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ORIGINAL RESEARCH

Long-Term Tai Chi Practice Modulates Cortical-Muscular Interactions During Walking in Older Adults: A Cross-Sectional Study

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Purpose: The possible effects of Tai Chi exercise on neural coordination during walking in older adults remain unclear. This study aimed to compare cortical functional connectivity (FC) and corticomuscular coupling (CMC) during walking among older Tai Chi practitioners, older brisk walkers, and non-exercise controls.

Methods: A total of 62 participants were recruited in this study, including older Tai Chi practitioners (n=20), older brisk walkers (n=22), and non-exercise controls (n=20). Participants performed a walking test during which data were collected. The FC was measured using cortical oxygenated hemoglobin (HbO_2) concentration via a functional near-infrared spectroscopy device, and CMC was calculated between HbO_2 signals and surface electromyography signals.

Results: The Tai Chi practitioners showed greater FC in right primary motor cortex-left supplementary motor area ($_{r}$M1-$_{l}$SMA, p=0.006, d=1.081), right primary motor cortex-right supplementary motor area ($_{r}$M1-$_{r}$SMA, p=0.003, d=1.318), right primary motor cortex-left primary somatosensory cortex ($_{r}$M1-$_{l}$S1, p=0.002, d=1.150), and $_{r}$M1-$_{r}$S1 (p=0.011, d=1.015) compared with the non-exercise controls, and greater FC in $_{r}$M1-$_{r}$S1 (p=0.015, d=0.856) compared with the brisk walkers. In addition, the Tai Chi practitioners demonstrated greater CMC in the left tibialis anterior-right supplementary motor area ($_{l}$TA-$_{r}$SMA, p=0.015, d=0.991), $_{l}$TA-$_{r}$S1 (p=0.006, d=1.096), $_{l}$MG-$_{r}$SMA (p=0.002, d=1.118), right medial gastrocnemius-right supplementary motor area ($_{r}$MG-$_{r}$SMA, p=0.015, d=0.962), and $_{r}$MG-$_{r}$S1 (p=0.017, d=0.939) compared to the non-exercise controls.

Conclusion: Older Tai Chi practitioners exhibited greater functional connectivity and corticomuscular coupling, which may contribute to improved postural control and reduced fall risk in older adults.

Keywords: Tai Chi, aged, near-infrared spectroscopy, functional connectivity, corticomuscular coupling

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Introduction

Older adults are at a high risk of falls, and falls often occur during locomotor activities such as walking.[1] According to the World Health Organization,[2] the occurrence of falls in the elderly population is an important public health problem, representing the second leading cause of unintentional injury deaths worldwide. Falls among older adults result in moderate to severe injuries, loss of independence,[3] and also cause the economic burden of falls for families and society.[4]

Falls are generally associated with impaired postural control in older adults.[5] Postural control is a complex neuromuscular process that involves integration of sensorimotor information in the central nervous system, and appropriate programming and execution of neuromuscular responses.[6,7] In addition, evidence suggests that multiple cortical regions are involved in postural control,[8] such as the primary motor cortex, supplementary motor area,[9] and prefrontal cortex.[10] Furthermore, walking engages a complex brain network, network efficiency and functional connectivity between different cortical regions are considered critical for cortical modulation.[11]

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With aging, declines in postural control are often associated with impairments in the cortical-muscular interaction. Exercise enabled by high-tech may be effective in postponing the decline in postural control.[12,13] As a traditional intervention, Tai Chi has been shown to effectively reduce falls and fall risk in older adults with the advantages of easy accessibility and wide population acceptance.[14] Proprioceptive training combined with dual-task exercises may have the effect of improving gait speed, an important indicator of fall risk.[15] Since Tai Chi practicing involves complex motor-cognitive integration and postural control, which is similar to proprioceptive and dual-task training, this characteristic of Tai Chi may contribute to its enhancement in cortical function and postural control in older adults, which reduces the number of falls and fall risk.[16]

A previous study reported that Tai Chi practitioners exhibited greater resting-state functional connectivity among the prefrontal cortex, motor cortex, and occipital cortex than the controls without Tai Chi experiences.[17] However, most studies have primarily focused on individual cortical functions during resting state, with insufficient emphasis on the coordinated interactions during walking, which is essential for maintaining independence in older adults and is also when most falls occur.

Corticomuscular coupling (CMC) refers to the functional interaction between the cerebral cortex and muscles, characterized by synchronized activity between cortical and neuromuscular signals. A previous study has reported a high consistency between movement related cortical areas and thigh muscle activation during postural control in older adults.[18] CMC has been shown to decline with aging, which indicates older adults have poorer neuromuscular control than young adults during voluntary motor tasks.[19] To our knowledge, the effects of Tai Chi on neuromuscular control as indicated by CMC during walking in older adults have not been investigated.

The purpose of this study was to compare the differences in the functional connectivity and CMC during walking among older Tai Chi practitioners, older brisk walkers and non-exercise controls. We hypothesized that: (1) the older Tai Chi practitioners would demonstrate significantly greater functional connectivity compared to both the older brisk walkers and non-exercise controls; (2) the older Tai Chi practitioners would demonstrate significantly greater CMC compared to both the older brisk walkers and non-exercise controls.

Materials and Methods

Sample Size Calculation

As no previous study fully comparable to the target population and primary outcome was available, a post hoc power analysis was performed using the observed effect size of the primary outcome in G*Power software (Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany). The significance level was to be 0.05, the effect size was calculated to be 0.45. With a sample size of 51, the statistical power was calculated to be 0.81, which was above 0.8.

Participants

A total of 62 participants were recruited by distributing leaflets in the local communities in Jinan, China. The inclusion criteria were (1) ≥ 65 years of age; (2) Without cardiovascular, respiratory, musculoskeletal or neurological diseases; (3) Able to live independently and perform daily activities. Twenty participants with more than 5 years of regular Tai Chi practice were recruited, 22 with more than 5 years of regular brisk walking, and 20 without regular exercise for more than 5 years. The exclusion criteria were (1) visual impairment; (2) Using any medication affecting physical balance or the nervous system in the last 6 months. There was no significant difference in age, sex, height, or weight among the participants (Table 1).

A cross-sectional study was conducted at the Sports Biomechanics Laboratory of Shandong Sport University to investigate differences in measures among groups. The trial was registered in the International Traditional Medicine Clinical Trial Registry under the registration number ITMCTR2025002399. This study was approved by the Ethics Committee of Shandong Sport University (approval number: 2024054, November 5, 2024) and informed consent was obtained from all participants. The study was conducted in accordance with the Declaration of Helsinki.

Data Collection

fNIRS and sEMG Data Collection

Functional near-infrared spectroscopy (fNIRS) and sEMG data were obtained during walking test, which consisted of a 30-s baseline, a 60-s walking and followed by 30-s rest using an fNIRS system (NirSmartII-3000A, Danyang Huichuang Medical

Table 1 Basic Information of the Participants (Mean ± Standard Deviation)

	Tai Chi Practitioners (n=20)	**Brisk Walkers (n=22)**	**Non-Exercise Controls (n=20)**	**p**
Age (years)	66.8±3.1	67.0±4.1	69.2±3.5	0.069
Sex (female/male)	16F, 4M	15F, 7M	10F, 10M	0.130
Height (cm)	160.4±6.6	159.9±7.5	160.0±9.1	0.971
Weight (kg)	64.9±8.6	67.5±12.1	68.5±12.4	0.567
BMI (kg/m^2)	25.2±2.9	26.2±2.9	26.7±4.2	0.357

Notes: M, F are abbreviations for male and female. Sex was analyzed using the chi-square test, while other variables were analyzed using one-way analysis of variance (ANOVA). A p value < 0.05 was considered statistically significant.

Equipment Co., Ltd., Danyang, Jiangsu, China) and a 16-channel EMG system (Ultium EMG, Noraxon Inc., USA). During the baseline, participants maintained quiet standing and stayed relaxed. During the walking, participants walked back and forth along the walkway at their preferred speed. During the rest, the participants were instructed to sit quietly with eyes closed. Three trials were conducted for the walking test (Figure 1). The fNIRS signals were synchronized with the sEMG data. The sEMG signals were collected from the tibialis anterior (TA), medial gastrocnemius (MG) of both legs. The arrangement of the fNIRS channels is shown in Figure 2.

Data Processing

fNIRS Data Processing

The fNIRS signals were sampled at 11 Hz and processed using NirSpark software[20] (Danyang Huichuang Medical Equipment Co., Ltd., Danyang, Jiangsu, China). Eight regions of interest (ROIs) were defined based on the corresponding positions of the channels in the cortex. Channels 8, 9, 10, 11, 20, 22 and 23 corresponded to the left prefrontal cortex ($_l$PFC). Channels 3, 5, 6, 7, 17, 19 and 21 corresponded to the right prefrontal cortex ($_r$PFC). Channels 30, 31 and 44 corresponded to the left primary

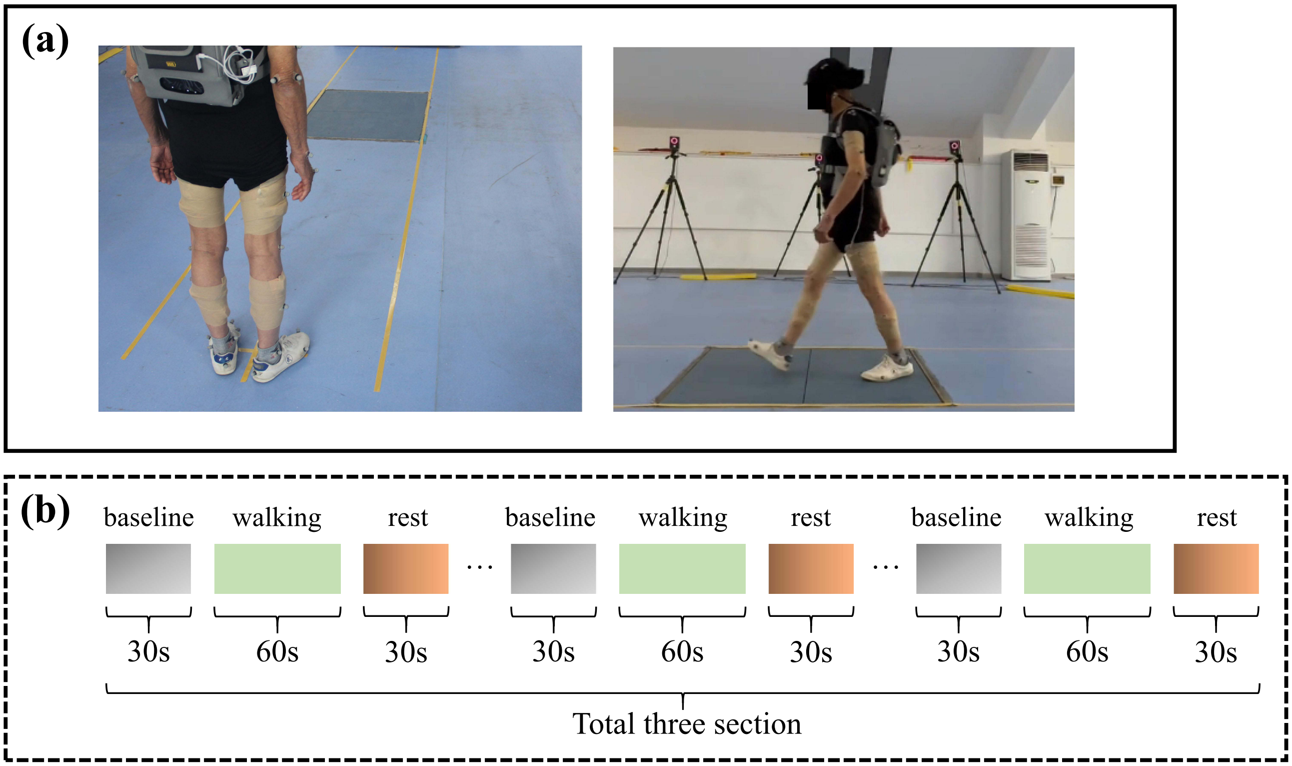

Figure 1 Experimental data acquisition paradigm. (**a**) walking test setup (**b**) walking test procedure.

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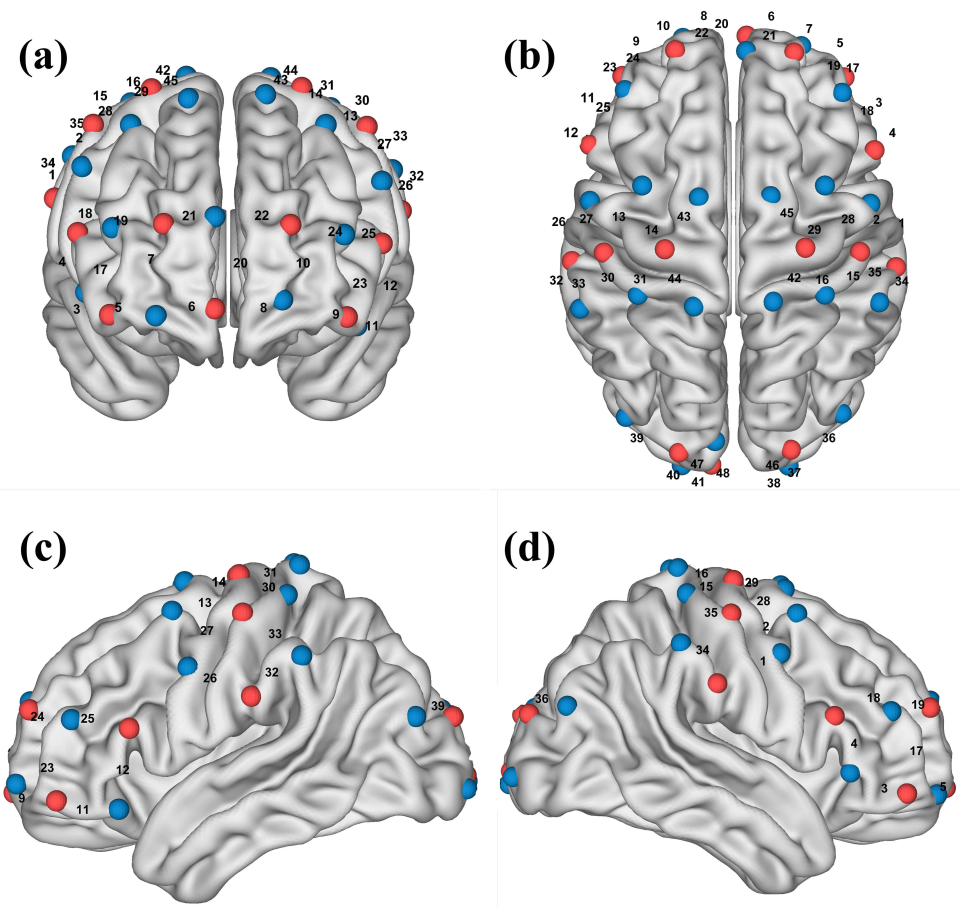

Figure 2 Arrangement of the fNIRS channels. The red colour represents the source probes, and the blue colour represents the detector probes. (**a**) Front, (**b**) top, (**c**) left-lateral, (**d**) right-lateral views of the locations of the channels in the MNI brain.

motor cortex ($_l$M1). Channels 15, 16 and 42 corresponded to the right primary motor cortex ($_r$M1). Channels 32 and 33 corresponded to the left primary somatosensory cortex ($_l$S1). Channels 34 and 35 corresponded to the right primary somatosensory cortex ($_r$S1). Channels 13, 14, 27 and 43 corresponded to the left supplementary motor area ($_l$SMA). Channels 2, 28, 29 and 45 corresponded to the right supplementary motor area ($_r$SMA). All HbO$_2$ concentration signals from the above regions were collected.

Channels with obvious spikes in the time-domain signal and high frequency noise in the frequency-domain were excluded from further analysis. Motion correction was done in the first step, any signal change beyond 5 standard deviations (std_thr > 6) and 0.5 amplitude (amp_thr > 0.5) of the entire time series was considered a motion artifact for tighter control of data quality.[21] The signals from each channel were band-pass filtered with cut-off frequencies of 0.01–0.2 Hz to remove physiological noise. The filtered raw light intensity signals were converted to HbO$_2$ concentration data based on the modified Beer-Lambert law. After preprocessing, functional network analysis was performed, and Pearson correlation analysis was applied to calculate correlation coefficients over a 5-min time window (from the first walking to the last sitting) between each pair of channels and ROIs.[22] Fisher's transformation was used to convert the r values into z values, which exhibit better normality for statistical analysis. The resulting z values were used for statistical analysis.

Corticomuscular Coupling Analysis

CMC analysis was performed using Python (Spyder IDE, Anaconda distribution). Before CMC analysis, the sEMG signals were sampled at 2000 Hz and band-pass filtered using a fourth-order Butterworth filter with cut-off frequencies of 20–450 Hz, followed by a 50 Hz notch filter. Subsequently, the filtered fNIRS data from the three walking trials were extracted for CMC calculation with the sEMG data. For segmented data, we mainly focused on the sEMG and fNIRS data for the first 15 seconds of each walking test.[23]

Time-series causality analysis using transfer entropy (TE) was applied for CMC calculation, allowing the assessment of connectivity strength between physiological signals in various states and providing an objective characterization of information flow direction.[24] If given two-time series $X = \{x_1, x_2, \ldots, x_N\}$ and $Y = \{y_1, y_2, \ldots, y_N\}$, where N is the length of the time series, the TE from Y to X is defined as $TE_{Y\to X}$, the equation is calculated as follows:

$$TE_{Y\to X} = \sum P\left(x_{t+1}, x_t^l, y_r^k\right) \log\left(\frac{p\left(x_{t+1}\middle|x_t^l, y_r^k\right)}{p\left(x_{t+1}\middle|x_t^l\right)}\right) \tag{1}$$

Where t is any point in time ($1 \leq t \leq N$); p represents the probability distribution. In general, the most natural choice for l = k = 1 is computational. At the same time, because TE is inherently asymmetric, $TE_{Y\to X}$ does not equal $TE_{X\to Y}$. Thus, when $TE_{X\to Y} < TE_{Y\to X}$, we call Y cause and X effect, and thus establish a causal relationship between the two signals.

Considering the hysteresis of physiological signal interaction, the time parameter u can be introduced into the formula of TE. Therefore, the TE from Y to can be written as:[25]

$$TE_{Y\to X} = \sum P\left(x_{t+u}, x_t, y_t\right) \log\left(\frac{p(x_{t+u}|x_t, y_t)}{p(x_{t+u}|y_t)}\right) \tag{2}$$

The resulting TE can measure transmitted information to detect asymmetries in subsystem coupling and measure hysteresis in physiological signal interactions. To distinguish functional connections in muscle and cortex, TE values in the cortico-muscular and muscle-cortical directions were calculated with u from 1 to 50.

Statistical Analysis

Means and standard deviations were calculated for each measure. The normal distribution of data was evaluated with the Shapiro–Wilk test. The one-way ANOVA was used for comparison on measures with normal distribution. The Kruskal–Wallis test for comparison on measures with abnormal distribution. The Bonferroni method was used for post-hoc tests, with the significance level adjusted to 0.017 (p = 0.05/3).

The effect sizes were expressed with Eta squared (η^2), $\eta^2 < 0.06$: small effect size, $0.06 < \eta^2 < 0.14$: medium effect size, $\eta^2 > 0.14$: strong effect size.[26] Cohen's d was used to report effect sizes in post-hoc tests, with the following thresholds: 0.2 to 0.5 indicates a small effect; 0.5 to 0.8 represents a medium effect; and > 0.8 denotes a large effect.[27]

Results

Functional Connectivity

One-way ANOVA revealed significant differences in the FC of ${}_{r}$M1-${}_{l}$SMA (p=0.008, η^2=0.153), ${}_{r}$M1-${}_{r}$SMA (p=0.004, η^2=0.175), ${}_{r}$M1-${}_{l}$S1 (p=0.003, η^2=0.181), and ${}_{r}$M1-${}_{r}$S1 (p=0.005, η^2=0.171) among the three groups. Post-hoc analyses using the Bonferroni method indicated that the older Tai Chi practitioners exhibited significantly greater FC than the non-exercise controls in the ${}_{r}$M1-${}_{l}$SMA (p=0.006, d=1.081), ${}_{r}$M1-${}_{r}$SMA (p=0.003, d=1.318), ${}_{r}$M1-${}_{l}$S1 (p=0.002, d=1.150), and ${}_{r}$M1-${}_{r}$S1 (p=0.011, d=1.015); the older Tai Chi practitioners had significantly greater FC than the older brisk walkers in ${}_{r}$M1-${}_{r}$S1 (p=0.015, d=0.856) (Figure 3).

Corticomuscular Coupling

One-way ANOVA revealed significant differences in the TE between ${}_{l}$TA-${}_{r}$SMA (p=0.003, η^2=0.194), ${}_{l}$TA-${}_{r}$S1 (p=0.006, η^2=0.165), ${}_{l}$MG-${}_{r}$SMA (p=0.002, η^2=0.199), ${}_{r}$MG-${}_{r}$SMA (p=0.004, η^2=0.173), ${}_{r}$MG-${}_{r}$S1 (p=0.020, η^2=0.126). Post-hoc analyses using the Bonferroni method indicated that the older Tai Chi practitioners had significantly greater TE in ${}_{l}$TA-${}_{r}$SMA (p=0.015, d=0.991), ${}_{l}$TA-${}_{r}$S1 (p=0.006, d=1.096), ${}_{l}$MG-${}_{r}$SMA (p=0.002, d=1.118), ${}_{r}$MG-${}_{r}$SMA (p=0.015, d=0.962), and ${}_{r}$MG-${}_{r}$S1 (p=0.017, d=0.939) compared to the non-exercise controls; the older brisk walkers had significantly greater TE in ${}_{l}$TA-${}_{r}$SMA (p=0.003, d=1.068), ${}_{l}$MG-${}_{r}$SMA (p=0.016, d=0.953), and ${}_{r}$MG-${}_{r}$SMA (p=0.009, d=0.940) compared to the non-exercise controls (Figure 4).

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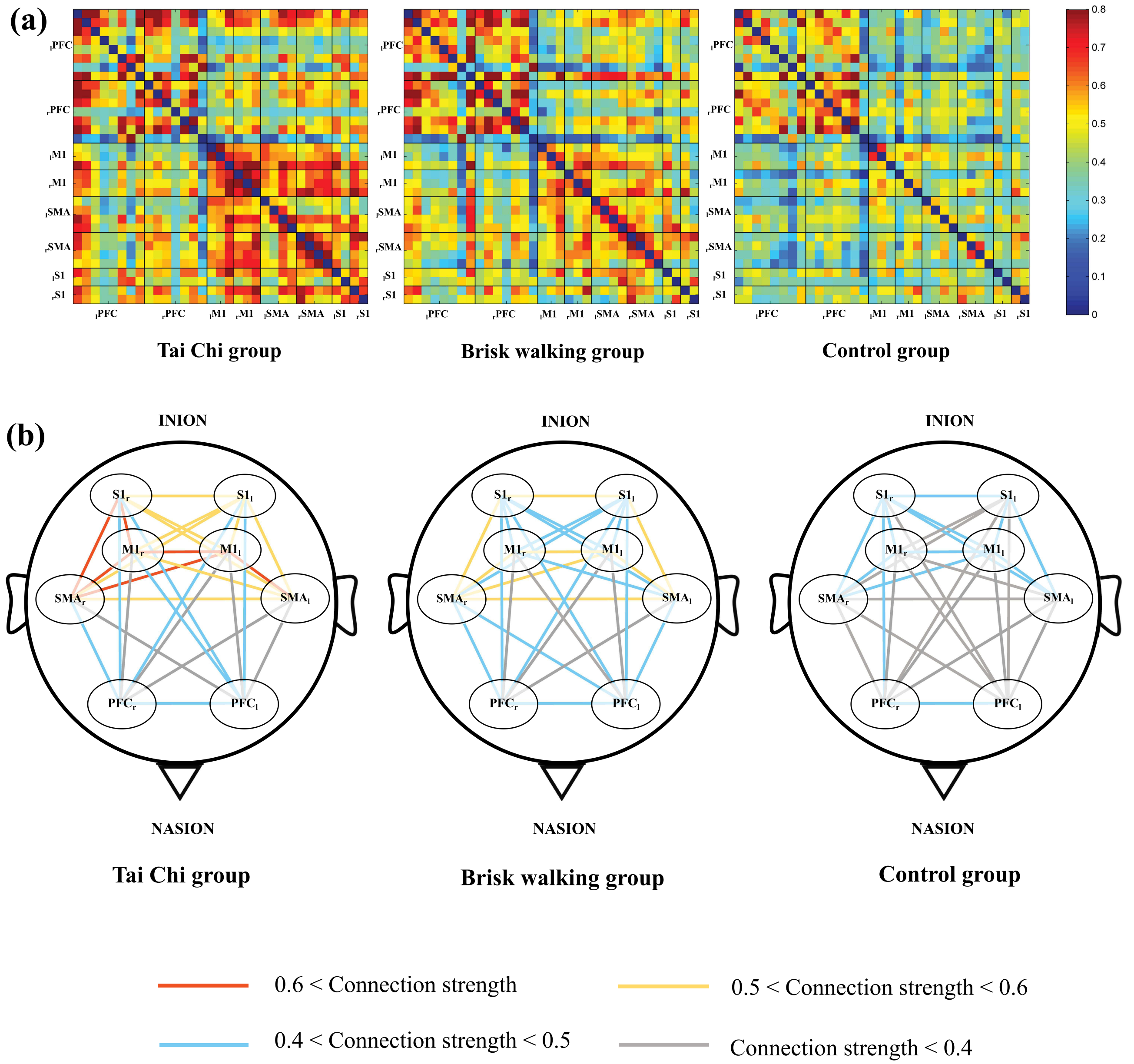

Figure 3 (**a**) Functional connectivity matrices among channels, channels were arranged according to their corresponding cortical regions. The vertical axis (top to bottom) and horizontal axis (left to right) represent the following regions: left prefrontal cortex ($_{l}$PFC), right prefrontal cortex ($_{r}$PFC), left primary motor cortex ($_{l}$M1), right primary motor cortex ($_{r}$M1), left supplementary motor area ($_{l}$SMA), right supplementary motor area ($_{r}$SMA), left primary somatosensory cortex ($_{l}$S1), and right primary somatosensory cortex ($_{r}$S1). (**b**) The intensity of functional connectivity among ROIs, line color indicates the connectivity intensity between two ROIs.

Discussion

This study compared the differences in the FC and CMC during walking among older Tai Chi practitioners, older brisk walkers and non-exercise controls. Our results partially support the hypothesis that the older Tai Chi practitioners have greater FC and CMC than the older brisk walkers and non-exercise controls.

Our results indicated that older Tai Chi practitioners exhibited greater functional connectivity than older adults with no exercise habits. According to the hypothesis proposed by Daselaar et al,[28] aging brains exhibit “more firing, less wiring.” Due to limited neural resource capacity, older adults appear to recruit neural resources from various ROIs and rely on increased local cortical activation to compensate for age-related declines and maintain task performance.[11,29] Compared with non-exercise controls, older Tai Chi practitioners exhibited greater functional connectivity and lower

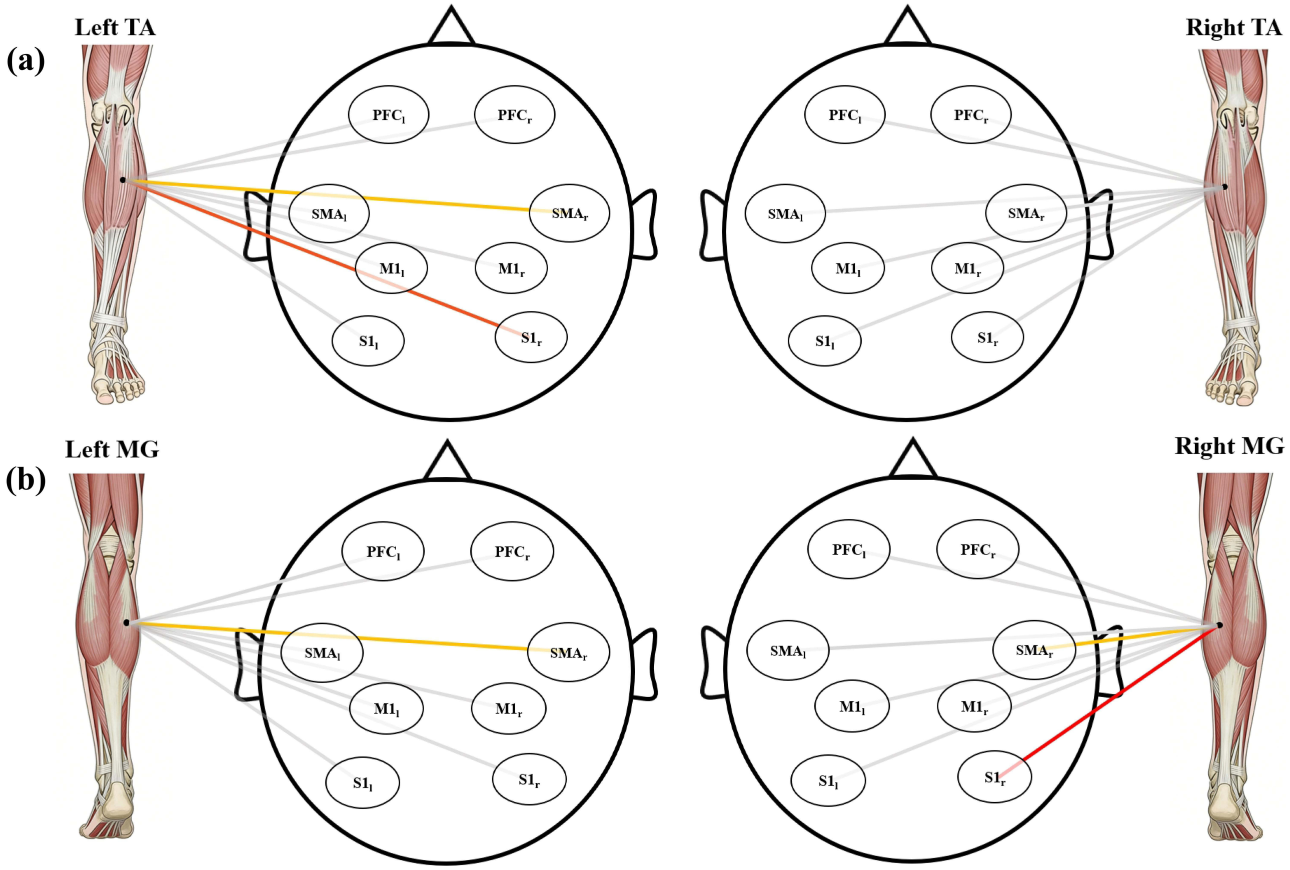

Figure 4 Differences in transfer entropy (TE) among the older Tai Chi practitioners, older brisk walkers, and non-exercise controls. (**a**) Tibialis anterior (TA), (**b**) medial gastrocnemius (MG). Red lines indicate significantly greater TE in the Tai Chi practitioners than in the non-exercise controls, yellow lines indicate significantly greater TE in the older Tai Chi practitioners and brisk walkers than in the non-exercise controls. The regions of interest are: left prefrontal cortex (PFC_l), right prefrontal cortex (PFC_r), primary motor cortex (M1), supplementary motor area (SMA), and primary somatosensory cortex (S1).

local cortical activation during walking,[30] which may reflect a more distributed neural resource recruitment across multiple brain regions.

A possible explanation for our results is that during Tai Chi exercise, spatial orientations and movement directions are often inconsistent, so people need to deal with the conflicting information so as to select the correct action.[31] This process includes both cognitive and motor control functions and involves multiple brain regions. Another possible explanation is that Tai Chi exercise emphasizes precise control of body and limb joint positions, and repeated practice may lead to plastic changes in the cortex,[32] such as structural changes in the organization and number of connections among neurons.[33]

Notably, older Tai Chi practitioners exhibited significantly greater FC in the rM1-rS1 than both older adults with no exercise habits and older adults with brisk walking habits. The S1 is responsible for processing various peripheral sensory information from the body,[34] among which proprioception plays a critical role in maintaining postural stability, particularly in older adults. A previous study demonstrated that Tai Chi training resulted in better improvements in ankle proprioception compared with brisk walking, and the training effects were maintained after an eight-week detraining period.[35] The greater $_r$M1-$_r$S1 functional connectivity observed in older Tai Chi practitioners may reflect more efficient coordination between cortical motor control and peripheral sensory input. Specifically, enhanced proprioceptive input and stronger sensorimotor network connectivity may enable Tai Chi practitioners to achieve superior postural stability and refined motor control during walking, thereby contributing to improved postural control.

The CMC analysis revealed that TE in the cortico-muscular direction was greater than in the muscle-cortical direction (Supplementary Table 1), indicating predominant cortical control over muscle activity. Furthermore, older Tai Chi practitioners exhibited greater TE values in the TA and MG than non-exercise controls, indicating greater neuromuscular information transmission between the cerebral cortex and distal lower-limb muscles. These findings are consistent with previous reports showing greater β-band CMC in older Tai Chi practitioners than in older adults during ankle dorsal flexion and plantar flexion under balance-demanding conditions,[36] suggesting that Tai Chi training enhances sensorimotor integration for distal lower-limb muscles. Increased CMC was also found to correlate with decreased medial/lateral postural sway in older adults, suggesting that greater CMC may contribute to improved postural control. Tai Chi has the potential to become a clinically effective intervention for fall prevention and balance enhancement, particularly among older adults. As Tai Chi has effects on improving neuromuscular control, it may be used as a new intervention for neuromuscular control impairments.

This study has some limitations. We only analyzed overground walking rather than more complex conditions (eg., dual-task walking), as it represents a fundamental daily activity in older adults. Although more complex tasks may provide additional insights, this is unlikely to affect the validity of the present findings. Although Tai Chi has demonstrated benefits in cognitive and physical performance, the underlying neurophysiological mechanisms remain unclear. More research is necessary to investigate the long-term changes associated with Tai Chi exercise.

Conclusions

Older Tai Chi practitioners exhibited greater cortical functional connectivity and corticomuscular coupling. These findings suggest that Tai Chi exercise may enhance cortico-muscular information transmission, which may contribute to improved postural control and reduced fall risk in older adults. Further research is needed to clarify the neurophysiological mechanisms underlying these adaptations.

Data Sharing Statement

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Ethics Approval and Informed Consent

The trial was registered in the International Traditional Medicine Clinical Trial Registry under the registration number ITMCTR2025002399. This study was approved by the Ethics Committee of Shandong Sport University (approval number: 2024054, November 5, 2024) and informed consent was obtained from all participants. The study was conducted in accordance with the Declaration of Helsinki.

Consent for Publication

Written informed consent for publication of the image was obtained from the participant.

Acknowledgments

The corresponding author affirms that all individuals who contributed significantly to this work have been appropriately listed.

Author Contributions

All authors made a significant contribution to the work reported, whether that is in the conception, study design, execution, acquisition of data, analysis and interpretation, or in all these areas; took part in drafting, revising or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

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Disclosure

The authors declare that they have no competing interests in this work.

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