Intuitive Operability Evaluation of Robotic Surgery using Brain Activity Measurement to Identify Hand-Eye Coordination

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Abstract—Surgical robots have undergone considerable improvement in recent years, but the intuitive operability, representing user-inter-operability, has not been quantitatively evaluated. Thus, we propose a method for measuring brain activity to determine intuitive operability in order to design a robot with intuitive operability. The objective of this paper is to clarify the angle between the endoscope and the manipulator that facilitates users perceiving the manipulator as part of their body. In the experiments, while subjects controlled the hand controller to position the tip of the virtual slave manipulator on the target in the surgical simulator, we measured the brain activity through brain imaging devices. We carried out the experiment a number of times with the virtual slave manipulator configured in a variety of ways. The results show that activation of the brain is significant with the slave manipulator configured such that the angles are slanted with respect to the horizontal. We conclude that the body image affects hand-eye coordination, which is related to visual and somatic sense feedback.

I. INTRODUCTION

A. Background

ROBOTIC SURGERY has undergone considerable improvement in recent years [1]. Such surgery has the potential to reduce scarring and shorten recovery times [2].

The method of operation in surgical robots is often a master-slave system where the surgeon controls the master manipulator, while the slave manipulator performs the operation instead of the surgeon’s own arm. It is often stated that robotic surgery is more difficult than open surgery because the surgeon needs to ascertain the internal condition and operate indirectly through a screen [1]. Therefore, robotic surgical machines need intuitive operability if the surgeon were operating directly as in open surgery. This intuition is known as “tele-existence” [3] since robotic surgery is an indirect surgical approach [4].

In related work, intuitive operability is evaluated using a working score, such as the time to complete the task, average speed, movement curvature, or all of the above under the test conditions [5].

Fig. 1. Our motivation image. If the user were to operate directly, in the user’s mind, the displayed manipulator represents his hand. The representation has an influence on operability.

B. Motivation

The surgical robots described in related research have been designed and evaluated using the only mechanical measurement method. That is, the higher the machine specification, the better is the working score. But, quantitative conditions that facilitate user control as expected by the user have not been clarified because there is no defined method for measuring user-inter-operability. Therefore, developers have created surgical robots from a vague motivation, ignoring the achievement of intuitive operability.

We propose a measurement method for user-inter-operability by measuring brain activity with brain imaging devices. We can investigate brain activation compared with the recognition function reports to measure user introspection. We focus on medical robotics because greater “tele-existence” is required due to the need for dexterous manipulation in surgery.

Our motivation is to develop a surgical robot system that allows the surgeon to perceive the manipulator as part of his body evaluated by measuring brain activity as shown in Fig. 1. A master-slave system is too indirect to allow users to move as expected. The most direct feedback system is where the robot is part of the surgeon’s body. Therefore, we define intuitive operability by how strongly the user perceives the manipulator to be part of his body. We consider data from brain measurements to be useful in designing a robot with intuitive operability.

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Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.
Objective parameter in -ye position to be determined by the Angle θ
Endoscope
Slave arm

Fig. 2. The angle between the endoscope and the slave arm in the robotic surgery manipulator [10] [11] as the objective parameter in designing a robot with intuitive operability.

Fig. 3. View from the endoscope. Angle θ is the objective parameter because it has the greatest influence on the configuration of the manipulator.

C. Objective

In this study, we investigate hand-eye coordination that would facilitate the user regarding the manipulator as part of his body. Typically, hand-eye coordination is influenced by the difference between the hand positions of the human and robot relative to the eye. In endoscopic surgery, the hand-eye position is called “triangulation” [6]. Moreover, as has been indicated by many earlier reports, hand-eye coordination has an effect on the difference between visual and somatic feedback [7] [8] [9].

The objective of this study is to clarify the appropriate hand to eye position based on a user’s recognition function. We consider the hand to eye position to be determined by the angle and distance between the endoscope and position of the arm (Figs. 2 and 3). Since the endoscope and robot arm are effectively substitutes for the human eyes and arm, respectively, the angle and radius between the endoscope and robot arm instead of between the eyes and arm of the surgeon determine how the human operator and robot match.

More specifically, we propose an angle that makes it easier to perceive the manipulator as being part of the user’s body, based on the brain activity measured by the brain imaging device while the user controls the hand-controller to position the tip of the virtual arm on the target in the robotic surgical simulator. Activation of the brain is more significant when the user strongly perceives the manipulator to be part of his body, and this determines whether the user can control the robot intuitively.

II. Method

We used a brain imaging device to measure the brain activity of the subjects while controlling the virtual arm in the surgical simulator through a hand controller, shown in Fig. 4.

A. Subjects

Five healthy adults, (three males and two females; mean age 23.4 years and range: 23-24 years; four right-handed and one left-handed) participated in the experiment. All had normal or corrected-to-normal vision. The subjects were informed about measuring their brain activity and the purpose of the experiment and informed consent was obtained from all the subjects. The experiments were conducted following the Declaration of Helsinki.

B. Brain Imaging Device – Optical Topography

For the brain imaging device, we used Optical Topography (OT) because OT equipment is reasonable compact and its measurement is relatively non-invasive, which enables monitoring of human cortical activity in a variety of experimental tasks, such as those requiring body movement [12]. OT is a relatively new brain imaging technique, which measures the relative change in the hemoglobin concentration [13]. OT can separately measure changes in the concentration of oxygenated hemoglobin (oxy-Hb) and deoxygenated hemoglobin (deoxy-Hb).

C. Display

The robotic surgery simulator is presented on a 19-inch LCD monitor (Dell 1905FPe) with a pixel resolution of 1280 × 1024 and vertical refresh rate of 60 Hz. The monitor cannot display 3D images because wearing 3D glasses would have annoyed the subjects, causing their brain activity to be influenced by other factors. The time course of the stimulus presentation is controlled by a PC. Subjects observe the monitor from a viewing distance of 600 mm with their heads resting on a chin-rest.

The simulator displays the green cube and the 3-DOF manipulator coupled with the hand controller against a black
background. The ground is black because this color places the least burden on human eyes. The green cube is placed randomly in the same plane when touched by the tip of the virtual manipulator. The cube is green because this color stands out best against the black background.

D. Robotic Surgery Simulator

We implemented the robotic surgical simulator in C using the Open Graphics Library (OpenGL). The virtual manipulator is controlled by the hand controller, PHANTOM-Omni® [14]. The virtual manipulator has 3-DOF: 2-DOF for rotation (yaw and roll) and direct action with 1-DOF (z-axis). The mechanism for the virtual manipulator is illustrated in Fig. 5.

We conducted tests with 5 different virtual arm configurations using different values for angle $\theta$, that is, -90°, -45°, 0°, 45°, and 90°. Fig. 6 illustrates the 5 virtual arm configurations with the five different angles.

For the experiments with all the arm configurations, the hand controller was set at the same position. In addition, the subjects controlled the hand-controller in the same way, that is, by gripping it like a pen as shown in Fig. 7. By varying only the arm position, we could evaluate the relation between hand-eye coordination and brain activity.

E. Visuomotor Task

In the experiment, the subjects controlled the hand controller, a PHANTOM-Omni®, to position the tip of the virtual manipulator on the target in the surgical simulator. No haptic information was fed back to the subject in this experiment. The target was set as a green box that appeared randomly in the same plane when the tip of the manipulator reached the target. The reason that the target appeared in the same plane is because the monitor cannot display 3D images. The subjects repeatedly attempted to position the tip on a randomly placed target. At the beginning of each measurement session, the tip of the hand-controller’s stylus is set as the base, synchronizing with the tip of the virtual arm placed behind the green box.

The visuomotor task in which subjects position the arm tip on the target is appropriate for this study because touch prompts a user to identify the boundary between his own body and that of others, affording him the greatest opportunity of perceiving his own body [15] [16] [17]. By making a user repeatedly touch the target encourages perception of his body, enabling us to measure how strongly the user perceives the manipulator as part of his body.

Fig. 5. Denavit-Hartenberg parameter skeleton [21]. Manipulator in the simulator has 3-DOF.

Fig. 6. Robotic surgical simulator. To identify the best hand-eye coordination, the arm position changes according to the rotation of angle $\theta$. $r$ is the constant radius.

F. Stimulation Measurement Mode

We measured the brain activity in a stimulation measurement mode. The measurement time was separated into two parts, that is, task and rest periods, to ensure high precision analysis by integrating the brain activity observed in each task period.

The subjects performed the positioning task in both the task and rest periods. However, the two periods differed with respect to angle $\theta$ between the eye and virtual arm, since in our opinion, the most valuable experiment is to measure the difference in success rate between the task and rest periods.

At the beginning of each period, the cube was positioned at the center of the display and the tip of the virtual arm remained synchronized with the tip of the stylus. Throughout the measurement period, the subjects held the stylus to prevent other factors from influencing brain activity.
Fig. 7. Stylus for position control of the manipulator in the robotic surgery simulator. The tip of the virtual arm moves by direct action with 1-DOF on the z-axis and rotates with 2-DOF on the X-Y plane.

Fig. 8. One measurement session. The session consisted of an initial 180 s rest period and three repetitions of a stimulus sequence, comprising a 30 s task period followed by a 40 s rest period. The order of task cases was randomized for each subject.

**G. Angles in Rest Periods**

During the rest period, subjects controlled the virtual arm with \( \theta = -90.0^\circ \). We excluded the case of \( \theta = -90.0^\circ \) from those measured since this case implies the greatest disparity in the relative position of the eyes to the human-robot hand.

**H. Angles in Task Periods**

In the task period, subjects performed the positioning task in the simulator with \( \theta = -45, 0, 45, \) and \( 90^\circ \) interspersed between rest periods.

**I. Single Measurement Session**

A single measurement session consisted of an initial 180 s rest period and three repetitions of a four stimulus sequence, consisting of a 30 s task period followed by a 40 s rest period, as shown in Fig. 8. In the measurement session, subjects tried to maintain their posture and minimize body movement. An initial rest period was sufficient to steady brain activity. The order of stimulation was randomized for each subject based on the three rules of R.A. Fisher in his “experimental design”.

**J. Condition**

The subjects practiced controlling the virtual arm (\( \theta = -90.0^\circ \)) to ascertain the depth of the simulator and to master control of the virtual arm once the investigator had set up the OT probe positions and postures. Until all the OT channels yielded good signals, the investigator continually reset each probe. After completing the probe settings, the investigator asked subjects whether they were sufficiently familiar with it to move the virtual arm as expected. Once subjects were satisfied with the simulator training, the experiment was started. Each subject performed a single measurement session.

**K. Measured Brain Area**

The measured brain area is the intraparietal sulcus (IPS), which is located on the lateral surface of the parietal lobe, and consists of an oblique and a horizontal position. The IPS contains a series of functionally distinct subregions that have been intensively investigated using both single cell neurophysiology in primates [18] [19] and human functional neuroimaging [20]. The principal functions of this area are related to perceptual-motor coordination (for directing eye movement and reaching) and visual attention [15]. To identify which channel on the subject’s head corresponds to the brain area, we used a 3D-digitizer and NIRS-SPM software to reveal that the IPS is above channel 6. The 3D-digitizer was used to measure where the point exists on the head, while the NIRS-SPM software for MATLAB validated the standard brain model and data from the 3D-digitizer. Our evaluation yielded channel 6 on average.

**L. OT Recording**

A 22-channel OT instrument (ETG-4000, Hitachi Medical Co.) generated two wavelengths of OT light (635 and 830 nm) and measured temporal changes in the concentration of oxy-Hb and deoxy-Hb with a temporal resolution of 0.1 s.

We used a 3 × 5 matrix of photodiodes consisting of eight light transmitters and seven receivers for the measurement, as shown in Fig. 9. The blood oxygen level was measured in a 30 mm area between each transmitter and receiver pair. Thus, the 15 photodiodes formed 22 measurement channels. These photodiodes were attached to a flexible silicon frame and placed on the subject’s parietal area. The photodiodes covered a 9 × 15 cm area of the scalp, including Pz following the international 10/20 system [22].

**M. Data Analysis**

We corrected the raw data using the following procedures. First, the raw data were digitally low-pass filtered at 0.1 Hz to remove measurement noise. Next, a baseline correction was performed to remove the linear trend in hemoglobin concentration. We fitted a linear function to the data points.
Fig. 10. Activation maps which show that activity in channel 6 is significant.

Fig. 11. The time course of channel 6 changes in the oxy-Hb, deoxy-Hb, and total-Hb concentrations during a task.

III. RESULTS

A. Consideration of Evaluation Indices

To validate a user’s recognition measurement, we first investigated quantitative indices to evaluate the ease with which the manipulator is perceived as being part of the user’s body. The activation map during a task period is shown in Fig. 10. An example of the time course of changes in oxy, deoxy and total-Hb concentrations during a task period, expressed in red, blue, and green, respectively, is shown in Fig. 11. The results confirm that a significant increase in oxy-Hb concentration is found in the IPS area during a task period while a decrease in oxy-Hb concentration is measured during the rest periods.

We used the oxy-Hb concentration as a quantitative value indicating how easy it is for the user to perceive the virtual arm as a part of his body. We subsequently used oxy-Hb to validate the angle between the eyes and arm that enables users to perceive the virtual arm as being part of their body.

Fig. 12. Results for five subjects. We constructed a pie chart of all the results. The pie chart shows the relation between brain activation and arm position angles. The total result includes both groups, A and B. The separate group A and B line graphs show the results for different groups of the five subjects.

B. Results for all Angles between Eyes and Virtual Arm Positions

The pie chart in Fig. 12 shows the relationship between the IPS activation and arm position angles for five subjects. Since OT data represent relative values, we cannot directly compare the values among subjects. But, we can compare the values for different arm position angles of each subject.

We divided the subjects depicted in the pie chart into two different line graphs: groups A and B. These line graphs show the relationship between IPS activation and the angles between the eyes and arm positions. Group A illustrates the results for three subjects and group B for the remaining two of the five subjects.
IV. DISCUSSION

A. Validating the angle that facilitates users perceiving the virtual manipulator as part of their body

The results of the activation map in Fig. 10 indicate that channel 6 is the correct position for IPS activation measurement because activation of channel 6 was significant during the task period.

The trend in Fig. 11 suggests that IPS can be used to reflect the user’s introspection for physical human-robot correspondence because the activity is significant during the task period, whereas it is small in rest periods. The rest period, with $\theta = 90.0^\circ$, shows the greatest disagreement in the relative position of the eyes and human-robot hand. As such, the activation in the task period is more significant than that in rest periods because users perceive the virtual arm to be part of their body in task periods rather than in rest periods, which indicates the user’s introspection.

The trend in group A in Fig. 12 shows that IPS activity is significant in the -45.0 and 45.0$^\circ$ cases, but for 0.0$^\circ$ and 90.0$^\circ$, the activity decreases. We considered two reasons that could cause these results. One is that the difference in the posture influences brain activation. The skew angles, -45.0 and 45.0$^\circ$, are included in both the longitudinal and horizontal components, whereas the others, 0.0 and 90.0$^\circ$ are included in only one. Another reason is that brain activation was influenced by the body image which is the spatial body symbol in the brain. It is known that IPS is deeply related to body image [15] [23] [24] [25]. Therefore, IPS activation might be influenced by the body image. With $\theta = 45.0^\circ$, the arm position is similar to the human arm mechanism from the shoulder to the tip of the finger, as shown in Fig. 13. That is, for $\theta = -45.0^\circ$, subjects may recognize the slave manipulator instead of their arm. On the other hand, with $\theta = 45.0^\circ$, the arm position is close to the stylus gripped by the hand, as shown in Fig. 14. It has been stated that when a human uses a tool, he perceives it within his body representation as an extension of his arm [15] [23]. In this case, the subject perceives the stylus within his representation as an extension of his arm. He may see the master and slave manipulators as a new arm link and their hand as a new joint. The other angles have no association with the body image. The body image theory yields two interesting conclusions; the best manipulator may be similar to the human mechanism or may be used as a new arm link.

The results for group B are similar to those for group A, except that IPS activity is significant for $\theta = 90.0^\circ$, which is contrary to the results for group A. We believe the master manipulator mechanism caused the difference. For $\theta = 90.0^\circ$, the arm position is closest to the mechanism of the master manipulator. Group A were aware of the master manipulator mechanism, group B were not. This difference between groups A and B may have caused the difference in these IPS activities.

Moreover, all the subjects rotated their ankles to correspond with changes in the arm position since the posture of the stylus matches the posture of the virtual arm. For example, in a position with the arm facing upwards towards the center of the display, e.g., $\theta = 45^\circ$, the subject holds the stylus like a pen. However, with the arm positioned downwards towards the center of the display, e.g., $\theta = -45^\circ$, the subject tends to break his wrist to adapt the stylus posture to correspond with the virtual arm posture. In this case, ankle rotation is one of the best methods of adapting the robot control.

B. Body image

Our investigation of hand-eye coordination in this research clarified the angle between the eye and hand that best allows users to perceive the manipulator as part of their body. Hand-eye coordination represents the visual and somatic sense feedback. It has been stated that the correspondence between visual and somatic sense feedback includes the human body image, which is the spatial body symbol in the mind [15] [23] [24] [25]. Body image is one of the internal models [23].

When a person uses the tools, he makes use of the body image by seeing the instrument as a part of his body [15]. If a person has no such image, he cannot use the tool correctly because the tool is not part of his body. By visualizing the tool to be part of his body, the user derives intuitive operability and can master the tool.

We think that body image most affects intuitive operability including hand-eye coordination because the essence of operability is the interface between the human and the robot. It would be useful if we could match the robot with the human body image when designing a robot with intuitive operability. To clarify the quantitative condition that facilitates users perceiving the manipulator as being part of their body, we should investigate factors of the body image such as the distance between the eyes and hand, how to grip the master manipulator, and so on.
V. CONCLUSION

Surgical robots have undergone considerable improvement in recent years. However, intuitive operability has not yet been evaluated quantitatively. We define intuitive operability in terms of how strongly users perceive the manipulator to be part of their body. We proposed a brain activity measurement method to measure intuitive operability. In this paper, our objective was to clarify the angle between the endoscope and the manipulator that makes it easy for users to perceive the manipulator to be part of their body, based on the brain activity measurement. The design of a robot with intuitive operability can benefit from the angle thus determined. In the experiment, users controlled the hand controller, a PHANTOM-Omni® to position the tip of the virtual arm on the target in the surgical simulator, while their brain activity was measured by an Optical Topography brain imaging device. Four measurement cases were used with the arm position rotated 45.0° around the eye focus position. We validated the evaluation in each case based on brain activity. Brain activity was significant for -45.0 and 45.0°. The results support the fact that body image affects hand-eye coordination, which is related to visual and somatic sense feedback. In the future, we will investigate factors of the body image such as the distance between the eyes and hand, how to grip the master manipulator, and so on.

REFERENCES