# Brain Wave Measurement while Touching Task of a Virtual Arm for Intuitive Robotic Surgery

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*Abstract*— **This paper presents a novel evaluation method for designing an intuitive surgical robot by measuring a user's brain activity. Conventionally, surgical robots have been designed based on their mechanical performance. However, an improvement in a robot's mechanical performance does not necessarily represent the embodiment that the user feels. In this paper, we evaluate intuitive operability based on the user's brain activation. Previously, we used functional near-infrared spectroscopic-topography (fNIRS) brain imaging; however, it is better to use a brain measurement technique possessing a high time resolution, as brain activity is has a higher time resolution than fNIRS. The objective was to measure changes in brain activity as a function of a change in the slave arm positioning. In the experiment, the brain activity of four participants was measured using fNIRS while they used a hand controller to move the virtual arm of a surgical simulator. The experiment was carried out with the virtual arm in two positions: one easy to control and the other difficult. The spectrum of the brain activity increased at the easy position more than at the difficult position. We conclude that the brain activity changed as the user perceived that the virtual arm belonged to their body.**

*Index Terms*—**EEG, fNIRS, Robotic Surgery, tele-operation**

## I. INTRODUCTION

Robotic surgery offers the advantage of minimally invasive surgery, which can reduce both scarring and patient recovery time because the surgical manipulator is small and precise [1][2]. Surgical robots are therefore used worldwide [3]. For example, 2,000 da Vinci surgical robots have been sold worldwide, and these surgical robots were used in more than 278,000 cases prior to 2010 [4].

The method of operation when using a surgical robot mainly involves a master–slave arrangement, where the surgeon inserts the slave manipulators and an endoscope into the patient's body, and then operates the slave manipulators using the master console. The surgeon controls the master console to move the slave manipulators within the patient's body while simultaneously observing the operative field through the endoscope. In robotic surgery, the surgeon's control depends on a combination of visual observation of the slaves via the endoscope and the proprioceptive senses of the operator's hand via the stimulation from the nerves [5]. When the surgeon moves the master, they depend on proprioceptive feedback from their hand. Simultaneously, when the surgeon examines the slave's movement, they depend on visual feedback about the slave's movement from the endoscope. When the surgeon feels that the use of visual and proprioceptive senses to control the slaves and endoscope are as intuitive as their own hands and eyes, the instruments can be operated as intuitively as the surgeon can operate their own body.

Surgical robots must be designed to make the best use of the surgeon's skill and experience when operating, and maximize the intuitiveness of operation. Although intuitiveness has been studied by many scientists in a variety of fields, the master-slave system used in surgical robots has some problems. One is how exactly the posture and position of the manipulator's tips are synchronized between master and slave. In endoscopic surgery, the direction that the surgeon's hand moves is contrary to the direction that the forceps moves through the endoscope in the monitor. The surgeon, in endoscopic surgery, does not feel that their visual and proprioceptive senses are in agreement. However, robotic surgery resolves the problem of the agreement of the tip's kinematics between surgeon and manipulator. Another issue is how much the surgeon feels that the manipulator belongs to their body, because they are operating using the manipulator and endoscope instead of their hands and eyes. This feeling is called hand–eye coordination. When the trocar port point changes to a different part, the surgeon's cognitive sense of hand–eye coordination changes. From the viewpoint of robotics, hand–eye coordination caused by the physical difference between the human body and the robot mechanism is known as embodiment [6][7][8]. Embodiment means cognition that is strongly influenced by aspects of the human body beyond the brain itself. Hand–eye coordination is one such type of embodiment [7][8].

Although a surgical robot must be designed with embodiment as a consideration, there is currently no good method for evaluating embodiment. Conventionally, engineers design surgical robots taking mechanical performance aspects into account, such as the time taken to complete a given task, and the average speed and curvature of a movement under test conditions [9]. These working scores are so useful, in fact, that the mechanical performance of surgical robots has improved considerably in recent years, but the improvement in the mechanical performance of a robot does not necessarily represent the embodiment that the user feels.

In the field of cognitive neuroscience, many related studies have reported that the intraparietal sulcus is the specific brain area that is important in the function of embodiment. Some have reported that the intraparietal sulcus shows how strongly a human perceives that a tool belongs to their body [10][11]. In Iriki's experiment, the intraparietal sulcus of the macaque changes before and after tool-use. Iriki reported that this result occurs because the macaque perceives the tool as belonging to its body [12][13]. The intraparietal sulcus was also activated as the macaque saw its hand in the virtual space [14] and was measured in real time while using the tool with positron emission computerized-tomography (PET) [15]. The function of the intraparietal sulcus is reported to be applicable to not only macaques but also humans [16][17]. In addition, activity in the intraparietal sulcus has been found using not only fMRI but also fNIRS [18][19][20].

In previous work, we have studied a method to evaluate the intuitive operability related to embodiment by directly measuring brain activity [21][22][23][24][25][26][27][28][29]. We have proposed a design method to optimize the construction and control method on the basis of the user's brain activation, shown in Fig. 1. We measured the user's brain activity using fNIRS when the user moved the virtual arm, and reported that the brain changed moment by moment according to the phase of the operation. When the user sutured using a curved needle, the brain activation increased or decreased according to the reaching, insertion, or twisting phase [25]. It is better to have a high resolution for brain activity measurement, because the brain changes quickly in proportion to the suturing phase. We used fNIRS because fNIRS has a high spatial resolution; however, this method has a low time resolution. Thus, it is necessary to use a brain activity measurement device that has a higher time resolution. Electroencephalography (EEG) has a higher time resolution than fNIRS, but very few attempts have been made to apply these findings to robotics design in the field of engineering.

The objective is to validate the feasibility of a method for evaluation of the intuitive operability using not fNIRS but EEG. We measured the brain wave using EEG when the user controlled a virtual arm. In the experiment, the user moves the virtual arm positioned in different configurations to change the embodiment. The different configurations is two conditions. One is that the user can move the master naturally. On the other hand, another is that the user cannot move the master without twisting the wrist. This paper shows the brain wave compared with two conditions. The paper shows the change in brain activity as a function of the change of the slave arm position.

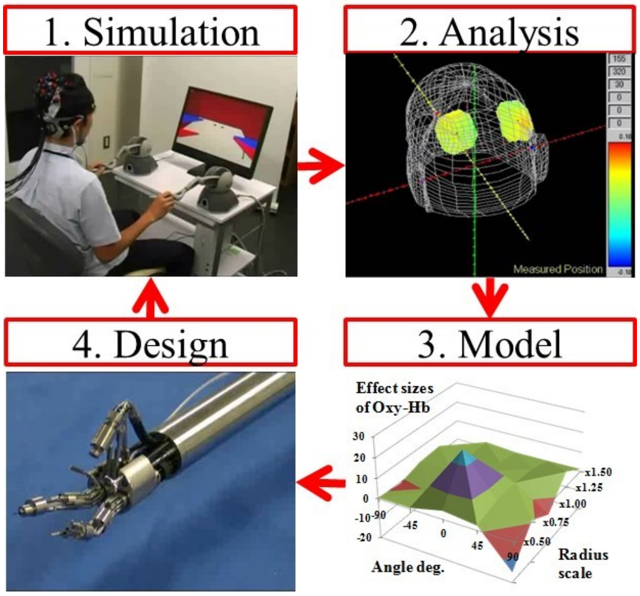



Fig. 1 Proposed method. First, the user's brain activity when they control the virtual arm is measured. Second, the user's brain activity is analyzed. Third, the intuitive operability in the user's brain is modeled. Fourth, the robot is designed based on the model.

## II. Method

### *A. Experimental Setup*

We used EEG to measure brain activity. The EEG system we used was the g.USBamp (g.tec, USA). EEG has a high time resolution; the time resolution of fNIRS is only 10 [Hz] but that of EEG is 256 [Hz]. In addition, EEG is portable, inexpensive, and can be used to measure brain activity during a movement task. However, fNIRS can measure the oxygenated hemoglobin in the cortex at high spatial resolution. In contrast, EEG measures the electrical activity on the scalp that is generated by the brain activity in the cortex.

The measurement points were the P3 and P4 points on the international 10-20 system (Fig. 2), because P3 and P4 are around the intraparietal sulcus as reported by Iriki. The measurement method was bipolar. We used 4 channels to measure each P3 and P4, with 2 channels each. The reference was put on the left ear.

During measurement of brain activity, each participant moved a hand controller (Geomagic Touch; Geomagic, Raleigh, NC, USA) to control the virtual arm in the surgical simulator (Fig. 3). The simulation was presented to the user on a 24-inch liquid crystal display monitor with a vertical refresh rate of 60 Hz. The time course of the stimulus presentation was controlled using a personal computer. The participants individually set the monitor position to be perpendicular to their line of sight. The virtual manipulator has three degrees of freedom (Fig. 4). The simulator with the virtual arm and a green cube displayed against a black background is shown in Figure 3.

*B. Experimental Conditions*

Four healthy adults (three men and one woman; mean age of 21.5 years; three right-handed and one left-handed) participated in this study. Informed consent was obtained from all individual participants included in the study. All procedures performed in the human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. These experiments were approved by the Waseda University Institutional Review Board (No. 2013-201).

The experimental conditions consisted of varying the virtual arm between two positions. The virtual arm position changed the location according to the fixed camera. The conditions were 45 and –90°.

*1) The virtual arm located at 45°*

45° means that the virtual arm appeared obliquely upward on the screen. The participants moved the controller naturally because it was easy to grip and move.

*2) The virtual arm located at –90°*

–90° means the virtual arm appeared on the lower right. The participants had to twist their wrist to move the controller.

*C. Experimental Procedure*

First, we placed the measurement device for EEG on the participants' head. Next, we measured brain activity during a single measurement session consisting of an initial 30-s rest period and four timed sets consisting of a 60-s task period followed by a 70-s rest period. The initial rest period was sufficient to stabilize brain activity. During the rest periods, the virtual arm was not displayed on the monitor and the participant focused continuously on the green box under all conditions. By contrast, during the task the participant was engaged in each task. In each of the task periods, the virtual arm was shown and moved. During a measurement session, the participant tried to maintain the same posture and minimize body movement. Five experimental trials were executed with the order of the experimental conditions randomly determined.

## III. Results

We calculated the power spectrum from the measured brain activity and derived the average value of the spectrum. Fig. 6 shows the average values of the longitudinal data among all participants. In task period, the power spectrum at 45° was higher than –90°. At 45, the maximum was 208.673 [$\mu V^2$], the minimum was 25.881 [$\mu V^2$] and the standard deviation was 21.376[$\mu V^2$]. On the other hand, at –90, the maximum was 208.673 [$\mu V^2$], the minimum was 34.026 [$\mu V^2$] and the standard deviation was 37.453[$\mu V^2$].

Fig. 7 shows the average of all time for each participant. The high power spectrum means the high brain activation. In this paper, when the high power spectrum showed, the intraparietal sulcus activated. In participant 1, 2 and 4, the power spectrum at 45° was obviously higher than –90°. Especially, in participant 1, the power spectrum at 45° was 130.554, but at -90° was 60.846.

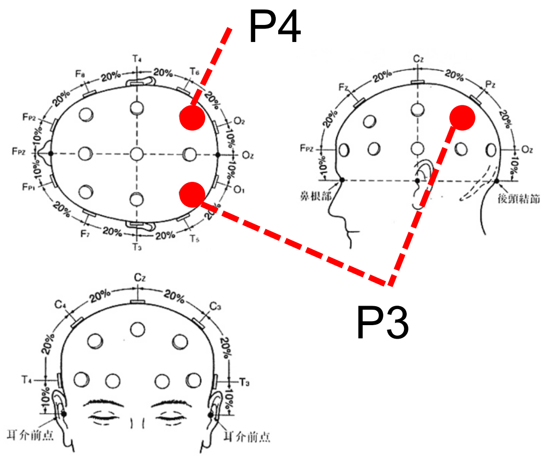



Fig. 2 P3 and P4 point on the international 10-20 system

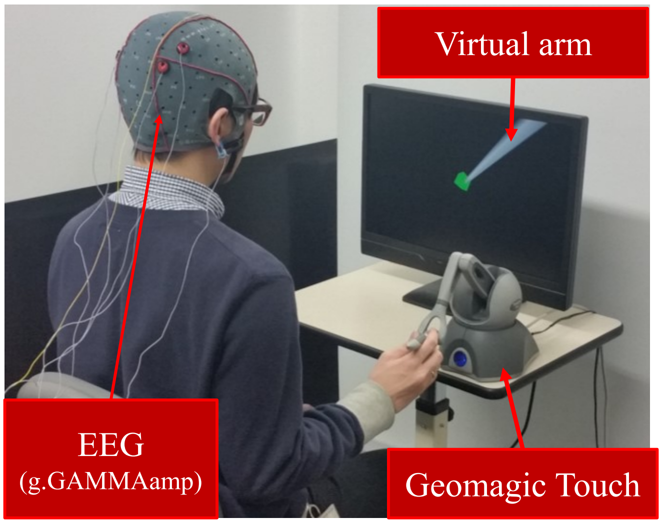



Fig. 3 EEG measurement during controlling VR arm.

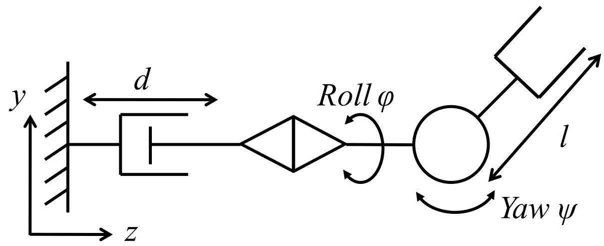
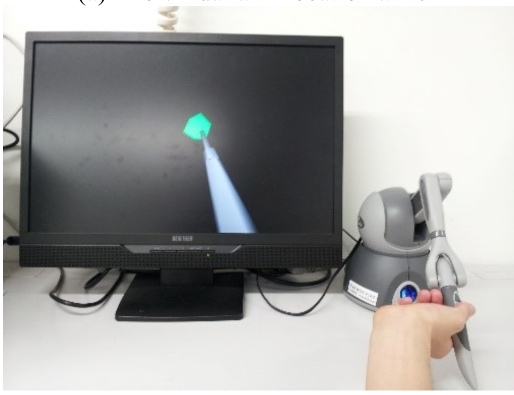



Fig. 4 DH parameters of virtual arm

However, about participant 3, there was no significant deference. The power spectrum at 45° was 20.58 and at –90° was19.802.

Fig. 8 shows that the mean brain activity across all four participants at 45° was significantly higher than that at –90° ($t = 1.681$, $df = 7$, $p < 0.1$). At 45°, the average was 62.123[$\mu V^2$] and the standard deviation was 41.289[$\mu V^2$]. On the other hand, the average was 36.179[$\mu V^2$] and the standard deviation was 15.337[$\mu V^2$].

(a) The virtual arm location at 45°



(b) The virtual arm location at –90°

Fig. 5 The virtual arm positioning. (a) At 45°, the participant moved naturally. However, (b) at –90°, the participant twisted the wrist.

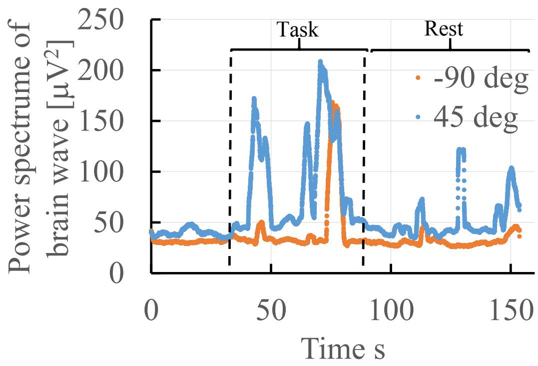



Fig. 6 Longitudinal data of the average of the power spectrum among all participants.

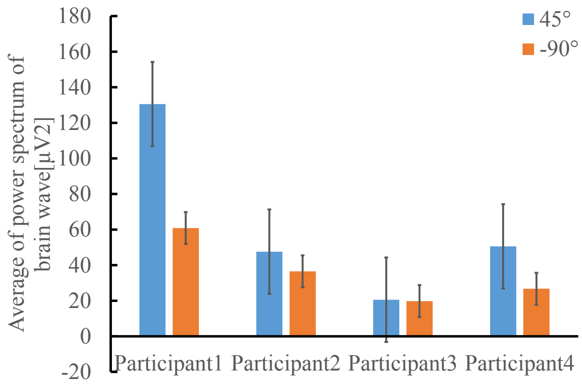



Fig. 7 Spectral power of the EEG for each of the four individual participants.

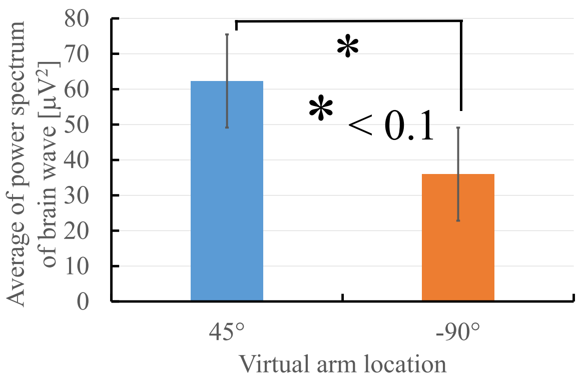



Fig. 8 Average of the spectral power of EEG.

## IV. Discussion

Fig. 6 showed that the power spectrum of the brain wave was in task period higher than in rest period. In task period, the brain activated because the participant would perceived the virtual arm as part of the body. Especially, the power spectrum of brain wave at 45° was higher than at –90° because the 45° was more intuitively than -90°. In addition, in around 75.0[s], both power spectrum at 45° and –90° was rising because the participant would become skilled. However, in around 50[s], power spectrum at only 45° was rising. This indicates that the participant would control intuitively in a moment from beginning of the task period.

Fig. 7 and 8 showed that the brain activity at 45° was higher than that at –90°. This indicates that controlling the virtual arm naturally is more intuitive than controlling it by twisting the wrist. At 45°, the participant controlled the arm naturally, so they felt embodiment because of the agreement between the position of their body and the position of the master–slave manipulator. However, at –90°, the participant had to twist the controller to control the virtual arm because the posture of the tip of the master was synchronized with the posture of the tip of the virtual arm positioned at lower right of the screen. The physical difference between the 45° and –90° positions would affect the intuitive operability that the participant felt. Thus, the brain activity changes should mirror the changes in intuitive operability.

Among each of the four participants, there were no significant differences because EEG is inferior to fNIRS in terms of spatial resolution. When performing an evaluation during a quick task such as controlling the camera, EEG would be useful it has high time resolution. However, if the engineer evaluates a time-consuming task such as cutting and suturing tissue, fNIRS would be useful because it has high spatial resolution. In future work, we will study methods to determine which brain activity measurement method is appropriate.

## V. Conclusion

In this study, we validated a method to evaluate the intuitive operability of master–slave surgical robots by measuring brain activity using EEG when the user controlled a virtual manipulator. The objective was to measure the change in brain activity as a function of the change of the slave arm positioning. We measured participants' brain activity while they used a hand controller to move a virtual arm under two conditions: (i) moving naturally to control the virtual arm position obliquely upward on the screen, (ii) twisting the wrist to control the virtual arm position on the lower right of the screen. The spectral power of the brain activity increased at the easy position more than at the difficult position. These results suggest that brain activity reflects changes in intuitive operability. We conclude that brain activity changes as the user perceives that the virtual arm belongs to their body. These findings provide a basis for further refinement of the single port surgical robot, artificial arms and other master–slave systems, such as infrastructure-building robots.

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## References

[1] J. Leven, D. Burschka, R. Kumar, G. Zhang, S. Blumenkranz, X. D. Dai, M. Awad, G. D. Hager, M. Marohn, M. Choti, C. Hasser, and R. H. Taylor, "DaVinci canvas: a telerobotic surgical system with integrated, robot-assisted, laparoscopic ultrasound capability.," *Med. Image Comput. Comput. Assist. Interv.*, vol. 8, no. Pt 1, pp. 811–8, Jan. 2005.

[2] T. Osa, C. Staub, and A. Knoll, "Framework of automatic robot surgery system using Visual servoing," *2010 IEEE/RSJ Int. Conf. Intell. Robot. Syst.*, pp. 1837–1842, Oct. 2010.

[3] G. H. Ballantyne, "Robotic surgery, telerobotic surgery, telepresence, and telementoring. Review of early clinical results.," *Surg. Endosc.*, vol. 16, no. 10, pp. 1389–402, Oct. 2002.

[4] G. Turchetti, I. Palla, F. Pierotti, and A. Cuschieri, "Economic evaluation of da Vinci-assisted robotic surgery: a systematic review.," *Surg. Endosc.*, vol. 26, no. 3, pp. 598–606, Mar. 2012.

[5] F. Wang, E. Su, E. Burdet, and H. Bleuler, "Development of a microsurgery training system.," *Conf. Proc. IEEE Eng. Med. Biol. Soc.*, vol. 2008, pp. 1935–8, Jan. 2008.

[6] J. Hawkins and S. Blakeslee, *On intelligence*. 2007.

[7] R. Wilson and L. Foglia, "Embodied cognition," *The Standard Encylopedia of Philoscopy*, 2011. [Online]. Available: http://plato.stanford.edu/entries/embodied-cognition/.

[8] E. Rosch, E. Thompson, and F. Varela, *The embodied mind: Cognitive science and human experience*. 1991.

[9] I. Suh and K. Siu, "Training program for fundamental surgical skill in robotic laparoscopic surgery," *Int. J. Med. Robot. Comput. Assist. Surg.*, vol. 7, pp. 327–333, 2011.

[10] A. Maravita and A. Iriki, "Tools for the body (schema)," *Trends Cogn. Sci.*, vol. 8, no. 2, pp. 79–86, 2004.

[11] A. Maravita, C. Spence, S. Kennett, and J. Driver, "Tool-use changes multimodal spatial interactions between vision and touch in normal humans.," *Cognition*, vol. 83, no. 2, pp. B25–34, Mar. 2002.

[12] C. L. Colby and M. E. Goldberg, "Space and attention in parietal cortex.," *Annu. Rev. Neurosci.*, vol. 22, pp. 319–49, Jan. 1999.

[13] J. S. Bladen, A. Anderson, G. D. Bell, and D. J. Heatley, "A non-radiological technique for the real time imaging of endoscopes in 3 dimensions," *1993 IEEE Conf. Rec. Nucl. Sci. Symp. Med. Imaging Conf.*, pp. 1891–1894, 1993.

[14] a Iriki, M. Tanaka, S. Obayashi, and Y. Iwamura, "Self-images in the video monitor coded by monkey intraparietal neurons.," *Neurosci. Res.*, vol. 40, no. 2, pp. 163–73, Jun. 2001.

[15] S. Obayashi, T. Suhara, Y. Nagai, J. Maeda, S. Hihara, and A. Iriki, "Macaque prefrontal activity associated with extensive tool use," *Neuroreport*, vol. 13, no. 17, pp. 2349–2354, 2002.

[16] L. Cardinali, F. Frassinetti, C. Brozzoli, C. Urquizar, A. C. Roy, and A. Farnè, "Tool-use induces morphological updating of the body schema.," *Curr. Biol.*, vol. 19, no. 12, pp. R478–9, Jun. 2009.

[17] T. R. Makin, N. P. Holmes, and E. Zohary, "Is that near my hand? Multisensory representation of peripersonal space in human intraparietal sulcus.," *J. Neurosci.*, vol. 27, no. 4, pp. 731–40, Jan. 2007.

[18] J. Fuster, M. Guiou, A. Ardestani, A. Cannestra, S. Sheth, Y.-D. Zhou, A. Toga, and M. Bodner, "Near-infrared spectroscopy (NIRS) in cognitive neuroscience of the primate brain.," *Neuroimage*, vol. 26, no. 1, pp. 215–20, May 2005.

[19] T. J. Germon, P. D. Evans, N. J. Barnett, P. Wall, a R. Manara, and R. J. Nelson, "Cerebral near infrared spectroscopy: emitter-detector separation must be increased.," *Br. J. Anaesth.*, vol. 82, no. 6, pp. 831–7, Jun. 1999.

[20] a Villringer, J. Planck, C. Hock, L. Schleinkofer, and U. Dirnagl, "Near infrared spectroscopy (NIRS): a new tool to study hemodynamic changes during activation of brain function in human adults.," *Neurosci. Lett.*, vol. 154, no. 1–2, pp. 101–4, May 1993.

[21] S. Miura, Y. Kobayashi, K. Kawamura, M. Seki, Y. Nakashima, T. Noguchi, Y. Yokoo, and M. Fujie, “Configuration of Slave and Endoscope in Surgical Robot based on Brain Activity Measurement,” in *The 6th International Conference on Soft Computing and Intelligent Systems and The 13th International Symposium on Advanced Intelligent Systems (SCIS-ISIS 2012)*, 2012, pp. 1195–1200.

[22] S. Miura, Y. Kobayashi, K. Kawamura, M. Seki, Y. Nakashima, T. Noguchi, Y. Yokoo, and M. Fujie, “Distance between Slave and Endoscope for a Surgical Robot Using Brain Activity Measurement to Evaluate the User’s Feelings,” in *The 9th Asian Conference on Computer Aided Surgery (ACCAS 2013)*, 2013, pp. 80–81.

[23] S. Miura, Y. Kobayashi, K. Kawamura, M. Seki, Y. Nakashima, T. Noguchi, M. Kasuya, Y. Yokoo, and M. Fujie, “Brain Activity Measurement to Evaluate Hand-Eye Coordination for Slave and Endoscope in a Surgical Robot,” in *2013 IEEE International Conference on Robotics and Automation (ICRA13)*, 2013, pp. 4341–4347.

[24] S. Miura, Y. Kobayashi, M. Seki, T. Noguchi, Y. Yokoo, and M. Fujie, “Intuitive Operability Evaluation of Robotic Surgery Using Brain Activity Measurement to Identify Hand-Eye Coordination,” in *2012 IEEE International Conference on Robotics and Automation (ICRA’12)*, 2012, pp. 4546–4552.

[25] S. Miura, Y. Kobayashi, K. Kawamura, Y. Nakashima, and M. G. Fujie, “Brain activation in parietal area during manipulation with a surgical robot simulator,” *Int. J. Comput. Assist. Radiol. Surg.*, 2015.

[26] S. Miura, Y. Kobayashi, K. Kawamura, M. Seki, Y. Nakashima, T. Noguchi, M. Kasuya, Y. Yokoo, and M. Fujie, “Intuitive Operability Evaluation of Surgical Robot Using Brain Activity Measurement to Determine Immersive Reality,” in *the 34th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC’12)*, 2012, pp. 337–343.

[27] S. Miura, Y. Kobayashi, K. Kawamura, M. Seki, and Y. Nakashima, “Evaluation of Hand-Eye Coordination Based on Brain Activity,” *J. Adv. Comput. Intell. Intell. Informatics*, vol. 19, no. 1, pp. 143–151, 2015.

[28] S. Miura, Y. Kobayashi, K. Kawamura, Y. Nakashima, and M. G. Fujie, “Brain activation in parietal area during manipulation with a surgical robot simulator,” *Int. J. Comput. Assist. Radiol. Surg.*, vol. 10, no. 6, pp. 783–790, 2015.

[29] S. Miura, Y. Kobayashi, K. Kawamura, M. Seki, Y. Nakashima, T. Noguchi, M. Kasuya, Y. Yokoo, and M. Fujie, “IntuitiveOperability Evaluation of Robotic Surgery Using Brain Activity Measurements to Clarify Immersive Reality,” *J. Robot. Mechatronics*, pp. 162–171, 2013.