35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

Mechanical Vibrotactile Stimulation Effect in Motor Imagery based Brain-computer Interface

Lin Yao, Xinjun Sheng*, Jianjun Meng, Dingguo Zhang, and Xiangyang Zhu

***Abstract*— Sensory stimulation played a critical role in both motivating subject's anticipation in brain-computer interface but also enhancing the sensory-motor interaction and closing the sensory motor loop. In this paper, mechanical vibrotactile stimulation effect in motor imagery was evaluated on 10 healthy subjects, and preliminary results showed that 5 subjects would achieve a reliable control above 80% with sensory stimulation as comparable with motor imagery without any stimulation. Besides, 3 subjects reached a better control with approximately 70% as compared with a chance level of 50% in motor imagery without sensory stimulation. Further analysis showed subject who was poor in conventional motor imagery condition exhibited enhanced R^2 value distribution in motor imagery with sensory stimulation condition. Meanwhile there was sensorimotor rhythmic enhancement both at upper alpha band and upper beta band in some subjects. But these rhythmic changes resulted performance reduction as incongruence of training and testing sets effect from off-line analysis. This research provided some guidance in integration of the sensory stimulation channel with motor imagery based BCI system.**

I. INTRODUCTION

A brain computer interface (BCI) provides a new non-muscular channel for communication and control with external world[1]. A common way to gain BCI control is to use motor imagery of left and right hands, which is intensively investigated in the literature [2], [3], [4] with promising significance that this non-invasive method would establish the direct interaction channel between human brain and outside environment.

Lots of works have been carried out in closing the sensory motor loop. In [5], haptic information is incorporated for biofeedback, subjects are able to control the BCI using only vibrotactile feedback with an average accuracy of 56% and as high as 72% comparing to the random chance of 15%. Meanwhile proprioceptive feedback [6] with robotic orthosis fixed to the subject's hand is chosen, which shows a clear enhanced desynchronization of mu and beta rhythms. These changed event-related desynchronization(ERD) would further influence the continues on-line decoding process, as investigated from the study [7] that there exists incongruence between training and testing phase under haptic and no haptic feedback conditions. Besides, graded feedback led to improved modulation of ipsilesional activity as reported in [8], enhancing the interactive process within the sensory motor loop.

*This work is supported by the National Basic Research Program (973 Program) of China (Grant No.2011CB013305), and the Science and Technology Commission of Shanghai Municipality (Grant No. 11JC1406000), and the National Natural Science Foundation of China (Grant No.51075265).

Lin Yao, Xinjun Sheng, Jianjun Meng, Dingguo Zhang, and Xiangyang Zhu, State Key Laboratory of Mechanical System and Vibration, Shanghai Jiao Tong University, 800 Dongchuan Road, Minhang District, Shanghai, China. (xjsheng@sjtu.edu.cn)

In this paper mechanical vibrotactile stimulation is adopted as a sensory input channel to interact with subject's motor imagery process. Subject's left and right hand wrist skins are simultaneously stimulated with equal intensity. Naturally these two same afferent inputs will receive different cortical processing as modified by either left or right motor imagery under gating effects phenomenon[9], [10]. These discriminative processes of sensory inputs would further increase the discrimination between left hand and right hand motor imagery, thus might improve the classification accuracy in brain-computer interface. Comparative experiments are carried out with and without mechanical vibrotactile stimulation to further investigate the problem related to sensory stimulation. So the question arises, could left and right motor imagery be discriminated when the stimulation is on as compared to motor imagery without sensory stimulation? Will there be any sensorimotor rhythm enhancement under the motor and periphery integration? A carefully designed experiment is presented to better investigate these neural mechanisms.

II. METHODS

A. Subjects

10 able-bodied subjects participated in these experiments, 7 male, 3 female, all right handed with mean age of 25 years old. They were all informed about the whole experiment process. This study was approved by the Ethics Committee of Shanghai Jiao Tong University. All participants signed the informed consent forms before participating in the experiments.

B. EEG Recording and Stimulation Unit

62 channel EEG signals were recorded using a SynAmps2 system (Neuroscan, U.S.A.), and the electrodes were placed according to the extended 10/20 system. The reference electrode was located on the vertex, and the ground electrode was located on forehead. An analog bandwidth filter with 0.5Hz to 70Hz and a notch filter with 50Hz to diminish power line interference were applied to the original signals, which were sampled at 250Hz.

Left and right wrist skins were simultaneously stimulated with equal amplitude and the same modulation frequency. The linear resonant actuators (10mm, C10-100, Precision Microdrives Ltd.) were used for vibrotactile stimulation.

Electrical signal of 175Hz sinusoidal carrier frequency modulated with 27Hz sinusoidal frequency was produced via computer soundcard, and amplified with audio amplifier to drive the actuators. The amplitude of vibration was individually adjusted within the range of 0.5 times the device normalized amplitude to maximum amplitude of $11.3um$ at resonant frequency.

C. Experimental paradigm

The subject sat in a comfortable armchair in an electrical shielded room, with both forearms and hands rested in the armrest. The experiment was carried out on two sessions, and the subject was required to have 5 to 10 minutes rest between sessions. Every session contained four runs of 40 trials each, and right hand and left hand motor imagery were counterbalanced. In the first session, the vibrations stimulated at the wrist skins during the motor imagery period. At the beginning of each trial, a fixation cross appeared in the screen. At the 1st second, a vibration burst of the same intensity stimulated both hands to attract the subject's attention mentally ready for the subsequent task, with the vibration time lasted for 200ms. Then at the 3rd second, a red cue bar pointing either left or right was presented, which superimposed on the fixation cross and lasted for 1.5s. The subjects should perform the mental task after appearance of the cue bar. The mental task continued until to the 8th second, at which time point the fixation cross disappeared. At the 4.5th second, the vibration applied to both hands with the same intensity, till to the end of the motor imagery. In the second session, the subject's task was the same, but there was no vibration stimulation during motor imagery period. During the first run of all the two sessions, there was no feedback after the termination of the mental task. All the subsequent three runs of each session, there would be vibration feedback according to the on-line classification algorithm implemented within the experiment system. The feedback stimulus was applied according to the decoded task type, lasting for about 500ms. After the feedback, there was a relaxation time period lasting for about 1s, during which the subjects should get relaxed and could blink his or her eyes. Then a random time period of about 0 to 2s was inserted after the relaxation period to further avoid subject's adaptation, after that the next trial began.

D. Algorithms

Decoding algorithm for both motor imagery with sensory stimulation and without sensory stimulation is mainly based on Common Spatial Pattern (CSP) [11], [12]. The raw EEG signal is represented as X_k with dimensions $ch \times len$, where ch is the number of recording electrodes, and len is the number of sample points. The normalized spatial covariance of the EEG can be obtained from

$$C_k = \frac{X_k X_k^T}{trace(X_k X_k^T)} \tag{1}$$

where X_k^T denotes the transpose of the matrix X_k, and $trace(X_k X_k^T)$ is the sum of the diagonal elements of the matrix $X_k X_k^T$. Let

$$C_l = \sum_{k \in S_l} C_k \qquad C_r = \sum_{k \in S_r} C_k \tag{2}$$

where S_l and S_r are the two index sets of the separate classes.

The projection matrix W could be gained from augmented generalized decomposition problem, $(C_l + C_r)W = \lambda C_r W$. The rows of W are called spatial filters, and the columns of W^{-1} are called spatial patterns. To the k-th trial, the filtered signal $Z_k = W X_k$ is uncorrelated. In this work, the log variance of the first three rows and last three rows of Z_k corresponding to largest three eigenvalues and smallest three eigenvalues are chosen as feature vectors, and linear discriminative analysis (LDA) was used as the classifier.

III. Results

The time interval for on-line and off-line analysis (motor imagery with and without sensory stimulation) was chosen from the 4th second to the 7th second at the beginning of the trial, and the frequency band was chosen to cover the alpha and beta band of 8Hz to 26Hz, using 4th-order butterworth filter. A 5×5 fold cross validation was adopted to evaluate the classification accuracy between left and right. Table I outlined the on-line classification accuracy of the 2nd run to the 4th run(the 1st run was used as calibration data set). Fig. 1 showed the discrimination accuracy of 10 subjects respecting to left and right hand motor imagery with and without sensory stimulation. 5 subjects achieved a reliable control above 80% with sensory stimulation as comparable to motor imagery without sensory stimulation. Besides, 3 subjects reached a better control of approximately 70% as compared with a chance level of 50% of motor imagery without sensory stimulation.

TABLE I
On-line Classification Accuracy Across the Two Sessions.

	Session One(%)			Session Two(%)		
	2nd Run	3rd Run	4th Run	2nd Run	3rd Run	4th Run
s1	82.5	72.5	82.5	85.0	82.5	67.5
s2	100.0	100.0	100.0	97.5	92.5	92.5
s3	97.5	95.0	95.0	97.5	100.0	87.5
s4	52.5	55.0	60.0	42.5	52.5	62.5
s5	50.0	77.5	80.0	52.5	70.0	67.5
s6	67.5	65.0	60.0	47.5	57.5	50.0
s7	67.5	52.5	72.5	52.5	60.0	42.5
s8	47.5	65.0	65.0	67.5	67.5	65.0
s9	100.0	92.5	100.0	97.5	97.5	100.0
s10	87.5	100.0	80.0	90.0	72.5	87.5

Time/frequency decomposition of each trial was carried out to construct the spatial-spectral-temporal structure corresponding to each mental task[13], [14]. The R^2 index [15] was used to localize the discriminative information distribution among the spatial-spectral-temporal space between two corresponding mental tasks. In the Fig. 2, the subject who had difficulty in both motor imagery without sensory stimulation shown plain discriminative information among

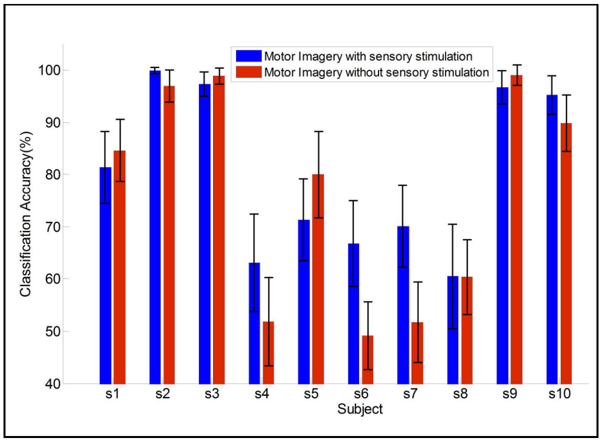

Fig. 1. Comparison between motor imagery with sensory stimulation and motor imagery without sensory stimulation. The blue bar indicated discrimination accuracy of left and right hand motor imagery with sensory stimulation. The red bar indicated the discrimination accuracy of left and right hand motor imagery without sensory stimulation.

the spatial-spectral space, but in motor imagery with sensory stimulation condition, discriminative information emerged out in the spatial-spectral space, and the discriminative information had a well physiological localization concentrated on the sensorimotor area, which was responsible for motor output and processing of afferent input.

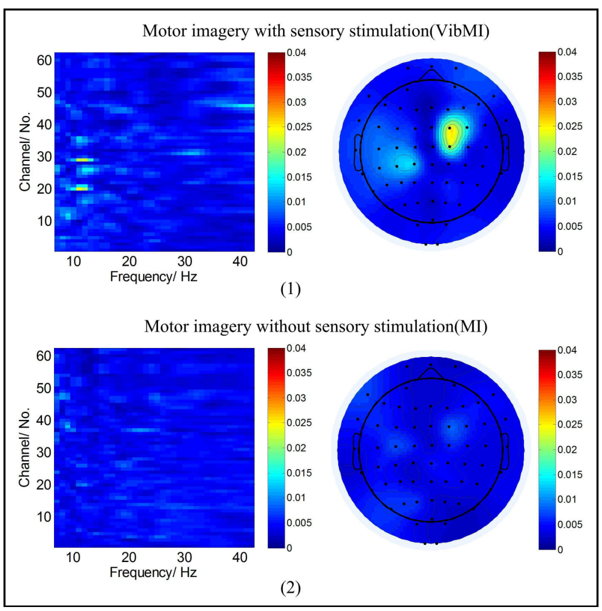

Fig. 2. R^2 value distribution in spatial-spectral space from subject s7. (1) R^2 value distribution across frequency and spatial domain in motor imagery with sensory stimulation and the topoplot of R^2 value averaged in upper alpha band(10 to 13Hz), the color bar indicated the R square values. (2) R^2 value distribution across frequency and spatial domain in motor imagery without sensory stimulation and the topoplot of R^2 value averaged in upper alpha band(10 to 13Hz).

In order to better understand the effect of vibrotactile stimulation, motor imagery of left and right with sensory stimulation was used as training set while motor imagery of left and right without sensory stimulation as testing set (vice versa), so difference effect of training and testing was evaluated off-line as shown in Fig. 3. Clearly, there was a performance reduction with incongruence of training and testing sets as comparing to congruence of training and testing sets shown in Fig. 1. Besides, motor imagery with sensory stimulation as training data set, while motor imagery without sensory stimulation as testing data set, showed better performance among the two incongruent conditions.

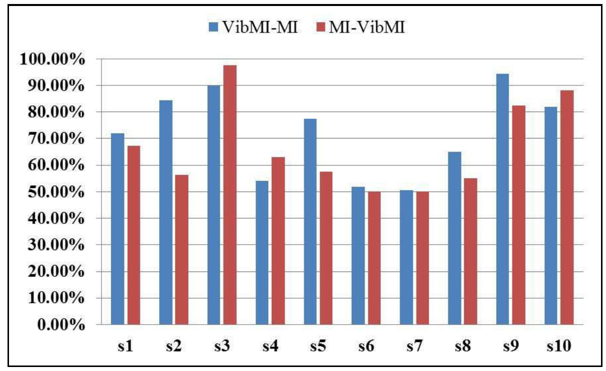

Fig. 3. Training and Testing effects on classification accuracy. The blue bar indicates the classification accuracy under the condition that motor imagery of left and right with sensory stimulation as training set while motor imagery of left and right without sensory stimulation as testing set, and the red bar vice versa.

IV. Discussion

The discrimination results between left and right motor imagery in session one with sensory stimulation and those in session two without sensory stimulation, shown that subjects could comparatively achieve reliable motor imagery control in both conditions. The method of introducing sensory stimulation during motor imagery period was at least not negative distractive facts in BCI system, and the subjects could still success in modulating their EEG rhythm in gaining control. While 3 subjects shown approximately 70% accuracy with the help of sensory stimulation, as compared to the chance level of 50% accuracy without stimulation. This finding that the stimulation was more useful for subjects with poor performance at the non-stimulation condition was interesting, and this approach might have potentialities for making the motor imagery based BCI applicable for more people.

Besides of producing additional discriminative information beneficial for decoding in brain-computer interface, the enhanced sensorimotor rhythm was expected as interacting process between motor and peripheral compared to solely motor process. As shown in Fig. 4, some subjects shown enhanced sensorimotor rhythm in upper alpha band(10 to 13Hz) and upper beta band(20 to 26Hz). In the work [6], where there was an enhancement in both alpha and beta band as a result of proprioception feedback driven by an orthosis, the receptor of Ruffini corpuscles in the skin was stimulated which was responsible for the skin stretch and used for joint positioning in fingers. In this experiment, stimulation was applied to the wrist skins, with 175Hz sinusoidal carrier frequency, modulated with 27Hz to induce flutter sensation. Both Pacinian corpuscles and Meissner corpuscles were stimulated, which were especially sensitive to frequency above 100Hz and 20 to 50Hz respectively [16]. Similarly, these sensory receptors enhanced the sensorimotor oscillation.

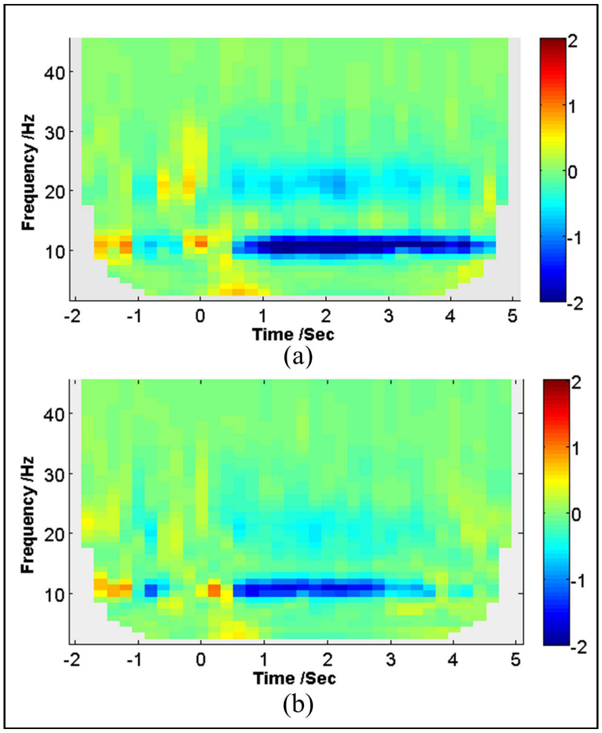

Fig. 4. Powerspectrum across the time and frequency at channel C4 corresponds to left motor imagery. (a) Motor imagery of left hand with sensory stimulation. (b) Motor imagery of left hand without sensory stimulation.

These enhanced sensorimotor rhythms could be very relevant for the motor-neuron rehabilitation field, and would be beneficial for the motor recovery of patient from the point of view enhancing cortical oscillations and closing the sensory motor loop. While the motor imagery process with and without sensory stimulation clearly introduced bias in incongruence of training and testing conditions as seen from Fig. 3. Motor imagery with and without sensory stimulation produced different rhythmic changes, on which the decoding algorithm was based. So the enhancement of sensorimotor rhythm induced the bias in decoding motor imagery types. As the parameters of a BCI system was usually determined from a calibration session, during which there was no feedback (without sensory stimulation), while during the evaluation session there was feedback (with sensory stimulation). This also introduced the incongruence, further, more intelligent algorithm should be considered to better pursuit this changes and adaptively modify the decoding algorithm.

V. Conclusion

Subjects could effectively realized the motor imagery based control with sensory stimulation as comparable to motor imagery without sensory stimulation, whilst some chance level subjects achieved 70% accuracy with sensory stimulation. Still careful consideration with respect to rhythmic changes with and without sensory stimulation should be taken to better decoding subject's motor intention. This research provided some preliminary guidance in integration of the sensory stimulation channel with motor imagery based BCI system.

Acknowledgment

The authors thank Gan Huang and Guangquan Liu for their preliminary work in the setting up of the BCI system.

References

[1] J. Wolpaw, N. Birbaumer, D. McFarland, G. Pfurtscheller, T. Vaughan, *et al.*, "Brain-computer interfaces for communication and control," *Clinical neurophysiology*, vol. 113, no. 6, pp. 767–791, 2002.

[2] G. Pfurtscheller, C. Brunner, A. Schlögl, S. Lopes, *et al.*, "Mu rhythm (de) synchronization and eeg single-trial classification of different motor imagery tasks." *NeuroImage*, vol. 31, no. 1, p. 153, 2006.

[3] C. Neuper, R. Scherer, S. Wriessnegger, and G. Pfurtscheller, "Motor imagery and action observation: modulation of sensorimotor brain rhythms during mental control of a brain–computer interface," *Clinical neurophysiology*, vol. 120, no. 2, p. 239, 2009.

[4] H. Zhang, C. Guan, K. Ang, and C. Wang, "Bci competition iv–data set i: learning discriminative patterns for self-paced eeg-based motor imagery detection," *Frontiers in neuroscience*, vol. 6, 2012.

[5] C. Aniruddha, A. Vikram, R. Ander, A. Soumyadipta, and T. Nitish, "A brain-computer interface with vibrotactile biofeedback for haptic information," *Journal of NeuroEngineering and Rehabilitation*, vol. 4, 2007.

[6] A. Ramos, S. Halder, and N. Birbaumer, "Proprioceptive feedback in bci," in *Neural Engineering, 2009. NER'09. 4th International IEEE/EMBS Conference on*. IEEE, 2009, pp. 279–282.

[7] M. Gomez-Rodriguez, J. Peters, J. Hill, B. Scho?lkopf, A. Gharabaghi, and M. Grosse-Wentrup, "Closing the sensorimotor loop: Haptic feedback facilitates decoding of arm movement imagery," in *Systems Man and Cybernetics (SMC), 2010 IEEE International Conference on*. IEEE, 2010, pp. 121–126.

[8] S. Soekadar, M. Witkowski, J. Mellinger, A. Ramos, N. Birbaumer, and L. Cohen, "Erd-based online brain–machine interfaces (bmi) in the context of neurorehabilitation: Optimizing bmi learning and performance," *Neural Systems and Rehabilitation Engineering, IEEE Transactions on*, vol. 19, no. 5, pp. 542–549, 2011.

[9] M. Severens, J. Farquhar, P. Desain, J. Duysens, and C. Gielen, "Transient and steady-state responses to mechanical stimulation of different fingers reveal interactions based on lateral inhibition," *Clinical Neurophysiology*, vol. 121, no. 12, pp. 2090–2096, 2010.

[10] J. Voisin, C. Mercier, P. Jackson, C. Richards, and F. Malouin, "Is somatosensory excitability more affected by the perspective or modality content of motor imagery?" *Neuroscience letters*, vol. 493, no. 1, pp. 33–37, 2011.

[11] K. Fukunaga, "Introduction to statistical pattern recognition," *Academic Press, New York, 2nd edtion*, vol. 1, p. 2, 1990.

[12] H. Ramoser, J. Muller-Gerking, and G. Pfurtscheller, "Optimal spatial filtering of single trial eeg during imagined hand movement," *Rehabilitation Engineering, IEEE Transactions on*, vol. 8, no. 4, pp. 441–446, 2000.

[13] B. J. Roach and D. H. Mathalon, "Event-related eeg time-frequency analysis: an overview of measures and an analysis of early gamma band phase locking in schizophrenia," *Schizophrenia bulletin*, vol. 34, no. 5, pp. 907–926, 2008.

[14] R. Oostenveld, P. Fries, E. Maris, and J. Schoffelen, "Fieldtrip: open source software for advanced analysis of meg, eeg, and invasive electrophysiological data," *Computational intelligence and neuroscience*, vol. 2011, p. 1, 2011.

[15] T. H. Wonnacott and R. J. Wonnacott, *Introductory statistics*. Wiley Chichester, 1990, vol. 19690.

[16] C. Breitwieser, V. Kaiser, C. Neuper, and G. Müller-Putz, "Stability and distribution of steady-state somatosensory evoked potentials elicited by vibro-tactile stimulation," *Medical and Biological Engineering and Computing*, pp. 1–11, 2012.