Brain Imaging and Behavior (2019) 13:1324–1332
https://doi.org/10.1007/s11682-018-9948-3

ORIGINAL RESEARCH

Increased interhemispheric synchrony underlying the improved athletic performance of rowing athletes by transcranial direct current stimulation

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Published online: 25 August 2018

Abstract

To explore the mechanism of transcranial direct current stimulation (tDCS) on the improved performance of professional rowing athletes. Twelve male professional rowing athletes were randomly divided into two groups (low-stimulation group, 1 mA, $n = 6$; high-stimulation group, 2 mA, $n = 6$), and they accepted tDCS for two consecutive weeks while undergoing regular training (20 min each time, five times a week, totally ten times). The assessments of depression, anxiety, executive function, fatigue perception, lactate threshold power (LTP) and isokinetic muscle strength as well as the collection of functional magnetic resonance imaging (fMRI) data were performed at baseline and at follow-up (the end of the fourth week). The voxel-mirrored homotopic connectivity (VMHC) value was calculated in the whole brain. After stimulation, there were significant increases in executive function and athletic performance. Analysis of variance (ANOVA) analysis indicated time factor, stimulation intensity factor had a main effect on LTP and 60RK, respectively. There was no significant difference of VMHC value between the high- and low-stimulation groups at baseline. Comparing with low-stimulation group, significant increased VMHC values of the bilateral middle temporal gyrus (MTG), precentral gyrus and superior frontal gyrus (SFG) were found in high-stimulation group at follow-up. Correlation analyses showed that in high-stimulation group, the VMHC values of bilateral MTG and SFG were both positively correlated with the measures of athletic performance. tDCS may contribute to the improvement of athletic performance in professional rowing athletes, and the increased interhemispheric coordination may be involved in the mechanism of the improved athletic performance.

Keywords tDCS · Rowing athletes · Athletic performance · VMHC

Introduction

On the first day of the Rio Summer Olympics in 2016, Science Daily reported that a handful of athletes used an unbanned brain stimulation technique to improve their athletic performance, that resulting in long-term discussions about brain doping among the media.

This technology is called transcranial direct current stimulation (tDCS), which is a noninvasive brain stimulation technique that uses weak direct electrical currents (usually 1–2 mA) via two saline-soaked sponge electrodes placed on the scalp. Researchers have demonstrated that tDCS anode and cathode can simultaneously activate and suppress the cortical excitability of targeted brain areas (Reis and Fritsch 2011). Nitsch and Paulus found that these effects could persist for up to 90 min after a stimulation of 9–13 min (Nitsche and Paulus 2001). The degree and duration of the after-stimulation effects of tDCS on cortical excitability are believed to depend upon the

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dosage of current delivered (Nitsche and Paulus 2000; Williams et al. 2013). The acute tDCS is suggested to be both cheap and safe and has only limited side effects (Poreisz et al. 2007). In a previous study, good feasibility and tolerance of tDCS were also showed in children (Andrade et al. 2013).

This technique has already been studied extensively as a treatment for neuropsychiatric disorders, such as depression (Meron et al. 2015), chronic pain (Antal and Paulus 2010), Alzheimer's disease (Boggio et al. 2011), Parkinson's disease (Benninger et al. 2010), stroke (Bolognini et al. 2011) and also has an effect on the regulation of appetite sensations in overweight adults (Montenegro et al. 2012). In healthy individuals, the effects of tDCS have been demonstrated in such as arithmetic ability, visuo-motor learning and balance control (Antal et al. 2004; Foerster et al. 2017; Grabner et al. 2015). In recent years, it was reported that tDCS could also improve cognitive function and athletic performance of athletes (Reardon 2016).

Rowing is a paddle sport which not only requires good explosive and stamina power, but also needs preferable balance ability. During the single-oar paddling motion, continuous body adjustment and compensation are needed to maintain balance, and that require athletes have high degree of flexibility and coordination (Lee et al. 2018; Weber et al. 2014). Voxel-mirrored homotopic connectivity (VMHC) is used to reflect the synchrony of spontaneous brain functional activities between symmetrical regions in bilaterally hemispheric architecture and is highly related to bilateral brain information communication and high-order cognitive domains especially in executive function (Zuo et al. 2010). While, the flexibility and coordination are believed to depend in part on bilateral brain information communication and high-order cognitive function. So, we inferred that interhemispheric coordination may play an important role in the athletic performance of the rowing athlete (Heppe et al. 2016; Wang et al. 2015).

As far as we know, there is no study to explore the possible relationship between the VMHC and athletic performance influencing by tDCS in rowing athlete. In the present study, we first investigated the longitudinal variation features of athletic performance, executive function and VMHC in the rowing athlete. Secondly, we explored the differences of above features in the two stimulation intensity groups. Furthermore, to further study the underlying mechanism of the improved athletic performance.

Methods

Subjects

With the approval of the Medical Ethics Committee for Clinical Research of Zhongda Hospital Affiliated to Southeast University, 12 rowing athletes (all males) were recruited in this study. They were all 16 years old and had trained for more than 3 years. All subjects were naturally and unequivocally right-handed and all blinded for the stimulation intensity. Subjects were excluded with any serious somatic diseases, mental illness or family history, history of alcohol or substance dependence, history of epilepsy, and contraindications to MRI scanning. All subjects provided written informed consents.

Experimental paradigm

The research included three steps. First, the demographic data were recorded and the depression, anxiety, executive function, fatigue perception, lactate level as well as isokinetic muscle strength were measured at baseline. Meanwhile, all subjects underwent functional magnetic resonance imaging (fMRI). Second, 12 subjects were randomly divided into two groups and accepted a two-week tDCS for 20 min each time (five times a week, totally ten times) with stimulation intensity of 1 mA (low-stimulation group) or 2 mA (high-stimulation group), respectively. Stimulation was delivered by a specialized device which has two 3×5 cm^2 rubber electrodes with a saline-soaked sponge. The anode stimulation was put over the left primary motor cortex (M1) and the cathode on the contralateral shoulder. After a rest for two weeks, the measurements of step one were repeated at the end of the fourth week. Twelve subjects all completed this study while undergoing regular training.

Neuropsychological tests

All subjects were evaluated for depression by the Patient Health Questionnaire-9 (PHQ-9) (Kroenke 2012), anxiety by the Generalized Anxiety Disorder-7 (GAD-7) (Spitzer et al. 2006), executive function by Stroop A, Stroop B, Stroop C (Koss et al. 1984) and Trail-Making Test-A (TMT-A), Trail-Making Test-B (TMT-B) (Gordon 1972), and fatigue perception by the Fatigue Scale-14 (FS-14), which includes mental fatigue (MF) and physical fatigue (PF) (Chalder et al. 1993).

Lactate threshold measures

The point at which the activities of the muscle become anaerobic and the lactic level has a sudden rise during exercise is called lactate threshold (LT). LT is usually represented by the corresponding strength when the lactic level reaches 4 mmol/L (Beneke 1995).

According to the method recommended by the International Rowing Federation (IRF), we selected an indoor dynamometer (Concept2, UAS) to measure the power of pulling the oars with a distance of 1000 m. The initial power was 170 watts with an increase of 30 watts per level. Subjects had a 30-s intermission before the subsequent level. During every intermission, a portable blood lactic tester (EKF Blood Lactate, German) was used to test blood acid level by collecting ear blood. After five levels of incremental experimentation, we drew the curve of power-acid and determined the corresponding power when the lactic level reached 4 mmol/L, that is lactate threshold power (LTP).

Isokinetic muscle strength evaluation

The quadriceps and the latissimus dorsi are the most important muscles for rowing. Isokinetic dynamometry provides an objective measure of muscle strength and the two most common angular velocities used are 60°/s and 180°/s. Peak torque during isokinetic movements is a good measure of maximal strength (Undheim et al. 2015). In this study, we used an isokinetic dynamometer (Biodex Medical Systems 4, USA) to measure the quadriceps and latissimus dorsi strength in the extended process of bilateral knee and shoulder joints. First, these athletes were asked to perform 5 slow traits at 60 °/s. We recorded the highest peak torque as the index of explosive force. 60LS, 60RS, 60LK, 60RK represent the highest peak torque of the left shoulder, right shoulder, left knee and right knee joints at 60 °/s, respectively. Then, the participants were indicated to do 10 quick traits at 180 °/s. We recorded the average peak torque as the index of stamina force. M180LS, M180RS, M180LK, M180RK represent the mean peak torque of the left shoulder, right shoulder, left knee and right knee joints at 180°/s, respectively. Each athlete was required to try their best to do every movement.

Brain image acquisition

All subjects underwent MRI scans using a Siemens 3.0 Tesla scanner (Erlangen, Germany) with a standard head coil at the Affiliated Nanjing Brain Hospital of Nanjing Medical University. Subjects were instructed to lie supine with their heads snugly fixed by a belt and foam pads to avoid or minimize head motion. All subjects were asked to relax, to remain awake, to keep their eyes closed and not to think of anything specific during scanning. High-resolution 3-dimensional T1-weighted scans were acquired via prepared fast spoiled gradient echo sequences using the following parameters: repetition time (TR) = 1900 ms, echo time (TE) = 2.48 ms, flip angle (FA) = 9°, acquisition matrix = 256 × 256, field of view (FOV) = 250 × 250 mm^2, thickness = 1.0 mm, gap = 0 mm, 176 slices and an acquisition time of 4 min 18 s. The parameters of the resting-state fMRI(RS-fMRI) were as follows: TR = 2000 ms, TE = 25 ms, FA = 90°, acquisition matrix = 64 × 64, FOV = 240 × 240 mm^2, thickness = 4.0 mm, gap = 0 mm, 36 axial slices, 226 volumes, 3.75 × 3.75 mm^2 in-plane resolution parallel to the anterior-posterior commissure line and an acquisition time of 8 min 6 s.

Functional image preprocessing

The functional images were preprocessed utilizing the Data Processing Assistant for Resting-State Function (DPARSF 2.3 advanced edition) MRI toolkit (Yan and Zang 2010), which synthesizes procedures based on a statistical parametric mapping software package (SPM8, http://www.fil.ion.ucl.ac.uk/spm) and the Resting-State Functional MR imaging toolkit (REST, http://www.restfmri.net) (Song et al. 2011). The first 10 time points were discounted in order to ensure stable-state longitudinal magnetization and adaptation to inherent scanner noise. The remaining images were processed sequentially according to the following steps: (1) slice-timing with the 36th slice as the reference slice, corrected for temporal differences and head motion (participants with head motion greater than 1.5 mm of maximum displacement in any direction (x, y, or z) or 1.5° of angular motion were ruled out from the present study); (2) co-registered T1 to functional images and then reoriented; (3) for spatial normalization, T1-weighted anatomic images were segmented into white matter, grey matter and cerebrospinal fluid components and then normalized the images to the Montreal Neurological Institute space using the transformation parameters estimated with a unified segmentation algorithm (Ashburner and Friston 2005). Then, the above transformation parameters were applied to the functional images and the images were resampled with isotropic voxels of 3 mm; (4) spatial smoothing with a 4 mm full-width at half-maximum isotropic Gaussian kernel; (5) removed the linear trend within each voxel's time series; (6) nuisance signals (white matter and cerebrospinal fluid signals, head motion parameters calculated by rigid body six correction) and spike regressors were regressed out; (7) finally, temporal bandpass filtering (0.01–0.08 Hz) to minimize low-frequency drift and the high-frequency noise filtered.

VMHC analysis

For the calculation of the VMHC value, the preprocessed functional images were first transformed to a symmetric space according to the following procedure: (1) averaged the normalized grey matter images for all subjects, and a mean image was generated; (2) created a group-specific symmetrical template by averaging the above mean image with a bilateral mirrored version; and (3) registered every individual normalized grey matter image to the generated symmetric template and then transformed the functional images according to the nonlinear strategy. The details of the VMHC acquisition were elucidated in a previous study (Zuo et al. 2010).

Statistical analysis

The statistical analyses were performed using SPSS 19.0. The data was reported as the means ± standard deviation (SD).

Performance comparisons between groups used two independent-samples t-test or paired-samples t-test. ANOVA for a 2 × 2 factorial design was performed to determine the stimulation intensity and time factor effects and the interactions. Correlation analyses were performed to examine the relationships among the VHMC values, executive function and athletic performance. The threshold for statistical significance was defined as $P < 0.05$, unless specifically mentioned.

Results

No significant differences in the scores for PHQ-9, GAD-7, FS-14, PF, MF, stroop A, Stroop C, TMT-A were observed between baseline and follow-up (all $P > 0.05$). Significant differences were observed in the scores of stroop B, TMT-B, LTP, M180LK and 60LS between two groups (all $P < 0.05$) (Table 1).

Analysis of variance (ANOVA) analysis on athletic performance indicated that time factor and stimulation intensity factor had a main effect on LTP and 60RK, respectively. No significant interaction effects were found (Table 2).

There was no significant difference of VMHC value between the high- and low-stimulation groups at baseline. Comparing with low-stimulation group, significant increased VMHC values of the bilateral middle temporal gyrus (MTG), precentral gyrus and superior frontal gyrus (SFG) were found in high-stimulation group at follow-up (the fourth week) (Table 3, Fig. 1). Correlation analyses suggested that in the high-stimulation group, the VMHC value of bilateral MTG was positively correlated with M180RS (rho = 0.986, $P =$ 0.006) (Fig. 2), the VMHC values of bilateral MTG and SFG were positively correlated with M180LK at follow-up ($r = 0.853$, 0.886, $P = 0.031$, 0.019, respectively) (Fig. 3). However, no significant correlation between the VMHC value and executive function was observed.

Discussions

To our knowledge, this is the first study to explore the mechanism of tDCS on athletic performance in the rowing athlete. Our preliminary results are as follows.

Changes in mood and cognitive function after tDCS

Physiological conditioning and gaming techniques are basic for elite athletes to achieve better records during games and competitions. However, mental health is not only essential for a better athletic performance, but also for a more stable

Table 1 Demographic data, neuropsychological and athletic performance between baseline and follow-up

	Baseline	Follow-up	Paired T	P
Gender (male/female)	12/0	–	–	–
Age (years)	16 ± 0	–	–	–
Education (years)	10.33 ± 0.49	–	–	–
BMI	22.79 ± 2.53	–	–	–
PHQ-9	5.33 ± 3.68	4.00 ± 2.92	2.111	0.058
GAD-7	3.58 ± 3.29	2.83 ± 3.33	1.431	0.180
Fatigue scale				
FS-14	3.50 ± 2.35	3.83 ± 2.04	−0.586	0.570
PF	2.42 ± 1.93	2.92 ± 1.78	−0.897	0.389
MF	1.08 ± 1.08	0.92 ± 1.00	0.561	0.586
Stroop test (seconds)				
Stroop A	22.03 ± 3.44	22.52 ± 3.16	−0.605	0.557
Stroop B	33.73 ± 4.14	31.33 ± 4.47	2.289	0.043
Stroop C	59.30 ± 11.92	53.84 ± 10.94	2.081	0.062
TMT (seconds)				
TMT-A	34.24 ± 7.78	35.26 ± 7.27	−0.519	0.614
TMT-B	101.13 ± 20.85	82.19 ± 14.54	3.495	0.005
LTP (watts)	212.50 ± 23.79	240.00 ± 14.77	−4.750	0.001
M180LK (newton-meters)	133.75 ± 16.31	141.83 ± 16.97	−2.277	0.044
60LS (newton-meters)	112.17 ± 22.68	119.08 ± 23.19	−2.468	0.031

BMI Body Mass Index, *PHQ-9* Patient Health Questionnaire-9, *GAD-7* Generalized Anxiety Disorder-7, *FS-14* Fatigue Scale-14, *PF* Physical Fatigue, *MF* Mental Fatigue, *TMT-A* Trail-Making Test-A, *TMT-B* Trail-Making Test-B, *LTP* Lactate Threshold Power, *M180LK* the average peak torque of left knee joint at 180 °/s, *60LS* the highest peak torque of the left shoulder joint at 60 °/s

Table 2 The ANOVA analysis on athletic performance

Athletic perfermonce	High stimulation (2 mA)		Low stimulation (1 mA)		Main effect		Interactive effect F (*P*)
	Baseline (*n* = 6)	Follow- up (*n* = 6)	Baseline (*n* = 6)	Follow-up (*n* = 6)	Intensity F (*P*)	Time F (*P*)	
LTP (watts)	220.00 ± 24.50	245.00 ± 16.43	205.00 ± 22.58	235.00 ± 12.25	2.451(0.133)	11.863(0.003)	0.098(0.757)
60RK (newton-meters)	253.37 ± 50.72	241.52 ± 40.41	210.93 ± 42.15	209.23 ± 39.95	4.420(0.048)	0.145(0.707)	0.082(0.778)

LTP Lactate Threshold Power, *60RK* the highest peak torque of the right knee joint at 60 °/s

and long-lasting sports career (Markser 2011). According to the current literatures, professional athletes are more likely to suffer from psychological problems, particularly depression and anxiety (Rice et al. 2016). In this study, the athletes had no anxiety or depression in baseline, which could eliminate the influence of psychological factors on athletic performance. For decades, many studies suggested that tDCS has an antidepressant effect although there were a few negative findings (Loo et al. 2010; Meron et al. 2015). A case study has reported the efficacy of tDCS in generalized anxiety disorder (Shiozawa et al. 2014). Resent studies showed that tDCS could not only improve mood such as depression and anxiety, but also can increase diverse cognitive functions such as attention, learning, naming reaction time and memory function (Coffman et al. 2014; Fridriksson et al. 2011). In the present study, significantly enhance in executive function was found. It was demonstrated that the improvement in cognitive function might lead to better well-being, faster recovery and performance gains in professional athletes (Borducchi et al. 2016).

The correlation between fatigue perception and athletic performance

Fatigue which involved the nervous system and the muscles is a multi-factorial physical and perceptual experience to intense and sustained activity (Gandevia 2001). It can reduce muscular endurance, impair response time and decision-making skills (Fitts 2008; Rattray et al. 2015). Previous studies revealed that after tDCS, the fatigue perception reduces, and that may be attributed to the improved athletic performance (Angius et al. 2016; Okano et al. 2013). Thus, it is suggested that fatigue may play an important role in athletic performance.

Our results showed significant increases in athletic performance, but no significant changes in fatigue perception after tDCS. So we speculated that improvements in athletic performance may be due to other ways.

Increased interhemispheric synchrony underlying the improved athletic performance

The most important finding of this study is that the VMHC values of bilateral MTG and SFG were both positively correlated with measures of athletic performance in high-stimulation group.

The SFG which located at the superior part of the prefrontal cortex is suggested to be an important part of the default mode network (DMN) and believed to be intimately related to emotion as well as a variety of cognitive functions, especially executive function (Andrews-Hanna et al. 2010; Yuan et al. 2007). Hou et al. also found that the decline in executive function in late-onset depression (LOD) was significantly correlated with the disrupted VMHC (Hou et al. 2016). However, we found no correlation between VMHC values and executive function. Therefore, the improvement in athletic performance which significantly associated with VMHC may not be

Table 3 The VMHC values between high- and low-tDCS stimulation group at follow-up

Brain regions	BA	Voxel number	Coordinates MNI			T
			X	Y	Z	
Right Middle Temporal Gyrus	21	301	45	−9	−27	6.486
Left Middle Temporal Gyrus	21	278	−45	−9	−27	6.486
Right Precentral Gyrus	4	623	24	0	54	8.572
Left Precentral Gyrus	4	598	−24	0	54	8.572
Right Superior Frontal Gyrus	8	356	21	42	39	6.931
Left Superior Frontal Gyrus	8	349	−21	42	39	6.931

Comparing with low-stimulation group, significant increased VMHC values of the bilateral middle temporal gyrus, precentral gyrus and superior frontal gyrus were found in high-stimulation group at follow-up. Note: The threshold was set at a corrected $P < 0.05$ (corrected with $P < 0.05$ for each voxel and cluster volume >=228 voxels). Abbreviations: VMHC: Voxel-mirrored Homotopic Connectivity

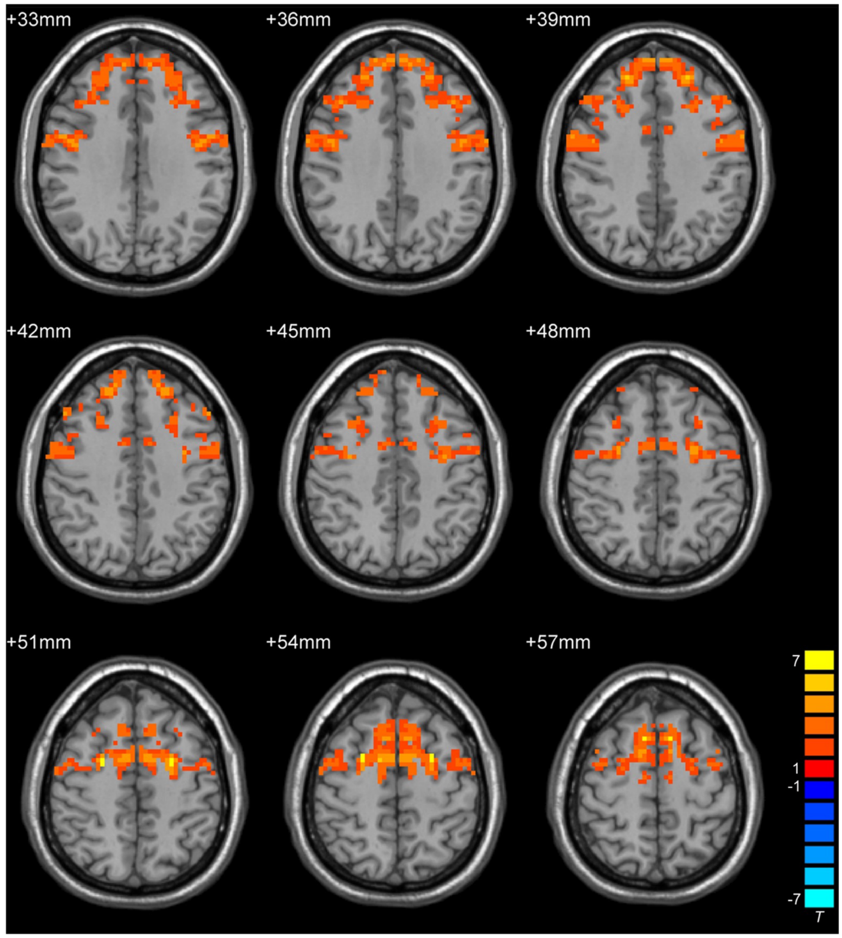

Fig. 1 Comparing with low-stimulation group, significant increased VMHC values of the bilateral middle temporal gyrus (MTG), precentral gyrus and superior frontal gyrus (SFG) were found in high-stimulation group at follow-up. The red color represents increased VMHC value

because of the increased executive function, and the mechanism deserves further investigation.

Supplementary motor area (SMA) which located in the posterior part of the SFG is mainly activated by motor tasks. In addition, numerous neuroimaging studies have demonstrated the role of the SMA in the motor programming, and the preparation, initiation as well as monitoring of complex movements (Martino et al. 2011). So, we suggested that the motor function of SFG might participate in the increased athletic performance by tDCS.

MTG is not only involved in DMN but also involved in semantic memory network. Its function is complex and diverse, and the precise function is still unclear (Binder et al. 2009). Previous researches clearly demonstrated that MTG

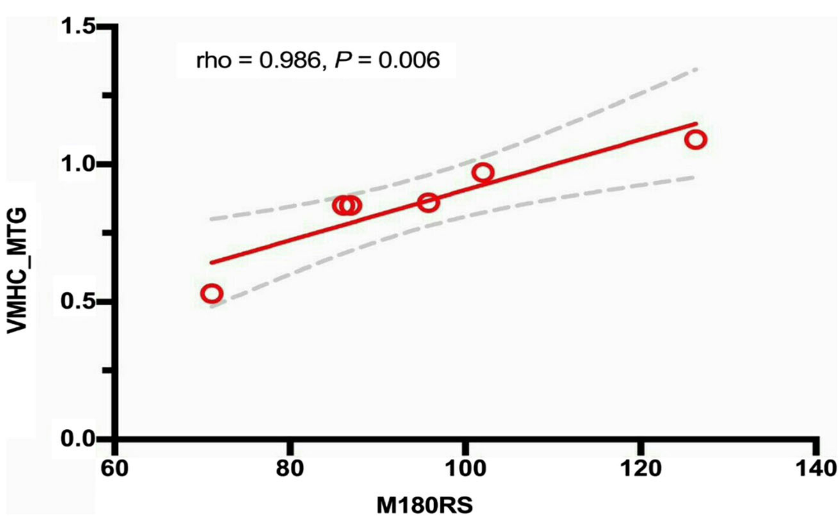

Fig. 2 Spearman correlation analysis suggested that the VMHC value in the bilateral MTG was positively correlated with M180RS at follow-up (rho = 0.986, $P = 0.006$)

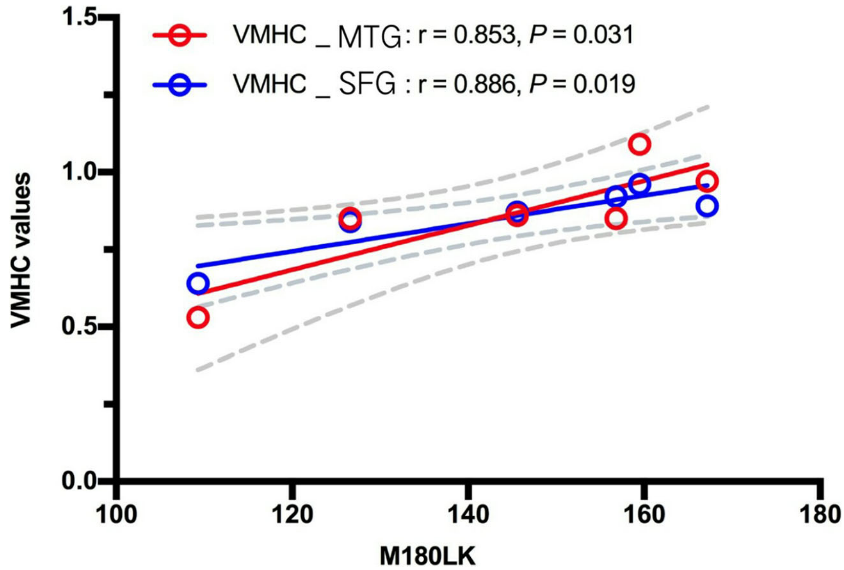

Fig. 3 Pearson's correlation analysis suggested that the VMHC values in bilateral MTG and SFG were positively correlated with M180LK at follow-up ($r = 0.853$, 0.886, $P =$ 0.031, 0.019, respectively)

participated in a key cognition function, action observation (Rizzolatti et al. 1996). The action observation allows one to infer others' intentions, can influence the motor response of a subsequent action, and is important for improving motor skill learning (Stefani et al. 2015). Thus, we reasoned that tDCS might influence the interhemispheric information communication for action observation processing, and as a result increased the athletic performance.

There are some limitations in the present study that must be acknowledged. First, this is a pilot study with a relatively small sample. Second, this study lacks a sham group, so caution should be taken in generalizing these findings. Third, a limitation common to RS-fMRI studies is the inability to control the subjects' thoughts during imaging. Even though all participants are instructed to stay relaxed, to keep their eyes closed and not to move their heads, there are still some small head movements and rotations. Fortunately, after inspecting each image, we found the head movements of all subjects were less than 1.5° or 1.5 mm which is an acceptable range (Hou et al. 2016). Given these limitations, the results should be considered preliminary, and future studies should be well-designed and include larger numbers of subjects as well as an additional sham group.

Conclusions

tDCS might contribute to the enhancement of athletic performance in professional rowing athletes, and the increased interhemispheric synchrony may be underlying the improved athletic performance. However, the potential effect of tDCS and its long-term effect remain areas of controversy. Thus, future studies should make more efforts to clarify the effect of tDCS.

Acknowledgments This work was supported by the National Key Research and Development Program of China (2016YFC1306700), the National Key Technology Research and Development Program of the Ministry of Science and Technology of China (2015BAI13B01) and the National Natural Science Foundation of China (81371488, YY). And the State Scholarship Fund of the China Scholarship Council (Hou, 201706090193); the Scientific Research Foundation of the Graduate School of Southeast University (Hou, YBJJ1742).

Compliance with ethical standards

Conflicts of interest All authors declare that they have no conflicts of interest.

References

Andrade, A. C., Magnavita, G. M., Allegro, J. V. B. N., Neto, C. E. B. P., Lucena, R. D. C. S., & Fregni, F. (2013). Feasibility of transcranial direct current stimulation use in children aged 5 to 12 years. *Journal of Child Neurology, 29*(10), 1360–1365.

Andrews-Hanna, J. R., Reidler, J. S., Sepulcre, J., Poulin, R., & Buckner, R. L. (2010). Functional-anatomic fractionation of the brain's default network. *Neuron, 65*(4), 550–562.

Angius, L., Pageaux, B., Hopker, J., Marcora, S. M., & Mauger, A. R. (2016). Transcranial direct current stimulation improves isometric time to exhaustion of the knee extensors. *Neuroscience, 339*, 363–375.

Antal, A., & Paulus, W. (2010). Transcranial magnetic and direct current stimulation in the therapy of pain. *Schmerz, 24*(2), 161–166.

Antal, A., Nitsche, M. A., Kruse, W., Kincses, T. Z., Hoffmann, K. P., & Paulus, W. (2004). Direct current stimulation over V5 enhances visuomotor coordination by improving motion perception in humans. *Journal of Cognitive Neuroscience, 16*(4), 521–527.

Ashburner, J., & Friston, K. J. (2005). Unified segmentation. *NeuroImage, 26*, 839–851.

Beneke, R. (1995). Anaerobic threshold, individual anaerobic threshold, and maximal lactate steady state in rowing. *Medicine and Science in Sports and Exercise, 27*(6), 863–867.

Benninger, D. H., Lomarev, M., Lopez, G., Wassermann, E. M., Li, X., Considine, E., & Hallett, M. (2010). Transcranial direct current

stimulation for the treatment of Parkinson's disease. *Journal of Neurology, Neurosurgery and Psychiatry, 81*(10), 1105–1111.
Binder, J. R., Desai, R. H., Graves, W. W., & Conant, L. L. (2009). Where is the semantic system? A critical review and meta-analysis of 120 functional neuroimaging studies. *Cerebral Cortex, 19*(12), 2767–2796.
Boggio, P. S., Valasek, C. A., Campanhã, C., Giglio, A. C. A., Baptista, N. I., Lapenta, O. M., & Fregni, F. (2011). Non-invasive brain stimulation to assess and modulate neuroplasticity in Alzheimer's disease. *Neuropsychological Rehabilitation, 21*(5), 703–716.
Bolognini, N., Vallar, G., Casati, C., Latif, L. A., El-Nazer, R., Williams, J., et al. (2011). Neurophysiological and behavioral effects of tDCS combined with constraint-induced movement therapy in poststroke patients. *Neurorehabilitation and Neural Repair, 25*(9), 819–829.
Borducchi, D. M. M., Gomes, J. S., Akiba, H., Cordeiro, Q., Borducchi, J. H. M., Valentin, L. S. S., et al. (2016). Transcranial direct current stimulation effects on athletes' cognitive performance: An exploratory proof of concept trial. *Frontiers in Psychiatry, 7*, 183.
Chalder, T., Berelowitz, G., Pawlikowska, T., Watts, L., Wessely, S., Wright, D., & Wallace, E. P. (1993). Development of a fatigue scale. *Journal of Psychosomatic Research, 37*(2), 147–153.
Coffman, B. A., Clark, V. P., & Parasuraman, R. (2014). Battery powered thought: Enhancement of attention, learning, and memory in healthy adults using transcranial direct current stimulation. *NeuroImage, 85*, 895–908.
Fitts, R. H. (2008). The cross-bridge cycle and skeletal muscle fatigue. *Journal of Applied Physiology, 104*(2), 551–558.
Foerster, Á., Melo, L., Mello, M., Castro, R., Shirahige, L., Rocha, S., & Monte-Silva, K. (2017). Cerebellar transcranial direct current stimulation (ctDCS) impairs balance control in healthy individuals. *Cerebellum, 16*(4), 872–875.
Fridriksson, J., Richardson, J. D., Baker, J. M., & Rorden, C. (2011). Transcranial direct current stimulation improves naming reaction time in fluent aphasia: A double-blind, sham-controlled study. *Stroke, 42*(3), 819–821.
Gandevia, S. C. (2001). Spinal and supraspinal factors in human muscle fatigue. *Physiological Reviews, 81*(4), 1725–1789.
Gordon, N. G. (1972). The trail making test in neuropsychological diagnosis. *Journal of Clinical Psychology, 28*(2), 167–169.
Grabner, R. H., Rütsche, B., Ruff, C. C., & Hauser, T. U. (2015). Transcranial direct current stimulation of the posterior parietal cortex modulates arithmetic learning. *European Journal of Neuroscience, 42*(1), 1667–1674.
Heppe, H., Kohler, A., Fleddermann, M. T., & Zentgraf, K. (2016). The relationship between expertise in sports, visuospatial, and basic cognitive skills. *Frontiers in Psychology, 7*, 904.
Hou, Z., Sui, Y., Song, X., & Yuan, Y. (2016). Disrupted interhemispheric synchrony in default mode network underlying the impairment of cognitive flexibility in late-onset depression. *Frontiers in Aging Neuroscience, 8*, 230.
Koss, E., Ober, B. A., Delis, D. C., & Friedland, R. P. (1984). The stroop color-word test: Indicator of dementia severity. *International Journal of Neuroscience, 24*(1), 53–61.
Kroenke, K. (2012). Enhancing the clinical utility of depression screening. *Canadian Medical Association Journal, 184*(3), 281–282.
Lee, M. M., Lee, K. J., & Song, C. H. (2018). Game-based virtual reality canoe paddling training to improve postural balance and upper extremity function: A preliminary randomized controlled study of 30 patients with subacute stroke. *Medical Science Monititor, 24*, 2590–2598.
Loo, C. K., Sachdev, P., Martin, D., Pigot, M., Alonzo, A., Malhi, G. S., Lagopoulos, J., & Mitchell, P. (2010). A double-blind, sham-controlled trial of transcranial direct current stimulation for the treatment of depression. *International Journal of Neuropsychopharmacology, 13*(1), 61–69.
Markser, V. Z. (2011). Sport psychiatry and psychotherapy. Mental strains and disorders in professional sports. Challenge and answer to societal changes. *European Archives of Psychiatry and Clinical Neuroscience, 261*, S182–S185.
Martino, J., Gabarrós, A., Deus, J., Juncadella, M., Acebes, J. J., Torres, A., & Pujol, J. (2011). Intrasurgical mapping of complex motor function in the susperior frontal gyrus. *Neuroscience, 179*, 131–142.
Meron, D., Hedger, N., Garner, M., & Baldwin, D. S. (2015). Transcranial direct current stimulation (tDCS) in the treatment of depression: Systematic review and meta-analysis of efficacy and tolerability. *Neuroscience and Biobehavioral Reviews, 57*, 46–62.
Montenegro, R. A., Okano, A. H., Cunha, F. A., Gurgel, J. L., Fontes, E. B., & Farinatti, P. T. V. (2012). Prefrontal cortex transcranial direct current stimulation associated with aerobic exercise change aspects of appetite sensation in overweight adults. *Appetite, 58*(1), 333–338.
Nitsche, M. A., & Paulus, W. (2000). Excitability changes induced in the human motor cortex by weak transcranial direct current stimulation. *Journal of Physiology (London), 527*(Pt 3), 633–639.
Nitsche, M. A., & Paulus, W. (2001). Sustained excitability elevations induced by transcranial DC motor cortex stimulation in humans. *Neurology, 57*(10), 1899–1901.
Okano, A. H., Fontes, E. B., Montenegro, R. A., Farinatti, P. T. V., Cyrino, E. S., Li, L. M., et al. (2013). Brain stimulation modulates the autonomic nervous system, rating of perceived exertion and performance during maximal exercise. *British Journal of Sports Medicine, 49*(18), 1213–1218.
Poreisz, C., Boros, K., Antal, A., & Paulus, W. (2007). Safety aspects of transcranial direct current stimulation concerning healthy subjects and patients. *Brain Research Bulletin, 72*(4–6), 208–214.
Rattray, B., Argus, C., Martin, K., Northey, J., & Driller, M. (2015). Is it time to turn our attention toward central mechanisms for post-exertional recovery strategies and performance? *Frontiers in Physiology, 6*, 79.
Reardon, S. (2016). 'Brain doping' may improve athletes' performance. *Nature, 531*(7594), 283–284.
Reis, J., & Fritsch, B. (2011). Modulation of motor performance and motor learning by transcranial direct current stimulation. *Current Opinion in Neurology, 24*(6), 590–596.
Rice, S. M., Purcell, R., De Silva, S., Mawren, D., McGorry, P. D., & Parker, A. G. (2016). The mental health of elite athletes: A narrative systematic review. *Sports Medicine, 46*(9), 1333–1353.
Rizzolatti, G., Fadiga, L., Matelli, M., Bettinardi, V., Paulesu, E., Perani, D., & Fazio, F. (1996). Localization of grasp representations in humans by PET: 1. Observation versus execution. *Experimental Brain Research, 111*(2), 246–252.
Shiozawa, P., Leiva, A. P. G., Castro, C. D. C., da Silva, M. E., Cordeiro, Q., Fregni, F., & Brunoni, A. R. (2014). Transcranial direct current stimulation for generalized anxiety disorder: A case study. *Biological Psychiatry, 75*(11), e17–e18.
Song, X. W., Dong, Z. Y., Long, X. Y., Li, S. F., Zuo, X. N., Zhu, C. Z., He, Y., Yan, C. G., & Zang, Y. F. (2011). REST: A toolkit for resting-state functional magnetic resonance imaging data processing. *PLoS One, 6*(9), e25031.
Spitzer, R. L., Kroenke, K., Williams, J. B., & Lowe, B. (2006). A brief measure for assessing generalized anxiety disorder: The GAD-7. *Archives of Internal Medicine, 166*(10), 1092–1097.
Stefani, E. D., De Marco, D., & Gentilucci, M. (2015). Factors affecting athletes' motor behavior after the observation of scenes of cooperation and competition in competitive sport: The effect of sport attitude. *Frontiers in Psychology, 6*, 1648.
Undheim, M. B., Cosgrave, C., King, E., Strike, S., Marshall, B., Falvey, É., & Franklyn-Miller, A. (2015). Isokinetic muscle strength and readiness to return to sport following anterior cruciate ligament reconstruction: Is there an association? A systematic review and a

protocol recommendation. *British Journal of Sports Medicine, 49*(20), 1305–1310.

Wang, Z., Wang, J., Zhang, H., Mchugh, R., Sun, X., Li, K., & Yang, Q. X. (2015). Interhemispheric functional and structural disconnection in Alzheimer's disease: A combined resting-state fMRI and DTI study. *PLoS One, 10*(5), e0126310.

Weber, M. J., Messing, S. B., Rao, H., Detre, J. A., & Thompson-Schill, S. L. (2014). Prefrontal transcranial direct current stimulation alters activation and connectivity in cortical and subcortical reward systems: A tDCS-fMRI study. *Human Brain Mapping, 35*(8), 3673–3686.

Williams, P. S., Hoffman, R. L., & Clark, B. C. (2013). Preliminary evidence that anodal transcranial direct current stimulation enhances time to task failure of a sustained submaximal contraction. *PLoS One, 8*(12), e81418.

Yan, C. G., & Zang, Y. F. (2010). DPARSF: A MATLAB toolbox for "pipeline" data analysis of resting-state fMRI. *Frontiers in Systems Neuroscience, 4*, 13.

Yuan, Y., Zhang, Z., Bai, F., Yu, H., Shi, Y., Qian, Y., Zang, Y., Zhu, C., Liu, W., & You, J. (2007). White matter integrity of the whole brain is disrupted in first-episode remitted geriatric depression. *NeuroReport, 18*(17), 1845–1849.

Zuo, X. N., Kelly, C., Di Martino, A., Mennes, M., Margulies, D. S., Bangaru, S., et al. (2010). Growing together and growing apart: Regional and sex differences in the lifespan developmental trajectories of functional homotopy. *Journal of Neuroscience, 30*(45), 15034–15043.