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Effects of force load, muscle fatigue and extremely low frequency magnetic stimulation on EEG signals during side arm lateral raise task

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Abstract

The aim of this study was to quantitatively investigate the effects of force load, muscle fatigue and extremely low frequency (ELF) magnetic stimulation on electroencephalography (EEG) signal features during side arm lateral raise task.

EEG signals were recorded by a BIOSEMI Active Two system with Pin-Type active-electrodes from 18 healthy subjects when they performed the right arm side lateral raise task (90 degrees away from the body) with three different loads (0kg, 1kg and 3 kg; their order was randomized among the subjects) on the forearm. The arm maintained the loads until the subject felt exhausted. The first 10s recording for each load was regarded as non-fatigue status and the last 10s before the subject was exhausted as fatigue status. The subject was then given a five-minute resting between different loads. Two days later, the same experiment was performed on each subject except that ELF magnetic stimulation was applied to the subject’s deltoid muscle during the five-minute resting period. EEG features from C3 and C4 electrodes including the power of alpha, beta and gamma and sample entropy were analyzed and compared between different loads, non-fatigue/fatigue status, and with/without ELF magnetic stimulation.

The key results were associated with the change of the power of alpha band. From both C3-EEG and C4-EEG, with 1kg and 3kg force loads, the power of alpha band was significantly smaller than that from 0kg for both non-fatigue and fatigue periods (all $p<0.05$). However, no significant difference of the power in alpha between 1 kg and 3kg was observed ($p>0.05$ for all the force loads except C4-EEG with ELF simulation). The power of alpha band at fatigue status was significantly increased for both C3-EEG and C4-EEG when compared with the non-fatigue status ($p<0.01$ for all the force loads except 3kg force from C4-EEG). With magnetic stimulation, the powers of alpha from C3-EEG and C4-EEG were significantly decreased than without stimulation (all $p<0.05$), and the difference in the power of alpha between fatigue and non-fatigue status disappeared with 1kg and 3kg force loads, The powers of beta and gamma bands and SampEn were not significantly different between different force loads, between fatigue and non-fatigue status, and between with and without ELF magnetic stimulation (all $p>0.05$, except between non-fatigue and fatigue with magnetic stimulation in gamma band of C3-EEG at 1kg, and in the SampEn at 1kg and 3kg force loads from C4-EEG). Our study comprehensively quantified the effects of force, fatigue and the ELF magnetic stimulation on EEG features with difference forces, fatigue status and ELF magnetic stimulation.

Keywords: Electroencephalography (EEG); Extremely low frequency (ELF) magnetic stimulation; Fatigue; Force; Lateral raise task.

1. Introduction

Electroencephalographic (EEG) signals have been recorded and analyzed during handgrip voluntary contraction task to understand their physiological association. Handgrip has been researched as part of the rehabilitation program for stroke patients with upper extremity movement disorder. However, from clinical application point of view, the handgrip task is not easy to perform for these stroke patients. Similar to the handgrip task, the side arm lateral raise task also generates isometric contractions, in which muscles generate tension without changing muscle length (Widmaier et al., 2010). Therefore, the brain activity with various motor tasks using the side arm lateral raise task should be studied to provide more evidence in the motor control. It is expected that performing the side arm lateral raise task could be easier in developing alternative rehabilitation programs for stroke patients in comparison with handgrip task.

Fatigue, defined as the decline in force-producing capacity may originate from central and peripheral mechanisms (Berchicci et al., 2013; Cifrek et al., 2009). Peripheral muscular fatigue during isometric contraction has been studied (Hussain et al., 2009), while central neuromuscular fatigue associated with reduced voluntary activation of muscle needs more consideration. It would be important to investgate the characteristics of EEG signal on motor cortex between fatigue and non-fatigue status. On the other hand, it has been reported that peripheral electrical stimulation could induce a significant reduction of muscle fatigue and increase general excitability of the motor cortex (Jubeau et al., 2007; Thompson et al., 2004; Charlton et al., 2003). However, in practice, neuromuscular electrical stimulation is unpleasant and even painful (Lesser et al., 1979). Therefore, more comfortable stimulation techniques need to be investigated. A published study has suggested that, using transcranial brain stimulation, the extremely low frequency (ELF) magnetic fields may produce an enhancement in cortical excitatory neurotransmission (Capone et al., 2009). Although the peripheral magnetic stimulation has been recently studied on nerve system, it has not been applied on peripheral muscle (Liu et al., 2013). Whether the peripheral ELF magnetic stimulation could affect the brain activities, leading to the feasibility of alleviating fatigue is still unknown.

It is well accepted that analysis of EEG signals is useful to measure the brain activity during the motor task. Different approaches have been applied to investigate the changes of EEG signal characteristics during motor tasks of varying muscle force or fatigue levels. Some studies have applied linear analysis, including the typical power spectra analysis (Rosenberg et al., 1989). The alpha, beta and gamma spectra of the EEG signal are associated with the excitability of the brain functional area. With the rapid development of non-linearity theory, non-linear approaches, including the complexity analysis, the analysis of Lyapunov exponent (Übeyli, 2009, Yao et al., 2009) and Fractal dimension (Liu et al., 2005a) have been used for quantifying nonlinear dynamics of EEG time series. Among them, one big advantage of complexity analysis is that it only requires relatively small number of points to describe the whole system, in comparison with other non-linear parameters such as Lyapunov exponent and correlation dimension which often need more than ten thousand data points. Sample entropy, as one of complexity measures, has been often used to quantify the amount of regularity and the unpredictability of fluctuations over time-series data. For instance, it has been used as a feature extraction method for detecting epileptic seizures in EEGs (Song and Liò, 2010). In this study, sample entropy, in combination with the powers of alpha, beta and gamma spectra of the EEG signal, are therefore applied for a comprehensive analysis of EEG signal characteristic changes with force load, fatigue, and ELF stimulation.

This study aimed to investigate the effects of different force loads on the forearm on the powers of alpha, beta and gamma and sample entropy derived from EEG signals during the side arm lateral raise task, and compare their difference between fatigue and non-fatigue status, and between with and without ELF magnetic stimulation.

2. Materials and methods

2.1 Subjects

18 healthy male subjects (aged 25±3years) without any history of neurological or psychiatric disorders were recruited. All subjects were right-handed, according to the Oldfield’s Edinburgh inventory (Oldfield, 1971). Informed and written consent was obtained from the volunteers after the aims, potential benefits and risks were explained. The study was carried out according to the Declaration of Helsinki of the World Medical Association, and approved by the Local Ethics Committee of Beijing University of Technology.

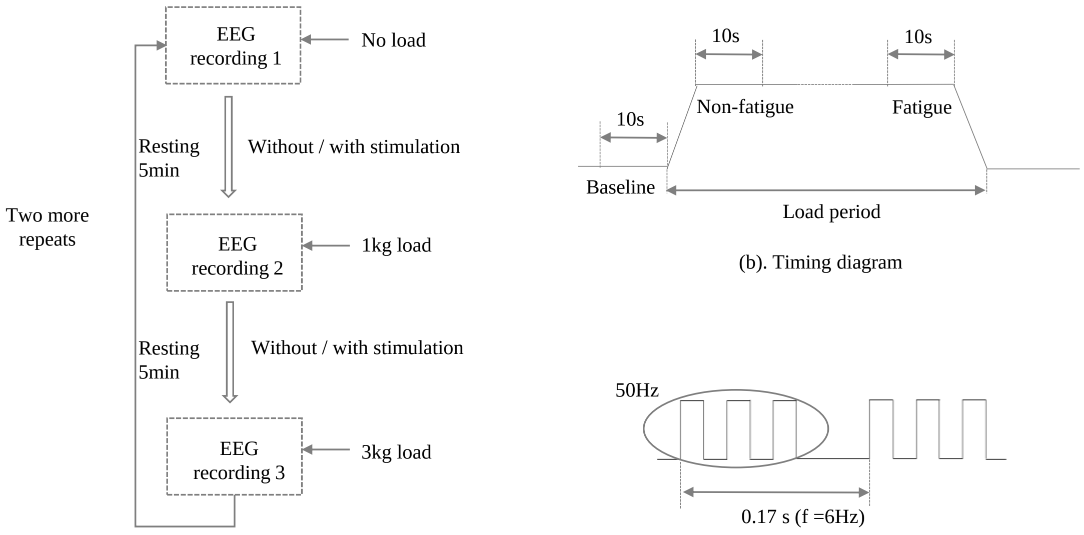
2.2 Experimental devices

2.2.1 EEG recording device

32-channel EEGs were recorded with a sampling rate of 1024Hz from the BioSemi ActiveTwo (BioSemi, Netherlands) system using pin-type active-electrodes mounted in a headcap. BioSemi system is a bio-potential measurement system up to 280-channel with 24-bit resolution. Common Mode Sense (CMS) active electrode and driven Right Leg (DRL) passive electrode were selected as ground electrodes according to system specification. These 2 electrodes form a feedback loop, which drives the averages potential of the subject (the common mode voltage) as close as possible to zero ADC reference voltage.

2.2.2 Magnetic stimulation device

A magnetic stimulation device was developed in our lab. Four-circular coil was designed and the stimulus signal was generated and driven by an ARM microprocessor and power amplifier. The intensity and frequency of the stimulation were adjustable between 10-40 mT and 1-10 Hz, respectively. In this study, their corresponding values were 30 mT and 6 Hz. Within each simulation cycle, there were three 50Hz pulses, as shown in Fig.1(c).



(a). Measurement protocol

(b). Timing diagram

(c). Stimulus signal

Fig.1 Measurement protocol, timing diagram and stimulus signal

2.3 Experimental procedure

During the experiment, the subjects were asked to sit comfortably with the right arm side lateral raise (90 degrees away from the body). Three different loads (0kg, 1kg and 3kg) on the forearm were used to generate the isometric force at the upper limb muscle. The sequence order of the loads was randomized among the subjects.

While the arm was laterally raised with one of the three loads, EEG signals were digitally recorded and saved for off-line analysis until the subject was exhausted. The subject was then given a five-minute rest between different loads. The same procedure was then repeated twice with a total of 9 EEG recordings, as shown in Fig.1 (a).

Two days later, the same experiment was repeated with additional 9 EEG recordings from each subject, except that the magnetic stimulation was applied to the subject’s deltoid muscle during the five-minute resting period.

2.4 EEG signal pre-processing and analysis

In this study, EEG signals from electrodes C3 and C4 were further analyzed because they were positioned over sensorimotor regions which have close relationship with motor control (Liu et al., 2007, 2005b). Next, for the EEG signal recorded at a certain load, the first 10s recording was regarded as non-fatigue status and the last 10s before the subject was exhausted as fatigue status, as shown in Fig.1 (b). The 10s baseline EEG before each loading task and the two segments of 10s EEG signals during the loading task were extracted for further analysis. There 54 segments in total for each subject (3 segments from each recording 3 repeats; 3 loads; with and without stimulation)

After the signal segmentation, the noise was removed from the EEG with a 0.5~45 Hz band-pass filter since the main frequency band of EEG signals are related to alpha (7-13Hz), beta (13-30Hz) and gamma (30-45Hz) bands. Next, the influences of blinks and eye movements were effectively identified and corrected using independent component analysis.

Current source density transformations were then applied to reduce the effect of volume conduction on EEG signals.

2.5 EEG features

EEG features, including the powers of alpha, beta and gamma and sample entropy (SampEn, a nonlinear feature), were calculated in this study. They were selected because they can reflect the excitability of the brain functional area and the variety of complexity.

Power of EEG within a given frequency band

Power spectra density was calculated by the method of averaged periodograms. The 10s EEG signal sequence x(n), n=0, 1, … , N-1, was divided into K segments with J samples overlapping, and each of the segment has L samples. The recording was subdivided as: xi(n)=x(n+i(L-J)), i=0, 1, …, k-1, n=0, 1 , …, L-1. The periodogram of the K segments was described by equation (1). In this study, N=10240, L=2048, K=9, J=1024.

$$S_x(e^{jw}) = \frac{1}{KL}\sum_{i=0}^{K-1}\left|\sum_{n=0}^{L-1} x_i(n+i(L-J))e^{-jwn}\right|^2 \qquad (1)$$

Next, the power in the frequency band of alpha (7-13Hz), beta (13-30Hz) and gamma (30-45Hz) was calculated respectively by equation (2):

$$E = \sum_{f=f_1}^{f_2} s_{x(e^{jw})} \qquad (2)$$

where f_1 and f_2 represent the lowest and the highest frequency within the frequency band $[f_1, f_2]$.

Sample entropy

Entropy is a non-linear measurement of the complexity of EEG signal. For a given embedding dimension m, tolerance r and number of data points N, SampEn(m, r, N) is the negative logarithm of the probability that if two sets of simultaneous data points of length m have distance<r then the two sets of simultaneous data points of length m+1 also have distance<r.

For the time-series EEG of length N= $\{x_1, x_2, x_3, \ldots, x_N\}$ with a constant time interval τ, we defined a template vector of length m, such that $X_m(i)= \{x_i, x_{i+1}, x_{i+2}, \ldots, x_{i+m-1}\}$ and the distance function $d[X_m(i), X_m(j)]$ ($i \neq j$). We counted the number of vector pairs in template vectors of length m and m+1 having $d[X_m(i), X_m(j)] < r$ and denoted it by B and A respectively. The sample entropy was defined as:

SampEn= -log(A/B) (3)

A= number of template vector pairs having d[Xm+1(i), Xm+1(j)] < r of length m+1

B= number of template vector pairs having d[Xm(i), Xm(j)] < r of length m

The value of m was set to be 2 and the value of r to be 0.2×stand deviation (std) of 18 subjects at the same status.

It could be seen from the definition that A has a value smaller or equal to B. Therefore, SampEn (m, r, N) is always either be zero or positive value. A smaller value of SampEn indicates better self-similarity in EEG.

2.6 Data and statistical analysis

The median, lower and upper quartiles of EEG features (the powers in the different frequency bands and SampEn) were calculated, separately for different force loads, for fatigue/non-fatigue status and without/with ELF stimulation. ANOVA test was performed using software SPSS 22 (SPSS Inc.) to assess the effects of different forces, fatigue/non-fatigue, with/without stimulation on EEG features (between different days), and their interaction effects. The ANOVA test was independently performed for the baseline EEGs before the tasks and the EEG segments during loading tasks. Post-hoc multiple comparisons were applied to compare the effects of different force loads，fatigue/non-fatigue and with/without stimulation and their interactions. A P-value below 0.05 was considered statistically significant.

3. Results

3.1 Lateral raise task duration

The raise duration varied between subjects and between different force loads. As shown in Fig.2, the lateral task duration decreased significantly with increased force loads (P<0.001). However, the duration was not significantly different between with and without stimulation (P>0.05).

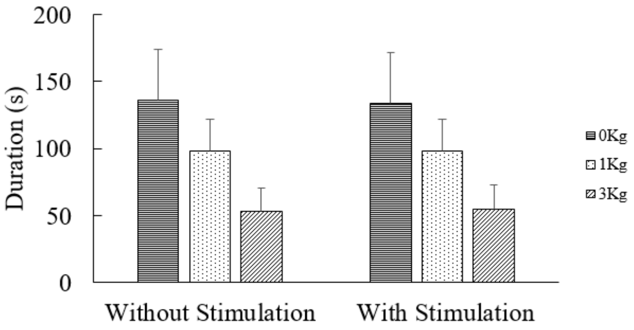


Fig. 2 Lateral raise task duration with different force loads, separately between with and without ELF stimulation. The data was presented as mean±SD.

3.2 Overall of change EEG features

The powers of alpha, beta and gamma bands and SampEn of baseline EEG segments were not significantly different between repeat measurements, between different force loads, and between with and without magnetic stimulation (all p>0.05), demonstrating that baseline EEG features of resting interval was not statistically different across different conditions.

Table 1 and 2 give the overall results of all the EEG features with their values of median, lower and upper quartiles, separately for different force loads, for the fatigue/non-fatigue status and without/with stimulation. The key effects are summarized below.

Table 1. Summary of C3-EEG features, separately for different force loads, for the fatigue/non-fatigue status and without/with stimulation. The data was presented as median (lower quartiles ~ upper quartiles).

Electrode --C3	Force (kg) Feature	0		1		3	
		Non-fatigue	Fatigue	Non-fatigue	Fatigue	Non-fatigue	Fatigue
Without stimulation	Power-Alpha	15.7 (1.9~39.8)	19.8 ** (6.6~53.3)	5.3 (1.6~11.7)	10.1 ** (1.9~21.0)	2.9 (1.9~4.2)	3.9 (2.3~4.7)
	Power-Beta	2.0 (1.2~7.8)	1.8 (1.1~8.1)	1.9 (1.4~7.4)	2.0 (1.2~9.6)	2.1 (1.3~8.5)	2.2 (1.0~8.4)
	Power-Gamma $(\times 10^{-4})$	3.0 (2.0~14.9)	3.5 (2.5~20.1)	3.9 (2.2~25.9)	2.6 (2.0~21.2)	3.7 (2.8~25.6)	4.6 (2.5~53.8)
	SampEn	0.33 (0.31~0.33)	0.32 (0.30~0.33)	0.32 (0.31~0.33)	0.32 (0.28~0.32)	0.31 (0.29~0.33)	0.30 (0.28~0.32)
With stimulation	Power-Alpha	5.3 (3.7~6.5)	6.5 * (4.9~7.9)	1.7 (1.3~2.3)	1.7 (1.2~2.2)	1.8 (1.2~2.4)	1.7 (1.2~4.4)
	Power-Beta	2.4 (1.4~6.1)	2.4 (1.1~4.0)	1.7 (1.2~5.6)	1.8 (1.2~3.5)	2.0 (1.1~5.2)	1.8 (1.3~5.3)
	Power-Gamma $(\times 10^{-4})$	3.3 (2.6~6.3)	16.5 * (12.0~45.0)	3.1 (2.1~4.8)	18.4 * (8.8~30.0)	9.6 (6.3~22.1)	8.5 (4.3~15.4)
	SampEn	0.33 (0.27~0.36)	0.30 (0.28~0.35)	0.31 (0.29~0.33)	0.29 (0.27~0.33)	0.31 (0.28~0.33)	0.29 (0.28~0.32)

$^{*}p<0.05$; $^{**}p<0.01$. Comparison the same force level at non-fatigue and fatigue.

Table 2. Summary of C4-EEG features, separately for different force loads, for the fatigue/non-fatigue status and without/with ELF stimulation. The data was presented as median (lower quartiles ~ upper quartiles).

Electrode --C4	Force (kg) Feature	0		1		3	
		Non-fatigue	Fatigue	Non-fatigue	Fatigue	Non-fatigue	Fatigue
Without stimulation	Power-alpha	33.1 (10.4~127.3)	73.1 * (12.5~187.2)	11.5 (4.9~27.3)	16.6 * (6.9~44.0)	12.4 (8.1~17.2)	15.4 * (11.0~29.5)
	Power-beta	8.1 (5.6~16.6)	9.2 (4.8~13.6)	9.5 (4.6~14.5)	8.6 (5.6~14.8)	8.5 (5.7~14.2)	9.6 (6.7~14.2)
	Power-gamma $(\times 10^{-4})$	13.6 (6.6~22.7)	14.5 (7.5~19.4)	12.3 (6.8~22.5)	11.4 (5.8~20.7)	11.6 (5.5~17.2)	9.9 (6.9~23.3)
	SampEn	0.34 (0.30~0.36)	0.33 (0.32~0.36)	0.34 (0.31~0.36)	0.33 (0.29~0.35)	0.32 (0.28~0.35)	0.33 (0.30~0.35)
With stimulation	Power-alpha	20.7 (16.7~28.3)	30.8 * (16.5~34.3)	6.0 (5.0~7.7)	6.2 (4.6~9.2)	10.3 (6.5~12.9)	12.1 (8.1~14.7)
	Power-beta	9.8 (5.2~32.1)	7.9 (5.5~17.0)	8.2 (6.1~18.5)	8.1 (4.8~17.5)	8.4 (4.7~15.4)	9.4 (6.0~17.7)
	Power-gamma $(\times 10^{-4})$	2.8 (2.3~6.6)	17.4 * (10.0~44.8)	10.8 (5.6~25.6)	7.9 (5.3~20.8)	11.5 (6.5~40.4)	11.2 (7.9~16.3)
	SampEn	0.34 (0.29~0.37)	0.34 (0.32~0.37)	0.33 (0.31~0.36)	0.29 * (0.28~0.32)	0.33 (0.28~0.35)	0.29 * (0.28~0.32)

$^{*}p<0.05$. Comparison the same force level at non-fatigue and fatigue.

3.3 Effect of force on EEG features

3.3.1 Effect of force on power spectra and SampEn without magnetic stimulation

Fig.3 (a+c) and Fig.4 (a+c) show the powers in alpha and gamma bands from C3-EEG and C4-EEG when there was no magnetic stimulation during the resting period. Their difference between different force loads are given for both non-fatigue and fatigue periods.

From both C3-EEG and C4-EEG, the powers in alpha band with 1kg and 3kg force were significantly smaller than 0kg for both non-fatigue and fatigue periods (all $p<0.05$). However, there was no significant difference of the power in alpha between 1 kg and 3kg (all p>0.05). The powers of beta and gamma bands and SampEn were not significantly different between all the different force loads (all p>0.05).

3.3.2 Effect of force on power spectra and SampEn with magnetic stimulation

Fig.3 (b+d) and Fig.4 (b+d) show the powers in alpha and gamma band from C3-EEG and C4-EEG with magnetic stimulation during the resting period.

From both C3-EEG and C4-EEG, the powers of alpha band with 1kg and 3kg force were significantly smaller than 0kg for both non-fatigue and fatigue periods (all p<0.01). For the comparison of EEG features between 1kg and 3kg force, it was observed that only the power of alpha of C4-EEG from 3kg force was significantly larger than 1kg force at both non-fatigue and fatigue status (both p<0.01). There was no significant difference between different force levels for the other EEG features (all p>0.05).

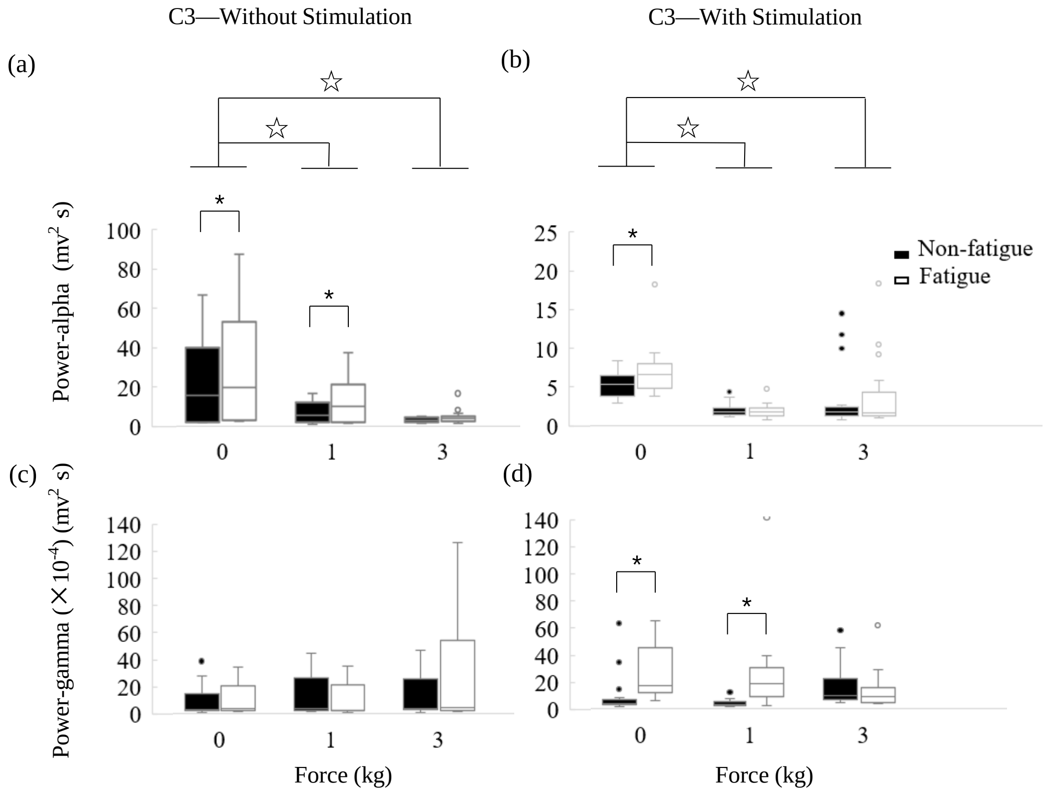


Fig.3 Effects of force and fatigue on the powers in alpha and gamma bands from C3-EEG, separately for with and without stimulation during resting periods, and between different force loads. The data was presented with median, lower and upper quartiles.

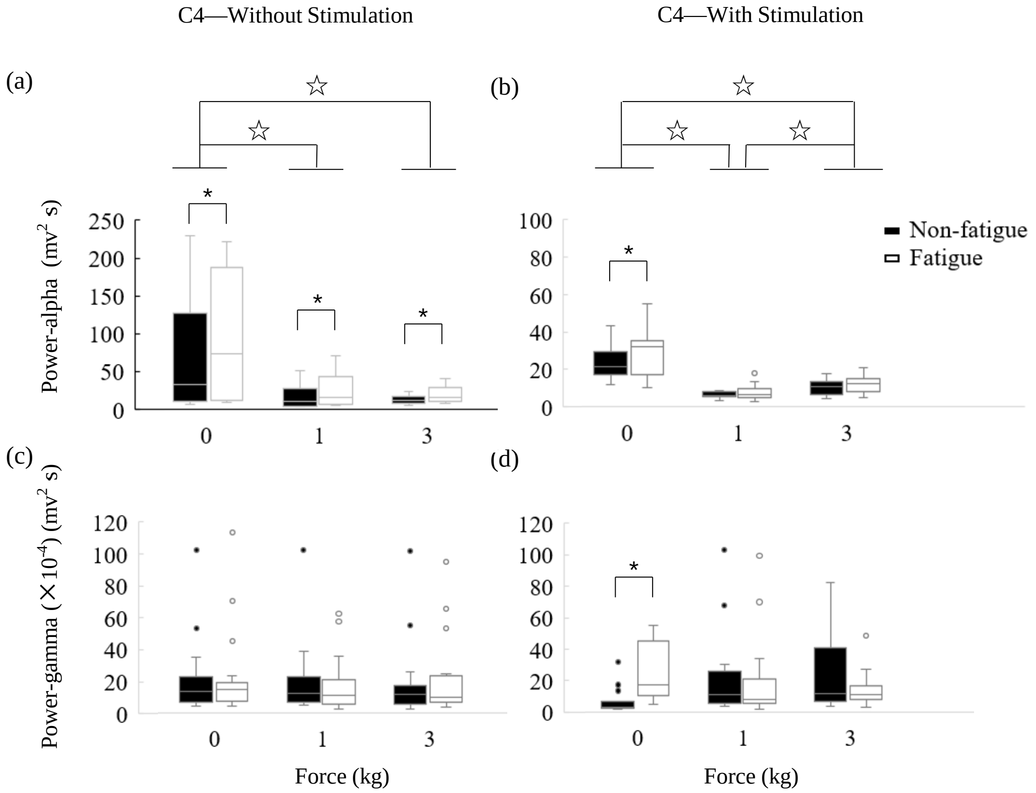


Fig.4 Effects of force and fatigue on the powers in alpha and gamma bands from C4-EEG, separately for with and without stimulation during resting periods, and between different force loads. The data was presented with median, lower and upper quartiles.

3.4 Effect of fatigue on EEG features

3.4.1 Effect of fatigue on power spectra and SampEn without magnetic stimulation

In the absence of magnetic stimulation, as shown in Fig.3 (a+c) and Fig.4 (a+c), when compared with the non-fatigue status, the powers of alpha band from both C3 and C4 electrodes were significantly increased at fatigue status ($p<0.01$ for all the force loads except 3kg force from C3-EEG). There was no significant difference between non-fatigue and fatigue status for the power of beta and gamma bands, and for the SampEn (all $ps>0.05$).

3.4.2 Effect of fatigue on power spectra and SampEn with magnetic stimulation

In the presence of magnetic stimulation, as shown in Fig.3 (b+d) and Fig.4 (b+d), the key results were that, for both C3-EEG and C4-EEG, the difference in power of alpha and gamma bands between fatigue and non-fatigue status was only observed at 0kg force load (all $p<0.05$). There was no significant difference between non-fatigue and fatigue for the other EEG features (all $p>0.05$, except in gamma band of C3-EEG at 1kg, and the SampEn at 1kg and 3kg force loads from C4-EEG).

3.5. Comparison of the different effects of force and fatigue on EEG features with and without magnetic stimulation

As shown in Fig.3 and Fig.4, with magnetic stimulation during the resting period, at all levels of force loads, the powers of alpha from C3-EEG and C4-EEG were significantly decreased than with stimulation (all $p<0.05$). More importantly, with magnetic stimulation, the difference between fatigue and non-fatigue status in the power of alpha band only existing with 0 kg force load, and then disappeared with 1kg and 3kg force loads.

There were no significant differences in the power of beta and gamma bands and SampEn between with and without stimulation (all $p>0.05$, except the SamEns at 1kg and 3kg force from C4-EEG at fatigue status were significantly decreased).

3.6. Interaction effects of force, fatigue and magnetic stimulation on EEG features

No interaction effect was obtained between loads, fatigue and stimulation (all $p> 0.05$ for the powers of alpha, beta and gamma bands and SampEn from both C3 and C4 EEGs).

Discussion and conclusion

This study quantitatively investigated the baseline EEG features (the powers of alpha, beta and gamma bands and SampEn) and the changes of these EEG features with different force loads on the forearm during the side arm lateral raise task. The difference between fatigue and non-fatigue status and the effect of magnetic stimulation on these changes were also quantified.

In this study, similar patterns have been observed in EEG features change with force loads and fatigue, suggesting that both contralateral and ipsilateral primary sensorimotor cortex involved in the task modulation. This phenomenon of ipsilateral involvement has been previously reported, where it has been shown that the fMRI signal of the contralateral sensorimotor area increased with the signal of the ipsilateral sensorimotor area at the same time during the intermittent submaximal fatigue muscle contractions, (Crone et al., 1998; Dettmers et al., 1995; Ehrsson et al., 2000; Tanaka et al., 2011).The previous study (Paus et al. 2001) have demonstrated that peripheral electrical stimulation could led to the increase of corticospinal excitability without increased cortical inhibition, which may enhance the reorganization of the motor cortex or strengthening some of the synaptic connections within a certain cortical area thereby minimizing the extent of central fatigue. Concurrently, the cutaneous and muscle sensory afferent activity is fed back in the central nervous system (CNS) and plastic changes can be induced in the motor cortex. Thus, the peripheral stimulation by the integration of descending and afferent inputs in the CNS may modulate cortical activity (Thompson et al., 2004; Jubeau et al., 2007).

Regarding the force effect on EEG features, the key finding is that the power in alpha band at 1kg and 3kg force were significantly smaller than 0kg regardless of whether fatigue was involved in the motor performance. The reason could be that the number of neurons participating in controlling force increase with force from 0 to 1 kg. Alpha band activity is often described as a form of cortical idling with its amplitude inversely related to the activated number of neuronal populations during cognitive and sensorimotor processes (Baumeister et al., 2012; Niedermeyer et al., 2005). If the participant keeps the arm elevated, more or different motor units will be required as an expression of forced effort, leading to the decrease of alpha. Meanwhile, the increase of fatigue leads to the raise of alpha activity. Therefore, it is speculated that the change of alpha activity varies across different period of motor task. This could be explained by the combined effects of the abovementioned two physiological mechanisms. We also found that there was no significant difference in alpha band between

1kg and 3kg, indicating that, with the increase of force from 1kg to 3kg, only a minor amount of if any additional neurons were activated.

For the comparison of EEG features between fatigue and non-fatigue status, the increased power values of alpha band with muscle fatigue suggests that, with the reduction of cortical excitability, the brain may fail to fully activate the performing muscles. Our results agreed with a previously published study, where a significant increase in the power of alpha of EEG was observed as a result of fatigue induced by repetitive handgrip maximal voluntary contractions (Liu et al., 2005b). In addition, Ribeiro et al. (Ribeiro et al., 2007) reported that fatigue impairs the proprioceptive and kinesthetic properties of muscles by changing the threshold of muscle spindle discharge. Consequently, that may lead to an altered afferent feedback (Pedersen et al., 1999), and a decrease in excitatory input to the primary motor cortex induced a decrease in the responsiveness of the motoneurons in the primary motor cortex through a change in their motoneuron adaptation.

With ELF stimulation during the resting period, it was noticed that the power values of alpha band were smaller than those without stimulation. This can be explained by the fact that the stimulation increased the excitability of the motor cortex and thus reduced the alpha activity. Earlier study also showed that the somatosensory evoked potential related to median nerve stimulation can be evoked by peripheral magnetic stimulation (Biller et al., 2011). In addition, it has been observed that, with stimulation, the power of gamma frequency band at fatigue were greatly higher than non-fatigue, especially from C3-EEG, which suggested the activation may shift from lower to higher frequency band. However, whether the shift of cortex activation from lower (alpha) to higher frequency (gamma) is continuous or discrete needs to be investigated in the further study. The previous study also suggested that local regional activation by an external stimulus via a sensory pathway entailed attenuated alpha and increased gamma oscillatory activity (Doesburg et al. 2015). More importantly, with magnetic stimulation, the difference in the power of alpha between fatigue and non-fatigue status disappeared with 1kg and 3kg force loads, providing scientific evidence on its potential clinical application to reduce fatigue.

The present work has the following limitations. Firstly, the fatigue was subjectively determined by each individual, leading to big variation in the observed EEG features. A future study could include a consistent criterion for fatigue determination to reduce the subjective determination. Secondly, a questionnaire should be filled by participants and used to assess whether the applied weights or other factors resulted in a different subjective impression with and without stimulation. Thirdly, the effect of using different stimulus modes including the waveform, intensity and frequency, could be investigated, as well as the comparison with simultaneous EEG recording during magnetic stimulation. Fourthly, only electrodes C3 and C4 for cortical sensorimotor regions were used for preliminary analysis. In the future, Cz over the supplementary motor area, Fz over the central frontal area and Pz over the central parietal field could also be investigated to analyze the movement-related EEG signals comprehensively. Finally, as a preliminary study, only male subjects were recruited because it is more convenient to place electrodes on their head with short hair. Nevertheless, a published study (Carrier et al., 2001) has investigated the gender difference of EEG features, where they concluded that there was no gender difference.

In conclusion, our study comprehensively quantified the effects of force, fatigue and the ELF magnetic stimulation on EEG features, demonstrating the brain activation changes with arm force modulation, fatigue status and ELF magnetic stimulation.

Compliance with Ethical Standards: All procedures performed in studies involving human participants were in accordance with the ethical standards of local ethics committee of Beijing University of Technology and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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