Recent Progress of Non-invasive Optical Modality to Brain Computer Interface: A Review Study

Jae-Ho Han[1*], Seungbae Ji[1], Chang Shi[1], Seung-Beom Yu[1], and Jaeyoung Shin[2]
[1]Dept. Brain and Cognitive Engineering, Korea University, Seoul, South Korea
[2]Dept. Software Engineering and Theoretical Computer Science, Technical University of Berlin, Germany
[*] Corresponding author: hanjaeho@korea.ac.kr

Abstract— **Brain activity is usually measured by non-invasive modalities. Inter alia, the electroencephalogram (EEG) is used most commonly. However, EEG is very sensitive to other bio-signals, so other bio-signal detection modalities must be used as supplementary systems. Functional near-infrared spectroscopy (fNIRS) has good characteristics for use as such a supplementary modality, because brain activities can be measured by fNIRS through hemodynamic responses. Therefore, many scientists have adopted fNIRS for brain machine interface (BCI). Recently, fNIRS has become more compact and is robust to noise, so it could bring us to the development of an effective wearable BCI.**

Keywords-biomedical optical imaging; brain-computer interface; optical signal detection; spectroscopy.

I. Outline

Brain machine interfaces use brain activities as commands, for which brain activities are usually measured by electroencephalogram (EEG). However, EEG is very sensitive to the other bio-signals: heart rate, eye movement, motion, and so on. Therefore, the use of BCI employing only EEG has limitations, so other bio-signal detection modalities are usually included as supplementary modalities, including those such as electrocardiogram (ECG), electromyography (EMG), photoplethysmography (PPG), electrooculogram (EOG), and galvanic skin reflex (GSR) [1-4]. However, while brain activities cannot be directly measured by such modalities, they can be directly measured by the use of functional near-infrared spectroscopy (fNIRS) through hemodynamic responses.

Figure 1 presents information on the common modalities which can measure brain activity, including functional magnetic resonance imaging (fMRI), magnetoencephalography (MEG), fNIRS, and EEG. The resolutions of the non-invasive modalities can be seen in the figure, with temporal resolution, from msec to days, and spatial resolution, from cells to organs, presented on the horizontal and vertical axes, respectively. As can be seen, fMRI can take anywhere from seconds to hours for image acquisition, whereas the other methods produce results in real time. In addition, fNIRS and EEG have at least as good of resolution as fMRI and MEG, while also being able to measure information at the tissue size in real time.

Although fMRI and MEG are good modalities for the measurement of brain activity, they are not appropriate as a supplementary modality because they require huge equipment. In contrast, fNIRS needs only small equipment, while it has equivalent resolution to the other modalities. As a result, hybrid fNIRS-EEG brain computer interface systems have already been developed, improving the classification accuracy of motor imagery [5]. In addition, comparison has also been done between the fNIRS-EEG system and the fMRI-EEG system [6]. Such papers demonstrated fNIRS to have sufficient performance for use with BCI. However, fNIRS still has some difficulties, so many scientists have been challenged to improve its performance [7-14].

A. Principles

Neural activation leads to metabolic demand, which increases blood flow and oxy-hemoglobin. These then wash out deoxy-hemoglobin. fNIRS analyzes brain activity through the properties of the near-infrared in blood using the modified Beer-Lambert law. The Beer-Lambert law is only valid in non-scattering media, so it is not useful for biological tissue. Therefore, a modified version of the Beer-Lambert law was proposed by Delpy, using the properties of near-infrared in blood [15].

Figure 2 shows the mechanism of the modified Beer-Lambert law. Some of the incident light is reflected by the surface of the scattering medium, while some is absorbed and scattered in the medium. Finally, the amount of transmitted light coming out from the medium is measured, and brain activity can be analyzed by fNIRS through use of the following values: incident light, absorptivity, concentration of absorber, differential path length factor, scattering loss factor, and transmitted light.

B. Recent progress

Recently, a robot was operated using EEG and fNIRS. It showed good performance, but required huge equipment. However, fNIRS is getting more portable. Brain activities have now been measured by the portable fNIRS during the performance of extreme activities, such as plank, pushups, jumping jacks, and running up and down stairs. Consequently, fNIRS is also becoming more robust to noise. It is used as a supplementary modality to EEG, because BCI systems often misclassify the EEG signals as commands. The paired system has already shown good performance, but it was too big to use as a portable system. With the increased portability and robustness of fNIRS to noise, we can expect the development of an effective and wearable BCI.

Acknowledgment

This work was partly supported by the ICT R&D program of MSIP/IITP [14-824-09-014, Basic Software Research in Human-level Lifelong Machine Learning (Machine Learning Center)] and was supported in part by the Basic Science Research Program through the National Research Foundation of Korea (2013R1A1A2062448).

References

[1] J. G. Gil, I. S. J. Gonzalez, L. F. N. Alonso, and S. A. Garcia, "Steering a tractor by means of an EMG-based human-machine interface," *Sensors*, vol. 11, no. 7, pp. 7110–7126, 2011.

[2] N. Xu, X. Gao, B. Hong, X. Miao, S. Gao, and F. Yang, "BCI competition 2003—data set IIb: Enhancing P300 wave detection using ICA-based subspace projections for BCI applications," *IEEE Trans. Biomed. Eng.*, vol. 51, no. 6, pp. 1067–1072, 2004.

[3] C. Guger, A. Schlögl, C. Neuper, D. Walterspacher, T. Strein, and G. Pfurtscheller, "Rapid prototyping of an EEG-based brain–computer interface (BCI)," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 9, no. 1, pp. 49–58, 2001.

[4] Y. H. Lin, I. C. Jan, P. C. I. Ko, Y. Y. Chen, J. M. Wong, and G. J. Jan, "A wireless PDA-based physiological monitoring system for patient transport," *IEEE T. Inf. Technol. Biomed.*, vol. 8, no. 4, pp. 439–446, 2004.

[5] S. Fazli, J. Mehnert, H. Steinbrink, G. Curio, A. Villringer, K. R. Müller, and B. Blankertz, "Enhanced performance by a hybrid NIRS–EEG brain computer interface," *Neuroimage*, vol. 59, no.1, pp. 519–529, 2012.

[6] P. Pouliot, J. Tremblay, M. Robert, P. Vannasing, F. Leporec, M. Lassonde, M. Sawan, D. K. Nguyen, and F. Lesagea, "Nonlinear hemodynamic responses in human epilepsy: A multimodal analysis with fNIRS-EEG and fMRI-EEG," *J. Neurosci. Methods*, vol. 204, no. 2, pp. 324–340, 2012.

[7] R. Zimmermann, L. M. Crespo, J. Edelmann, O. Lambercy, M. C. Fluet, R. Riener, M. Wolf, and R. Gassert, "Detection of motor execution using a hybrid fNIRS-biosignal BCI: A feasibility study," *J. NeuroEng. Rehabil.*, vol. 10, no. 4, pp. 213–228, 2013.

[8] T. H. Falk, M. Guirgis, S. Power, and T. T. Chau, "Taking NIRS-BCIs outside the lab: Towards achieving robustness against environment Noise," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 19, no. 2, pp. 136–146, 2011.

[9] G. Bauernfeind, S. C. Wriessnegger, I. Daly, and G. R. Müller-Putz, "Separating heart and brain: On the reduction of physiological noise from multichannel functional near-infrared spectroscopy (fNIRS) signals," *J. Neural Eng.*, vol. 11, no. 5, pp. 056010-056027, 2014.

[10] M. A. Yücel, J. Selb, D. A. Boas, S. S. Cash, and R. J. Cooper, "Reducing motion artifacts for long-term clinical NIRS monitoring using collodionfixed prism-based optical fibers," *Neuroimage*, vol. 85, no. 1, pp. 192–201, 2014.

[11] L. Gagnon, M. A. Yücel, D. A. Boas, and R. J. Cooper, "Further improvement in reducing superficial contamination in NIRS using double short separation measurements," *Neuroimage*, vol. 85, no. 1, pp. 127–135, 2014.

[12] F. B. Haeussinger, T. Dresler, S. Heinzel, M. Schecklmann, A. J. Fallgatter, and A. C. Ehlis, "Reconstructing functional near-infrared spectroscopy (fNIRS) signals impaired by extra-cranial confounds: An easy-to-use filter method," *Neuroimage*, vol. 95, no. 15, pp. 69–79, 2014.

[13] N. H. Berivanloua, S. K. Setarehdana, and H. A. Noubaria, "Evoked hemodynamic response estimation using ensemble empiricalmode decomposition based adaptive algorithm applied to dual channel functional near infrared spectroscopy (fNIRS)," *J. Neurosci. Methods*, vol. 224, no. 15, pp. 13–25, 2014.

[14] S. K. Piper, A. Krueger, S. P. Koch, J. Mehnert, C. Habermehl, J. Steinbrink, H. Obrig, and C. H. Schmitz, "A wearable multi-channel fNIRS system for brain imaging in freely moving subjects," *Neuroimage*, vol. 85, no. 1, pp. 64–71, 2014.

[15] D. T. Delpy, M. Cope, P. V. Zee, S. Arridge, S. Wrayt, and J. Wyatt, "Estimation of optical pathlength through tissue from direct time of flight measurement," *Phys. Med. Biol.*, vol. 33, no. 12, pp. 1433–1442, 1988.

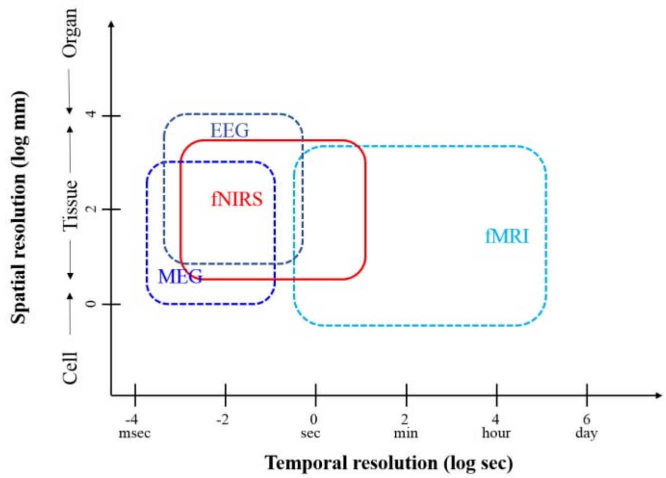

Fig. 1. Resolutions of various non-invasive modalities.

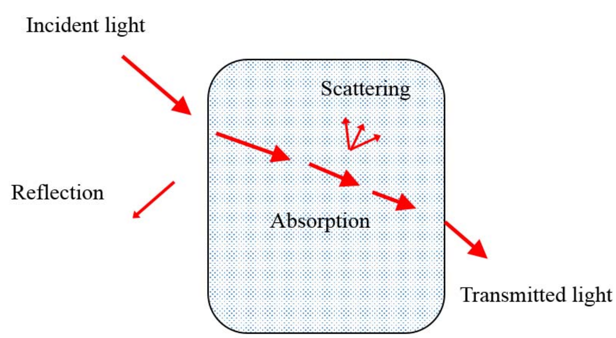

Fig. 2. Schematic properties of incident light in tissue.