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EEG based analysis of lower limb exercise for neurorehabilitation according to the linkage between motor execution and visual feedback in immersive VR: A feasibility study with healthy adults

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Abstract— **Stroke causes physical dysfunction due to brain damage, leading to aftereffects, such as hemiplegia. Until now, a lower limb rehabilitation system was developed by us to help patients to restore leg function owing to brain plasticity in neurorehabilitation. Visual Feedback (FB) in the system, together with a mechanical assistant for lower limb, linked to the motor execution is presented to form a FB learning model matching the motor execution and its imagination. This feasibility study on the healthy subjects aims to apply the knowledge to rehabilitation program in the future. Meanwhile, the feasibility study aims to investigate the effect of linked visual FB on the imagination of motor execution and furthermore, to clarify an effective design of visual FB conditions focusing on the similarity between visual FB and motor execution. The experiments under three different conditions were conducted using the system: (i) no visual FB, (ii) with visual FB and motion in the FB different from motor execution, (iii) with visual FB and motion in the FB closer to motor execution. Electroencephalogram (EEG) was performed as an indicator to evaluate the imagination of motor execution, being the reduction of EEG values during motion recall - Event Related Desynchronization (ERD) mainly used. According to the results, by comparing (i) and (ii), significantly greater ERD in (ii) verified that visual FB helps acquire the imagination of motor execution ($p = 0.028$). Moreover, between (ii) and (iii), ERD in β-band were significantly greater in (iii) ($p = 0.028$), but no significant difference showed for ERD in α-band ($p = 0.600$) that further confirmation might be needed. In conclusion, the linkage between visual FB and motor execution was verified in this study, which helps to acquire the imagination and may be related with brain recovery.**

Clinical Relevance— **The robot proposed is expected to be used in the patients' acute phase motor recover of the lower limbs post stroke. In addition, the results of this experiment will allow to understand the appropriate approach to give visual FB with immersive VR system.**

I. INTRODUCTION

Approximately 1.18 million people suffer a stroke in Japan [1]. Brain damage caused by a stroke can lead to a variety of physical functional disabilities, resulting in serious sequelae, including. However, with a proper rehabilitation, the brain may undergo plastic changes, restoring their function [2]. One of the factors effectively eliciting this plasticity is the temporal coincidence between the motor output from the brain and the sensory information conveyed [3] since in rehabilitation, voluntary motion exercise with the patient's own intention is more important than the passive movements performed assisted with the help of others [4].

Meanwhile, the acute phase, consisted in the first 30 days after the onset of stroke [5], is considered to be the most effective time for the rehabilitation through plastic changes in the brain [6]. In addition, when the acute rehabilitation is delayed, several problems may occur, including disuse syndromes, namely immobility muscle weakness and orthostatic hypotension [7], thereby reducing the efficiency of prognosis rehabilitation. Therefore, in the acute phase of rehabilitation, rolling over and sitting training are recommended to prevent muscle weakness and orthostatic hypotension [8]. A report about brain plasticity, known as Critical Time Window, indicated that the time within two to three weeks after stroke onset is the most effective period to maximize the brain plasticity with rehabilitation intervention [9]. Base on above, an appropriate early rehabilitation to bring out brain plasticity is demanding to effectively recover the brain function. Furthermore, based on the reorganization system of motor execution and imagination networks [10], it can be concluded that being able to effectively elicit a patient's imagination to move during the acute phase, realizing movement according to that imagination, effectively leads to rehabilitation. Taken this in consideration, we have developed a lower limb rehabilitation system for the recovery of lower limb functions, enabling stroke patients to start rehabilitation training before they can stand [11]. The system developed is divided into two parts, a mechanical assistant for lower limb by a robotic device and a visual feedback (FB) linked to the lower limb motions in immersive VR. In the system, visual FB linked to the motor execution is presented to form a FB learning model, matching the motor execution and its imagination.

In this feasibility study, the EEG was measured and analyzed to evaluate the imagination of the motor execution, being the reduction of EEG values during motion recall - Event Related Desynchronization (ERD) mainly used [12].

Based on the above-mentioned, this study aims to first verify the effect of linked visual FB on motor execution based on EEG analysis and furthermore, to clarify an effective design of visual FB conditions, focusing on the similarity between visual FB and actual motion. The result of this feasibility study is desirable to be applied to the rehabilitation program in the future.

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II. System Overview

A. Rehabilitation system

As above-mentioned, the training system proposed to enable patients to train in the supine position almost without physical burden associated. The system used in this study is divided in two parts as demonstrated in Fig. 1: a) the motion support part with a mechanical assistance device for the lower limb and b) the sensory (*i.e.*, visual information) support part with a head-mounted display (HMD), showing visual FB in VR interlocking to the motor execution at the same time. When using the system, the user fastens the legs to the mechanical assistance device by a belt, wearing the HMD on the head.

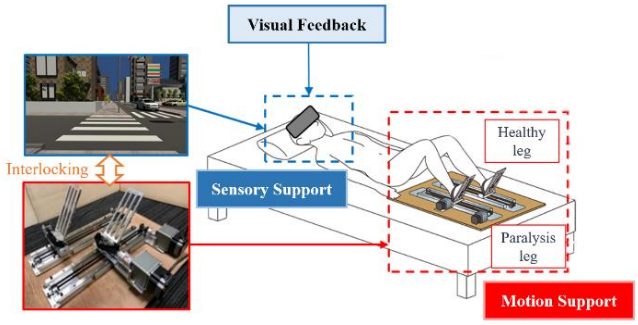

Fig.1. Overview of the bedside lower limb rehabilitation system.

B. Mechanical assistance device for lower limb

The appearance of the mechanical assistance device and the rotating mechanism of the device is shown in Fig. 2 [13]. In the device, the pedals that fix the feet are controlled by the belt slider mechanism to adjust the direction of extension and flexion of the lower limb. The pedals can be moved in a uniaxial direction. In addition, the pedal does not interfere with the movement of the ankle joint because the pedal has a degree of freedom in the direction of basal flexion and dorsiflexion.

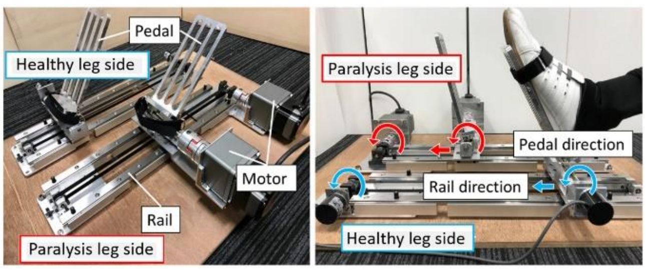

Fig. 2. Device appearance and rotating mechanism of the device. [12]

A stepping motor (belt slider side: Oriental Motor Co. Ltd., AR98AA-T3.6) is attached to the belt rotation axis of the belt slider on the paralyzed leg side. By driving the motor, the pedal of the foot can be moved in translation and the leg can be transversely flexed and extended. Moreover, an encoder (Omron, E6B2-CWZ6C) is attached to the rotation axis of the belt on the healthy leg side of the rail via a shaft and therefore the position and speed of the leg can be measured. Based on the lower limb motion information obtained by the encoder on the healthy leg side, the motion controller (CONTEC, SMC-4DF2-PCI) to the motor on the side of the paralyzed leg, move to the symmetrical position of the healthy leg. This master-slave control of the robot enables the paralyzed leg being moved passively depending to the movement of the healthy side, which is considered making the patient feel as if they are moving of their own volition, leading to brain recovery. At the same time, in a similar manner the visual FB in VR correspond to move.

C. VR visual FB

Visual FB interlocking to the motor execution was presented through a VR HMD during training. The visual FB was designed as a situation of walking around the neighborhood. There were two kinds of walking pattern designed including walking on level ground and climbing stairs as shown in Fig. 3.

Fig. 3. Two patterns of situation in the VR visual FB designed.
(Left: walking on level ground; Right: climbing stairs)

The preciseness of the interlocking between the visual presentation and the motor execution on the mechanical assistance device was experimentally verified to be enough so that the user will not sense any time lag between them. It was also shown that the healthy subjects felt that they were moving due to their own lower limb movements in the VR according to the survey.

III. Experiment

A. Participants

The experiment was conducted on six healthy subjects (24.4 ± 2.6 years old).

B. Experimental design

The experiments were conducted using the system described in III, to verify the influence of visual FB linked to lower limb movements on the imagination of motor execution. Three types of visual FB conditions were performed in the experiment in a random order: (i) without visual FB; (ii) visual FB different from the actual movement pattern (walking) presented in VR; (iii) visual FB closer to the actual motion pattern (stair climbing) presented in VR.

For the lower limb motion support device used in the experiment, the foot motion in (iii), climbing stairs, is considered to have higher similarity to the motion pattern on the device than that in (ii), walking in the visual FB condition since the foot moves a straight route rather than gait training which is an ellipse route [14].

Each set of the experiments consisted of three phases: preparation phase, exercising phase and rest (Fig. 4). The preparation phase aiming to cause more obvious imagination for the subjects, while getting ready to the coming motor execution, where the timekeeping was presented in VR. During the exercising phase, the paralyzed leg (the right side in the experiment) was passively moved depending on the healthy side (the left side in the experiment) on the robot, while at the same time, visual FB linked with the motor execution were presented in VR. In the rest phase, a still screen was displayed to calm down the brain waves (EEG). The subjects were asked to repeat consecutively, 30 sets of each condition, being the experiment for each condition conducted in a random order every 5 to 7 days to allow the brain activity in each condition to not be influenced by each other, which leads to more accurate experimental results.

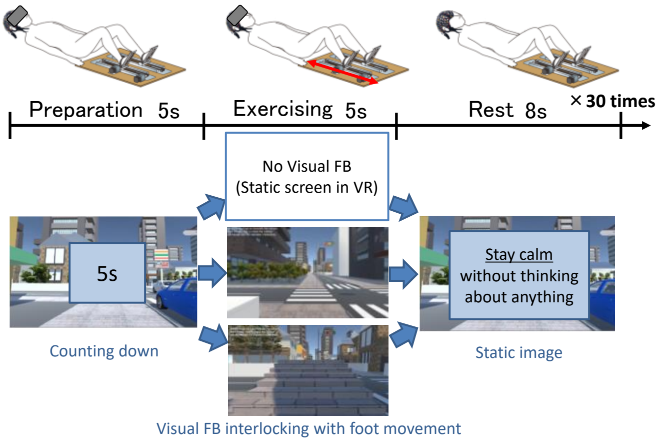

Fig.4. Procedure of each set of the experiment.

C. Ethical approval

All procedures were approved by the Waseda University Ethics Committee for Human Research. (Approval Number: 2020-044).

IV. Measurement and Analysis of EEG Data

This study focus on ERD, which is a decrease in EEG values during motor recall in the alpha and beta zones, as an evaluation index that reflects the imagination of the motor execution [15]. Meanwhile, as an experiment on motion of lower limbs, we focused on the motor area of the legs, analyzing the electrode Cz that controls the motor area of the legs [16]. The reference electrode for the measurement voltage was A2 (right earlobe), being the body ground the frontal pole Fz, as shown in Fig. 5. [17]

EEG Measuring Conditions
• Electroencephalograph equipment: EEG-1200 (Nippon Kohden) • Electrodes and caps equipments: g.GAMMAbox, g.ACTIVEelectrode, g.EEGcap (g.tec) • Sampling frequency: 1000 Hz • 0.5 to 60 Hz band filter • 50 Hz notch filter

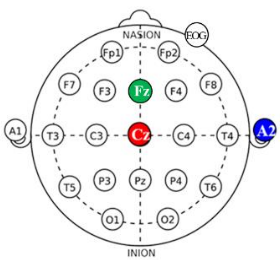

Fig. 5. EEG measuring conditions and electrodes used in the experiment [16].

The EEG is mainly divided into δ (0.5~4 Hz), θ (4~7 Hz), α (8~14 Hz), and β (15~30 Hz) band waves depending on the frequency range, and each wave has a different relation to the brain function. The δ-band and θ-band appear in non-REM sleep, while α-band dominates during wakefulness, resting, and closing of the eye or attenuates during eye opening, intellectual activity, and other movement. In addition, β-band appears during intellectual activity and motor cessation [18].

In this study, α-band and β-band were mainly measured and analyzed to observe the brain activity during the movement.

For the EEG data analysis, raw waveforms were first subjected to a band-pass filter [19] in the range of 4.0~40.0 Hz to select the α and β waves with a margin that we pretended to investigate in this study, which are in 8.0~30.0 Hz range of the brain wave bands. Next, we performed a wavelet transform to obtain the amplitude of the motion with the information of the time frequency and eventually calculated the ERD intensity during the motor execution by (1).

$$ERD[\%] = \frac{Y_{mean} - X_1}{Y_{mean}} \times 100 \tag{1}$$

According to Cassims *et al* [20], Y_{mean} is the average of the 1-second period before the motor execution; X_1 is the rise of the ERD intensity shown within 0.5 seconds after the motor execution started as shown in Fig. 6.

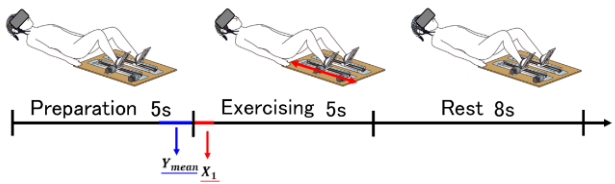

Fig. 6. Power values used in ERD calculations.

V. Results and Discussions

The EEG data comparison versus time between with and without the visual FB (condition (i) and (ii)) of the α-band (8~14Hz) and β-bands (15~30Hz) are shown in Fig. 7.

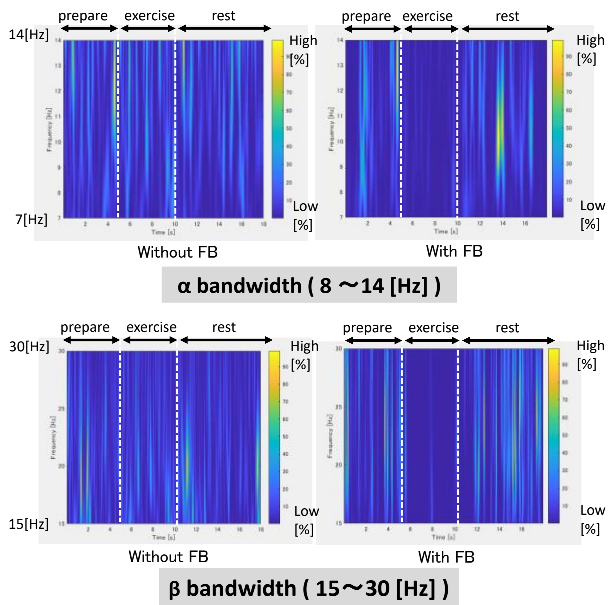

Fig. 7. The EEG data comparison of α-band and β-band versus time.

The average ERD intensities of the α-band and β-bands for each condition for the six subjects studied are shown in Fig. 8. Because of the small sample size collected from participants, the evaluation indices of all conditions were analyzed using Friedman's test, with significant differences set as $p < 0.05$ [21]. In the presence of a significant difference, a Wilcoxon signed-rank test was performed to observe the difference between condition (i), (ii) and (ii), (iii).

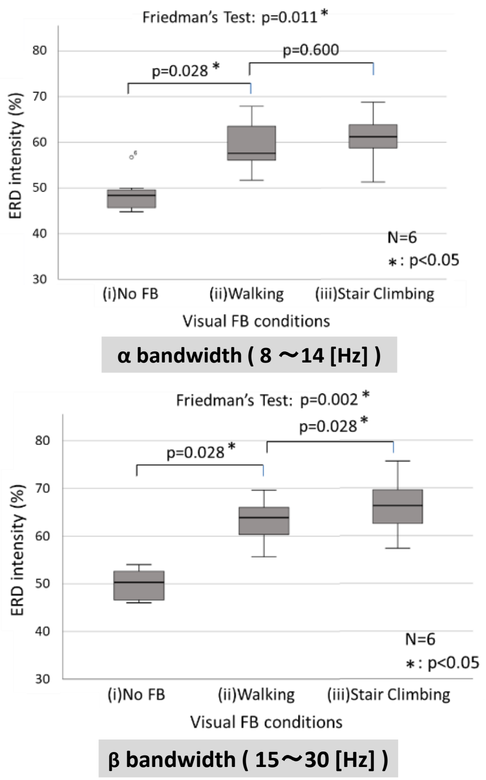

Fig. 8. The ERD intensity of α -band and β -band under each condition.

As the result of Friedman's test, significant differences were observed in both α and β-band (p = 0.011 and p = 0.002, respectively).

As the result of the Wilcoxon signed-rank test, in conditions (i) and (ii), a significant difference was observed between the ERD intensity in both α and β-band (p = 0.028 and p = 0.028, respectively), confirming the influence of the linked visual FB on the imagination of motor execution. On the other hand, in conditions (ii) and (iii), the ERD intensity in β-band was significantly higher (p = 0.028) with visual FB of (iii) stair climbing, which was more similar to the real motion. This suggests that the more similar the linked visual FB was to the motor execution, the more effective it might be in the perspective of the imagination of the motor execution. On the other hand, there was no significant difference in the ERD intensity for the α-band (p = 0.600).

The possible reason for the difference between α-band and β-band might be that individual EEG frequencies and their relative power bands exist for each person, especially for alpha bandwidth [22]. The ERD analysis in α and β in this study is calculated as 7~14Hz for α-band and 15~30Hz for β-band, according to the general frequency range. However, it is often known that an EEG has the individual characteristic that the alpha and beta frequency range for each person is actually different from each other. Therefore, instead of calculating ERDs using general frequency range, individual analysis of the alpha frequency and power might lead to more accurate results. As suggested in a previous study [23], referencing to the individual frequency analysis (IAF), it is possible to calculate the edges of bands of our interest. Meanwhile, the insufficient number of subjects can also be considered as one of the possible reasons of the obtained results.

To further elucidate the limitation of the experiment in this study, the subjects were asked some simple questions as a survey after each experiment related to the possible factors affecting the similarity of the visual FB and the motor execution. Therefore, several parts in the experiments could be improved to get a better result or lead to a further research. Firstly, there were opinions that the presented walking scene in the VR was in a slower pace comparing to the actual imagery of their walking speed on the lower limb assistant device, which brought a sense of disharmony and this might influence the similarity. Regarding this problem, since individual difference exists in the walking speed (the pace of each step) of each human being, it is difficult to adjust the speed presented in visual FB for everyone, especially when this is a system designed for the hemiplegia patients whose walking speed are quite different from healthy human beings'. However, a method of evaluating the users' general walking speed to adjust the visual FB to their comfort zone before the system applied should be considered after the system being applied to the stroke patients.

Through this study, some improvements could be considered on the whole system, including the hardware of the mechanical assistant device for lower limb. During the experiment, the lower limb movements of the subjects in visual FB condition (iii) - stair climbing were observed more powerful and faster comparing to the other conditions. One possibility that should be considered is that the motivation to move hard in order to climb the stairs in VR is greater than walking. To confirm this hypothesis, it was considered necessary to add a force sensor on the device especially on the paralyzed foot to notice and to record the change on the force of lower limb. It might also further relate to the evaluation of the recovery level of hemiplegia patients in the future.

Another important limitation addressed is that the experiment in this study was conducted only in healthy males. Since stroke is due to brain damage, the brain activity including ERD might be fainter or different comparing to healthy people. Therefore, a further study focus on patients with hemiplegia patients will allow a validation in real patients.

VI. Conclusion

In this feasibility study, it can be concluded that visual FB helps to acquire the imagination of the motor execution, which might relate to the brain recovery through the internal FB learning model. Furthermore, in order to clarify the effective design of visual FB conditions, this study took the perspective of the similarity between visual FB and motor execution, and the results showed that the higher similarity of visual FB contributes to acquire the imagination of the motor execution. Although further studies are needed, this study demonstrates that visual FB with higher similarity to motor execution relates to the more effective design when developing the rehabilitation system. It is desirable to apply this result to the rehabilitation program in the future.

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REFERENCES

[1] Ministry of Health, Labor and Welfare, Overview of the national life basic survey, 2013, Accessed on November 13, 2017. [Online]. Available: http://www.mhlw.go.jp/toukei/saikin/hw/k-tyosa/k-tyosa11/index
[2] C. Ami, and C. M. Robert, "Synaptic plasticity: multiple forms, functions, and mechanisms," *Neuropsychopharmacology*, vol. 33, no. 1, pp. 18–41, 2008.
[3] K. Ohata, "Neuro rehabilitation and physical therapy [In Japanese]," *Physical Therapy MOOK 19*, vol. 1, pp. 5, 2016.
[4] M. Lotze, and LG. Cohen, "Volition and imagery in neurorehabilitation," *Cogn Behav Neurol.,* vol. 19, pp. 135–140, 2006.
[5] M. Murie-Fernández, S. Ortega-Cubero, M. Carmona-Abellán, M. Meyer, R. Teasell, "Time is brain: only in the acute phase of stroke?" *Neurología*, vol. 27, no. 4, pp. 197–201, May 2012.
[6] K. Salter et. al., "Impact of early vs delayed admission to rehabilitation on functional outcomes in persons with stroke," *J. Rehabil. Med.,* vol. 38, no. 2, pp. 113–117, Mar. 2006.
[7] W. M. Bortz II, "The disuse syndrome," *West. J. Med.,* vol. 141, no. 5, pp. 691–694, Nov. 1984.
[8] M. Abo, W. Kakuda, "Rehabilitation for cerebrovascular disease: current and new methods in Japan," *JMAJ* vol. 55, no. 3, pp. 240–245, 2012.
[9] H. Hara, "Stroke Rehabilitation based on cortical plasticity and the stage theory of motor output reorganization [In Japanese]," *J. Neurosurg.,* vol. 21, no. 7, pp.516–526, 2012.
[10] S. Lehéricy, "Motor execution and imagination networks in post-stroke dystonia," *NeuroReport*, vol. 15, no. 12, Aug. 2004.
[11] M. Iwaki, K. Saichi, K. Yasuda, and H. Iwata, "Development of a supine walking training system in the acute phase rehabilitation aiming at training information processing in walking [In Japanese]," the *Society of Instrument and Control Engineers,* Dec. 2018.
[12] Steven Lemm, Klaus-Robert Müller, Gabriel Curio, "A generalized framework for quantifying the dynamics of EEG event-related desynchronization," *PLoS Computational Biology*, vol. 5, no. 8, e1000453, 2009.
[13] M. Iwaki, R. Tagooka, K. Yasuda, and H. Iwata, "Lower limb rehabilitation of acute hemiplegic patients. Development of a master-slave bipedal coordination device to induce voluntary functions [In Japanese]," *Japan Robotics Conference,* 2017, pp. 1B2–02, 2017.
[14] Sumiko Yamamoto, Basic Biomechanics: Biomechanics of Walking, Apr. 2010.
[15] M. Takahashi, M. Goko, and K. Ito, "Verification of event-related desynchronization (ERD) appearance by motor recall feedback training [in Japanese]," *Transactions of the Institute of Systems, Control and Information Engineers*, vol. 22, no. 5, pp. 199–205, 2009.
[16] G. Pfurtscheller, C. Neuper, G. Krausz, "Functional dissociation of lower and upper frequency murhythms in relation to voluntary limb movement," *Clin. Neurophysiol.,* vol. 111, no. 10, pp. 1873–1879, 2000.
[17] Tatum, O. William, "Ellen R. Grass lecture: extraordinary EEG," *Neurodiagn. J.,* vol. 54, no. 1. 54 (1), pp. 3–21, 2014.
[18] R. Oostenveld, P. Praamstra, "The five percent electrode system for high-resolution EEG and ERP measurements," *Clin. Neurophysiol.* vol. 112, no. 4, pp. 713–719, 2001.
[19] H. Iridono and K. Onoda, "Effects of filters on the waveform of event-related potentials," *Physiological Psychology and Psychophysiology*, vol. 26, no. 3, pp. 237–246, 2008.
[20] F. Cassim, "Brief and sustained movements: differences in event-related (de)synchronization (ERD/ERS) patterns," *Clin. Neurophysiol.,* vol. 111, no. 11, pp. 2032–2039, Nov. 2000.
[21] F. Wilcoxon, "Individual comparisons by ranking methods," *Biometrics*, vol. 1, no. 6, pp. 80–83, Dec. 1945.
[22] Davide V. Moretti, "Individual analysis of EEG frequency and band power in mild Alzheimer's disease," *Clin. Neurophysiol.,* vol. 115, no. 2 (2004), pp. 299–308, 2004.
[23] Babiloni C et al., "Cortical sources of resting state EEG rhythms are abnormal in dyslexic children," *Clin Neurophysiol*., vol. 123, no. 12, pp. 2384–2391, 2012.