which the slave robot’s tip corresponded was set 80 mm from the gimbal center, O.

![Fig. 3. The manner in which a pair of surgical tweezers is held. C is the working point, H is the holding point, and O is the center of revolution.](image)

Surgeons were not satisfied with the usability of the master manipulators, regardless of the similarity of the gripping pose, although the dexterity was sufficient to perform a complicated task with high precision. It was also difficult for us to identify which design parameters to change because the design process was not systematic. Therefore, the design process was reviewed. In many master manipulators reported in literature, the working point of a surgical tool, \( x'_c \), (Fig. 4(a)) is correlated to the center of the gimbals, \( O \) (Fig. 4(b)) of the master manipulator. For example, in the \( x \)-coordinate whose origin was set at the gimbal center (Fig. 4(b)), the corresponding slave manipulator position coincides with the origin \( (x_c = 0) \) and the surgeon holds the proximal side of the gripper \( (x_b < 0) \). Both the holding and corresponding points were set at the distal side of the gripper \( (x_c > x_b > 0) \) in our previous master manipulator design, as shown in Fig. 4(c). It seems that the configuration shown in Fig. 4 (b) is more intuitive, whereas the configuration in Fig. 4(c) was designed to replicate the actual holding position used in microsurgery. Therefore, the ways in which the similarity to the actual surgical situation may affect the performance and workload in a robotic microsurgery scenario were investigated. A prototype of the master manipulator was designed in order to quantify the influence of the design parameters \( x_c \) and \( x_b \).

![Fig. 4. Master-slave position correspondence. (a) Working point of the surgical tool mounted on the slave manipulator, (b) Corresponding and holding points of the master manipulator in [5], and (c) Corresponding and holding points of the master manipulator of the master-slave microsurgical robotic system [12].](image)

B. Master manipulator prototype design

A PHANTOM Omni device (SensAble, USA) was used to measure the positioning DoFs (three DoFs) and a gimbal mechanism with a stylus was attached in order to measure the orientation DoFs (three DoFs), as shown in Fig. 5. The original gimbals of the PHANTOM Omni were glued and fixed. The advantage of using a commercial device is that the results can be shared with the research community and used for the design of a new manipulator for a master-slave surgical robotic system.

Three miniature encoders with a resolution of 0.0225° (MES-9-1000PST16E, Microtech Laboratory Inc., Japan) were implemented in the gimbals and provided higher pose measurement accuracy in comparison to the original PHANTOM Omni gimbals. This was necessary in order to avoid the effect of the relatively low angular resolution of the original gimbals on slave manipulator performance. The pen-like stylus was attached to the gimbal structure, which
provides more configurable holding point positions. The holding point, \( x_h \), is a mechanical design parameter, whereas the corresponding point, \( x_c \), is a parameter to be set in the control program.

\[ X_h = -x_h \]

III. EXPERIMENTS

A. Experimental Setup

The experimental setup is shown in Fig. 6 and the system overview is shown in Fig. 7. The experiments were performed for the right hand only because all subjects were right-handed and used their right hands for needle manipulation in microsurgery. The Libralis library [13] was used for PHANTOM gravity compensation. The communication between the master and slave systems was updated at 100 Hz and the servo rate of the slave robotic system was 1 kHz. The response was sufficient, and it was assumed that slave performance and operator workload were not influenced by the mechanical setup or control.

B. Design of Experiments

The microscopic magnification was set such that a 10 mm circle could fit in the view. A 27 G needle with its tip painted red was attached to the distal end of the surgical tool unit, and the position of the needle was estimated and tracked using the image processing method described in the next subsection. The position of the tip of the needle was set to coincide with that of the remote center of motion of the slave manipulator.

Three tasks were designed, namely, (1) a Tracing Task, (2) a Pointing Task, and (3) a Posture-changing Task, as illustrated in Fig. 9. The tasks were developed to contain some of the motion elements required in microsurgical tasks. The motion scaling ratio was set at 3x, which reflected a neurosurgeon’s opinion that the slave manipulators can be intuitively maneuvered at the ratio in neurosurgical tasks. The distance between the gimbal center and holding point \( X_h = -x_h \) and the distance between the corresponding point and holding point \( X_c = x_c - x_h \) were varied in the experiment, as shown in Fig. 8. Twelve pairs of parameters \((X_h = 20, 40, 60 \text{ mm} \text{ and } X_c = -30, 0, 20, 60 \text{ mm})\) were tested in the preliminary experiment. Two sets of twelve pairs were tested in random order for each subject. Each subject was asked to keep his forearm on the arm rest. In each task, the subject was asked to provide a Subjective Score ranging from 1 (uncomfortable) to 10 (comfortable).

1) Tracing Task

This task was designed to examine the usability of the master manipulator in the general position-changing maneuvers. The subject traced a circle with a diameter of 10 mm in the tracing task. The circle was printed on a piece of paper and the subject was asked to place the needle tip as close as to the paper as possible. The task completion time, RMS error, and the Subjective Score were evaluated.

2) Pointing Task

The purpose of this task was to examine the usability in precise targeting. The subject placed the needle tip in small circles of 0.3 mm in diameter in the order of 0, 1, 0, 2, 0, 3, 0, 4, 0, as shown in Fig. 9 (b). The task completion time, length of the trajectory, task completion ratio, and Subjective Score were evaluated. The trajectory length in 3D space was calculated from the position of the corresponding master manipulator point. Task completion evaluation success was defined as the precise placement of the needle tip within each small circle.

3) Posture-changing Task

This task was selected to evaluate the usability in changing the slave manipulator posture while maintaining the tip position. The subject aligned the needle with the horizontal line starting from the line with an angle of \(-45^\circ\), as shown in Fig. 9, and placed it back in the original posture while keeping the needle tip at the center of the cross. This set was repeated three times. The task completion time, RMS error, and the Subjective Score were evaluated.
C. Tool tip detection

Image-based tool tip detection was developed and used to obtain the position of the tip of the needle. The tracked position was used to calculate the RMS error in the three tasks mentioned in the previous subsection. As mentioned above, the needle tip was painted red to simplify the required image processing. It was easy to extract the red color region in the HSV image space (consisting of hue, saturation, and intensity) in the designed experimental setup because the background color was white. The extracted red colored region was converted to a binary image and the tool tip was estimated by detecting the upper and lower contours of the region.

Figure 10 shows an example of tool tip detection. The binary image was generated by extracting the red colored region in the microscopic image using predefined thresholds for the hue and saturation values. The intensity value was not used in the image processing because it was prone to error because of the specular effect observed in the obtained microscopic image. Next, several sets of two points were aligned to the upper and lower contours of the extracted region with a preset interval in order to find the lateral contours of the needle. Thereafter, upper and lower contour lines were generated by calculating the coefficients based on the least square estimation. The tool tip point was defined as the left-most point of the region located on the centerline of the two contour lines. The tip position was tracked at a rate of 30 Hz, with measurement accuracies of <50 \( \mu \)m RMS. Although there remains scope for improvement in the detection accuracy, it was assumed to be sufficient for master manipulator design parameter analysis.

D. Statistical Analysis

The statistical significance of the differences in the parameter sets was analyzed by a repeated-measures analysis of variance (ANOVA) with two within-subject factors \( X_c \) and \( X_h \), followed by post hoc analysis (Sidak’s multiple comparison test based on the estimated marginal means). The statistical difference was accepted at \( p < 0.05 \). The Greenhouse-Geisser method was used to adjust the degrees of freedom, where appropriate. All statistical analyses were conducted using Version 20 of SPSS Statistics (IBM, USA).

IV. RESULTS

A. Subjects

Two medical doctors and eight Engineering students participated in the experiments.

B. Tracing Task

The ANOVA revealed significant main effects of factor \( X_c \) on the Subjective Score \( F(3, 27) = 7.313, p < 0.05 \), whereas the main effects of factor \( X_h \) and the interaction \( X_c \times X_h \) on the Subjective Score were not significant. The Sidak-corrected pairwise comparisons revealed higher Subjective Scores for \( X_c = 0 \) or 20 mm than for \( X_c = -30 \) mm \( (p < 0.05) \) (Fig. 11, left). With regard to the RMS error, only the main effects of factor \( X_h \) were significant \( F(2, 18) = 4.456, p < 0.05 \). However, no significant differences were revealed after multiple comparisons of the error in each value of \( X_c \) (Fig. 11, right).

With respect to the task completion time, none of the main effects of the factors was detected (data not shown).

C. Pointing Task

The ANOVA revealed significant main effects of factors \( X_c \) \( F(1.476, 13.281) = 10.222, p < 0.05 \) and \( X_h \) \( F(2, 18) = 4.868, p < 0.05 \) on the Subjective Score, whereas the main effects of the interaction \( X_c \times X_h \) were not significant. Pairwise comparisons revealed higher Subjective Scores for \( X_c = 0 \) and 60 mm than for \( X_c = -30 \) mm \( (p < 0.05) \) (Fig. 12, left). It was also revealed that the Subjective Score for \( X_c = 20 \) mm was higher than that for \( X_h = 60 \) mm \( (p < 0.05) \) (Fig. 12, right).

With regard to the task completion time, the significant main effects of the factors \( X_c \) \( F(3, 27) = 15.656, p < 0.001 \) and \( X_h \)
acceptance. The ANOVA revealed significant main effects of factor \( X_c \) \((F(3, 27) = 7.293, p < 0.05)\) and the interaction \( X_h \times X_c \) \((F(6, 54) = 7.451, p < 0.05)\) on the Subjective Score, whereas the main effects of factor \( X_h \) were not significant. Fig. 15 (left) shows the estimated marginal means for \( X_h \) at three \( X_c \) levels, whereas Fig. 15 (right) shows the estimated marginal means for \( X_c \) at four \( X_h \) levels. Regarding the task completion time, the main effects of factor \( X_h \) \((F(1.439, 12.951) = 6.696, p < 0.05)\) and the interaction \( X_h \times X_c \) \((F(2.584, 23.255) = 3.831, p < 0.05)\) were significant, whereas no significant main effects were detected for factor \( X_c \). The results of the multiple comparison tests are shown in Fig. 16.

**Posture-changing Task**

D. Posture-changing Task

The ANOVA revealed significant main effects of factor \( X_c \) \((F(3, 27) = 7.293, p < 0.05)\) and the interaction \( X_h \times X_c \) \((F(6, 54) = 7.451, p < 0.05)\) on the Subjective Score, whereas the main effects of factor \( X_h \) were not significant. Fig. 15 (left) shows the estimated marginal means for \( X_h \) at three \( X_c \) levels, whereas Fig. 15 (right) shows the estimated marginal means for \( X_c \) at four \( X_h \) levels. Regarding the task completion time, the main effects of factor \( X_h \) \((F(1.439, 12.951) = 6.696, p < 0.05)\) and the interaction \( X_h \times X_c \) \((F(2.584, 23.255) = 3.831, p < 0.05)\) were significant, whereas no significant main effects were detected for factor \( X_c \). The results of the multiple comparison tests are shown in Fig. 16.

**E. Summary of Experimental Results**

Table I summarizes the experimental results, including the results that are not explained in detail in the previous subsection.

The performance of the slave manipulator in terms of accuracy was not influenced by the relative position of the holding point, corresponding point, and the center of the gimbals. The efficiency of the tasks, which was measured as the task completion time or trajectory length, was influenced by the relative positions for the pointing task and the posture changing task, and this was probably because both tasks required bigger or more frequent posture changes, which can
be more affected by the master manipulator design. The Subjective Score was influenced in most cases.

The result of the preliminary experiment suggested that the accuracy of the slave robot could be somehow independent of the mechanical design of the master manipulator, though the efficiency of the task and the operator workload could be influenced by the design parameters, especially for tasks requiring large or frequent posture changes.

Although more data should be collected for further investigation of the optimal design parameters, it was clarified that the relative position of the holding point, corresponding point, and the center of the gimbals are important for master manipulator design for microsurgery, especially for enhancing usability.

TABLE I Summary of the experiments: The significant influence of the parameters on each task; (a) the corresponding point should coincide with the holding point or be located at its distal side; (b) the holding point should be closer to the gimbal center; (c) the influence is proved, although the suitable parameter setting remains unclear; (d) the corresponding point should coincide with the holding point or be placed closer to the holding point at its distal side.

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<th>Trajectory</th>
<th>2) Pointing</th>
<th>3) Posture-changing</th>
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<td><strong>X1</strong></td>
<td>Subjective Score</td>
<td>N</td>
<td>Y (b)</td>
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<td>Performance</td>
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<td>Accuracy</td>
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<td><strong>X2</strong></td>
<td>Subjective Score</td>
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V. CONCLUSION

We developed a master manipulator prototype in order to investigate the master manipulator design parameters for microsurgery. The preliminary results showed that the relative position of the holding point, corresponding point, and the center of the gimbals are important for master manipulator design for microsurgery, especially for enhancing usability. The future work will include experiments with greater parameter variance in order to systematically define the design parameters.

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