Development of an MR-compatible Configurable Brush Stimulation Device

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***Abstract*— In order to evaluate sensory disturbance, a subjective method is performed, so that the evaluation result is influenced by subjective factors. fMRI is used for observing brain activity objectively. Therefore the brain response to a stimulation measured by fMRI could become a useful identification tool for the objective evaluation of the sensory disturbance. The purpose of this study is to develop an MR-compatible sensory stimulation device capable of providing brush stimulation to several positions with separate modules, and to confirm the feasibility of the device by a basic operation experiment and an fMRI experiment. The developed device consists of both an MR-compatible stimulator placed inside the MRI room, a tube-rod mechanism and a driver placed outside the MRI room. The tube-rod mechanism is adopted for power transmission from the driver to the stimulator. Also, in order to provide the stimulation to several positions in the limited space, the device consists of the stimulation module and the positioning module that moves the stimulation module. For the basic operation experiment, we measure a variation of the automated and manual brush stimulation period. For the fMRI experiment, the brush stimulation is provided to the middle fingertip and the palm of a subject in a trial using the developed device. As a result, the standard deviations of the automated brush stimulation period is less than 7.0 ms. This result was smaller than that of the manual stimulation period. Also, the brush stimulation to the fingertip and the palm activated the somatosensory areas respectively. In conclusion, we confirmed the feasibility of the developed device through the experiments.**

I. Introduction

Sensory disturbances are caused by lesions of central or peripheral nervous system, and too little sensation, numbness, too much sensation or paresthesias are common symptoms. In order to evaluate the sensory disturbance, a subjective method is performed, in which a patient answers yes or no orally to a stimulation given by a doctor. Therefore the evaluation result is greatly influenced by subjective factors [1]. An objective evaluation method could contribute to more detailed and correct diagnosis.

fMRI (functional magnetic resonance imaging) is used to investigate the response to sensory stimulation objectively [2]-[4]. fMRI can measure brain activity noninvasively and with high spatial resolution. Therefore fMRI is widely used in neurological field. Stimulating human bodies activates the somatosensory areas of the cortex. And, recent investigations have demonstrated that the activity in the somatosensory areas is related with pain intensity using fMRI [5]. Thus, the activation measured by fMRI could become a useful identification tool for evaluating the sensory disturbance objectively.

In previous studies about a brain activity, when a sensory stimulation is provided, the stimulation is provided manually inside of the MRI room [6]-[8]. The manual stimulation causes an examiner dependent spatial and temporal variance. Using an automated sensory stimulation device might solve this problem. However, use of the devices containing metals and magnetic materials is restricted, because the inside of the MRI room is a high magnetic field environment. Therefore, developing a specialized MR-compatible (magnetic resonance-compatible) device is essential.

In the traditional method of evaluating sensory disturbance subjectively, a variety of stimulation are provided to several positions for identifying affected areas and nerves. In the examination of light touch sensation and pain sensation, brush stimulation and pin prick stimulation are usually used [9]. Therefore we adopt those stimulations for use inside of the MRI room.

Among MR-compatible sensory stimulation devices that can provide those mechanical stimulations, a brush stimulation device [10] and a pin stimulation device [11] have been reported. These devices provide only one kind of stimulation respectively. Moreover, the brush stimulation device is limited to one position per setup [10]. The pin stimulation device can provide several positions by parallel systems [11], but an increase of stimulus varieties and stimulation positions makes the device big and complicate. The upsizing of the device should be avoided because the inside of the MRI is narrow. In order to provide some kinds of stimulation to several positions, separating stimulation module and positioning module that moves the stimulation module could be useful.

In this study, we focus the brush stimulation as the stimulation module. The purpose is to develop an MR-compatible sensory stimulation device capable of providing brush stimulation to several positions with separate modules for positioning and stimulation, and to confirm the feasibility of the device by a basic operation experiment and an fMRI experiment.

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978-1-4244-7929-0/14/$26.00 ©2014 IEEE

II. MR-COMPATIBLE SENSORY STIMULATION DEVICE

A. Concept of the Stimulation Device

Since fMRI uses a high magnetic field, a use of electromagnetic actuators, electrical circuits and computers inside the fMRI room is strictly limited. Therefore it is necessary to develop a stimulation device which is un affected by high magnetic field.

In this study, the concept of the MR-compatible sensory stimulation device is to consist of three parts, a stimulator inside the MRI room, a tube-rod mechanism and a driver outside the MRI room. An overview of the sensory stimulation device is shown in Fig.1. The stimulator and the tube-rod mechanism are composed entirely of non-magnetic and non-metallic materials. The driver includes actuators and control circuits. The tube-rod mechanism is adopted for the power transmission from the driver to the stimulator. The tube-rod mechanism is composed of a tube and a flexible rod [12]. By pushing and pulling the rod through the tube, a mechanical power is transmitted. Therefore, by using the MR-compatible stimulator and the tube-rod mechanism, the sensory stimulation device is available structurally inside the MRI room.

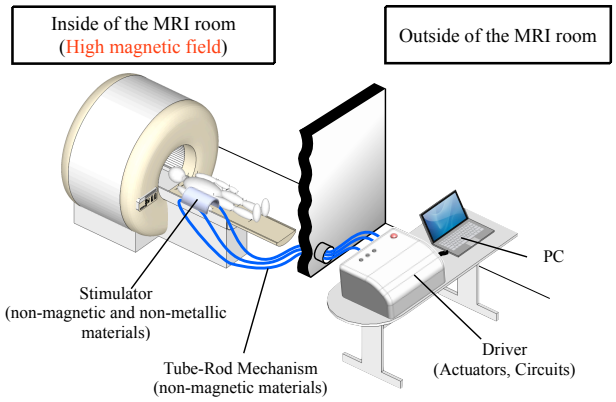


Figure 1. Overview of the sensory stimulation device composed of an MR-compatible stimulator, a tube-rod mechanism and a driver. The stimulator is placed inside the MRI room and the driver is placed outside the MRI room. The tube-rod mechanism is adopted for the power transmission from the driver to the stimulator.

B. System Design of the Stimulation Device

The system configuration of the developed prototype sensory stimulation device is shown in Fig. 2. This device is composed of two modules, a brush stimulation module and a positioning module. Actuators (a linear actuator and a stepping motor) of the driver are controlled by a microcomputer in a control circuit. The parameters for controlling the driver are sent from the PC to the microcomputer by using serial communication. The driver receives the MRI scan signal. Therefore the device can start and stop the stimulation automatically in synchronization with the MRI.

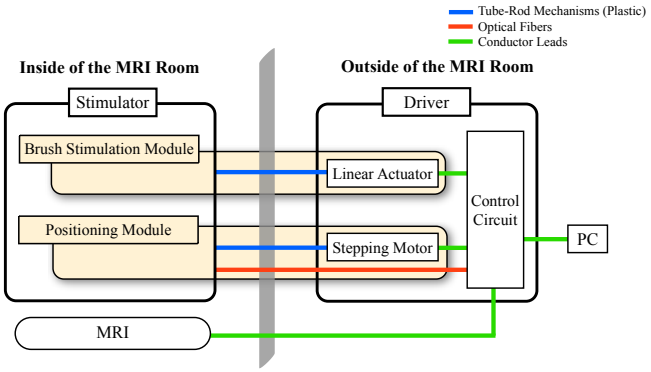


Figure 2. System configuration of the sensory stimulation device. The driver is controlled by PC. The driver receives the MRI scan signal. Since MRI uses a high magnetic filed, components using magnetic and metallic materials: a motor, a linear actuator, and a control circuit are included in the driver. The device is composed of two modules, a brush stimulation module and a positioning module.

C. Brush Stimulation Module

The configuration of the brush stimulation module is shown in Fig. 3. A linear actuator drives the tube-rod mechanism that transmits a mechanical power from the driver to the stimulator. By reciprocating the linear actuator, the rod in the tube is pushed and pulled. It drives a pinion mechanism, and provides brush stimulation to the human skin. The tube-rod mechanism consists of PTFE tube and acrylic rod. The length of the tube-rod mechanism is about 6m, considering the MRI room we use.

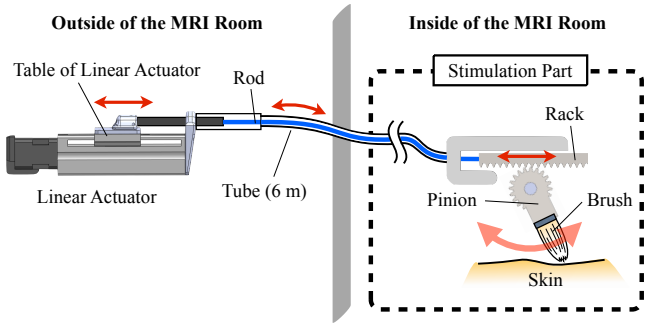


Figure 3. Configuration of the brush stimulation module. By reciprocating the table of the linear actuator, the stimulation head is pushed to human skin and pulled through the rod in the tube repeatedly.

D. Positioning Module

The configuration of the positioning module is shown in Fig. 4. A stimulation unit is moved by using two tube-rod mechanisms. The stimulation part of the brush stimulation module is attached to the stimulation unit of the positioning module. A stimulation position is changed by moving the stimulation unit. A stepping motor and a timing belt drive the two tube-rod mechanisms in parallel. A rod is pushed and the other is pulled synchronously. In order to detect the position of the stimulation unit, a two channels optical linear encoder is equipped in the stimulator. The linear encoder is composed of a slit, red LEDs, phototransistors and optical fibers.

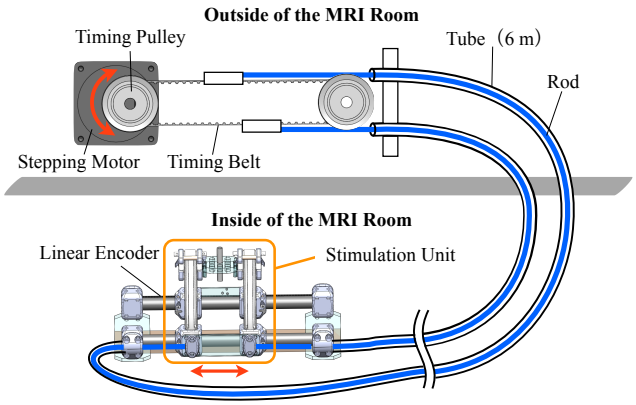


Figure 4. Configuration of the positioning module. The stepping motor drives 2 rods in the tubes at a time, and the stimulation unit is driven linearly. The position of the stimulation unit is detected by the linear encoder.

Because both the slit and the optical fibers used inside the MRI room are made of non-magnetic and non-metallic materials, this encoder system is MR-compatible. By using the encoder signal, the feedback control of the stimulation unit is possible with 1mm resolution.

III. Experiment

In this study, we perform a basic operation experiment and an fMRI experiment for confirming the feasibility of the developed device.

A. Basic Operation Experiment

The basic operation experiment is performed to evaluate the performance of the brush stimulation module of the developed device.

In this device, the brush stimulation is provided by reciprocating the brush. The variable parameter of this brush stimulation is the frequency. Therefore we examine the modulation performance of the frequency of the brush stimulation. Moreover, to examine the stability of the automated brush stimulation, we measure and compare a variation of the automated brush stimulation frequency of the developed device and a variation of the manual brush stimulation frequency. This experiment is conducted in the laboratory environment that separated the stimulator and the driver 6m. This 6m distance is the same as the condition in which the MRI experiment is conducted. In order to measure the frequency of the brush stimulation, in the case of the automated stimulation using the device, an experimental system shown in Fig. 5 (a) is used. And, in case of the manual stimulation, an experimental system shown in Fig. 5 (b) is used. A douser is attached in the stimulation head instead of a brush. A photo interrupter (CNZ1023, Panasonic) detects a moment that the douser passes through, and the period of the brush stimulation is calculated. In the case of automated stimulation, the input frequency is adjusted from 1Hz to 5Hz in steps 1Hz. In the case of manual stimulation, participants are given the reference of the frequency (1Hz, 3Hz and 5Hz) using a metronome. Three times of a 30 seconds measurement are performed, and an average and a standard deviation of the period are calculated. Experiment participants who perform manual brush stimulation are 5 participants.

B. fMRI Experiment

In the fMRI experiment, we verify that the brush stimulation of the developed device activates somatosensory areas.

Since the part used inside MRI room of the developed device is composed of non-magnetic and non-metallic materials, the device does not affect MR images and is not affected by high magnetic field of MRI. Therefore the safety of the device for MRI is secured structurally. In this experiment, the providing stimulation is 2Hz brush stimulation to right middle fingertip and right palm of a healthy subject alternately as shown in Fig. 6. A diagram of a task sequence is shown Fig. 7. A task consists of 30 seconds stimulation to a middle fingertip following 30 seconds rest then 30 seconds stimulation to a palm following 30 seconds rest. At the each rest, stimulation unit is moved from the palm to the fingertip or from the fingertip to the palm. The task is repeated 4 times in a trial.

In this experiment, the head of the subject is fixed by using sponges and headphone attached to the MRI. The subject lies supine and equipped the stimulator with right hand. Putting cushions under the right arm, the subject had relaxed posture. The environment of the experiment is shown in Fig. 8. And the subject's hand equipped with the developed stimulator is shown in Fig. 9. The fMRI experiment is performed in University of Tsukuba, on a 3.0T MRI (Achieva 3.0T TX Release 3.2.1.1, PHILIPS) equipped with a 32 channel SENSE head coil. In order to secure the enough safety of the subject, this experiment is performed with a radiological technologist and a medical doctor.

MR images obtained by the fMRI experiment are analyzed using SPM8 (Welcome Department of Cognitive Neurology, http://www.fil.ion.ucl.ac.uk/spm) on MATLAB (Math Works). Functional images are normalized into standard stereotactic space using the Montreal Neurological Institute template (MNI) [13]. A stringent statistical threshold with family-wise error correction $p < 0.05$ has been applied.

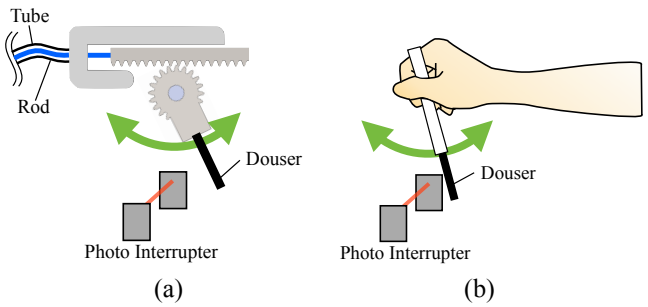


Figure 5. Diagram of the experimental system for measuring the stimulation period. The photo interrupter detects a moment that the douser passes through. (a) is the system in case of the automated stimultion by the developed device, and (b) is the system in case of the manual stimulation by the participants.

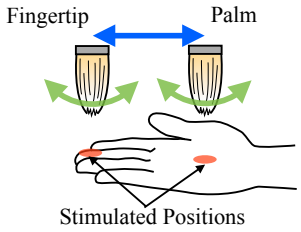


Figure 6. Diagram of the stimulation positions of the fMRI experiment. The brush stimulation is provided to the middle fingertip and the palm.

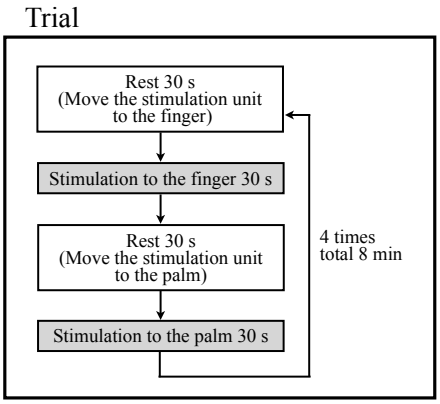


Figure 7. Diagram of the task sequence of the fMRI experiment. A task consists of 30 seconds stimulation to a middle fingertip following 30 seconds rest then 30 seconds stimulation to a palm following 30 seconds rest. At the each rest, stimulation unit is moved from the palm to the fingertip or from the fingertip to the palm. The task is repeated 4 times in a trial.

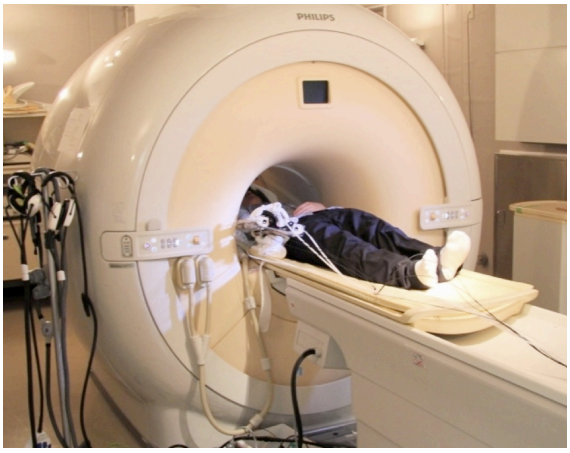


Figure 8. Environment of the fMRI experiment. Stimulation is peovided to right hand of a healthy subject by using developed sensory stimulation device in the MRI room.

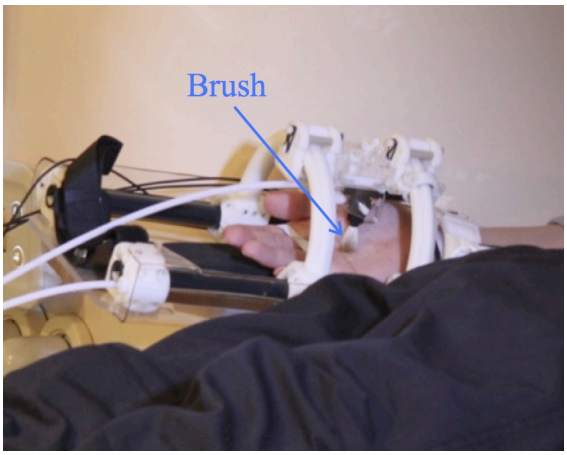


Figure 9. Subject's hand equipped with the developed stimulator. The brush stimulation is provicded to the palm in the MRI.

IV. Result

A. Basic Operation Experiment

A result of the basic operation experiment is shown Fig.10. Fig.10 (a) shows the relationship between the input frequency and the output frequency from 1 Hz to 5 Hz. The input frequency is the frequency of the linear actuator movement, and the output frequency is the frequency of the stimulation head movement. A correlation coefficient between the input frequency and the output frequency is 0.999. Therefore the frequency of the brush stimulation module can be linearly controlled between 1 Hz and 5 Hz.

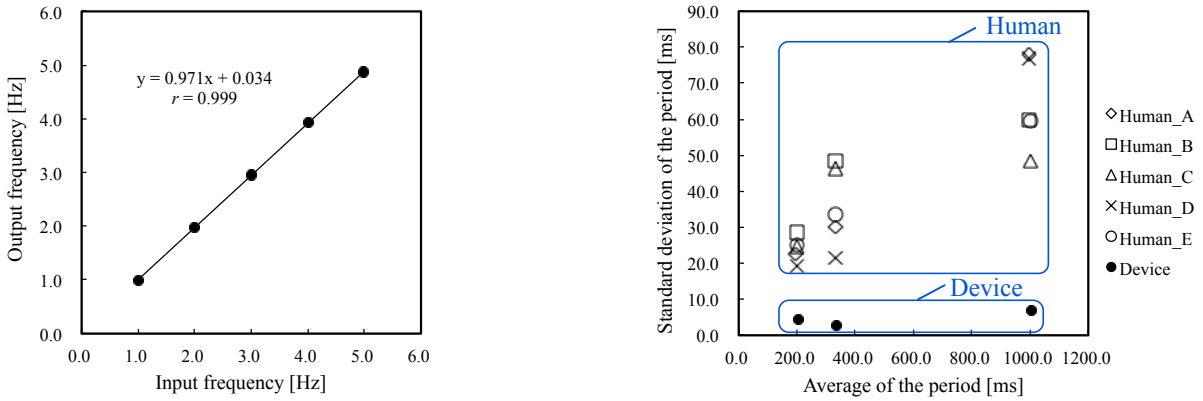
Fig. 10 (b) shows the relationship between the average and the standard deviation of the period of the manual and automated stimulation of 1 Hz, 3 Hz and 5 Hz. The standard deviation of the manual stimulation period is more than 19.3 ms and the standard deviation of the automated stimulation period is less than 7.0 ms. Therefore the standard deviation of the automated stimulation period is less than that of the manual stimulation period. Moreover, in the case of the manual stimulation, the standard deviation of the period increases as the average of the period increases compared with the automated stimulation.

B. fMRI Experiment

Brain responses of a subject according to the brush stimulation to the right middle fingertip and the right palm are shown in Fig. 11 (a) and Fig. 11 (b). Activation of the left somatosensory area was observed respectively.

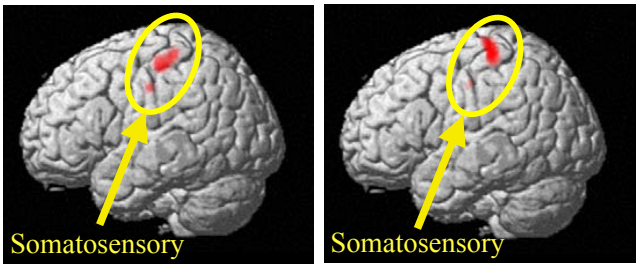
V. Discussion

In the basic operation experiment, we examined the modulation and stability of the brush stimulation frequency in the environment that separated the stimulator and the driver 6 m. The correlation coefficient between the input frequency and the output frequency was 0.999. Therefore we verified that the frequency of the brush stimulation module could be linearly controlled between 1 Hz and 5 Hz. Moreover, the standard deviation of the automated stimulation period was less than that of the manual stimulation period, and we



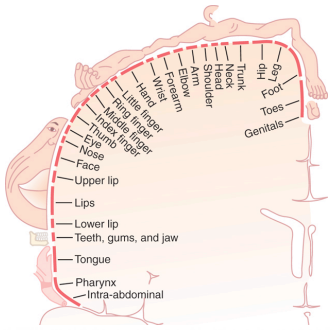
(a) (b)

Figure 10. Result of the frequency control experiment of the brush stimulation (a) The relationship between the input frequency and the output frequency of the brush stimulation by the developed device. (b) The relationship between the average of the period and the standard deviation of the period in the brush stimulation by human and the developed device.



(a) (b)

Figure 11. Brain responses of a subject according to the brush stimulation to the right middle fingertip (a) and to the right palm (b). (Family- wise error corrected $p<0.05$) Activation of left somatosensory area was observed respectivel.



Hall: Guyton and Hall Textbook of Medical Physiology, 12th Edition

Figure 12. Representation of the difference areas of the body in somatosensory area [14].

verified that the developed device could provide the brush stimulation with stable frequency. Thus, whoever performs the examination, the stable stimulation is available by using the developed device. This stability is very important for developing the objective method of the sensory disturbance with many subjects in the future.

In the fMRI experiment, the brush stimulation was provided to the middle fingertip and the palm of a subject in a trial using the developed device. As a result, the stimulation of the developed device can activate the somatosensory area in the both cases. Furthermore, positional relationship between the activated area of the stimulating fingertip and palm (Fig. 11) is similar to Fig. 12. Fig. 12 shows a somatotopic organization schematized correspondence of somatosensory and each part of human body. Therefore the developed device was able to stimulate the several positions and we observed the possibility of the somatotopic organization. Thus, providing the brush stimulation and moving stimulation position can be realized inside the MRI room in a trial using the developed device. Those functions could contribute to identifying affected areas of sensory disturbance.

In this study, the device is separated the stimulation module and the positioning module. The positioning module moves the stimulation module, and the device provides the stimulation to several positions. This configuration would avoid the upsizing and the complication of the device. Moreover, the change of stimulus varieties is easy using this configuration. It is assumed that this configuration is useful for providing a variety of the stimulation to the various positions.

In future applications, the device can be used for clinical examination identifying the degree or the affected areas of the sensory disturbance. And it also can be used for objectively evaluating the recovery degree of sensory function. Moreover, it could be applied to experiments using tactile stimulations in the cognitive psychology field.

VI. Conclusion

In this study, we developed a novel MR-compatible sensory stimulation device capable of providing brush stimulation to several positions with separate modules for positioning and stimulation, and confirmed the feasibility of

the device by the basic operation experiment and the fMRI experiment. In the basic operation experiment, we verified that the frequency of the brush stimulation module could be linearly controlled between 1 Hz and 5 Hz and that the developed device provided brush stimulation of less frequency variation as compared with that of the manual stimulation. In the fMRI experiment, we verified that the brush stimulation to the fingertip and the palm using the developed device activated the somatosensory areas respectively.

In our future work, we intend to develop other varieties of stimulation module, for example pin prick and vibration stimulation. Furthermore, we apply this device to various subjects and examine the relationship the stimulation of the device and brain response for developing the objective method of the sensory disturbance.

ACKNOWLEDGMENT

This study was supported by the "Center for Cybernics Research (CCR) - World Leading Human-Assistive Technology Supporting a Long-Lived and Healthy Society" granted the "Funding Program for World-Leading Innovative R&D on Science and Technology (FIRST Program)," initiated by the Council for Science and Technology Policy (CSTP).

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