On the Correlations of Motor Imagery of Swallow With Motor Imagery of Tongue Movements and Actual Swallow

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Abstract. This paper investigated the correlations between motor imagery of swallow (MI-SW) and motor imagery of tongue movements (MI-Ton), and correlations between MI-SW and actual swallow (Act-SW). EEG data of 10 healthy subjects and 1 dysphagia patient were analyzed. The group analysis results of using bin-based spectral power demonstrated that MI-SW and MI-Ton, and MI-SW and Act-SW were strongly correlated (p-value<0.001, examined at 'C3') for both mu and low beta frequency bands. Further, the correlation was weaken but still significant for MI-SW and Act-SW (p-value<0.05), and MI-SW and MI-Ton (p-value<0.01) for the dysphagia patient. These results further validated the use of MI-SW and MI-Ton for dysphagia rehabilitation.

1 Introduction

1.1 Stroke dysphagia rehabilitation

Swallowing is essential for feeding in our daily living. Lesions in the disparate cortical regions following stroke or other neuro-degenerative diseases may lead to dysphagia, which is the inability to swallow or difficulty in swallowing [1]. Dysphagia occurs in approximately 30%-42% of acute stroke patients who require hospital admission [2] and [3]. Conventional treatment methods include the compensatory techniques such as changing the viscosity of food and tongue strengthening exercise [4]; and thermal-tactile and deep pharyngeal neuromuscular stimuation to heighten the sensory inputs [5]. Motor imagery is used to enhance motor learning and neurological rehabilitation in stroke patients [6] and [7], which may be an alternative treatment. Swallowing is a complex process that requires integration of the respiratory center and motor function of multiple cranial nerves, the autonomic system and esophagus.

We were among the first to investigate the use of MI-SW for dysphagia rehabilitation [3], [8] and [9]. The objectives were to investigate the use of MI-SW Brain-Computer Interface (BCI) to train the swallow functions in sub-acute stroke survivors with dysphagia. The investigation focused on two aspects: the extent of detectable MI-SW from stroke patients and the functional improvements measured prior and post-training. The experimental setup was shown in Fig. 1. It is difficult to imagine swallowing especially for dysphagia patients.

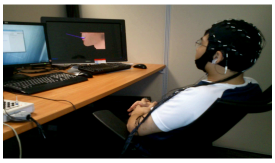


Fig. 1. A subject who was performing motor imagery of swallow training.

Tongue movements are swallow-related and share common activation cortical regions with swallowing [2]. Hence, we investigated the detectability of both MI-SW and motor imagery of tongue movements (MI-Ton) [3], [8] and [9], as validated by the high cross-validation (CV) and session-to-session classification accuracies. Thanks for the effective model selection criterion to address the non-stationarity of EEG signals [8] and [9]. This paper would focus on analyzing the correlations between MI-SW and MI-Ton to promote the use of MI-Ton model to detect MI-SW; and the correlations between MI-SW and actual swallow (Act-SW) to provide neural basis on the effectiveness of using MI-SW for dysphagia rehabilitation.

1.2 Materials

As an ongoing research and clinical trial, ten healthy subjects and a stroke dysphagia patient participated in the experiments at the current stage. The institutional review board approved the experimental protocol and clinical trial request. Written informed consents were given by the subjects. The healthy subjects were of ages of 35.9±7.7 years (mean±standard deviation), who do not have the respiratory, swallowing or neurological disorders. The stroke patient was a 56 year old ethnic Chinese male with severe brainstem haemorrhagic stroke involving the right hemipons and mid-brain. The experiments consisted of two sessions of MI-SW, one session of MI-Ton, and one session of Act-SW. Each session consisted of 80 trials of action and 80 trials of idle. The subject was advised to imagine swallowing a cup of water, or juice, or food for MI-SW, whereas the subjects swallowed his/her saliva during Act-SW. While the subject imagined protruding his tongue for MI-Ton and do nothing for idle [9]. The timing scheme of the protocol was shown in Fig. 2. The EEG measurements were obtained using Neuroscan EEG acquisition hardware. Two pairs of electrodes were taped beneath the sub-mental and infrahyoid muscle groups to monitor the electromyographic (EMG) activity. More details can be found in [9].

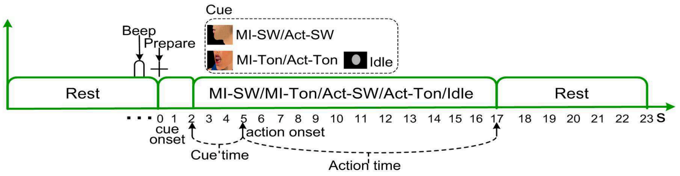


Fig. 2. Timing scheme of the experimental protocol.

2 Correlation Analysis of Task Pairs

'C3' and 'C4' were selected in the current analysis due to these regions are close to the activation regions reported in [1] and [2]. Significant ERD was observed at the primary motor cortex and primary somatosensory motor corex (e.g., broadmann areas 4 and 2) for water infusion and tongue thrust [1]. Further, the overlapping activation for swallow and tongue movements was observed in the supplementary motor area (SMA) [2].

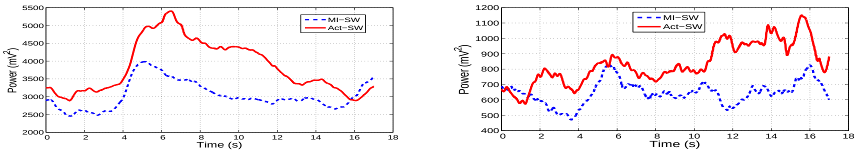
2.1 Grand averaged time-course analysis

The time course of EEG signals describes the characteristic patterns of EEG activity during the course of motor imagery and movements execution. To investigate the event-related synchronization/desynchronization (ERS/ERD) rhythmic activities, the EEG signal was taken from 2 s before onset of the visual cue to the end of action (i.e., [-2 17] s). The band powers of the EEG signal were averaged across trials and smoothed with a small moving window. Spike trial was identified if its mean power was larger than the mean power across all the trials plus a weighted standard deviation. The identified spike trials were then corrected with the mean of the clean trials. The time course of EEG rhythm for MI-SW versus Act-SW, and MI-SW versus MI-Ton was shown in Fig. 3. Note that the band powers were group-averaged for 10 healthy subjects (GA-H). The results clearly demonstrated the similarity between MI-SW and Act-SW, and between MI-SW and MI-Ton over the entire time course for both healthy subjects and the patient. The ERD/ERS reached its first peak immediately followed the disappearance of visual cue [10]. Further, the resemblance between MI-SW and Act-SW examined at 'C3' was not good as that examined at 'C4' for the stroke dysphagia patient due to the lesions at the right hemisphere.

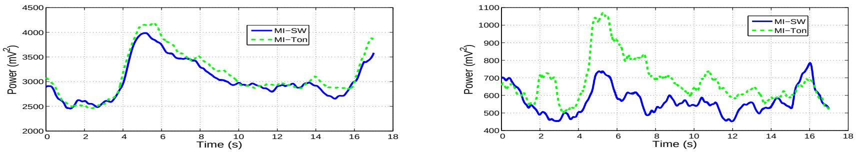
2.2 Correlation analysis based on bin-based spectral power

The bin-based accumulated spectral power was employed for robust correlation analysis of two pairs of tasks, i.e., MI-SW versus Act-SW, and MI-SW versus MI-Ton. The spectral power for the EEG signal of time segment t, at electrode e and filtered at frequency band f (denoted as $P_w(f,e,t)$) was calculated by

$$P_w(f,e,t) = \frac{1}{n_r}\sum_{i=1}^{n_r} F_w(i,f,e,t) \tag{1}$$



(a) GA-H (mu,C3) (b) 'sp' (mu,C4)



(c) GA-H (mu,C3) (d) 'sp' (mu,C3)

Fig. 3. Grand averaged time courses for MI-SW versus Act-SW ((a)(b)), and MI-SW versus MI-Ton ((c)(d)) for group-averaged of healthy subjects (GA-H) and patient ('sp').

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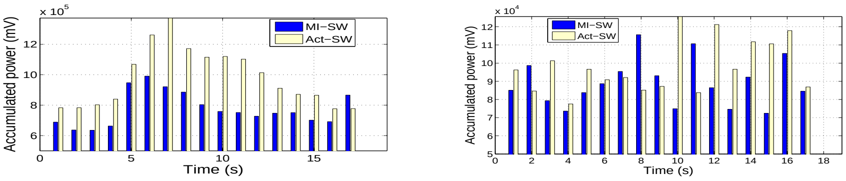
where $F_w(i, f, e, t)$ was the spectral power of ith trial, and n_r was total number of trials. The objective of employing bin-based analysis was to avoid small fluctuations in the power signals. Specifically, the averaged spectral power across trials was divided into n_b bins. The accumulated spectral power at the kth bin (denoted as $P_b(k, f, e, t)$) was calculated by

$$P_b(k, f, e, t) = \sum_{i=1}^{L_b} P_w(I_b(k), f, e, t) \tag{2}$$

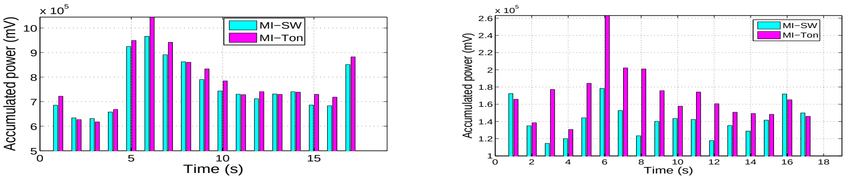
where the index i of kth bin ($I_b(k)$) was given by $I_b(k)$=(k-1)$\times L_b$+i; L_b was the bin length, which was given by L_b=$\lfloor |P_w|/n_b \rfloor$, $|X|$ gave the cardinality of X, and $\lfloor x \rfloor$ was the floor function. The pearson correlation coefficients ($\rho_r(m, n)$) between the bin-based accumulated spectral powers of two tasks m and n (denoted as $P_m(f, e, t)$ and $P_n(f, e, t)$) was computed by

$$\rho_r(m, n) = \frac{\sum_{i=1}^{n_b} D_m(i, f, e, t) D_n(i, f, e, t)}{\sqrt{\sum_{i=1}^{n_b} D_m(i, f, e, t)^2} \sqrt{\sum_{i=1}^{n_b} D_n(i, f, e, t)^2}} \tag{3}$$

$D_k(i, f, e, t)$ ($k \in \{m, n\}$) was given by $D_k(i, f, e, t)$=$P_k(i, f, e, t)$-$\bar{P}_k(f, e, t)$, where $\bar{P}_k(f, e, t)$ was the mean spectral powers across bins for the tasks of k. The analysis was based on the entire time segment (e.g., [-2 17]s) with the baseline power (e.g., [-2 0]s) being removed. The group-averaged bin-based powers and the correlation coefficients were shown in Fig. 4 and Table 1. The detailed correlation coefficients of MI-SW and MI-Ton for healthy subjects were shown in Table 2. The group analysis results in Table 1 demonstrated that MI-SW and MI-Ton, and MI-SW and Act-SW were significantly correlated with p-value<0.001. These results further validated the use of MI-SW or MI-Ton for dysphagia rehabilitation. It was also noticed that the correlation was decreased



(a) GA-H (mu, MI-SW Vs. Act-SW) (b) 'sp' (low-beta, MI-SW Vs. Act-SW)



(c) GA-H (mu, MI-SW Vs. MI-Ton) (d) 'sp' (mu, MI-SW Vs. MI-Ton)

Fig. 4. Accumulated powers for healthy subjects (GA-H) and patient 'sp'.

Table 1. Correlation coefficients for healthy (group-averaged) and patient.

Settings				Correlation coefficients (p-values)	
Channels	Frequency band	Subject category	Subject	MI-SW vs. Act-SW	MI-SW vs. MI-Ton
C3	mu	healthy	GA-H	0.91 (1.84e-7)***	0.99 (4.20e-17)***
		patient	sp	0.50(3.35e-2)*	0.83(2.23e-5)***
	low-beta	healthy	GA-H	0.89 (6.06e-7)***	0.98 (2.44e-12)***
		patient	sp	0.48(4.21e-2)*	0.81(4.62e-5)***

*, ** and *** denoted significant at p=0.05, 0.01 and p<0.001, respectively.

Table 2. Correlation coefficients between MI-SW and MI-Ton for healthy subjects.

Settings			Correlation coefficients (p-values)	
Channels	Subject category	Subject	low-beta ([13 16]Hz)	mu ([8 13]Hz)
C3	healthy	si	0.89(7.16e-7)***	0.96(1.92e-10)***
		lj	0.79(9.73e-5)***	0.73(6.09e-4)***
		hj	0.83(1.93e-5)***	0.95(2.86e-9)***
		aw	0.83(1.85e-5)***	0.79(9.77e-5)***
		cr	0.94(7.76e-9)***	0.93(3.05e-8)***
		wy	0.96(5.90e-10)***	0.84(1.35e-5)***
		cc	0.87(2.69e-6)***	0.86(4.89e-6)***
		mt	0.73(5.44e-4)***	0.50(3.52e-2)*
		zy	0.90(2.73e-7)***	0.96(4.42e-10)***
		cj	0.88(1.43e-6)***	0.88(1.55e-6)***

for the patient, nevertheless, the correlation was still significant (p-value<0.05). The detailed results shown in Table 2 further demonstrated that MI-SW and MI-Ton were strongly correlated examined at 'C3' for all the subjects at low-beta band (p-value<0.001) and mu band (p-value<0.05). The results supported the use of MI-Ton model to detect MI-SW. The high correlation values demonstrated that both MI-SW and MI-Ton suppressed mu and beta patterns during motor imagery [10].

3 Conclusions

In this paper, we investigated the correlations between MI-SW and MI-Ton, and correlations between MI-SW and Act-SW based on 10 healthy subjects and 1 dysphagia patient. The group analysis results of using bin-based spectral power demonstrated that MI-SW and MI-Ton, and MI-SW and Act-SW were strongly correlated (p-value<0.001, examined at 'C3') for both mu and low beta frequency bands. The correlation was decreased for the dysphagia patient, nevertheless, it was still significant for MI-SW and Act-SW (p-value<0.05) and MI-SW and MI-Ton (p-value<0.01). These results further validate the use of MI-SW and MI-Ton for dysphagia rehabilitation.

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