

## Walking patterns and cognitive performance in Tai Chi experts: Exploring the connection to motor control

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### Abstract:

**Purpose.** Tai Chi is an ancient Chinese martial art known for its physical and mental health benefits. This study explores the potential of Tai Chi to improve motor abilities and cognitive functions, with particular attention to the integration between movement and executive control processes. Given its emphasis on controlled, deliberate movements coordinated with attention and breath, Tai Chi may foster a deeper awareness of body mechanics and enhance neurocognitive functioning. **Methods.** We enrolled a group of individuals who regularly practiced Tai Chi and a control group of healthy individuals with no prior Tai Chi experience or involvement in comparable mind-body practices. Gait was assessed using the harmonic ratio, a widely recognized measure of movement smoothness, stability, and motor control ability derived from trunk acceleration during walking. Participants' cognitive condition was evaluated using a battery of standardized assessments targeting domains such as executive functioning, attention, and working memory, alongside self-report measures capturing perceived cognitive performance and daily functioning. **Results.** The results revealed lower harmonic ratio values (i.e., higher motor control) in Tai Chi practitioners compared to the healthy controls. The enhanced motor ability observed in the Tai Chi group may be attributed to the attentional focus operated on movement through the practice, which promotes enhanced cognitive-motor integration. These findings suggest that Tai Chi may lead to measurable changes in neuromuscular coordination. **Conclusions.** Furthermore, the study demonstrated a positive correlation between harmonic ratio values and executive functions' scores in the Tai Chi group, supporting the hypothesis that regular Tai Chi practice contributes to improved cognitive efficiency and sensorimotor performance.

**Keywords:** Gait, cognition, movement, martial art, physical and mental health, executive functions.

### Introduction

Tai Chi is a traditional Chinese martial art, originating centuries ago (Wolf et al., 1997). Historically, it emerged from Taoist philosophy and principles of Traditional Chinese Medicine, promoting harmony between body and mind, and a balance of yin and yang energies. Originally developed for self-defense, Tai Chi has evolved over time into a holistic form of mind-body exercise that blends meditative movement with breath control and focused attention. In recent years, it has been widely adopted in the West and globally as a means to enhance physical and mental well-being. Its benefits extend beyond physical health, touching upon emotional regulation, psychological resilience, and cognitive functioning.

Tai Chi combines elements of martial arts, self-defense techniques, and meditative practices (Field, 2011). It is characterized by a series of slow, continuous, and fluid movements designed to be performed with precision and relaxation. Each posture flows into the next, encouraging practitioners to maintain postural control, balance, and a heightened awareness of their body and breath. These characteristics distinguish Tai Chi from other forms of physical exercise by fostering an integrated engagement of both body and mind. As a multimodal mind-body exercise (Liparoti, 2021), Tai Chi promotes sustained attention, mental flexibility, and the ability to multi-task. Its practice has also been associated with reductions in anxiety and depression, indirectly enhancing overall cognitive functioning.

One of the reasons for Tai Chi's popularity is its accessibility and adaptability. It can be practiced by individuals of all ages and levels of physical fitness. It is particularly suitable for older adults due to its low-impact nature, which places minimal stress on joints and muscles. The slow and deliberate movements can be easily adjusted to accommodate varying physical conditions, making it ideal for individuals recovering from injury or managing chronic illnesses. Studies have consistently demonstrated that Tai Chi can improve physical attributes such as balance, coordination, muscular strength, and flexibility (Maciaszek & Osiński, 2010). These improvements are not only important for general health but are especially critical in aging populations, where the risk of falls and mobility impairments are prevalent.

From a public health perspective, the role of physical activity in promoting cognitive and psychological well-being has become increasingly recognized. A growing body of research supports the idea that engaging in regular physical activity has profound effects on brain health. Physical exercise has been shown to influence neuroplasticity, increase cerebral blood flow, and reduce neuroinflammation, all of which contribute to cognitive maintenance and delay the onset of cognitive decline. The cognitive benefits of exercise are particularly important in the context of aging, where maintaining executive functions, such as planning, attention, and memory, is vital for preserving independence and quality of life (Passarello et al., 2022).

While the general relationship between physical activity and cognition is well established, fewer studies have explored how specific types of exercise may differentially influence these outcomes. Tai Chi, with its distinctive blend of physical movement and cognitive engagement, offers a unique model for investigating this relationship. Its meditative aspects promote mindfulness and relaxation, which are known to mitigate stress and enhance emotional regulation. Studies suggest that Tai Chi can lead to improvements in mood, sleep quality, and self-efficacy. These psychological benefits, in turn, create a favorable environment for cognitive enhancement. Tai Chi's influence on cognitive function has been documented in several clinical trials and longitudinal studies. For example, Li et al. (2019) reported that regular Tai Chi practice was associated with improved executive functioning, working memory, and attention in older adults. These cognitive improvements are believed to arise from multiple biological mechanisms, including modulation of brain activity, increased connectivity in neural networks, and upregulation of neurotrophic factors. Additionally, Tai Chi has been found to regulate the autonomic nervous system, contributing to stress reduction and emotional stability. Kong et al. (2019) further highlighted that Tai Chi may enhance neurogenesis and reduce inflammation in the brain, creating a neuroprotective effect that supports cognitive aging.

From a biomechanical perspective, Tai Chi is known to influence gait dynamics and motor control. The slow and deliberate nature of Tai Chi movements emphasize proper alignment, controlled weight shifting, and coordinated use of the upper and lower body. These components contribute to improved proprioception, postural stability, and dynamic balance. Studies have shown that Tai Chi practitioners exhibit longer gait cycles, increased single-leg stance time, and greater joint flexion (Wu et al., 2004), all of which indicate improved neuromuscular coordination and strength. Pearlman et al. (2017) found that Tai Chi modifies the distribution of joint moments, increasing mechanical demands in a way that promotes muscular engagement and biomechanical efficiency.

These gait-related benefits are not only indicative of physical fitness but may also reflect underlying cognitive processes. Gait is increasingly recognized as a complex motor activity that requires executive control, attention, and sensorimotor integration. As such, changes in gait dynamics can serve as early indicators of cognitive decline. In this context, the Harmonic Ratio (HR) has emerged as a valuable metric for assessing gait stability and rhythmicity. HR quantifies the smoothness of movement by analyzing the frequency components of trunk accelerations during walking. Higher HR values suggest more stable and symmetric gait patterns, whereas lower values indicate irregularities or impaired motor control. Despite the growing interest in HR as a biomarker for motor function, its application in Tai Chi research remains limited. There is a need for empirical studies that directly assess how Tai Chi training influences HR and whether such changes correlate with cognitive performance. This gap in the literature presents a compelling rationale for our study, which aims to investigate the association between Tai Chi practice, gait dynamics, and cognitive function.

Within this framework, our study is designed to assess how proficient Tai Chi practitioners are in controlling their movements during everyday activities, such as walking, and to explore potential associations with cognitive function. Specifically, we hypothesize that individuals who regularly practice Tai Chi will exhibit enhanced motor control, as measured by HR, compared to age-matched healthy controls. Furthermore, we aim to determine whether higher HR values are associated with better cognitive performance in areas such as attention, executive functioning, and memory. To test these hypotheses, we recruited twenty participants, including ten individuals who regularly practice Tai Chi (TP) and ten healthy individuals without Tai Chi experience (HC). Participants were matched for age, sex, and general health status. Motor control was assessed using a stereophotogrammetric system, which captures three-dimensional kinematic data during normal walking. This method allows for precise analysis of trunk movement and HR calculation. Additionally, participants completed a battery of standardized neuropsychological tests, including assessments of attention, executive function, and processing speed. Self-report measures of mood and mental well-being were also collected to account for psychological variables that might influence cognitive performance.

By integrating biomechanical analysis with cognitive assessments, this study provides a comprehensive evaluation of the mind-body effects of Tai Chi practice. It contributes to the emerging field of psychomotor integration and highlights the potential of Tai Chi as an intervention that simultaneously targets motor and cognitive health. Therefore, this research seeks to bridge the gap between physical and cognitive health by examining the unique contributions of Tai Chi practice. As a holistic exercise that embodies principles of mindfulness, balance, and coordinated movement, Tai Chi offers a promising avenue for promoting well-being across multiple domains. Through our study, we aim to provide empirical evidence supporting the integration of Tai Chi into public health strategies, therapeutic interventions, and wellness programs aimed at enhancing both motor function and cognitive vitality.

## Materials and Methods

### Participants' description

We enrolled 20 participants divided in ten individuals practicing Tai Chi and ten age-matched healthy controls (that had not practiced sport in a structured and constant manner during the last ten years). The study's inclusion criteria included individuals with normal or corrected-to-normal vision, aged > 18 years, and native Italian speakers. Moreover, participants were considered eligible if they achieved a minimum score of 26 in the Mini-Mental State Examination (MMSE) (Measso et al., 1993). Conversely, exclusion criteria involved individuals with a history of psychopathology, psychiatric, neurological, or motor disorders, history of drug or alcohol abuse, or any other significant medical illnesses. The study was performed in accordance with the declaration of Helsinki and was approved by the Local Ethical Committee Asl Napoli 1 Centro (protocol number: 250-N. Reg. 17–2023 oss). Sample characteristics are reported in Table 1.

| Characteristics          | Tai Chi    | Control     | p-value |
|--------------------------|------------|-------------|---------|
| Age (years)              | 54.1 ± 7.7 | 51.6 ± 7.95 | n.s.    |
| Gender (m/f)             | 6/4        | 6/4         | n.s.    |
| Education (years)        | 15 ± 2.6   | 14.4 ± 4.1  | n.s.    |
| BMI (Kg/m <sup>2</sup> ) | 25.2 ± 3.3 | 25.4 ± 2    | n.s.    |
| BDI                      | 4.8 ± 1.4  | 5.3 ± 3.2   | n.s.    |
| Key search               | 8 ± 1.5    | 6.9 ± 3.1   | n.s.    |
| RAVLT                    | 43.7 ± 9.1 | 42.9 ± 7.1  | n.s.    |
| MMSE                     | 29.3 ± 0.8 | 28.1 ± 1.3  | n.s.    |
| Hamilton                 | 4.7 ± 2.9  | 7.3 ± 5.3   | n.s.    |

**Table 1. Participants' information.** No significant differences were found between Tai Chi practitioners and healthy controls. BMI: Body mass index; BDI: Beck Depression Inventory; RAVLT: Rey auditory verbal learning test; MMSE: mini-mental state examination; n.s.: non-significant ( $p > 0.05$ ).

### Cognitive assessment

The psychological assessment of the participants was conducted using the Beck Depression Inventory (BDI) (Beck et al., 1996) and the Hamilton test (Hamilton, 1959) to measure depression and anxiety, respectively. Cognitive aspects were evaluated through the MMSE, Rey auditory verbal learning test (RAVLT), Corsi test, and key search (Rabbitt, 2004). MMSE is a widely used cognitive screening tool to assess overall cognitive impairment, including orientation, memory, attention, and language; RAVLT is designed for memory performance (Carlesimo et al., 1996); the Key search test assesses the executive functions, the planning, and the problem-solving ability of the individuals (Canali et al., 2007).

### Motor assessment

The gait analysis was conducted at the Motion Analysis Laboratory of the University of Naples Parthenope. Motion capture was performed using a stereophotogrammetric system comprising eight infrared cameras (ProReflex Unit—Qualisys Inc., Gothenburg, Sweden). By recording the position of fifty-five markers placed on each participant, following the modified Davis protocol (Davis et al., 1991; Minino et al., 2021), we were able to monitor gait cycle phases. Participants from both groups were instructed to walk at a self-selected speed along a straight path within the laboratory. For each group we recorded four gait cycles (for each leg) in separate trials (Troisi Lopez et al., 2021).

### Harmonic ratio assessment

The Harmonic Ratio (HR) is derived from a spectral analysis of body acceleration using the Fourier transform. This approach enables the assessment of gait smoothness and stability by quantifying stride symmetry (Brach et al., 2011; Menz et al., 2003). Acceleration components are categorized as “in-phase” and “out-of-phase,” corresponding to even and odd harmonics, respectively. In the antero-posterior (AP) and vertical (V) directions, the acceleration signal exhibits a biphasic nature, as each stride comprises two consecutive steps. Consequently, the amplitude of even harmonics surpasses that of odd harmonics. Therefore, HR in the AP and V axes is computed as the ratio of the sum of even harmonic amplitudes to the sum of odd harmonic amplitudes (Buckley et al., 2020):

$$HR_{AP,V} = \frac{\sum \text{Amplitudes of even harmonics}}{\sum \text{Amplitudes of odd harmonics}} \quad (1)$$

Conversely, in the medio-lateral (ML) direction, the acceleration signal is monophasic due to its limb-dependent nature, resulting in greater odd harmonic amplitudes compared to even harmonics. As a result, HR in the ML axis is inverted:

$$HR_{ML} = \frac{\sum \text{Amplitudes of odd harmonics}}{\sum \text{Amplitudes of even harmonics}} \quad (2)$$

### Statistical analysis

Statistical analysis was performed using MATLAB (Mathworks®, version R2022a). The HR values of the two group were compared using a permutation test of the means, with 10'000 iterations (Nichols & Holmes, 2002). Correlations between the HR values and the psychological variables were investigated using Spearman's correlation coefficient test. The statistical significance was defined as  $p < 0.05$ .

## Results

We calculated Harmonic ratio values in ten Tai Chi practitioners (TP group), and ten matched healthy controls (HC group). This score was used to assess the ability of the participants to maintain motor control during gait. The comparison between the TP and the HC groups revealed that the individuals practicing Tai Chi showed higher HR values on the anteroposterior axis with respect to the HC group (HC mean  $\pm$  standard deviation =  $2.93 \pm 0.53$ , TP mean =  $3.64 \pm 0.51$ ,  $p = 0.004$ ) (Figure 1).

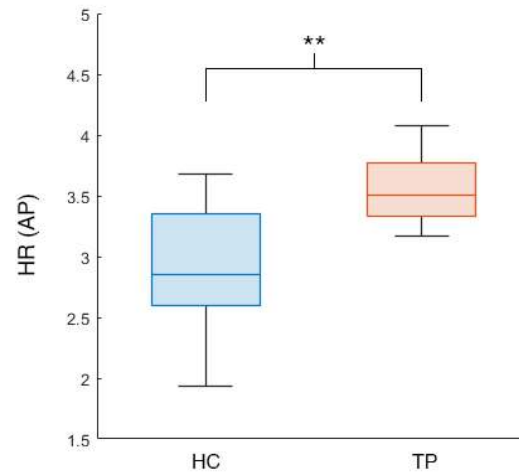


**Figure 1. Comparison of the Harmonic ratio (AR) values on the anteroposterior axis (AP).** HR scores were compared between healthy controls (HC) and Tai Chi practitioners (TP). Violin plots show that the TP group expressed significantly higher HR values on the anteroposterior axis.

Furthermore, we found a significant positive correlation between HR values on the anteroposterior axis and key search scores ( $r = 0.64$ ,  $p = 0.045$ ). It must be noted that no significant correlation with any other cognitive parameter was found.

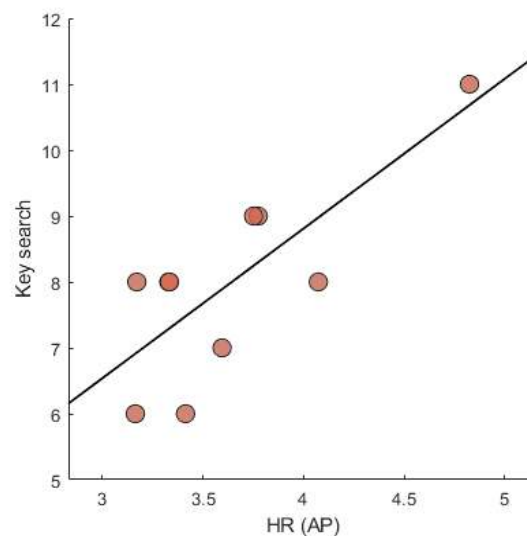


**Figure 2. Correlation with cognitive tests.** The scatter plot shows the significant correlation between harmonic ratio (HR) values on the anteroposterior axis (AP) and key search scores in Tai Chi practitioners.

## Discussion

The current study aimed to investigate the effect of Tai Chi practice on gait control and its relationship with cognitive aspects. The finding that Tai Chi practitioners showed higher smoothness during gait with respect to healthy controls suggests that Tai Chi practice may have specific effects on fine tuning motor control even in common tasks, such as walking. One possible explanation for this observation is that Tai Chi practice enhances the ability to focus attention effectively on motor control. The findings of this study further support studies reporting that Tai Chi practitioners exhibit greater motor control during gait compared to control groups. This

aligns with previous research showing that Tai Chi training enhances postural stability, gait regularity, and motor control (Wu et al., 2004). The observed improvements in movement smoothness could be attributed to Tai Chi's emphasis on slow, controlled movements, weight shifting, and continuous flow, which likely contribute to more efficient motor planning and execution.

We suppose that Tai Chi practice may facilitate neuromuscular synchronization, which plays a crucial role in maintaining stable and rhythmic gait patterns (McGibbon et al., 2005; Wang et al., 2017). Furthermore, several studies have consistently highlighted the positive effects of Tai Chi practice on gait and motor control, particularly among older adults and individuals with neurological conditions. They suggest that Tai Chi enhances balance, coordination, and proprioception, leading to improved gait stability and reduced fall risk (Zhong et al., 2020). Regular practice has been shown to increase stride length, decrease gait variability, and promote smoother weight shifting, all of which contribute to more efficient locomotion (Yang et al., 2024). Furthermore, Tai Chi's slow, controlled movements may involve neuromuscular pathways that enhance motor control and control postural responses. This would make the Tai Chi practice beneficial for individuals with neuromotor diseases (e.g., Parkinson's disease), and individuals with cognitive disorders or age-related motor decline (Minino et al., 2025; Morsanuto et al., 2023; Troisi Lopez et al., 2022a, 2022b; Zhao et al., 2025). Further studies also suggests that Tai Chi may improve reaction time and lower limb muscle strength, further supporting its role in motor function enhancement (Tang et al., 2025). Additionally, research has found that Tai Chi can be particularly effective when combined with gait training or perturbation-based exercises, further enhancing dynamic balance control (Smith et al., 2025). Overall, these studies contribute to a framework that confirms the ability of Tai Chi practitioners to carry out fine-tuned movements and our findings align with the literature. However, there is a lack of studies on HR in Tai Chi practitioners and a direct comparison of our results is unfeasible.

Furthermore, in our study we showed a positive correlation between motor control during gait and key search scores, a cognitive test evaluating executive functions, planning, and problem-solving abilities. This finding also aligns with the current literature that shows that executive function plays a crucial role in gait control, particularly in dual-task conditions (Liu et al., 2022). Several studies suggest that Tai Chi practitioners exhibit better executive function performance, with improvements in tasks requiring planning, working memory, and cognitive flexibility (Liao et al., 2021). Studies suggest that Tai Chi may enhance gait adaptability by involving frontal brain regions' activation (responsible for executive control), which may explain the observed correlation between motor control and key search performance (Chen et al., 2022). Supporting this, a study found that Tai Chi training reduces dual-task gait variability, suggesting that it strengthens cognitive-motor integration, a critical factor in executive function and problem-solving ability (Wayne et al., 2015). Moreover, Tai Chi has been associated with increased activation in the prefrontal cortex, which is responsible for planning and decision-making during movement (Chen et al., 2022b). Considering these findings, we may suggest that Tai Chi's cognitive benefits extend to specific domains like spatial problem-solving and strategic planning, as reflected in our key search score results. While our findings are promising, further research is needed to examine the neural mechanisms underlying this relationship and explore how Tai Chi interventions can be optimized for cognitive-motor training.

## Conclusions

In this study, we highlighted the potential benefits of Tai Chi practice on motor abilities, showing that this discipline can be considered a valid therapeutic approach for promoting physical and mental well-being, particularly in older populations. The results suggest that Tai Chi, due to its holistic and multimodal nature, can positively affect motor control, as indicated by improvements in the Harmonic Ratio (HR), and indirectly support cognitive functioning. These synergistic effects between body and mind confirm the value of Tai Chi within health promotion and functional decline prevention programs.

The practical implications of these findings are significant, especially from a clinical and public health perspective. For healthcare facilities, rehabilitation clinics, and organizations focused on active aging, Tai Chi can be integrated as part of therapeutic programs aimed at improving quality of life, preventing falls, and fostering autonomy in daily activities. Its inclusion in these contexts represents an effective, low-cost, and side-effect-free strategy, suitable for a wide range of individuals, including those with chronic conditions or in post-rehabilitation phases. Furthermore, the application of Tai Chi in workplace wellness programs, particularly for aging workers, could also offer benefits in terms of productivity, job satisfaction, and stress management.

From a research standpoint, the relevance of our work is implicit in the recommendations for future studies. One of the main limitations of this study is the small sample size and the lack of a longitudinal design, which limits the generalizability of the results. Therefore, future research should involve larger and more diverse samples, including different age groups, skill levels, and clinical conditions. Longitudinal studies would also help investigate the long-term effects of Tai Chi on motor abilities, mood, cognitive status, and their dynamic interplay over time.

Another valuable direction for the scientific and clinical community is to compare the outcomes of Tai Chi with those of similar or alternative disciplines. Comparisons with other mind-body exercises such as yoga, therapeutic dance, or gentle gymnastics, as well as with more traditional forms of physical activity like brisk walking or swimming, could help clarify which components are most critical for improving motor and cognitive

functions. In particular, systematic and controlled comparisons, as suggested by Mazzeo et al. (2016) and Troisi Lopez et al. (2025), could provide deeper insight into the mechanisms through which different types of exercise influence neuroplasticity, psychophysical balance, and motor behavior.

Lastly, the relevance of this study extends to the design of multidisciplinary interventions, where Tai Chi can be combined with cognitive training programs, rehabilitation technologies such as wearable sensors (Latino & Tafuri, 2024) or virtual reality, or psychoeducational strategies for emotional well-being. Integrating such approaches may amplify the observed benefits, offering tailored responses to the needs of older adults or individuals at risk of motor and cognitive decline. From this perspective, Tai Chi should not be regarded merely as a traditional or recreational practice, but rather as a truly evidence-based tool for promoting comprehensive health.

In conclusion, this research strengthens the scientific evidence supporting Tai Chi as an effective practice for enhancing motor control and, potentially, cognitive performance. Despite some methodological limitations, the results provide a promising foundation for further studies and practical applications. Tai Chi thus emerges as a valuable resource in the broader landscape of preventive and rehabilitative strategies, promoting active, sustainable, and person-centered aging.

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