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Intuitive Operability Evaluation of Surgical Robot Using Brain Activity Measurement to Determine Immersive Reality

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Abstract—**Surgical robots have improved considerably in recent years, but intuitive operability, which represents user inter-operability, has not been quantitatively evaluated. Therefore, for design of a robot with intuitive operability, we propose a method to measure brain activity to determine intuitive operability. The objective of this paper is to determine the master configuration against the monitor that allows users to perceive the manipulator as part of their own body. We assume that the master configuration produces an immersive reality experience for the user of putting his own arm into the monitor. In our experiments, as subjects controlled the hand controller to position the tip of the virtual slave manipulator on a target in a surgical simulator, we measured brain activity through brain-imaging devices. We performed our experiments for a variety of master manipulator configurations with the monitor position fixed. For all test subjects, we found that brain activity was stimulated significantly when the master manipulator was located behind the monitor. We conclude that this master configuration produces immersive reality through the body image, which is related to visual and somatic sense feedback.**

I. INTRODUCTION

A. Background

ROBOTIC SURGERY has the potential to reduce scarring and shorten patient recovery times [1], and considerable improvements have been made in robotic surgery in recent years [2].

The major operating system of a surgical robot is the master-slave system, whereby the surgeon controls the master manipulator and follows the movement of the slave manipulator, which operates in the patient's body, rather than following the surgeon's own arm [2]. Robotic surgery has the great merit of allowing precise operation with a manipulator that is smaller than the human hand [2].

However, a critical problem with the master-slave system is that surgeons operate more indirectly with it than in open surgery because they perceive and control both the position and the posture of the slave manipulator by means of a monitor via the endoscope [3]. Surgeons therefore require intuitive operability in robotic surgery, which will allow them to work as if they were operating directly on the patient [3]. This operability is also called "telepresence" [4]. For design of a robot with intuitive operability, surgical robot performance has been evaluated in terms of time taken to complete a task, average speed, and movement curvature, under test conditions [4].

B. Motivation

The master-slave systems described in related studies have been designed and evaluated using only mechanical measurement methods to improve their working performance. It was recently suggested that improvements in working performance require a robot design with intuitive operability [4]. However, we have doubts about this, because intuitive operability amounts to "user inter-operability," which is how the user perceives and controls the robot. Irrespective of improvements in the robot's working performance, it is not always the case that the user can operate a robot intuitively. It is thus important to evaluate the user inter-operability of the person operating the robot rather than the robot's specifications.

We propose a measurement method for user inter-operability by measuring brain activity via brain-imaging devices to determine the robot design parameters that provide intuitive operability. In several reports, brain-imaging devices have been used to study user inter-operability [5] [6]. We consider brain-imaging devices to be the only means of evaluating user inter-operability in terms of intuitive operability.

Our aim is to design a master-slave system that allows the surgeon to perceive the manipulator to be part of his own body, based on evaluation of the brain activity measurements, as

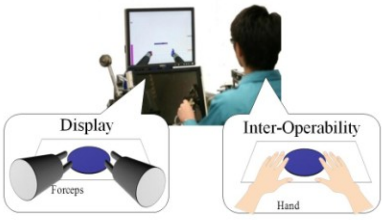

Fig. 1. Our target image. If the user were to operate directly, then in the user's mind, the displayed manipulator would represent his hand. This representation influences the operability.

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Fig. 2. Zeus console system.

Fig. 3. Da Vinci console system

Fig. 4. Experimental system. The subject controlled the hand controller, the PHANTOM-Omni, to position the tip of the virtual arm on the target (green box) while the user's brain activity was measured using an optical topography brain-imaging device.

shown in Fig. 1. The master-slave system that has the highest intuitive operability moves as expected and provides feedback to the user as if it were his own body performing the action.

We therefore define intuitive operability as how strongly the user perceives the manipulator to be part of his body. We consider the brain measurement data to be useful for design of a robot with intuitive operability. In this study, we present an original method using brain-imaging techniques to clarify the design parameters for a robot with intuitive operability.

C. Objective

In this study, we investigate the hand-eye coordination that would help the user to regard the manipulator as being part of his own body. We assume that hand-eye coordination is influenced by the difference between the hand positions of the user and the robot relative to the user's eyes. In endoscopic surgery, hand-eye positioning is called "triangulation" [7]. Also, as indicated in several previous reports, hand-eye coordination is an important factor in the difference between visual and somatic feedback [8] [9] [10].

We have studied the appropriate hand-to-eye position based on the user's recognition function. The hand-eye coordination can be configured through three factors: the user, the master, and the slave. We must clarify the master-slave system in terms of these factors to achieve intuitive operability.

In a previous study, we showed that the user-master interface has a greater effect on operability than the user-slave interface [11]. Regardless of the type of user-slave interface, the user can control the robot if the user-master interface provides intuitive operability. In this study, we focus on the user-master interface. In particular, we investigate the master configuration relative to the monitor because we consider the master configuration to be the most important element of an intuitive master-slave system. For example, with the Zeus console, the console is located in front of the monitor, as shown in Fig. 2. However, with the da Vinci system, the console is located behind the monitor, as shown in Fig. 3. We consider the da Vinci system to be superior to the Zeus in terms of intuitive operability, because it provides an immersive reality experience to give the user the illusion of putting his own arm into the monitor.

We assume that the master configuration must create the immersive reality of the user putting his arm into the monitor. In the past, such an assumption could have not been verified, because there was no way to evaluate user inter-operability. Our objective is to show that the proposed method of brain-activity measurement can verify this assumption quantitatively. In this study, we therefore examine the master configuration relative to the monitor through brain activity measurements.

II. METHOD

We used a brain-imaging device to measure the brain activity of test subjects while they used the hand controller to position the virtual arm in the surgical simulator, as shown in Fig. 4.

A. Subjects

Three healthy adults (three males; mean age of 23.0 years; age range from 22–24 years; all right-handed) participated in the experiment. All three had normal or corrected-to-normal vision. The subjects were informed about measurement of their brain activity and the purpose of the experiment, and informed consent was obtained from all subjects. The experiments were conducted in accordance with the Declaration of Helsinki.

B. Brain-Imaging Device - Optical Topography

For the brain-imaging device, we used optical topography (OT) because the equipment is reasonably compact and it provides a relatively non-invasive means of measurement. It allows human cortical activity monitoring in a variety of experimental tasks, including those requiring physical movement [5]. OT is a relatively new brain-imaging technique that measures the relative change in hemoglobin concentration [6]. OT can measure changes in the oxygenated hemoglobin (oxy-Hb) and deoxygenated hemoglobin (deoxy-Hb) concentrations separately.

C. Display

The robotic surgery simulator was presented on a 15-inch LCD monitor (Dell E156FPb) with a pixel resolution of 1024×768 and a 60 Hz vertical refresh rate. The time course of stimulus presentation was controlled via a PC. The subjects set the monitor position to be perpendicular to their line of sight at their own discretion.

The simulator displayed a green cube and the manipulator with 3 degrees of freedom (DOF) against a black background. The background was black because this places the lowest burden on the human eye. The green cube was placed randomly in the same plane when touched by the tip of the virtual manipulator. The cube was green because this color stands out best against a black background.

D. Robotic Surgery Simulator

We implemented the robotic surgical simulator described in section C using Open Graphics Library (OpenGL). The virtual manipulator has 3 DOF: 2 DOF for rotation (yaw and roll) and 1 DOF for direct action (*z*-axis*)*. The virtual manipulator mechanism is illustrated in Fig. 6. We initialized the tip of the virtual arm by synchronizing the tip of the master manipulator with the monitor at a 30° angle, because the subjects set the monitor at that angle to be perpendicular to their line of sight.

The virtual manipulator was controlled using the PHANTOM-Omni hand controller. The tip of the virtual manipulator was synchronized with the tip of the PHANTOM-Omni. The subjects controlled the hand-controller by gripping it like a pen.

In this study, we investigated the master configuration relative to the monitor. We did this by varying the PHANTOM-Omni hand controller position in five different ways, as shown in Fig. 5.

E. Visuomotor Task

In the experiments, the subjects used the PHANTOM-Omni to position the tip of the virtual manipulator on the target in the surgical simulator. The target was set as a green box that appeared randomly in the same plane when the manipulator tip reached the target. The target appeared in the same plane because the monitor could not display 3D images. The subjects repeatedly attempted to position the tip on the randomly placed target.

The visuomotor task, in which the subjects positioned the arm tip on the target, was appropriate for this study, because touch prompts the user to identify the boundary between his own body and that of others, and it provides the greatest opportunity to perceive one's own body [13] [14] [15]. Making the user repeatedly touch the target encourages his perception of his body, and it enabled us to measure how strongly the user perceived the manipulator as being part of his own body.

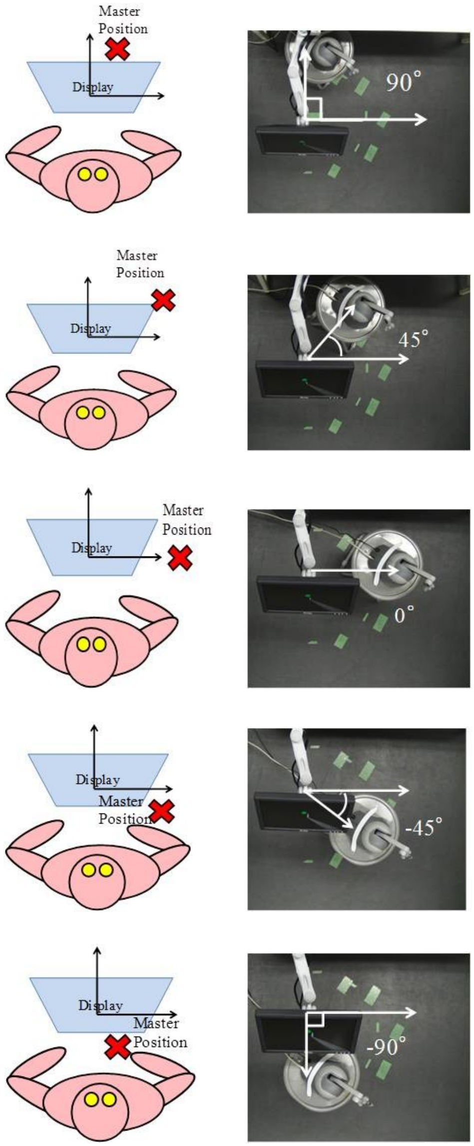

Fig. 5. Objective parameter. We kept the monitor position fixed and changed the hand controller position defined by the angle θ.

F. Stimulation Measurement

We measured each subject's brain activity by stimulation measurement. The measurement time was separated into two parts - task and rest periods - to ensure high-precision analysis by integrating the brain activity observed during each task period.

During the rest period, the subjects simply looked at the green cube. However, during the task periods, which alternated with the rest periods, the subjects performed the positioning task in the simulator. 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 master.

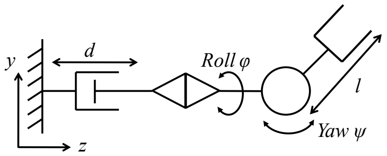

Fig. 6. Denavit-Hartenberg parameter skeleton [12]. The manipulator in the simulator has 3 DOF.

G. Single Measurement Session

For each master position, we measured the subject's brain activity in a single measurement session. A single measurement session consisted of an initial 40 s rest period and five repetitions of a four-stimulus sequence, which consisted of a 30 s task period followed by a 40 s rest period. The initial rest period was sufficient to stabilize subject brain activity.

During the measurement session, the subjects tried to maintain the same posture and minimize their body movement. The stimulation order was randomized for each subject, based on the three rules of R. A. Fisher in his work on experimental design [16].

H. Subject Positions

First, we informed the subjects of the objectives and the task of the study. Next, we set up the OT probe positions and postures. We reset each probe until all of the OT channels yielded good signals.

After the probe settings were complete, the PHANTOM-Omni was positioned at each angle θ, as shown in Fig. 5. The subjects set the seat position to allow movement of the hand controller or their hand and moved the monitor position to be perpendicular to their line of sight at their own discretion. We checked with the subjects that they were satisfied with the positioning of the seat and the monitor. We then started the single measurement session for each angle θ.

After each single measurement session, we changed the position of the PHANTOM-Omni hand controller, as shown in Fig. 5. In total, we used five PHANTOM-Omni position variations, so that the subjects performed all five measurement sessions for each of the five PHANTOM-Omni positions. When changing the PHANTOM-Omni position, the subjects reset the positions of the seat and the monitor.

I. Measured Brain Area

The brain area measured was the intraparietal sulcus (IPS), which is located on the lateral surface of the parietal lobe and has an oblique, horizontal position. The IPS contains a series of functionally distinct subregions that have previously been investigated intensively using both single-cell neurophysiology in primates [17] [18] and functional neuroimaging in humans [19]. The principal functions of this area are related to perceptual motor coordination (for direction of eye movement and reaching toward objects) and visual attention [14].

We verified that the IPS is located at channel 6 for each subject. To identify the channel on the subject's head that corresponded to that brain area, we measured the 3D coordinates of each point on the subject's head using a 3D digitizer, and compared the subject's brain with a standard brain model using NIRS-SPM software with MATLAB.

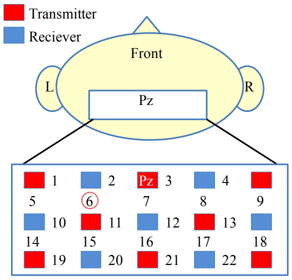

Fig. 7. Arrangement of the 15 photodiodes and the locations of the 22 measurement channels. The red and blue squares show the OT light transmitters and receivers, respectively. The numbers indicate the channels.

J. OT Recording

A 22-channel OT instrument (ETG-4000, Hitachi Medical Co.) generated two OT light wavelengths (635 nm and 830 nm) and measured temporal changes in the concentrations 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 measurements, as shown in Fig. 7. The blood oxygen level was measured over a 30 mm area between each transmitter and receiver pair. The 15 photodiodes thus 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, according to the international 10/20 system for electrode placement [20]. We set Pz to be located at the center of the scalp because it allows us to set the scalp position according to the head of each user.

K. 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 any measurement noise. Next, a baseline correction was performed to remove the linear trend in the hemoglobin concentration. We fitted a linear function to the data points sampled in the 5 s interval before and after the start of each task period. We performed a baseline correction using the mean values during half of the rest period as a baseline.

Because the raw data for NIRS consisted of relative values, we could not compare the data from the subjects or the channels directly. The data were therefore normalized by calculating the "effect sizes" for each channel within each subject. The effect sizes (d) were calculated using the following equation:

$$d = (m1 - m2) / s \tag{1}$$

where $m1$ is the mean value for a stimulation period, and $m2$ and s are the mean and the standard deviation of the values sampled during the rest period after stimulation, respectively. We used these effect sizes in subsequent analyses.

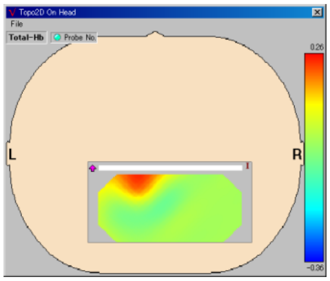

Fig. 8. Activation maps which show that significant activity occurs in channel 6 during the task.

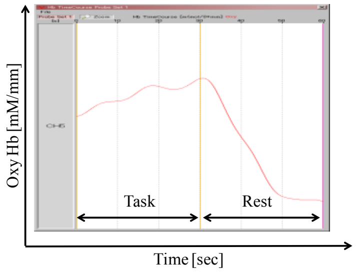

Fig. 9. The time course of channel 6 changes in oxy-Hb during a task.

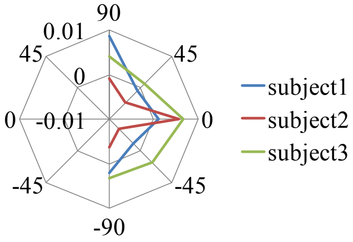

Fig. 10. IPS activation relative to the PHANTOM-Omni configuration angle for the three subjects.

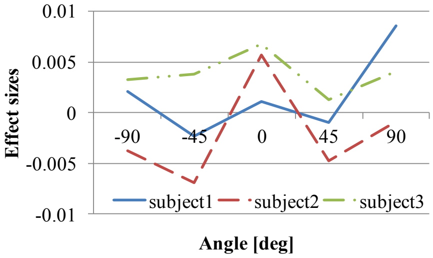

Fig. 11. The effect size variation with configuration angle for the three subjects.

III. RESULTS

A. *Consideration of Evaluation Indices*

To validate each user's recognition measurements, we first investigated quantitative indices to evaluate the ease with which the manipulator could be perceived as being part of the user's body. The activation map during each task period is shown in Fig. 8. An example of the time course of changes in oxy-Hb concentration during a task period, shown in red, is given in Fig. 9. The results confirm that a significant increase in the oxy-Hb concentration was found in the IPS area during a task period, while the oxy-Hb concentration fell during the rest periods.

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

B. *Results for All Angles Between Monitor and PHANTOM-Omni Position*

The pie chart in Fig. 10 shows the relationship between the IPS activation and the PHANTOM-Omni configuration angles for the three subjects. Because the OT data represent relative values, we cannot directly compare these values among the subjects. However, we can compare the effect sizes among the subjects.

We changed the subjects depicted in the pie chart into line graphs, as shown in Fig. 11. These line graphs show the relationship between the IPS activation and the angles between the eyes and the arm positions.

IV. DISCUSSION

A. *Contribution: Validation of the Angle that Lets Users Perceive the Virtual Manipulator as Part of their Body*

The results of the activation map in Fig. 8 show that channel 6 was the correct position for the IPS activation measurement, because there was significant activation of channel 6 during the task periods.

The trend in Fig. 9 suggests that the IPS can be used to reflect the user inter-operability for physical human-robot correspondence, because the activity was significant during the task periods, whereas it was low during the rest periods. The activation in the task periods was more significant than in the rest periods, because the users perceived the virtual arm to be part of their own body during the task periods rather than during the rest periods, which indicates user inter-operability.

The brain activity is influenced by the body image, which is a spatial body symbol in the brain. It is known that the IPS is closely related to the body image [13] [21] [22] [23]. The IPS activation should therefore be affected by the body image.

As shown in Fig. 11, the IPS activity was significant in the 90.0° configuration for all subjects. This configuration locates the master behind the monitor. This created an immersive-reality illusion such that the user felt as if his own arm were being used in the monitor, and thus created the impression that the virtual arm was part of the user's own body. We believe that this master configuration is able to produce immersive reality. Therefore, in having an immersive design, the da Vinci system appears to be superior to the Zeus in terms of intuitive operability.

We believe that this master configuration produces immersive operability through a matching process between the movement and the body image. This match gives the user the illusion that the robot is a part of their own body. It achieves matching between the movement and the body image through matching between the somatic and visual feedback.

B. *Limitation: Master Mechanism and Natural Arm Position*

In Fig. 11, brain activity was stimulated at 0.0° and -90.0°. This result contradicts our hypothesis that the brain activity should be stimulated at 90.0°. We consider that two factors, the master mechanism and the natural arm position, affect the intuitive operability to stimulate the brain activity.

In the 0.0° configuration, as shown in Fig. 11, the brain activity was significant. We believe that the master mechanism is influenced by the brain activity here. In the 0.0° configuration, the subjects might cause the PHANTOM-Omni to move. In future work, we should control the robot, irrespective of the master mechanism. For example, a tracking system would be useful.

In the -90.0° configuration, the brain activity was again significant, as shown in Fig. 11. We believe that the natural human arm position is influenced by the brain activity here. The subjects might cause the PHANTOM-Omni to move because the master configuration is similar to the natural human arm position. We should therefore adapt the master-slave system to suit the natural human arm position.

It would appear that the brain activity reflects intuitive operability. Intuitive operability appears to be influenced by two factors: the master mechanism and the natural arm position. In future work, to study immersive reality, it will be necessary to control the experimental design to retain the natural arm position and to use the master irrespective of the particular mechanism.

C. *Body Image*

Our investigation of hand-eye coordination in the present study revealed the master configuration angle that best allows the users to perceive the manipulator as part of their own body. Hand-eye coordination is the result of visual and somatic sense feedback. Some authors have stated that the correspondence between visual and somatic sense feedback includes the human body image, which is the symbol of the spatial body in the mind [14] [21] [22] [23]. The body image is an internal model [22].

When a person uses a tool, he uses the body image by seeing the instrument as being part of his body [15]. If a person has no such image, he cannot use the tool correctly because the tool cannot become part of his body. By visualizing the tool as part of his body, the user derives intuitive operability and can thus master operation of the tool.

We believe that body image greatly 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 to be able to match the robot with the human body image for design of a robot with intuitive operability. To clarify the quantitative condition that allows users to perceive the manipulator as part of their body, it is necessary to investigate body image factors, such as the natural arm position.

V. CONCLUSIONS

We have proposed a brain activity measurement method to measure intuitive operability of a surgical robot. We define intuitive operability in terms of how strongly users perceive the manipulator to be part of their own body. We believe that the design of a robot with intuitive operability can benefit from this study. In this paper, our objective was to determine the master configuration relative to the monitor that makes it easiest for users to perceive the manipulator to be part of their own body, based on brain activity measurement. We assumed that the master configuration produced the immersive reality experience of the user putting his arm into the monitor. In our experiments, the users controlled the tip of the virtual arm to reach the position of the target in the surgical simulator while their brain activity was measured with an OT brain-imaging device. For all of the subjects, the brain activity was found to be significant in the configuration where the master manipulator was located behind the monitor. This indicates that the brain activity reflects intuitive operability. Intuitive operability appears to be influenced by three factors: immersive reality, the master mechanism and the natural arm position. In future work to study the role of immersive reality, it will be necessary to control the experimental design to maintain the natural arm position and to use the master irrespective of any particular mechanism.

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