Brain Functional Connectivity Changes in Middle-Aged Hong Chuan Tai Chi Players

Zhenguo Shi

Shandong University

Lei Xu

Shandong University

Hui Xie

Beihang University

Xiangliang Zhang

Shandong University

Qiang He (✉ heqiang224@163.com)

Shandong University <https://orcid.org/0000-0002-7281-0200>

Research Article

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Abstract

Tai Chi has been shown an effective strategy to improve cognitive function in older populations while the underlying mechanism remains unclear. This cross-sectional study was performed to examine the brain functional connectivity changes in middle-aged Hong Chuan Tai Chi practitioners. The changes in cerebral oxygenation were measured by functional near-infrared spectroscopy. NIRS signals were obtained from left and right prefrontal cortex, motor cortex and occipital cortex in 18 Hong chuan Tai Chi practitioners (age: 55.78 ± 2.64 y) and 22 demographically matched healthy Tai Chi-naïve controls (age: 54.69 ± 3.10 y). Global cognition was measured by the Montreal Cognitive Assessment Scale, and spontaneous oscillations in cerebral oxygenation between three cortices in five frequency intervals (I, 0.6-2Hz; II, 0.145-0.6Hz; III, 0.052-0.145Hz; IV, 0.021-0.052Hz; V, 0.0095-0.021Hz) was analyzed by wavelet phase coherence. Compared with age-matched Tai Chi-naïve controls, Hong Chuan Tai Chi practitioners had better global cognition, showed higher functional connectivity between left and right prefrontal cortex, motor cortex, occipital cortex in intervals I, III, VI and V. These findings showed that middle-aged Hong Chuan Tai Chi practitioners had higher functional connectivity between prefrontal cortex, motor cortex and occipital cortex, as well as the coordination of left and right brain, which maybe the contributing factors to higher global cognition.

Introduction

Aging is a complex degenerative process in brain structure and function, accompanied by decline of cognitive performance which seriously affects physical health and independent living ability of older adults(Anderson 2019). How to delay aging-related decline of cognitive performance now becomes a critical public health issue to address. Tai Chi, as a form of mind-body exercise originated from ancient China, showed benefits to cognitive function in older adults(Ji et al. 2017;Matthews andWilliams 2008;Zhu et al. 2020). Tai Chi requires practitioners to control and move bodies consciously, which involves the coordination of eyes, hands and feet, regulated by different brain regions. A meta-analysis showed that Tai Chi can increase the strength, balance, attention and cognitive function of practitioners aged 60 or older(Wayne et al. 2014). Another meta-analysis showed Tai Chi is beneficial for global cognition of adults age ranged from 50–85(Wu et al. 2019). However, the underlying mechanism remains poorly understood. The formation of functional brain networks is closely associated with cognition behavior(Park andFriston 2013). Examining the neural connectivity patterns provide valuable insight into how human brain operates.

Functional near-infrared spectroscopy (fNIRS) is a non-invasive brain function imaging technology that can continuously monitor human brain neural activity at rest or during brain activation by detecting the absorption of oxyhemoglobin (HbO_2) and deoxyhemoglobin (HHb). Multichannel fNIRS can measure the HbO_2 changes ($\Delta[\text{HbO}_2]$) across several brain regions and their temporal correlation, and then analyze brain functional connectivity. The resting state reflects spontaneous or intrinsic brain activity and is a vital experimental paradigm for the study of brain function. The NIRS signals obtained from the cortical regions during the resting state mainly reflect regional hemodynamic fluctuations that originated from

spontaneous neural activity(Sasai et al. 2011). The power spectra of cerebral $\Delta[\text{HbO}_2]$ exists oscillations in various frequency bands. And the $\Delta[\text{HbO}_2]$ signals in different frequency, which indicates possible regulatory mechanisms of tissue oxygenation signal, have been identified by wavelet analysis(Han et al. 2014;Li et al. 2013). The cerebral oscillations in intervals I (0.6-2 Hz) and II (0.145-0.6 Hz) reflected the synchronization of cardiac and respiratory activities, respectively(Cui et al. 2014). The cerebral oscillations in intervals in III (0.05–0.15 Hz) were suggested to originate locally from intrinsic myogenic activity of smooth muscle cells in resistance vessels and this myogenic mechanism may be partly under autonomic control(Tan et al. 2016). Intervals IV (0.021–0.052 Hz) is closely regulated through tight neurovascular coupling and autonomic control(Zhang et al. 2002). Intervals V (0.0095-0.021Hz) were regarded as endothelial cell metabolic activities. The spontaneous oscillations in the cerebral hemodynamic signals might be used for monitoring of cerebrovascular pathology and functional activation. Previous studies showed that spontaneous oscillations of cerebral oxygenation in frequency I-V in elderly subjects was significantly lower than young subjects(Li et al. 2013). Wavelet coherence (WCO) discovers high common power of two signals at the same frequency, while wavelet phase coherence (WPCO) finds locally phase-locked behaviour and reveal possible relationships by evaluating how well the instantaneous phases from the two signals are matched. WPCO analysis has been used to analyze the relationship among oscillations in skin blood flow, blood pressure, brain oxygen saturation within certain specific frequency ranges(Bu et al. 2016;Cui et al. 2014;Han et al. 2014;Tan et al. 2016;Tankanag et al. 2014;Xie et al. 2019).

Robust spatial interactions over the prefrontal, temporal, occipital lobes exist evidenced by evaluating the resting state functional connectivity of whole brain through fNIRS(Mesquita et al. 2010;Xie et al. 2019). Prefrontal cortex (PFC), motor cortex (MC) and occipital cortex (OC) are involved in human physical behavior activities. PFC is the main cognitive region of human beings, and plays an important role in planning complex cognitive behaviors(Miller andCohen 2001). MC is located on both sides of the central sulcus of the brain and controls body movement through spatial sensation and motor planning. OC is related to visual perception in motion. The connection between these functional cortexes are critical for movement coordination which are required by Tai Chi. Previous study reported that the functional connection between these three regions in Tai Chi practitioners was higher than that of Tai Chi-naïve controls in 60 ~ 70 years old adults(Xie et al. 2019).However, there are several forms of Tai Chi, with Chen style the oldest while Yang style the most popular. Most existing studies examined these two styles, and consistently reported benefits to brain function(Xie et al. 2019;Zou et al. 2019). Different forms of exercise induce different modulation of brain functional network involved in cognitive control, such as Tai Chi and Baduanjin(Tao et al. 2017). And different forms of Tai Chi did induce different changes in terms of brain function(Zou et al. 2019). Hong Chuan Tai Chi is originated but different from classical Chen style Tai Chi, and is quite popular in Jinan, the capital city of Shandong province, China. As a branch of Chen style Tai Chi, this 81-form Tai Chi evolved with emphasis on art of attack and defense, which is much more strenuous than other forms of Tai Chi. Furthermore, although a previous review of the literature concluded that there was little evidence of cognitive decline before 60 years old(Hedden andGabrieli 2004). However, it is not universally accepted(Salthouse 2009). A study investigated

cognitive function in five age groups: 45-49y, 50-54y, 55-59y, 60-64y, and 65-70y, the results suggested that cognitive decline is already evident in middle aged (45–49) and increase with age (Singh-Manoux et al. 2012). And people aged below 60 also suffers cognitive disorders (Launer 2005). Moreover, current studies mainly focused on older people ≥ 60 y and did not distinguish age groups at all (Hedden and Gabrieli 2004; Yang et al. 2019). Thus we believe that the effects of Tai Chi practice on brain function of 50-60y middle aged population is worth specific exploration. Accordingly, the present study aims to examine Hong chuan Tai Chi related brain function changes in 50–60 years old middle-aged adults.

Materials And Methods

Subjects

A total of 40 healthy middle-aged adults (50~60 years old) volunteered and completed this fNIRS study, including 18 Hong Chuan Tai Chi practitioners (55.78 ± 2.64 years old) and 22 demographically matched Tai Chi-naive healthy controls (54.69 ± 3.10 years old). Control participants were recruited from a local community, with no history of physical exercise, yoga, or meditation treatment. Tai Chi practitioners need to have at least 3 years of Hong Chuan Tai Chi experience. On average, the Tai Chi practitioners had 4.61 (SD=0.89) years of Hong Chuan Tai Chi practice history (Table 1). Subjects with left-handedness, hypertension, history of brain trauma and nervous system diseases, neurological drugs or sleeping pills taken in the past three years and drug abuse were excluded.

Before starting the experiment, all the subjects were informed of the specific contents of the experiment in advance and gave their written informed consents. The experiment was conducted in accordance with the Declaration of Helsinki, and approved by the ethics committee of rehabilitation hospital affiliated to the National Research Center for Rehabilitation Technical Aids. The ethics committee approved all of the experiment procedures of this study.

Experiment procedures

The basic information including sex, age, body weight, height, educational background and medical history was recorded by self-reporting, the sleep quality was evaluated by Pittsburgh sleep quality index (PSQI) while global cognitive status was screened by the Montreal Cognitive Assessment Scale (MoCA). Sitting blood pressure were measured by an electronic sphygmomanometer. Each subject was allowed to be familiar with the experiment protocol. All subjects met the inclusion criteria had a MoCA score of 26 or above, and the PSQI ranged from 1 to 6. Before starting the fNIRS test, all the subjects are required to maintain a comfortable sitting position, close their eyes and stay awake. After the instrument is placed, all the subjects are required to sit and collect 15 minutes of resting data (without systematic thinking, keep in a relaxed state). A continuous recording of fNIRS signals were then obtained from the left and right PFC, MC and OC in 18 Hong Chuan Tai Chi practitioners and 22 age-matched controls. And the fNIRS measurement was strictly performed by a well-trained technician following the instructions.

Sleep quality

Before performing the fNIRS test, all the participants accomplished the sleep quality survey in this study. PSQI is a self-rated questionnaire used to evaluate the sleep quality of subjects over a 1-month time interval and has been validated and it was a reliable test for identifying sleep disorders in clinical and research settings. The score is 0-21 in 19 individual items that generate 7 components. The higher the score is, the worse the sleep quality is, and the score is lower than 6 points, indicating that the sleep quality of subjects is good(Buysse et al. 1989).

Global cognitive function

All the participants completed the global cognitive function test in this study before the fNIRS test using a Chinese version MoCA. MoCA is used to quickly screen mild cognitive impairment, mainly including different cognitive components such as visual space and executive function, memory, attention, language, abstraction etc., with a full score of 30 points. If the number of years of education is less than or equal to 12 years, 1 point will be added, and 26 points or above is considered normal(Nasreddine et al. 2005).

Functional near infrared spectroscopy

A multi-channel tissue oxygenation monitor with continuous-wave (NirSmart, Danyang Huichuang Medical Equipment Co., Ltd) was used in fNIRS measurements. The details had been elaborated in our previous studies(Xie et al. 2019). Briefly, each sensor of the instrument consisted of a three-wavelength light emitting diode, which emitted light at 740, 808 and 850 nm wave length, and a detector optode. The 14-channels of the fNIRS were symmetrically positioned over the regions of both left and right PFC, MC and OC. All the protocol was performed by well-trained technician followed the guidelines for Clinical Laboratory Safety. Figure 1 shows the distribution of 14 channels, consisting of 10 light source probes and 8 detector probes, in the brain. The sampling frequency was 10 Hz.

Wavelet-based coherence analysis

The fNIRS signal was always mixed with system physiological noise and tissue noise because some human system physiological activity cannot be stopped, which inevitably affects the hemodynamics, especially in task state. For example, cardiac activity (0.8~2HZ), respiration(0.13~0.33HZ) can induces global drift of the baseline measurements. In addition, before the near infrared light finally reaches grey matters, it needs to go through tissues including scalp, subcutaneous tissue, skull and cerebrospinal fluid which will influence the fNIRS signal. Finally, the brain spontaneous neural activity might mix cognitive task-induced neuroactivity, like low-frequency oscillations (~0.1HZ) and very low-frequency oscillations (~0.03HZ), although it's can be used in resting state. The aim of data pre-processing was to remove signals with a low signal-to-noise ratio in order to more accurately evaluate brain activity-induced hemodynamics response. To remove these effects, the data can be preprocessed by moving average method for subsequent analysis as described in previous studies(Xu et al. 2017). Briefly, MATLAB 2017 was used for data processing and the time window used for moving average filter was 3 seconds. As $\Delta[\text{HbO}_2]$ is more sensitive to brain activity, only $\Delta[\text{HbO}_2]$ is used in subsequent signals in this study.

After data pre-processing, continuous wavelet transformation is used to transform the pre-processed data in time-series from the time domain to the time-frequency domain. Then, the fNIRS signals from left and right PFC, MC and OC were analyzed according to five frequency intervals: I, 0.6-2Hz; II, 0.145-0.6Hz; III, 0.052-0.145Hz; IV, 0.021-0.052Hz; V, 0.0095-0.021Hz. The physiological meanings of each frequency intervals were: cardiac activity, respiration, vascular smooth muscle activity, neural activity and endothelial cell metabolism activity. Brain functional connectivity was calculated using the MATLAB 2017 version by methods of wavelet-based phase coherence (WPCO). The wavelet phase coherence is used to detect the correlation degree of two signals at a certain frequency interval. The value of wavelet coherence is between 0-1 and reflect the instantaneous phase difference between ΔHbO_2 . In the analysis of brain functional connectivity, the higher the WPCO value is, the stronger the functional connectivity between two brain regions indicated by close relationships between two $\Delta[\text{HbO}_2]$ is.

Statistical analysis

All data were analyzed by SPSS20.0 software. The results were expressed by mean $\pm$ sd and the raw data were processed by independent T test. A significance with $p < 0.05$ was considered statistically significant. Effect size (Cohen's d) and statistical power were also calculated for each dependent variable. Thresholds for effect sizes statistics were: 0.2, trivial; 0.6, small; 1.2, moderate; 2.0, large; and over 2.0, very large.

Results

Demographic characteristics

The demographic characteristics of all the participants in each group are analyzed and summarized in Table 1. There were no significant differences ($P \geq 0.05$) in age, years of education, BMI, blood pressure, sleep quality between the two groups. Hong Chuan Tai Chi practitioners scored higher in MoCA than healthy Tai Chi-naïve controls ($P < 0.001$).

Table 1
Subjects Characteristics

	Tai Chi(n = 18)	Control(n = 22)	P
Age(year)	55.78 ± 2.64	54.69 ± 3.10	0.401
BMI (kg/m ²)	22.10 ± 0.61	22.27 ± 0.68	0.556
Education(year)	12.67 ± 2.00	12.00 ± 2.12	0.467
Tai Chi Practice(year)	4.61 ± 0.89	NA	NA
Duration(hour/w)	13.89 ± 1.62	NA	NA
Right-handed	18	22	NA
Systolic pressure(mmHg)	116.00 ± 7.38	120.85 ± 6.79	0.128
Diastolic pressure(mmHg)	73.89 ± 3.48	76.61 ± 5.38	0.197
Sleep quality (PQSI)	3.61 ± 0.78	3.82 ± 0.85	0.432
Global cognitive function (MoCA)	28.06 ± 0.64	26.27 ± 1.2	0.000
NA: Not Available			

Wavelet Phase Coherence Analysis

Compared with Tai Chi-naïve controls, in interval I, Hong Chuan Tai Chi practitioners had higher WPCO values of LPFC-LMC (TC = 0.59, C = 0.40, t = 4.72, P < 0.001, Cohen's d = 1.54, large), LPFC-LOC (TC = 0.60, C = 0.39, t = 5.32, P < 0.001, Cohen's d = 1.78, large), LMC-LOC (TC = 0.53, C = 0.43, t = 2.08, P < 0.05, Cohen's d = 0.76, moderate) in the left hemisphere; and had higher WPCO values of RPFC-RMC (TC = 0.60, C = 0.37, t = 5.80, P < 0.001, Cohen's d = 1.91, large), RPFC-ROC (TC = 0.55, C = 0.40, t = 3.19, P < 0.01, Cohen's d = 1.12, moderate) in the right hemisphere. In addition, Hong Chuan Tai Chi practitioners had higher WPCO values of LPFC-RPFC (TC = 0.78, C = 0.44, t = 14.35, P < 0.001, Cohen's d = 4.67, very large), LPFC-RMC (TC = 0.60, C = 0.38, t = 5.59, P < 0.001, Cohen's d = 1.87, large), LPFC-ROC (TC = 0.55, C = 0.40, t = 3.39, P < 0.01, Cohen's d = 1.16, moderate), RPFC-LMC (TC = 0.59, C = 0.39, t = 4.57, P < 0.001, Cohen's d = 1.57, large), RPFC-LOC (TC = 0.60, C = 0.38, t = 5.57, P < 0.001, Cohen's d = 1.87, large), LMC-RMC (TC = 0.53, C = 0.42, t = 2.09, P < 0.05, Cohen's d = 0.72, moderate), LOC-RMC (TC = 0.53, C = 0.42, t = 2.32, P < 0.05, Cohen's d = 0.77, moderate) between the two hemispheres than those of Tai Chi-naïve controls.

As shown in Figure.3, compared with Tai Chi-naïve controls, Hong Chuan Tai Chi practitioners had higher WPCO values of LPFC-RPFC (TC = 0.48, C = 0.38, t = 2.14, P < 0.05, Cohen's d = 0.72, moderate), and there was no significant difference between other brain regions in interval II.

Figure.4 indicate that in interval III, Hong Chuan Tai Chi practitioners had higher WPCO values of LMC-LOC (TC = 0.47, C = 0.38, $t = 2.37$, $P < 0.05$, Cohen's $d = 0.76$, moderate) and RPFC-RMC (TC = 0.49, C = 0.37, $t = 3.16$, $P < 0.01$, Cohen's $d = 1.0$, moderate) than Tai Chi-naïve controls in the left and right hemisphere, respectively. In addition, Hong Chuan Tai Chi practitioners had higher WPCO values of LPFC-RPFC (TC = 0.63, C = 0.39, $t = 7.05$, $P < 0.001$, Cohen's $d = 2.26$, very large), LMC-RMC (TC = 0.60, C = 0.38, $t = 6.05$, $P < 0.001$, Cohen's $d = 1.99$, large), LOC-RMC (TC = 0.47, C = 0.39, $t = 2.04$, $P < 0.05$, Cohen's $d = 0.70$, moderate), LOC-ROC (TC = 0.50, C = 0.40, $t = 2.26$, $P < 0.05$, Cohen's $d = 0.74$, moderate) between the two hemispheres than Tai Chi-naïve controls.

Figure. 5 shows the comparison of WPCO values between the Hong Chuan Tai Chi group and the Control group in interval IV. Compared with Tai Chi-naïve controls, Hong Chuan Tai Chi practitioners had higher WPCO values of LPFC-LMC (TC = 0.46, C = 0.37, $t = 2.33$, $P < 0.05$, Cohen's $d = 0.73$, moderate), LMC-LOC (TC = 0.44, C = 0.36, $t = 2.07$, $P < 0.05$, Cohen's $d = 0.67$, moderate) in the left hemisphere and higher WPCO values of RPFC-RMC (TC = 0.47, C = 0.36, $t = 2.61$, $P < 0.05$, Cohen's $d = 0.90$, moderate) in the right hemisphere. In addition, Hong Chuan Tai Chi practitioners had higher WPCO values of LPFC-RPFC (TC = 0.59, C = 0.37, $t = 5.42$, $P < 0.001$, Cohen's $d = 1.78$, large), LMC-RMC (TC = 0.55, C = 0.36, $t = 5.39$, $P < 0.001$, Cohen's $d = 1.76$, large), LOC-RMC (TC = 0.43, C = 0.35, $t = 2.29$, $P < 0.05$, Cohen's $d = 0.72$, moderate), LOC-ROC (TC = 0.45, C = 0.36, $t = 2.25$, $P < 0.05$, Cohen's $d = 0.76$, moderate) between the two hemispheres compared with Tai Chi-naïve controls.

As Figure. 6 showed, in interval V, compared with Tai Chi-naïve controls, Hong Chuan Tai Chi practitioners had higher WPCO values of LPFC-LMC (TC = 0.48, C = 0.35, $t = 3.67$, $P < 0.01$, Cohen's $d = 1.24$, large), LMC-LOC (TC = 0.48, C = 0.38, $t = 2.97$, $P < 0.01$, Cohen's $d = 1.0$, moderate) in the left hemisphere and higher WPCO values of RPFC-RMC (TC = 0.49, C = 0.39, $t = 3.26$, $P < 0.01$, Cohen's $d = 1.04$, moderate), RMC-ROC (TC = 0.48, C = 0.41, $t = 2.31$, $P < 0.05$, Cohen's $d = 0.74$, moderate) in the right hemisphere. In addition, Tai chi practitioners had higher WPCO values of LPFC-RPFC (TC = 0.62, C = 0.36, $t = 6.92$, $P < 0.001$, Cohen's $d = 2.33$, very large), LPFC-RMC (TC = 0.48, C = 0.38, $t = 3.25$, $P < 0.01$, Cohen's $d = 1.11$, moderate), LMC-RMC (TC = 0.55, C = 0.34, $t = 6.18$, $P < 0.001$, Cohen's $d = 2.18$, very large), LOC-RMC (TC = 0.48, C = 0.36, $t = 3.61$, $P < 0.01$, Cohen's $d = 1.19$, moderate), LOC-ROC (TC = 0.53, C = 0.39, $t = 3.56$, $P < 0.01$, Cohen's $d = 1.21$, large) between the two hemispheres than that of Tai Chi-naïve controls.

Discussion

We performed a cross-sectional study aiming to examine the difference of brain functional connectivity between Hong Chuan Tai Chi practitioners and age-matched Tai Chi-naïve controls. And our results suggested that 50 ~ 60 years old Hong Chuan Tai Chi practitioners had higher brain functional connectivity between PFC, MC and OC, as well as better coordination of left and right brain than age-matched Tai Chi-naïve controls. And Hong Chuan Tai Chi practitioners showed higher global cognitive ability than age-matched Tai Chi-naïve controls.

It's well established that Tai Chi as a kind of mind-body exercise, is a prospective strategy for maintaining cognitive function and delaying cognitive decline of older adults. An early cross-sectional study compared the memory function of older adults aged 56 and older who regularly practiced mind-body or cardiovascular exercises with that of who did not engage in regular exercise, and apparently older adults who practiced Tai Chi showed better memory function(Chan et al. 2005). Another cross-sectional study suggested that the Tai Chi group demonstrated better performance in Mini-mental Status Examination, Color Trail Form attention test, and Rivermead Behavioral Memory Test than other exercise or control groups(Man et al. 2010). In fact, older adults with longer mind body exercise habits usually scored higher in most cognitive tests(Lam et al. 2009). In current study, we screened the global cognitive ability of 50–60 years old adults. MoCA is a 30-item test that has been extensively used to assess cognitive impairments in adults in many trials(Huang et al. 2019;Zou et al. 2019). Consistent with previous cross-sectional and cohort studies(Chan et al. 2005;Ji et al. 2017), our study found that Hong chuan Tai Chi practitioners had better global cognitive status than Tai Chi-naïve controls. Although a causal relationship cannot be assumed in this study, it still suggested a close association between Hong Chuan Tai Chi practicing and cognitive benefits.

The changes in brain functional connectivity might be associated with the decline of cognitive performance in older adults, evidenced by functional magnetic resonance imaging(Farras-Permanyer et al. 2019). In this study, we used fNIRS to assess resting state brain functional connectivity between PFC, MC and OC. The WPCO method was extensively used assess the correlation between two signals with their phase coherence information and evaluates the possible connectivity based on the degree of coincidence of the instantaneous phase(Xu et al. 2017). A significantly higher WPCO values of LPFC-LMC, LPFC-LOC, LMC-LOC, RPFC-RMC, RPFC-ROC and higher WPCO values of LPFC-RPFC, LPFC-RMC, LPFC-ROC, RPFC-LMC, RPFC-LOC, LMC-RMC, LOC-RMC in Hong Chuan Tai Chi practitioners than matched Tai Chi-naïve controls were observed in interval I. Interval I oscillations reflects the effect of cardiac activity on cerebral ΔHbO_2 . As the cerebrovascular system is a part of cardiovascular system, and the cardiovascular function of the elderly gradually declines with the increase of age. Our results lead to an inference that long-term Hong Chuan Tai Chi practice might improve the cardiac fitness as previous studies reported(Zheng et al. 2015). And the increased heart pumping function in resting state contributes to the improved functional connectivity between most brain regions. The increased functional connectivity between PFC, MC and OC in interval I indicate benefits of Hong Chuan Tai Chi on coordination of different brain regions and might be useful to explain the positive association between cardiovascular or aerobic fitness and cognition(Hyodo et al. 2016).

The oscillations in interval II closely resemble the oscillations of respiratory activity(Xie et al. 2019). Abdominal respiration used in Hong Chuan Tai Chi can increase the intensity of diaphragm relaxation and shrinkage so that it provides adequate oxygen to move body and increase cerebral blood flow, induce higher changes of cerebral ΔHbO_2 . As a study suggests, short-term Tai Chi exercise can enhance the pulmonary ventilation function in older adults which attributes to improved respiratory muscle strength(Song et al. 2014). It can be assumed that highly experienced Hong Chuan Tai Chi practitioners

had better synchronization of breathing and cerebral ΔHbO_2 . However, in our study, there's no significant difference in WPCO values between most interest brain regions in subjects from two groups, except the LPFC-RPFC connectivity. This results suggested that the oxygen supply of RPFC and LPFC was improved by the breathing activity of Tai Chi. A study suggested that the breathing frequency of Tai Chi skilled group was lower than that of the control group, but the breathing depth increased, indicating increased oxygen uptake and cerebral blood oxygen level in resting state(XXX 2016). In fact, Tai Chi exercise attach great importance to the coordination of body, mind and breath. The so-called "Qichen Dantian" means deep breathing, which is related to the subconscious control of PFC(Doll et al. 2016).

The oscillations in interval III is associated with myogenic activity of vascular smooth muscle cells which is partially under autonomic control(Tan et al. 2015). The contraction and relaxation of vascular smooth muscle directly regulates the diameter and blood vessels pressure, thus influence cerebral oxygen signals. Aging is accompanied by a degeneration of vascular system, which may have consequences for cerebral blood flow. Previous study found that aging induces a reduction of spontaneous very low-frequency (0.02-0.07Hz) and low-frequency (0.07-0.2Hz) oscillations of cerebral hemodynamics and blood pressure during cognitive task(Vermeij et al. 2014). The declined spontaneous activity in microvascular smooth muscle cells reflects the changes of microvasculature and increase of vessel stiffness. Long-term Tai Chi exercise can improve the autonomic nervous modulation in older adults(Lu andKuo 2003). So it seems that myogenic activity of cerebral vascular smooth muscle cells would be higher in Tai Chi practitioner than that of controls. In this study, Hong chuan Tai Chi practitioners had higher WPCO values between LMC-LOC, RPFC-RMC, LPFC-RPFC, LMC-RMC, LOC-RMC, LOC-ROC than those of Tai Chi-naïve controls. This suggests higher functional connectivity between those regions in highly experienced Hong Chuan Tai Chi practitioners. This result is consistent with the result reported in previous studies(Xie et al. 2019).

The oscillations in interval IV is related to neurogenic activity, which is regulated by neurovascular coupling and controls smooth muscle cells(Xie et al. 2019). The dense synapses on the cerebrovascular can release various types of vasodilator and contractile factors, and most of the vasodilator and diastolic activities of the cerebrovascular are regulated by sympathetic nerve. The robust coupling of neuronal activation to regional cerebral blood flow can be easily observed. For example, the activation of OC by visual stimulation can elicits ~ 20–30% increase in blood velocity in the posterior cerebral arteries(Willie et al. 2014). In this study, the WPCO values of LPFC-LMC, LMC-LOC, RPFC-RMC, LPFC-RPFC, LMC-RMC, LOC-RMC, LOC-ROC in Hong Chuan Tai Chi practitioners were significantly higher than that of controls, indicating higher functional connectivity in resting state. The higher functional connectivity suggested long-term Hong Chuan Tai Chi practice is associated with the synchronization of neurogenic activity and the coordination of PFC, MC and OC because Tai Chi requires the coordination of movement, mind and visual perception.

The oscillations in interval V is associated with metabolic activity of vascular endothelial cells(Stewart et al. 2007). Endothelial cells can release potent vasodilator nitric oxide (NO) and the NO-related metabolic activity of endothelial cells is closely integrated with neurovascular activity. Previous studies suggested that Tai Chi can improve endothelial function and arterial stiffness of elderly people(Shin et al. 2015). It's

assumed that Hong Chuan Tai Chi can improve metabolic activity of vascular endothelial cells. In this study, Hong Chuan Tai Chi practitioners had higher WPCO values of LPFC-LMC, LMC-LOC, RPFC-RMC, RMC-ROC, LPFC-RPFC, LPFC-RMC, LMC-RMC, LOC-RMC, LOC-ROC than that of Tai chi-naïve controls. This result suggests higher functional connectivity between these brain regions in Hong Chuan Tai Chi group.

However, a cross-sectional study design could not completely rule out confounding factors between the two groups of participants, such as lifestyles. In future studies, randomized controlled study may help to rule out these confounding factors and better establish the causal relationship between Hong Chuan Tai Chi practice and brain functional connectivity in these brain regions. In addition, as Hong Chuan Tai Chi is different from classical Chen style Tai Chi, it's necessary to compare their efficiency in brain-related changes in the future.

Conclusions

The middle-aged Hong Chuan Tai Chi practitioners had higher functional connectivity between prefrontal cortex, motor cortex and occipital cortex, as well as the coordination of left and right brain, which maybe the contributing factors to higher global cognition

Declarations

Author contributions ZS, LX contributed to the conception of this work. ZS, HX, XZ and QH designed this study. ZS, LX, HX, ZS carried out the experiments. ZS, LX, HX, XZ analyzed the experiments results. ZS, LX, XZ, QH completed the first draft of the manuscript. LX contributed same to ZS to this article and could be considered as common first author. XZ, HX contributed equally with QH to this article and could be considered as common corresponding author. All authors were involved in the manuscript revision and agreed with final approval of the version, and assured the accuracy of investigation. The authors declare that they have no competing interests.

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Ethical approval The Ethics Committee of Shandong University approved this study. All participants provided written informed consent.

Consent to participate Written informed consent was obtained from all individual participants as part of the conduct of the Human Connectome Project.

Informed consent All parents gave informed consent. All children gave assent. Participants were compensated for their time.

Conflict of interest The authors report no conflicts of interest.

Availability of data and materials The data and material will be provided to qualified researchers upon reasonable request.

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Figures

Figure 1

Probe arrangement of multichannel blood oxygen detection system. Red circle represents the detector, black circle represents the light source, the arrow is the channel of the light source points to the detector.

Figure 2

The wavelet phase coherence values between brain regions in frequency interval I in resting state. * ($P < 0.05$), ** ($P < 0.01$) and *** ($P < 0.001$) indicate significant difference between the Hong Chuan Tai Chi and Control groups.

Figure 3

The wavelet phase coherence values between brain regions in frequency interval II in resting state.

Figure 4

The wavelet phase coherence values between brain regions in frequency interval II in resting state.

Figure 5

The wavelet coherence values between brain regions in frequency interval IV in resting state.

Figure 6

The wavelet phase coherence values between brain regions in frequency interval V in resting state.