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Development of a Real-Time Brain-Computer Interface for Interactive Robot Therapy: An Exploration of EEG and EMG Features during Hypnosis

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Abstract**—**This study presents a framework for development of a new generation of therapy robots that can interact with users by monitoring their physiological and mental states. Here, we focused on one of the controversial methods of therapy, hypnotherapy. Hypnosis has shown to be useful in treatment of many clinical conditions. But, even for healthy people, it can be used as an effective technique for relaxation or enhancement of memory and concentration. Our aim is to develop a robot that collects information about user's mental and physical states using electroencephalogram (EEG) and electromyography (EMG) signals and performs cost-effective hypnosis at the comfort of user's house. The presented framework consists of three main steps: (1) Find the EEG-correlates of mind state before, during, and after hypnosis and establish a cognitive model for state changes, (2) Develop a system that can track the changes in EEG and EMG activities in real time and determines if the user is ready for suggestion, and (3) Implement our system in a humanoid robot that will talk and conduct hypnosis on users based on their mental states. This paper presents a pilot study in regard to the first stage, detection of EEG and EMG features during hypnosis.

Keywords**—**Hypnosis, EEG, robotherapy, brain-computer interface.

I. Introduction

WE live in a world where robots are becoming a normal part of our daily life. Over a century ago, the concept of social robots as human companions was simply science fiction. But today, we can find researches promoting educational robots at schools [1]-[3], entertainment robots at musicals [4], [5], and nursing/therapeutic robots at care facilities [6]-[12]. In this regard, humanoid or animal-like robots are particularly popular as they offer an opportunity for interaction with their life-like behavior. One of the emerging applications of these social robots is in providing therapy for patients with mental disabilities and cognitive impairments. In addition to their low cost –if used long term, there are evidences that show they can establish more efficient and positive communication with autistic kids [10], [11] and elderlies who suffer from dementia, Alzheimer, and etc. [9], [12]. Therefore, the future assist of robots in therapy, mental health care, and similar social services is not only beneficial but also crucial.

A key element in realizing human-robot interaction is to extract sufficient information for natural communication. The development of wide range of sensors along with such technological innovations as voice recognition, face-tracking, adaptive learning, etc. has made the current robots more autonomous than ever before [13]. However, in the case of therapy, individual difference is extremely large. The state of mind, emotions or even mood shifts in the human partner can extensively affect the communication regardless of the robot's behavior. Extracting such high-level information from user's behavior is not always possible nor is simple. Hence, detecting the cognitive state of user by other methods such as brain monitoring techniques can provide essential information. Nevertheless, such estimation has been disregarded in this field for a long time.

This research aims to develop a new generation of robots that monitor the cognitive state of users and provide therapeutic interaction. Here, we put our focus on hypnotherapy, as hypnosis is one of the most well-known therapeutic methods, used to create cognitive-behavioral changes in patients. Its application for treatment of depression, relaxation, pain modulation, and habit control is becoming popular today, even though it remains controversial in some cases. What is certain from science is that hypnosis can affect the basic activities of brain. In 1968, London et al. reported changes in alpha activities during hypnosis, measured by EEG recording [14]. The following experiments by Sabourin et al. [15] and Freeman et al. [16] failed to confirm the same effect. They found a larger theta power for highly susceptible subjects and reported a significant increase and subsequent decrease of theta activities in frontal, central and occipital areas as subjects entered a hypnotic induction and returned to the waking state. However, these finding could not be eplicated either. Williams and Gruzelier did not find any correlation between theta power and hypnosis [17] and Graffin et al. reported a decrease of theta activity for highly susceptible subjects [18]. Surprisingly, the number of works which have explored the EEG correlates of hypnosis is very few, and among those which have, the observations are highly inconsistent. This suggests an empty space left in this field that needs clarification. Moreover, by studying the cognitive mechanism of hypnosis, it is possible to develop brain-

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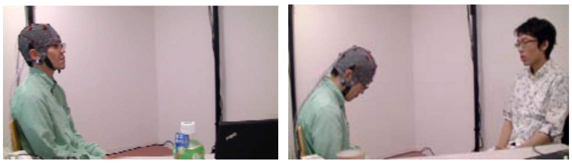
computer interfaces (BCIs) that can track user's EEG features and detect changes in mind states in real time. These systems can be used as assistant interfaces for psychological treatment or can be implemented in robots for autonomous interaction and therapy.

In this research, we plan to take three main steps to reach our goal: (1) clarify the mechanism of hypnosis and find neural measures that associate with hypnotic state and suggestibility, (2) develop a BCI system that monitors the temporal changes of physiological and cerebral activities during hypnosis and establishes a subject-specific mood recognition model. This system, which does the kind of job that expert hypnotists do based on observation of user's behavior, can indicate the right timing for execution of hypnotic suggestions and (3) promote the application of social robots in hypnotherapy by implementing our developed BCI system. The present study introduces our pilot experiments regarding the first step.

II. Method

A. Participants

Three subjects (two male and one female, age $M = 28$, $SD = 1.73$) were selected to participate in this experiment. They were all university students and volunteered to take part in the study.



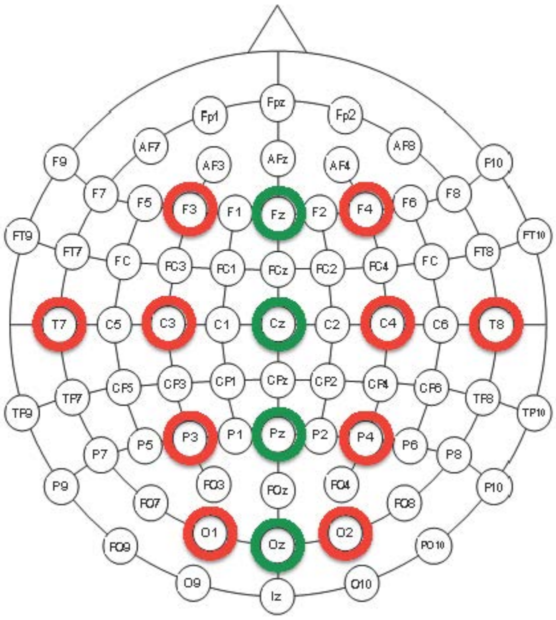
(a) Pre-hypnosis baseline (b) Induction

(c) Finger test (d) Arm levitation

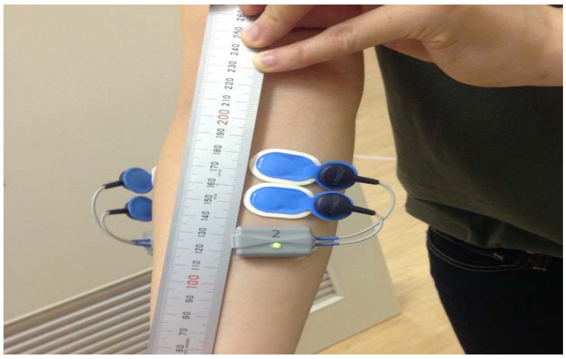
(e) Finger catalepsy (f) Post-hypnosis baseline

Fig. 1 Experimental procedure started with (a) a 5-min baseline without the presence of the experimenter. In the hypnosis session experimenter performed (b) a 5-min Induction followed by a 20-min segment of three suggestions: (c) finger test, (d) arm levitation, and (e) finger/arm catalepsy. The session ended with a 5-min awakening and when the experimenter left the room, (f) a 5-min final baseline was recorded

B. Procedure



(a)



(b)

Fig. 2 (a) 14 EEG channels installed at the frontal, central, temporal, parietal and occipital sites recorded brain activities during experiment. (b) EMG electrodes were placed on the anterior and posterior side of the dominant arm to record the muscular engagement during finger/arm catalepsy

Following the explanation and electrode placement, subjects were seated in a comfortable chair and instructed to avoid movement. Sessions were performed by one of the experimenters who has skill and experience in hypnosis. Before his arrival and start of session, a 5-min baseline was recorded (Fig. 1 (a)). After baseline recording, experimenter entered the room and conducted the session. The intervention took approximately 30 minutes and began with a 5-min segment of induction (Fig. 1 (b)) followed by a 20-min segment of suggestions. The hypnotic induction mainly included worded instructions and closed eyes, helping the subjects enter a state of deep relaxation and focused attention. Three specific suggestions, each repeated three times, were given to the subject. These suggestions were: (1) finger test (2) arm levitation, and finger or arm catalepsy (Figs. 1 (c)-(e)). Between each repetition, subjects closed their eyes and relaxed for 30 seconds. All instructions during this segment were tape-recorded and with the indication of another experimenter the software recorded the onset and offset of each suggestion interval. After the last suggestion interval, the experimenter continued to a 5-min segment of awakening without pause. Then he left the room and another 5-min baseline was recorded (Fig. 1 (f)).

C. EEG Recording

14 EEG channels recorded brain signals from the left and right frontal, central, temporal, parietal and occipital areas (F3, Fz, F4, T7, C3, Cz, C4, T8, P3, Pz, P4, O1, Oz, and O2) according to the 10/20 international system (Fig. 2 (a)). A reference electrode was mounted on the right ear and a ground electrode on the forehead. Recorded signals were amplified by g.USBamp developed at Guger Technologies (Graz, Austria).

In almost all the previous EEG studies of hypnosis, electrodes from only left and right hemispheres are recorded and normally an effect of lateralization is found. In this experiment, we also considered recoding the electrodes on the medial line (Fz, Cz, Pz, and Oz) for a broader investigation.

D. EMG Recording

EMG was recorded to particularly measure the electrophysiological correlates of the last suggestion, arm/finger catalepsy. Limb catalepsy is a sort of induced rigidity in the muscles of the limb that keeps them in any position in which they are placed. In such case, the muscular activity in the limb is expected to increase and one can measure them using EMG electrodes [19].

EMG was acquired through wireless Mini Wave Infinity developed by Cometa Inc. (Milano, Italy) and sampled at 2 KHz. Two pairs of wireless EMG active electrodes (inter-electrode distance 2 cm) were placed on the anterior and posterior side of the dominant arm, at locations of extensor digitorum and flexor carpi radialis. Both muscles become active during the extension and flexion of hand, wrist and fingers. Before the electrodes were placed, the experimenter wiped and prepared participant's skin by wet tissue. A trial record of maximum grip force was taken at the beginning of experiment for later use in normalization of data.

E. Data Processing

EEG data were processed offline using EEGlab version 13_4_4b [20]. Major artifacts were first excluded by eye, and then the EEG in all channels were bandpass filtered from 0.5 to 30 Hz. Eye-movement and rest of noises were rejected using independent component analysis (ICA) in EEGlab (eeg-runica function).

The cleaned EEG signals were then cut into five epochs: (1) Pre-hypnosis baseline, (2) Induction, (3) Hypnosis, (4) Awake, and (5) Post-hypnosis baseline. The epochs were selected based on the onset and offset of each segment that were registered during experiment. The rest time between the suggestions was excluded. Finally, mean power of each frequency band; theta (4 ~ 7.5 Hz), alpha (8 ~ 11.5 Hz) and beta (12 ~ 28 Hz) were calculated for all five epochs using MATLAB.

III. Results and Discussion

Among three subjects which participated in this study, two subjects were highly affected by the hypnotic procedure and responded to all suggestions. The other subject did not show much effect and will be considered as 'low' on the susceptibility scale. The results will be presented in the following two sections.

A. EEG

Fig. 5 demonstrates mean power for frequency band theta during five phases of experiment. A comparison between highly susceptible subjects (Sub1 and Sub3) and low susceptible subject (Sub2) shows that the former group had higher theta activity in frontal, central, and parietal areas, particularly at initial baseline and during hypnotic intervention. On the other hand, for all subjects (both highly and low susceptible), there is a gradual increase in the theta power from initial baseline to induction phase and to the hypnotic phase, at almost all areas except frontal. This result is largely consistent with the previous works [15], [18], [21], as they also found increase of theta activity during hypnosis and substantially stronger theta power for highly hypnotizable subjects than low ones. Theta activity has been proposed to be associated with high-level information processing and variety of cognitive functions in the hippocampus [22]. It is also correlated with a state of somnolence with reduced consciousness [23]. It is thus possible that the increase of theta activities, which in the present study happened during hypnosis for both high and low subjects, indicates that the subject was not only more relaxed, but also more facilitated to process information than in the baseline condition. This reflects the fact that all hypnosis subjects, regardless of the susceptibility score, can experience an influence in the cognitive state, which can lead to the intensification of intentional processes and enhancement of mental imagery.

Result for alpha activity on the other hand (Fig. 6) showed discrete distributions of mean power across phases as the experiment progressed. Especially high amplitudes are seen during Induction and Awake phases at almost all locations. This is due to the closing of subject's eyes during these two phases. Based on the experimenter's instructions, subjects were allowed to close their eyes if they felt relaxed enough. This shift of amplitudes was greater at the occipital areas, because of the influence of visual field on alpha activities. In most of the hypnosis studies, this effect is attended by conducting procedures of only closed or open eyes [15]. Future experiments should find a solution to perform homogeneous instructions.

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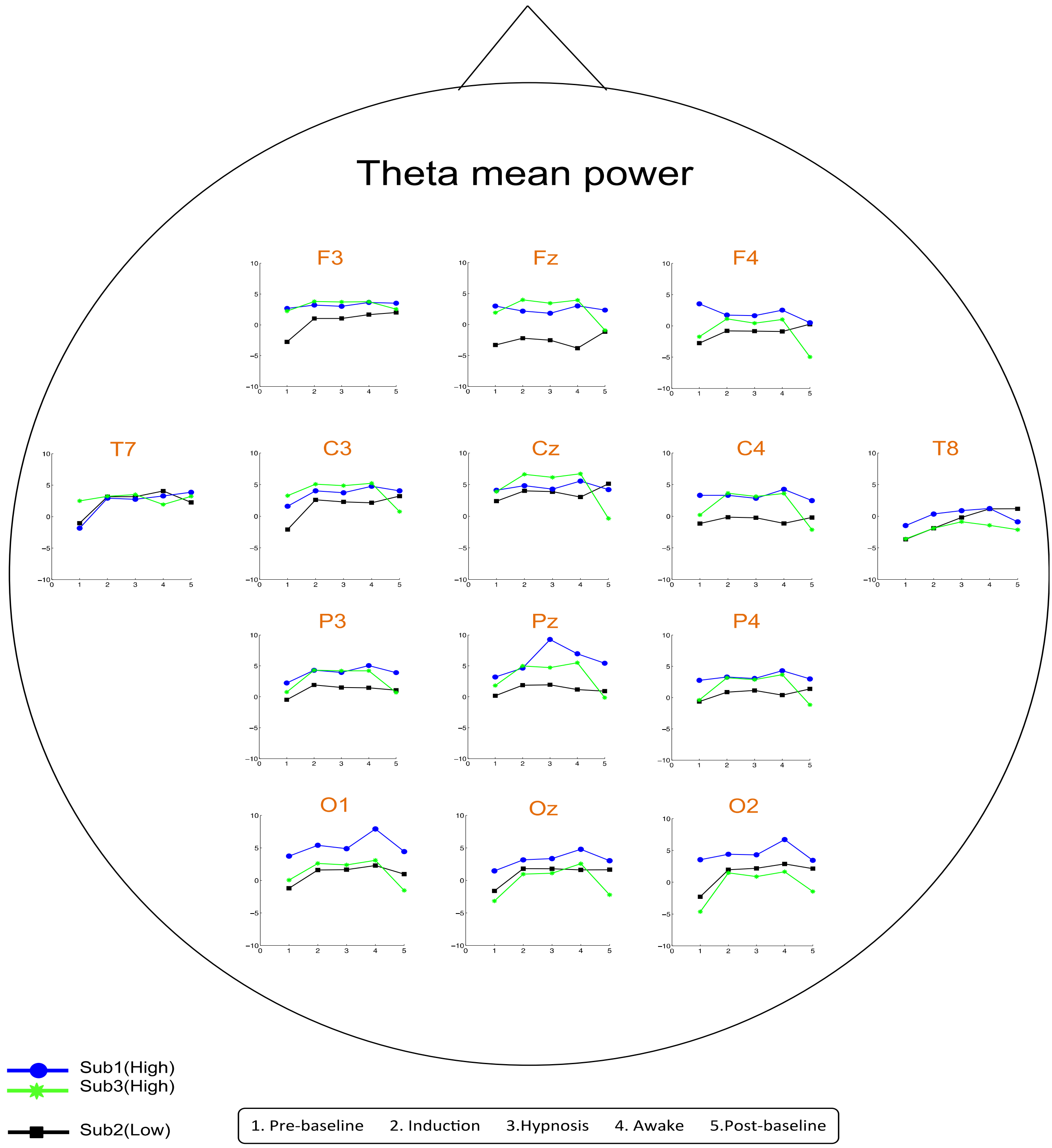

Fig. 3 Theta mean power at frontal (F3, Fz, F4), central (C3, Cz, C4), temporal (T7, T8), and occipital (O1, Oz, O2) locations for three subjects. Two subjects (Sub1 and Sub3) were highly hypnotizable, and one subject (Sub2) was low. Theta power was calculated in five time phases: 1. Initial waking baseline (Pre-baseline), 2. Hypnotic induction, 3. Hypnosis with three suggestions, 4. Awakening, and 5. Final waking baseline (Post-baseline)

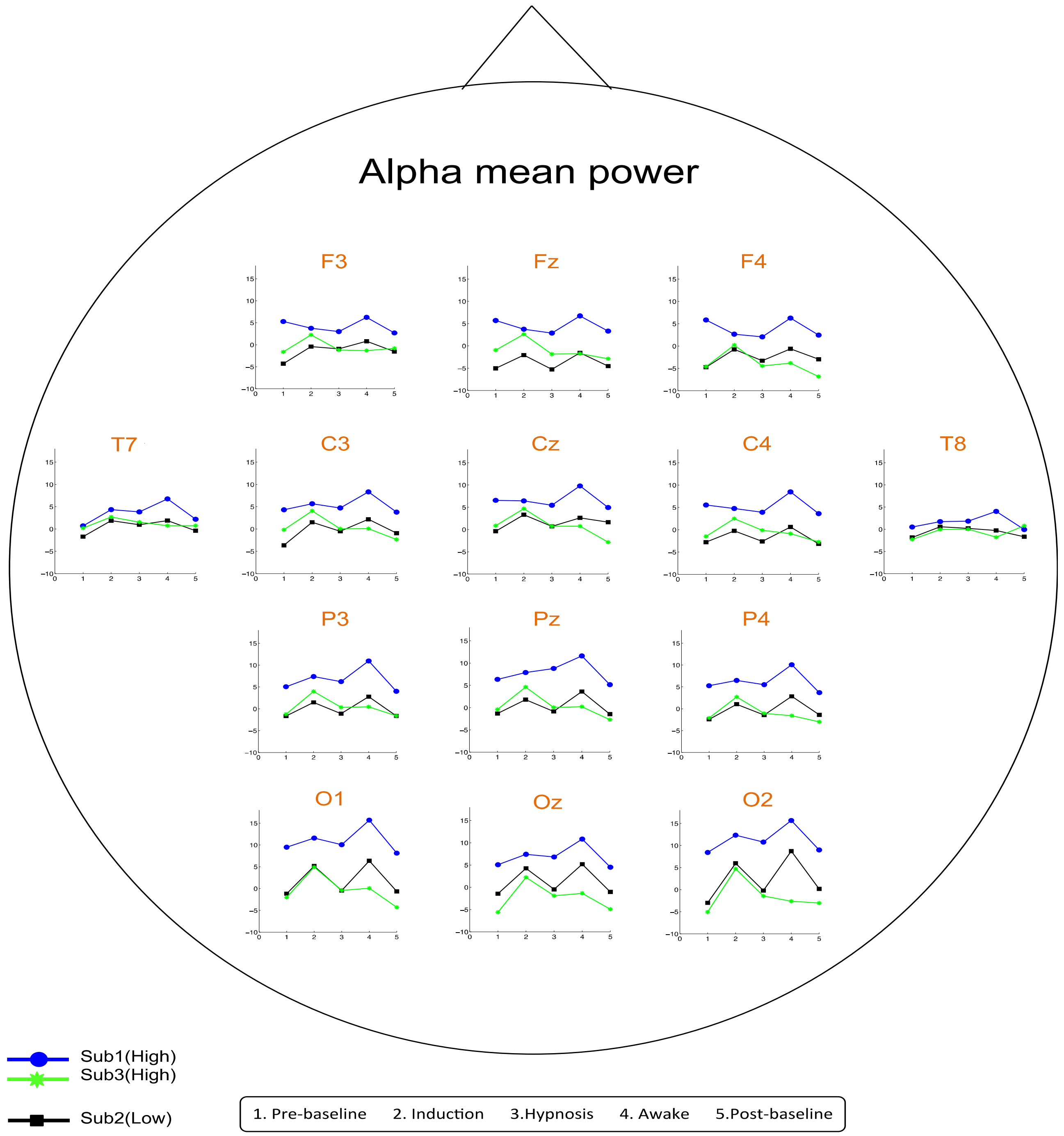

Fig. 4 Alpha mean power at frontal (F3, Fz, F4), central (C3, Cz, C4), temporal (T7, T8), and occipital (O1, Oz, O2) locations for three subjects. Two subjects (Sub1 and Sub3) were highly hypnotizable, and one subject (Sub2) was low. Theta power was calculated in five time phases: 1. Initial waking baseline (Pre-baseline), 2. Hypnotic induction, 3. Hypnosis with three suggestions, 4. Awakening, and 5. Final waking baseline (Post-baseline)

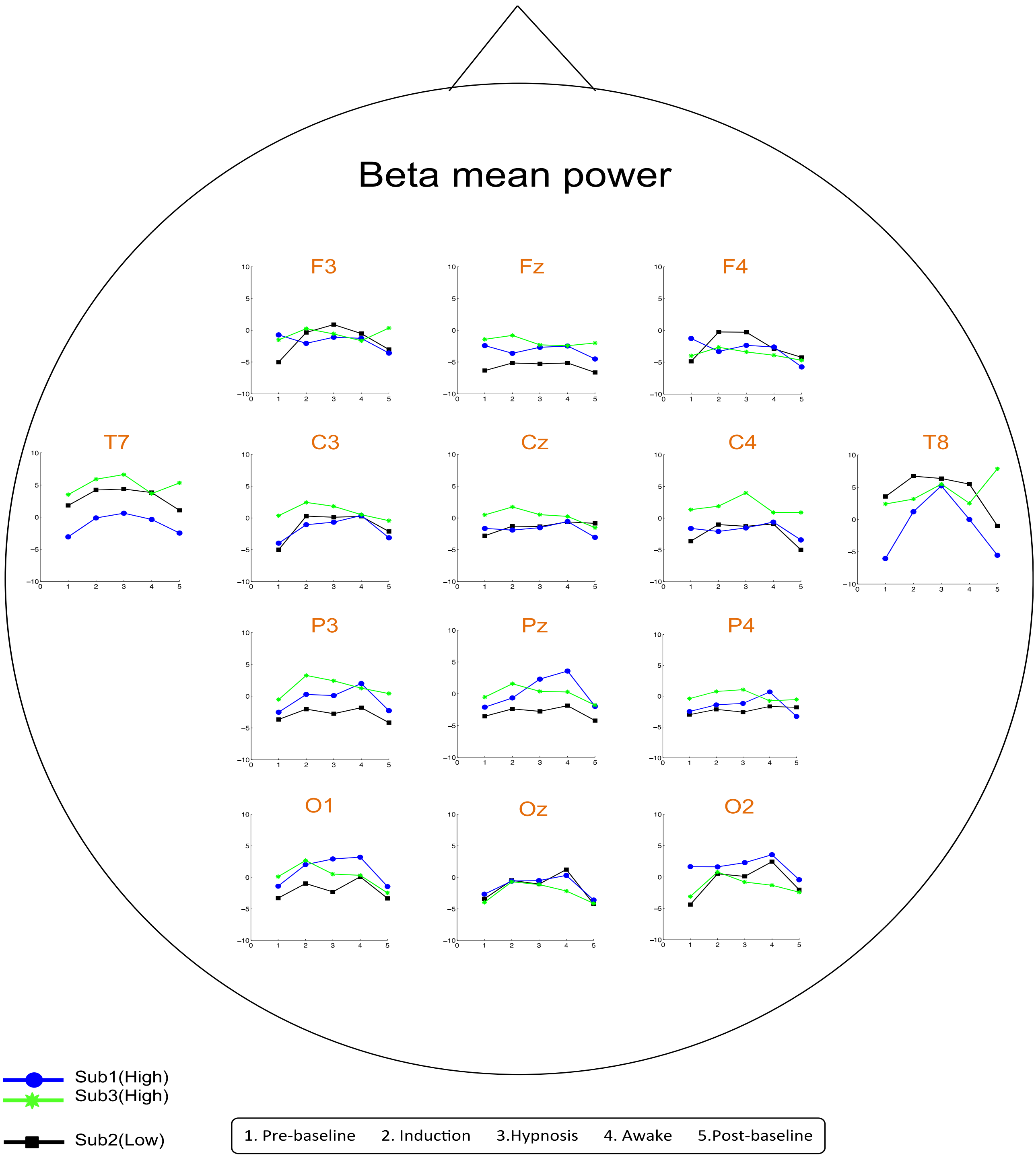

Fig. 5 Beta mean power at frontal (F3, Fz, F4), central (C3, Cz, C4), temporal (T7, T8), and occipital (O1, Oz, O2) locations for three subjects. Two subjects (Sub1 and Sub3) were highly hypnotizable, and one subject (Sub2) was low. Theta power was calculated in five time phases: 1. Initial waking baseline (Pre-baseline), 2. Hypnotic induction, 3. Hypnosis with three suggestions, 4. Awakening, and 5. Final waking baseline (Post-baseline)

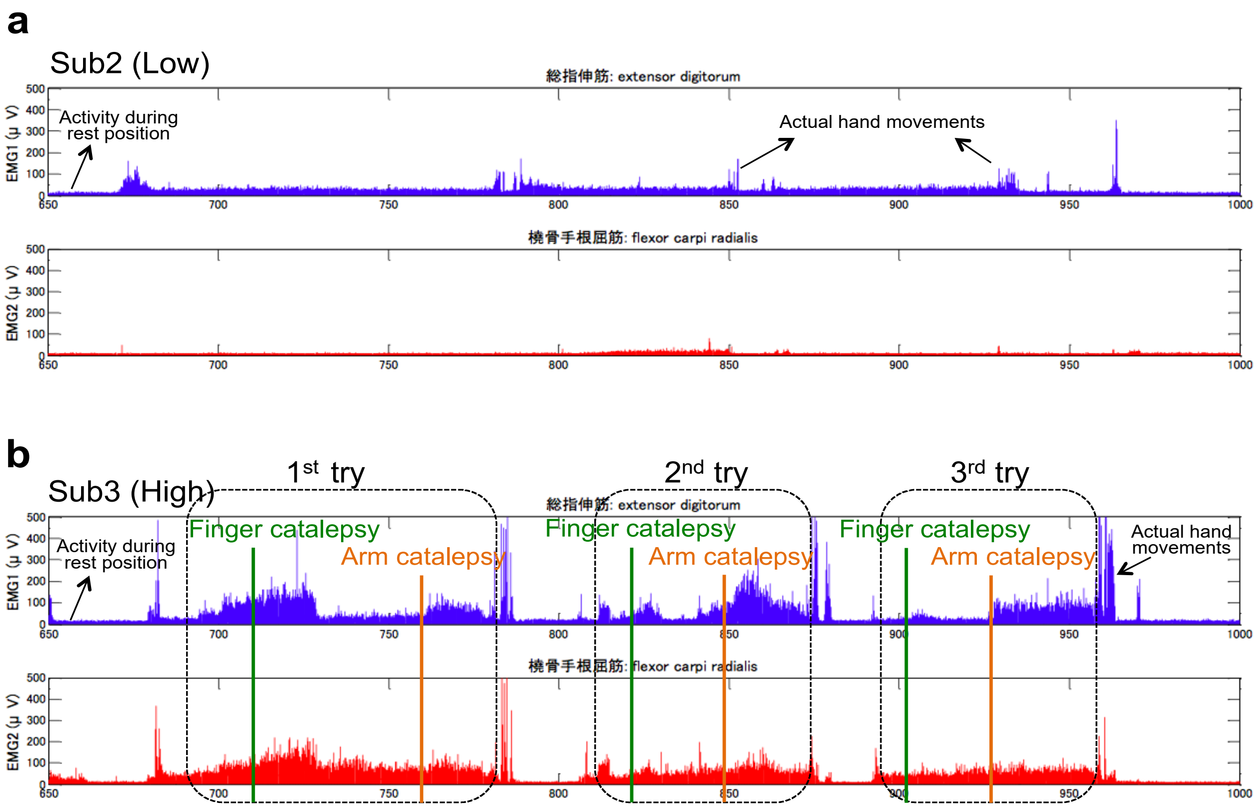

Fig. 6 Temporal changes of EMG activities during catalepsy suggestion for (a) the low susceptible Sub2 and (b) highly susceptible Sub3. The EMG observation of muscle activities during each try revealed stronger muscular engagement for highly hypnotizable subjects. The EMG amplitudes rising immediately after the rigidity instruction for Sub3 indicates the subject is intensive but ineffective effort to bend his finger or arm against the suggested catalepsy

The results of beta mean power (Fig. 5) were the most interesting. There is a common increase and subsequent decrease in the beta activities at temporal areas as subjects move from initial baseline to induction and hypnosis and return to the final baseline. This effect was more dominant for the left hemisphere. Similar increase with less intensity was found at the occipital and parietal areas. Unlike Sabourin et al. [15], we did not find a significant lateralization of beta power in favor of left hemisphere. Beta activities appear in varying frequencies when we are actively thinking, alert, busy or concentrating [24]. The increasing beta power over temporal, occipital and parietal areas indicates the increase of process in the auditory, visual and somasensory areas both for integration of different modalities and language processing.

B. EMG

Fig. 6 demonstrates the temporal changes of EMG activities during catalepsy suggestion for a low susceptible subject (Sub2) and a highly susceptible subject (Sub3). By comparing the EMG activities between these two subjects in Fig. 6 (a) and 6 (b), a clear difference between the amplitudes can be seen. In Fig. 6 (b), the timing for each repetition of suggestion and verbal instructions of finger and arm rigidity are also depicted. The strong appearance of amplitudes after each instruction shows the ineffective, but intensive effort of the subject to bend his finger or arm against the suggested catalepsy. We also witnessed trembling in subject's hands, which makes it more plausible that these subjects internally experience a motor response but exhibit no observable motor behavior [25].

Most of the suggestions practiced in this study are motor items that lead to changes in motor behavior. It may be argued how these suggestions are associated with therapy. In fact, motor suggestions have some uniquely attractive features as gateways to hypnotic phase. They are often enacted in hypnotic interventions to increase the malleability of behavior. Once subjects reach a high state of suggestibility, relaxation strategies can be used to induce the feeling of 'let go' -the releasing of negative thoughts, which has immense therapeutic effects [26].

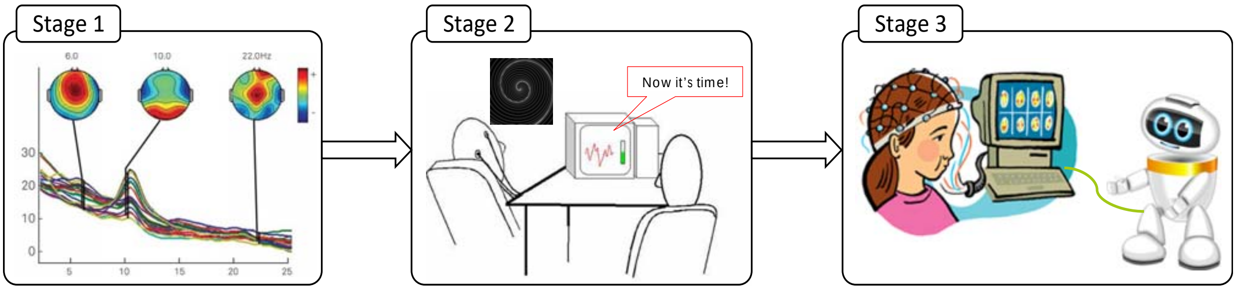

Fig. 7 Three main stages are planned for this research: (1) find the EEG-feature of brain activities during hypnosis, (2) develop a system that tracks changes in EEG and EMG activities in real time and predicts changes in user's mental state, and (3) implement a humanoid robot that conduct hypnosis on users based on their mental states. This paper introduces a preliminary study in Stage1

IV. Conclusion and Future Direction

In this work, we proposed an integrated framework for development of a hypnotherapy robot that can monitor EEG and EMG activities of the user and perform a hypnotherapy intervention. We presented a pilot study for the first step of this project that is measuring the temporal and spatial changes of EEG activities during hypnosis. Although the very small number of the subjects does now allow conclusions and generalization from these data, our preliminary results could partially confirm some of the previous work, which showed increase in theta activities in almost all areas. Besides, as a new piece of finding, we could detect considerable beta increase and decrease in temporal areas as the subject entered the induction and hypnosis phase and returned to baseline.

To our knowledge, this might be the first work that introduces BCI- therapy robots that interact with users based on their mental states. There have been many neuro-feedback therapy studies that use real-time displays of brain waves to teach the user self-regulation of brain activities for the improvement of cognitive functions [26]-[29]. However, this kind of interfaces which particularly require concentration and static bodies is not very playful or interactive and can get often tiresome and boring for the user. The implementation of an interactive robot that talks and communicates is assumed to motivate the user to engage with the interface more and maintain a long-term interest in the therapy sessions.

Future work will comprise three stages (Fig. 7). First, we focus on extending the size of data for analysis of EEG and EMG traits during hypnosis. Further we intend to develop a 'hypno-track' system that based on the user's mental states outputs an indicator for best timing of hypnotic instructions. Our last challenge will be the implementation of this system for practice of hypnotherapy by a humanoid robot.

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