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The effects of Tai Chi on clinical outcomes and gait biomechanics in knee osteoarthritis patients: a pilot randomized controlled trial

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Knee osteoarthritis (KOA) is a common degenerative joint disease that significantly reduces mobility and quality of life in elderly populations. Tai Chi, a low-impact mind-body exercise, has been suggested as a potential non-pharmacological intervention for managing KOA, but its biomechanical effects remain unclear. This study aimed to evaluate the effects of a 14-week Tai Chi program on clinical symptoms, lower limb biomechanics, and muscle activation patterns in elderly patients with KOA. A single-blinded randomized controlled trial was conducted, enrolling 24 participants aged 55–70 years with unilateral KOA. Participants were randomly assigned to a Tai Chi intervention group or a control group receiving health education only. Primary outcomes included joint range of motion, joint moments, and muscle activation, measured using a motion capture system and surface electromyography. Secondary outcomes, such as pain, stiffness, function (WOMAC), balance (BBS), and quality of life (SF-12), were also assessed pre- and post-intervention. The Tai Chi group demonstrated significant improvements in WOMAC pain (−1.58 ± 1.44 vs. 0.11 ± 0.78, p = 0.01), stiffness (−0.33 ± 0.78 vs. 0.56 ± 0.88, p = 0.02), and function scores (−2.58 ± 3.53 vs. 1.00 ± 2.78, p = 0.02) compared to the control group. Balance (BBS: 1.42 ± 1.88 vs. −0.89 ± 1.27, p = 0.01) and physical health (SF-12 PCS: 5.45 ± 6.76 vs. −1.05 ± 2.17, p = 0.01) were also enhanced. Biomechanically, Tai Chi reduced horizontal plane knee ROM (−3.03 ± 1.00°, p = 0.01) and maximum knee extension moments (affected side: −0.09 ± 0.04 N/kg, p = 0.04, Non-affected side: -0.11 ± 0.05 N/kg, p = 0.03). Tibialis anterior muscle activation increased significantly (5.66 ± 1.05%MVIC, p = 0.02), while other muscles showed non-significant trends. Tai Chi demonstrated significant clinical and biomechanical benefits for elderly KOA patients, suggesting its potential as a safe, accessible, and effective therapeutic intervention.

Abbreviations

KOA	Knee osteoarthritis
ROM	Range of motion
sEMG	Surface Electromyography
RMS	Root Mean Square
WOMAC	Western Ontario and McMaster Universities Osteoarthritis
BBS	Berg Balance Scale
SF-12	Short Form 12 Health Survey

Knee osteoarthritis (KOA) is a prevalent chronic degenerative joint disorder characterized by cartilage degradation, pain, stiffness, and functional impairment, significantly diminishing the quality of life and independence of affected individuals[1]. Globally, KOA impacts over 260 million people, making it one of the leading causes of disability, as reported in the 2021 Global Burden of Disease Study[2,3]. With an aging population

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and increasingly sedentary lifestyles, the prevalence of KOA is projected to rise, highlighting the urgent need for effective, safe, and sustainable management strategies[4].

Current pharmacological treatments, such as nonsteroidal anti-inflammatory drugs (NSAIDs), primarily alleviate symptoms. However, their prolonged use is associated with adverse side effects, including gastrointestinal complications and cardiovascular risks[5,6]. Consequently, non-pharmacological interventions, particularly exercise-based therapies, have gained attention for their low-risk and cost-effective nature in KOA management.

Tai Chi, a traditional Chinese mind-body exercise integrating slow movements, controlled breathing, and mindfulness, has emerged as a promising therapeutic approach. Robust clinical evidence from randomized trials and meta-analyses demonstrates its efficacy in alleviating pain, improving physical function, and enhancing psychological well-being in KOA patients[7,8]. Consequently, major clinical guidelines, including those from the American College of Rheumatology, now endorse Tai Chi as a first-line therapy for KOA management[1,6]. Despite these clinical advances, the biomechanical mechanisms underlying its therapeutic effects remain poorly understood.

Existing research has predominantly focused on clinical outcomes, with limited investigation into Tai Chi's effects on lower-limb biomechanics during functional activities such as gait[9,10]. Critical biomechanical factors—including abnormal joint loading, altered range of motion (ROM), and neuromuscular imbalances—are well-established contributors to KOA progression[11–13]. While studies like Wang et al. (2016) reported pain reduction following Tai Chi, they omitted joint kinetic analyses[14], and Zhu et al. (2016) documented gait improvements without electromyographic (EMG) data to elucidate neuromuscular adaptations[15]. These knowledge gaps hinder the development of biomechanically optimized rehabilitation protocols.

This randomized controlled trial (RCT) comprehensively evaluates the effects of a 14-week Tai Chi intervention on clinical outcomes and lower-extremity biomechanics in KOA patients. We hypothesize that Tai Chi training, compared to health education alone, will significantly improve pain and physical function, optimize knee joint kinematics and kinetics during gait, and enhance neuromuscular activation patterns, thereby elucidating its multidimensional therapeutic mechanisms.

Methods

This single-blinded RCT was conducted as a sub-study of a registered sarcopenia-related clinical research framework (Chinese Clinical Trial Registry No. ChiCTR2300078229; registered December 1, 2023), although this sub-study is not explicitly listed out in the trial registration. This sub-study aimed to evaluate the effects of a 14-week Tai Chi intervention on clinical outcomes and lower-limb biomechanical parameters in elderly patients with KOA. Prior to enrollment, all participants provided written informed consent following a comprehensive explanation of the study protocol.

Recruitment of participants

Participants were recruited from community centers in Guangzhou, China. The inclusion criteria were: (1) age 55–70 years; (2) body mass index (BMI) $\leq 28 \, kg/m^2$[16]; and (3) a clinical diagnosis of unilateral KOA according to the American College of Rheumatology criteria[17], to enable biomechanical comparisons. These criteria ensured cohort homogeneity and allowed focused analysis of Tai Chi's biomechanical effects and clinical symptom improvements in unilateral KOA.

Exclusion criteria included: (1) inability to walk 20 m independently; (2) knee surgery or corticosteroid injections within the past six months; (3) regular participation in lower limb strength training (e.g., weight training, resistance exercises); or (4) any musculoskeletal or mental condition that could interfere with participation. These exclusions minimized confounding variables and safety risks, thereby reducing interference in joint function assessments (e.g., biomechanical metrics, pain severity) and strengthening study validity.

Ultimately, 24 eligible participants were enrolled in the study. As a pilot trial, the sample size ($n = 24$) was determined based on feasibility considerations (e.g., recruitment capacity, resource availability) rather than formal power calculations, consistent with methodological recommendations for pilot trials prioritizing feasibility assessment and effect size estimation[18,19].

Intervention protocol

Participants were stratified by age, gender, and KOA severity and randomized using a computer-generated block sequence (block size = 4) created by an independent statistician via SPSS 26.0. Allocation details were concealed in sequentially numbered, opaque envelopes, which were opened after baseline assessments to notify participants of group assignments via text message. To maintain blinding, participants were informed that the study aimed to evaluate "knee health interventions," with no disclosure of group-specific details.

The experimental group underwent a 14-week Chen-style Tai Chi intervention based on the standardized 24-form protocol. Training sessions were overseen by a Class 1 National Martial Arts Athlete (certified by the Chinese Wushu Association) to ensure protocol adherence. The program consisted of three 60-minute supervised sessions per week, each comprising: (1) a 10-minute warm-up of gentle stretching and joint mobilization; (2) a 40-minute Tai Chi practice focusing on controlled weight-shifting, deep knee flexion through self-selected squat depth: high, medium, or low - with lower positions indicating greater exercise intensity, and multiplanar joint rotations; and (3) a 10-minute cool-down period with breathing exercises and static stretching. Certified instructors provided real-time feedback on movement precision including knee alignment and trunk posture though formal kinematic assessments were not conducted. The intervention progressed from fundamental posture acquisition during the initial two weeks to integrated form practice through weeks 3–14.

Both study arms participated in identical biweekly health education sessions (60 min each) covering KOA pathophysiology, lifestyle modification strategies, and pain management techniques, delivered by qualified

health educators. These parallel education components served to control for placebo effects while maintaining blinding through temporal and spatial separation of group sessions (conducted at different times/locations).

All participants were instructed to maintain their customary physical activity patterns throughout the study duration. Protocol adherence was strictly enforced, requiring attendance at ≥80% of scheduled sessions (Tai Chi: 34/42; control: 6/7 education sessions) for continued study participation. The experimental procedure is illustrated in Fig. 1.

Data collection and processing

Data collection was conducted at two time points: baseline (December 25, 2023-December 31, 2023) and post-intervention (April 14, 2024-April 20, 2024). The primary outcomes assessed were changes in lower limb biomechanics and muscle activation patterns, which are crucial indicators of motor function improvement and pain reduction. Secondary outcomes included assessments of pain, stiffness, and physical function using the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC); quality of life measured through the Short Form 12 Health Survey (SF-12); and balance quality, evaluated using the Berg Balance Scale (BBS). These measures provided a comprehensive understanding of the intervention's impact on participants' clinical and functional statuses.

The biomechanical evaluations were conducted in the biomechanics laboratory at Guangzhou Sport University, equipped with advanced instrumentation to capture precise movement data. Kinetic data were recorded using two three-dimensional force platforms (AMTI OR6-7, Watertown, MA, USA, 60 ×40 cm) embedded in the laboratory floor, which operated at a sampling rate of 1000 Hz. Concurrently, kinematic data were collected through a motion capture system (Nexus Vicon, Oxford, UK) at 100 Hz, which meticulously recorded the range of motion of the lower limb joints using 36 reflective markers placed on participants' lower limbs, as per the protocols established in prior research by our team[20].

Surface electromyography (sEMG) data were captured using a 16-channel Trigno Wireless EMG System (Trigno Wireless EMG System, Delsys Inc., Natick, MA, USA), which had a sampling rate of 2000 Hz. This system was specifically used to monitor muscle activity in key muscle groups including the gluteus maximus, gluteus medius, biceps femoris, rectus femoris, and tibialis anterior. To ensure optimal signal quality, hair was removed and the skin was thoroughly cleaned before placing the sensors, minimizing electrical impedance[21,22].
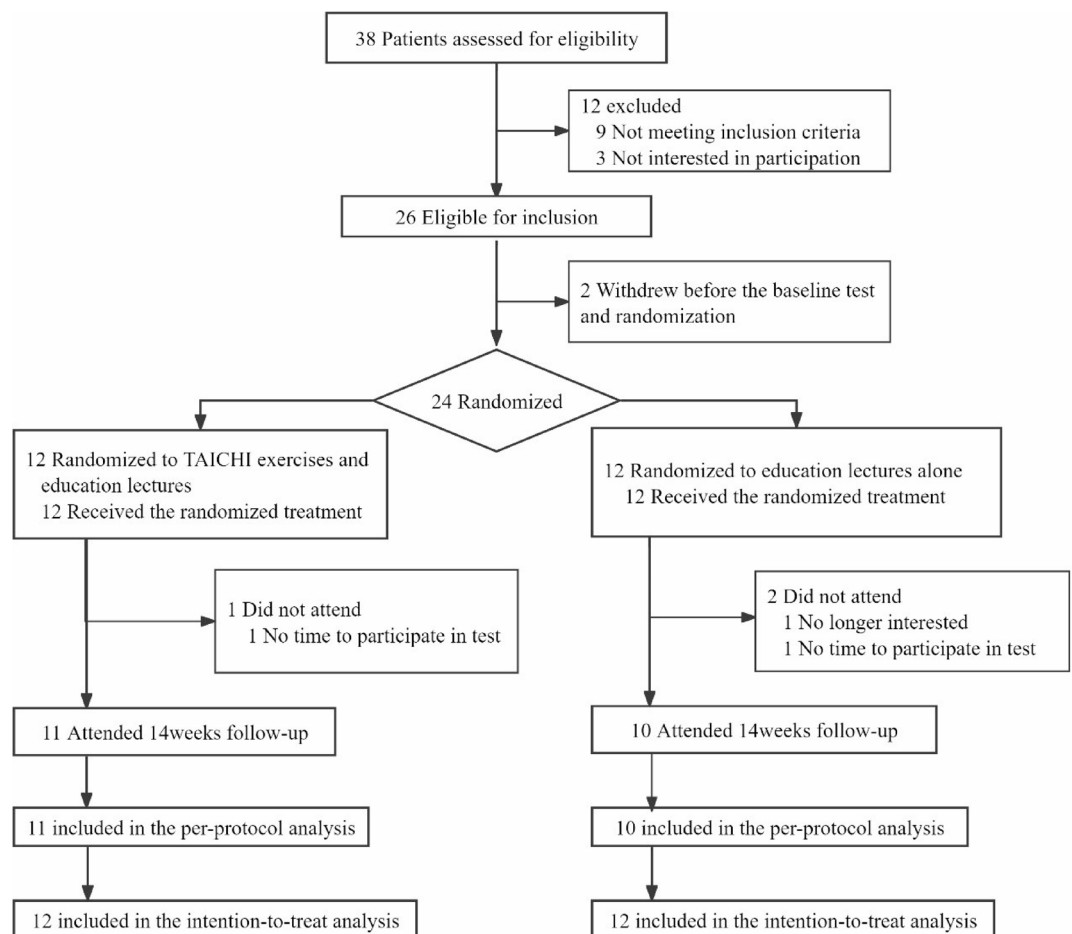

Fig. 1. CONSORT flow diagram.

Before the tests, participants changed into standardized black shorts and performed a series of stretching and warm-up exercises in the experimental hall. During this preparatory phase, researchers provided detailed explanations of the testing procedures and addressed any questions to ensure participants were fully informed. Reflective markers and sEMG sensors were carefully affixed to the designated joint areas and muscle groups using kinesiology tape, following established methodologies from previous studies[20].

Prior to gait tests, static data were collected to serve as a baseline reference. Participants were then positioned at the starting line, and upon hearing the start command, walked at a normal pace along a 6-meter pathway. To ensure data quality, force platform 1 recorded data from one foot while force platform 2 recorded data from the other, with three valid trials successfully captured per participant.

After completing the gait tests, participants performed maximum voluntary isometric contraction (MVIC) tests for the designated muscle groups, following the required protocols[20]. Additionally, before the experiments began, participants were allowed multiple practice trials to familiarize themselves with the equipment and procedures.

The collected data were processed using Vicon Nexus and Visual 3D software. Kinematic data were filtered with a cutoff frequency of 10 Hz, while kinetic data were filtered at 50 Hz. Key gait events, such as heel strike and toe-off, were identified, and gait cycles were defined as the period from one heel strike to the next on the same side. Joint moments were normalized to each participant's body weight for standardization. sEMG data underwent high-pass filtering at 400 Hz, rectification, and subsequent low-pass filtering at 20 Hz. All muscle signals were then normalized using MVIC values. The root mean square (RMS) was subsequently calculated to represent muscle activation levels during walking[23].

Data analysis

Statistical analyses were conducted using SPSS (version 26.0). The Shapiro-Wilk test was used to assess the normality of the data. Independent samples t-tests were performed to evaluate group differences in baseline characteristics as well as in the changes in clinical outcomes before and after the intervention. These changes were calculated as the difference between post-intervention and pre-intervention values. Paired samples t-tests were used to assess within-group differences before and after the intervention.

To analyze group differences in biomechanical and sEMG data after the intervention, generalized linear mixed models (GLMMs) were applied. An intention-to-treat (ITT) approach was utilized to include participants who dropped out during the study, with missing data imputed using the last observation carried forward (LOCF) method. All data are presented as mean ± standard deviation ($\bar{\chi} \pm sd$). A significance level of $p < 0.05$ was set for all statistical tests.

Results

Attrition and attendance rates

A total of 24 participants were enrolled and randomized into the Tai Chi group ($n = 12$) or the control group ($n = 12$). By the end of the 14-week intervention, the Tai Chi group had an attrition rate of 8.3% (1 participant), while the control group experienced an attrition rate of 16.7% (2 participants). The main reasons for dropout included scheduling conflicts and insufficient time for participation.

Changes in participant characteristics and clinical outcomes

Table 1 presents the characteristics outcomes before and after the intervention, while Figs. 2, 3 and 4 display the clinical outcomes (WOMAC scores, SF-12 scores, and BBS scores, respectively) across the study period. Baseline assessments revealed no significant differences in demographics or clinical outcomes between the two groups. Post-intervention, the Tai Chi group demonstrated significant weight reduction, but changes in BMI were not statistically significant (Table 1). Notably, the Tai Chi group exhibited significant improvements in WOMAC scores for pain, stiffness, and function, as well as better physical health quality (PCS of SF-12) and balance performance (BBS), compared to the education group (Figs. 2, 3 and 4).

Changes in Biomechanical outcomes

Tables 2 and 3 present the kinematic and kinetic outcomes, respectively. Prior to the intervention, there were no significant differences in lower-limb biomechanical parameters between the two groups. Following the intervention, the Tai Chi group showed a significant reduction in knee joint ROM in the horizontal plane compared to the control group. Although sagittal plane ROM exhibited a modest increase in the Tai Chi group, this change did not reach statistical significance (Table 2). Additionally, the Tai Chi group demonstrated significant reductions in maximum knee extension moments for both the affected and non-affected sides when compared to the control group (Table 3).

Changes in muscle activation

Table 4 presents the muscle activation patterns before and after the intervention. Muscle activation patterns did not differ significantly between groups at baseline. Significant increases in tibialis anterior muscle activation were observed in the Tai Chi group post-intervention. Although activation trends were noted for other muscles, including the gluteus maximus, gluteus medius, and rectus femoris, these changes did not reach statistical significance. A slight reduction in biceps femoris activation was observed, though this was also not statistically significant.

Parameters/Group	Pre-intervention	Post-intervention	P-value at baseline	δp	Change Score (post-pre)	△p
Age (years)						
Tai Chi Group	65.17 ± 5.02	–	0.28	–	–	–
Education Group	62.89 ± 3.95	–	–	–	–	–
Female/Male (n)						
Tai Chi Group	9/3	–	1.00	–	–	–
Education Group	8/4	–	–	–	–	–
Height (cm)						
Tai Chi Group	160.08 ± 6.86	–	0.42	–	–	–
Education Group	163.00 ± 9.41	–	–	–	–	–
Mass (kg)						
Tai Chi Group	61.47 ± 4.78[#]	60.52 ± 4.42	0.59	0.02	−0.94 ± 1.23	0.06
Education Group	60.30 ± 9.58	60.35 ± 9.72	–	0.88	0.05 ± 0.96	–
BMI (kg/m^2)						
Tai Chi Group	23.91 ± 1.92	23.68 ± 2.10	0.47	0.24	−0.22 ± 0.62	0.13
Education Group	22.42 ± 1.80	22.58 ± 1.86	–	0.28	0.16 ± 0.42	–

Table 1. Descriptive participant demographics between groups ($\bar{\chi}$ ± sd). Note: *VS Education Group, #VS Post-intervention. δp means within-group significance (Pre vs. Post);. $\triangle p$ means between-group significance for change score (post-pre).

Discussion

This study aimed to investigate the effects of Tai Chi training on lower limb biomechanics and muscle activation patterns in patients with KOA during walking. The findings demonstrate that a 14-week Chen-style Tai Chi intervention significantly improved clinical symptoms, biomechanical characteristics, and muscle activation patterns in KOA patients. These results provide empirical evidence for Tai Chi's role in optimizing knee joint mechanics and neuromuscular coordination during gait.

Participation rate and improvements in clinical outcomes

The Tai Chi group exhibited higher participation rates compared to the education group, likely due to its immediate benefits in pain relief and joint mobility[14]. These factors may have motivated participants to adhere to the intervention.

In terms of clinical outcomes, this study revealed significant improvements in WOMAC scores, encompassing pain, stiffness, and functional dimensions, among participants in the Tai Chi group. These results are consistent with findings from previous studies[14,24,25].

As a moderate intensity aerobic exercise, Tai Chi strengthens lower limb muscles, thereby reducing joint pressure and alleviating pain[15]. Additionally, the multi-directional, dynamic movements emphasized in Tai Chi, which are less commonly incorporated in traditional rehabilitation programs, may effectively improve joint flexibility, reduce soft tissue adhesions, and relieve muscle tension. These mechanisms contribute to improvements in stiffness, pain, and lower limb functionality in KOA patients[25,26].

Furthermore, Tai Chi's emphasis on precise movement control and smooth weight-shifting enhances dynamic balance, reduces the risk of falls, and improves daily activity capabilities[26,27]. Notably, the lack of significant BMI changes between groups replicates findings from earlier trials[14,24]. This null effect suggests that Tai Chi's clinical efficacy may result primarily from neuromuscular re-education and biomechanical optimization rather than anthropometric modifications.

Moreover, Tai Chi has been reported to alleviate psychological issues such as anxiety and depression[28]. Although no significant differences in mental health scores were observed between the groups in this study, both groups exhibited improvements, likely due to the social interactions involved in group-based activities.

In summary, Tai Chi demonstrated remarkable efficacy in relieving pain, improving joint function, and enhancing quality of life in KOA patients.

Improvements in biomechanical outcomes

Following the intervention, the Tai Chi group showed significant improvements in horizontal plane ROM and reductions in knee joint maximum extension moments, indicating Tai Chi's positive effects on optimizing joint movement patterns and reducing abnormal joint activities.

The observed reduction in horizontal plane ROM reflects enhanced rotational stability that may be a critical adaptation for mitigating cartilage degradation. Excessive tibiofemoral rotation during gait increases shear stress on articular surfaces, accelerating cartilage wear and exacerbating medial compartment loading through uneven force distribution[29,30]. Tai Chi's emphasis on axial alignment—such as maintaining knee-over-toe positioning during semi-squats—strengthens proprioceptive feedback and coordinates muscle activation (e.g., tibialis anterior, quadriceps), thereby suppressing aberrant rotational kinematics[31,32]. This neuromuscular optimization redistributes joint loads from shear-dominant to compression-dominant forces, which align with cartilage's structural tolerance, reducing pathological stress concentrations[33,34].
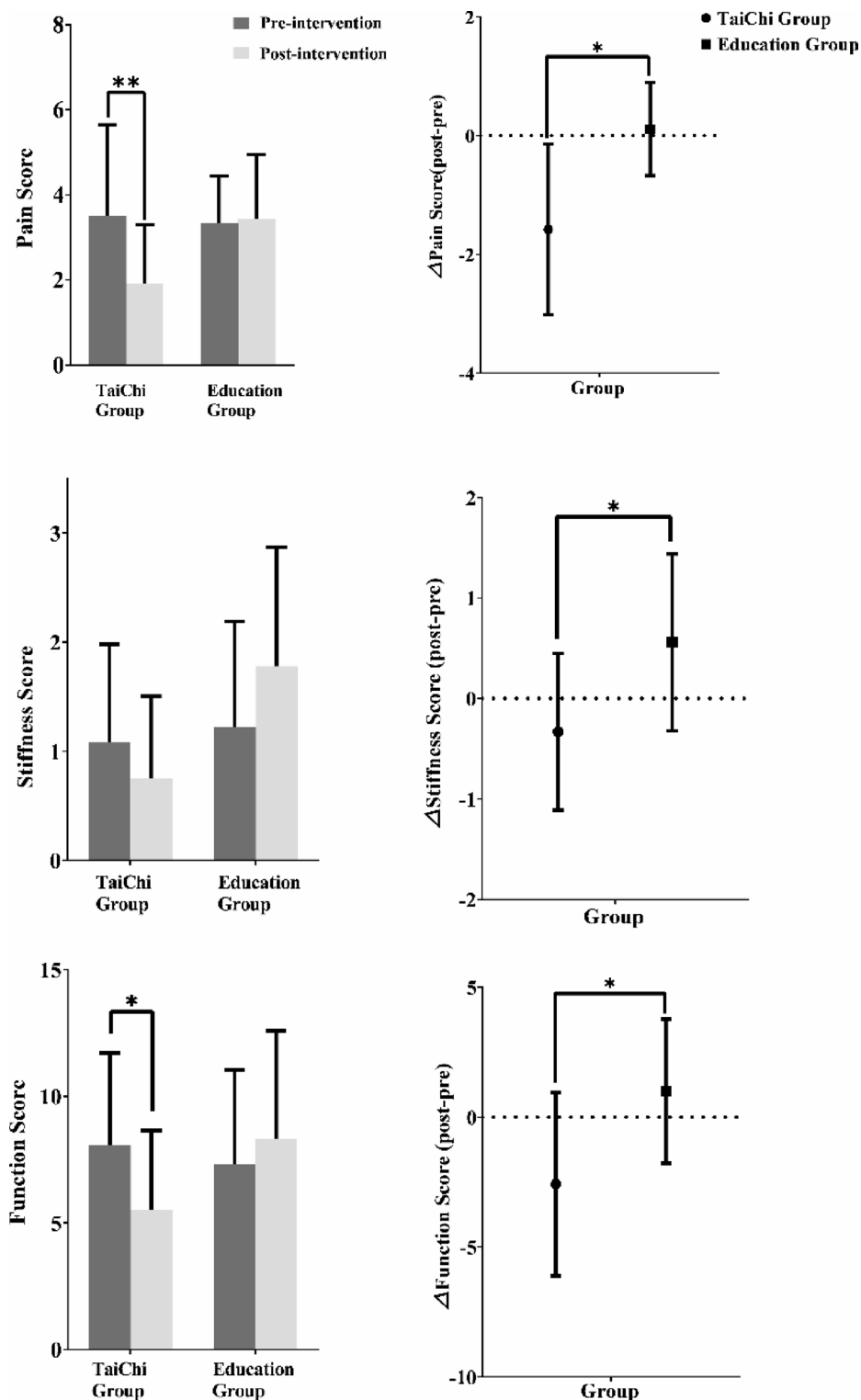
Fig. 2. Comparison of WOMAC scores between two groups (± sd). Note: *means $p < 0.05$, **means $p < 0.01$. △ indicates change score (post-pre).

While the modest increase in sagittal plane ROM (flexion-extension) did not reach statistical significance, prior studies have shown dose-dependent improvements in knee flexion-extension ROM with longer Tai Chi interventions[15]. These movement patterns, characterized by controlled multi-plane rotations and progressive squat depth, enhance joint flexibility while strengthening stabilizing musculature (e.g., hamstrings, gluteus medius), thereby improving dynamic stability[31,32], reducing focal stress peaks during weight-bearing activities[33].
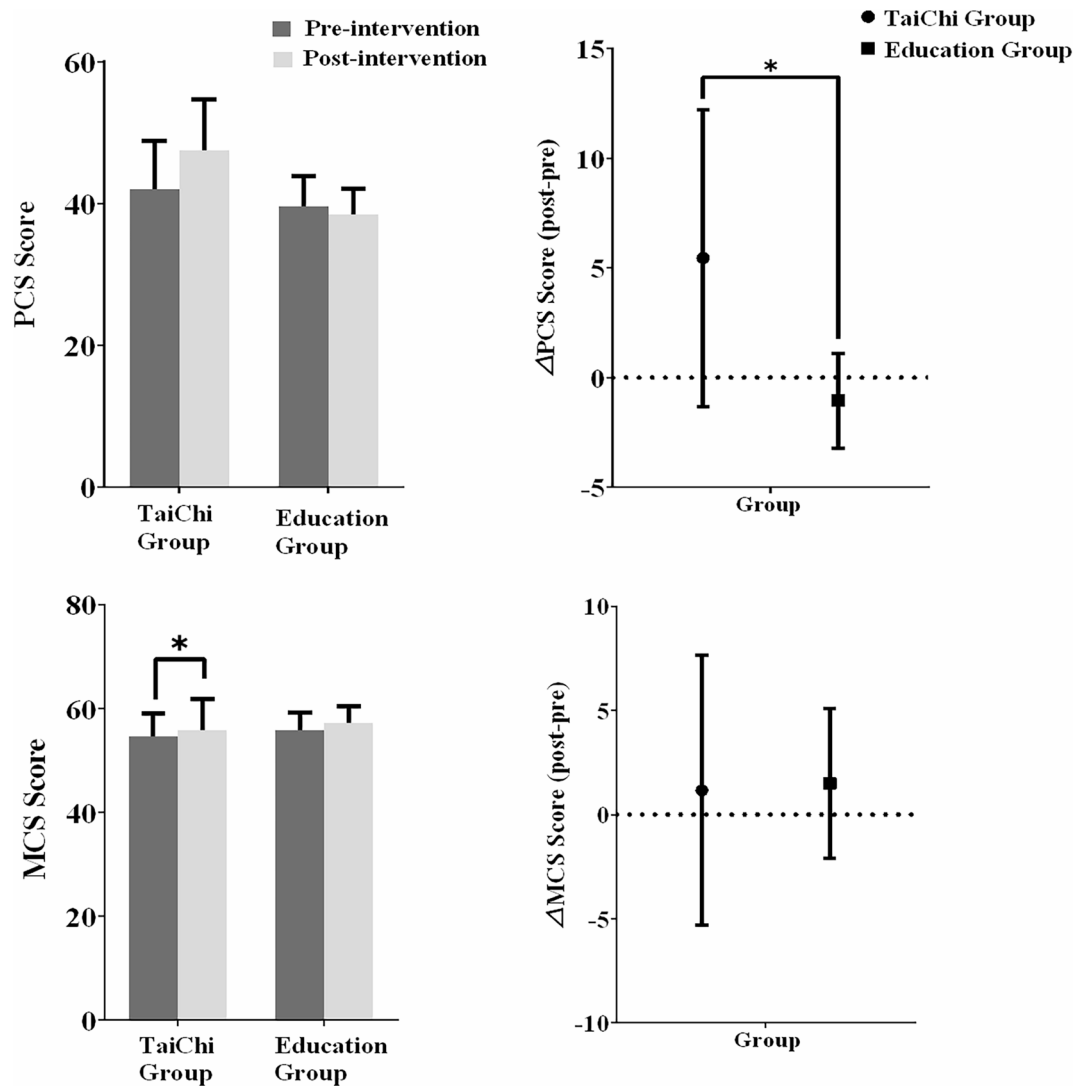
Fig. 3. Comparison of SF-12 scores between two groups (± sd). Note: *means $p < 0.05$; PCS means physical component summary of SF-12; MCS means mental component summary of SF-12; △ indicates change score (post-pre).

Notably, in addition to the reduction in knee joint maximum extension moments observed in this study, prior research has suggested that Tai Chi may also reduce the knee adduction moment, alleviating medial compartment joint loads and potentially reducing the risk of KOA progression[34]. This mechanism is likely associated with the observed reduction in abnormal horizontal plane movements.

In summary, Tai Chi improves knee joint movement patterns and load distribution, enhancing dynamic stability and supporting overall improvements in gait function.

Improvements in muscle activation

This study found that the Tai Chi intervention significantly increased the activation of the tibialis anterior muscle. Additionally, trends of increased activation were observed in the gluteus maximus, gluteus medius, and rectus femoris, while the activation of the biceps femoris slightly declined; however, none of these changes reached statistical significance.

The tibialis anterior plays a critical role in lower limb stability and weight-shifting control during the single-leg stance phase of the gait cycle. Insufficient activation of this muscle often leads to gait abnormalities and impaired balance[35,36]. The observed selective enhancement of tibialis anterior activation reflects the specific neuromuscular demands imposed by Tai Chi's characteristic movement patterns. During transitional postures such as *Single Whip* to *Cloud Hands*, precise dorsiflexion control is required to stabilize the ankle during weight-shifting phases[27]. The tibialis anterior may serve as a primary dynamic stabilizer through two key mechanisms: (1) eccentric control of plantarflexion during heel strike to attenuate impact forces, and (2) concentric activation during swing phase to ensure proper foot clearance[26,35]. This repetitive, task-specific activation pattern—
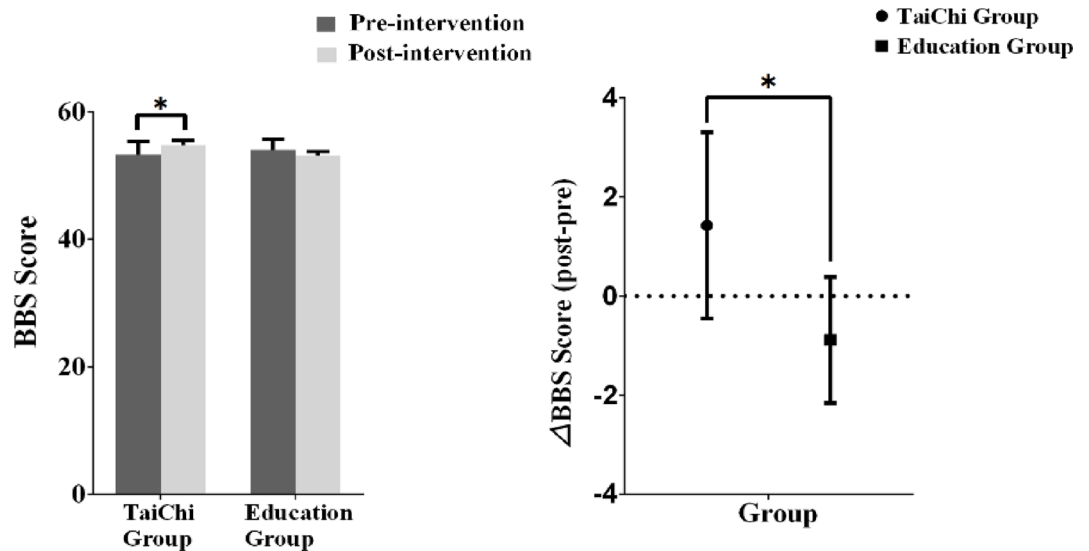
Fig. 4. Comparison of BBS scores between two groups (± sd). Note: * means $p<0.05$, **means $p < 0.01$. BBS means berg balance scale. △ indicates change score (post-pre).

Parameters/Group	Pre-intervention	Post-intervention	P-Value at Baseline	Coefficient	§p
Knee ROM in Sagittal Plane (°)					
Tai Chi Group	61.41 ± 5.45	63.86 ± 4.60	0.91	1.27 ± 1.59	0.43
Education Group	61.66 ± 3.87	61.05 ± 4.03	–	0ª	–
Knee ROM in Coronal Plane (°)					
Tai Chi Group	6.82 ± 2.75	6.96 ± 2.11	0.69	−0.48 ± 0.72	0.51
Education Group	7.27 ± 2.05	7.49 ± 0.94	–	0ª	–
Knee ROM in Horizontal Plane (°)					
Tai Chi Group	10.91 ± 2.84	10.20 ± 2.65	0.12	−3.03 ± 1.00*	0.01
Education Group	13.23 ± 3.57	13.94 ± 2.89	–	0ª	–

Table 2. Comparison of range of motion in joints between two groups ($\bar{\chi}$ ± sd). Note: 0ª means that this coefficient is a reference value, therefore set to zero. *VS Education Group. §p indicates the p-value for between-group differences post-intervention, calculated using a generalized linear mixed model (GLMM).

Parameters/Group	Pre-intervention	Post-intervention	P-Value at Baseline	Coefficient	§p
Knee Extension moment in Affected side (N/kg)					
Tai Chi Group	0.64 ± 0.18	0.57 ± 0.10	0.69	−0.09 ± 0.04*	0.04
Education Group	0.67 ± 0.10	0.68 ± 0.13	–	0ª	–
Knee Flexion moment in Affected side (N/kg)					
Tai Chi Group	0.82 ± 0.30	0.86 ± 0.16	0.99	0.01 ± 0.06	0.88
Education Group	0.81 ± 0.15	0.85 ± 0.10	–	0ª	–
Knee Extension moment in Non-affected side (N/kg)					
Tai Chi Group	0.34 ± 0.12	0.37 ± 0.13	0.70	−0.11 ± 0.05*	0.03
Education Group	0.31 ± 0.15	0.42 ± 0.23	–	0ª	–
Knee Flexion moment in Non-affected side (N/kg)					
Tai Chi Group	0.26 ± 0.08	0.31 ± 0.10	0.44	0.01 ± 0.06	0.83
Education Group	0.24 ± 0.06	0.32 ± 0.19	–	0ª	–

Table 3. Comparison of joint moment between two groups ($\bar{\chi}$ ± sd). Note: 0ª means that this coefficient is a reference value, therefore set to zero. *VS Education Group. §p indicates the p-value for between-group differences post-intervention, calculated using a generalized linear mixed model (GLMM).

Parameters/ Group	Pre-intervention	Post-intervention	P-Value at Baseline	Coefficient	§p
Gluteus maximus (%MVIC)†					
Tai Chi Group	27.14 ± 7.77	29.88 ± 6.81	0.28	4.29 ± 1.07	0.12
Education Group	25.69 ± 7 0.77	26.04 ± 7.25	–	0ᵃ	–
Gluteus medius (%MVIC)†					
Tai Chi Group	20.22 ± 10.7	22.42 ± 11.21	0.29	1.82 ± 0.03	0.05
Education Group	22.01 ± 7.03	21.31 ± 7.29	–	0ᵃ	–
Biceps femoris (%MVIC)†					
Tai Chi Group	27.05 ± 9.82	24.01 ± 9.57	0.33	−2.76 ± 0.09	0.33
Education Group	25.36 ± 7.45	25.98 ± 6.31	–	0ᵃ	–
Rectus femoris (%MVIC)†					
Tai Chi Group	21.96 ± 6.58	22.74 ± 7.83	0.51	0.94 ± 2.01	0.08
Education Group	22.64 ± 3.99	21.3 ± 4.33	–	0ᵃ	–
Tibialis anterior (%MVIC)†					
Tai Chi Group	30.41± 10.35	34.54 ± 10.5	0.67	5.66 ± 1.05*	0.02
Education Group	31.13 ± 8.04	30.29 ± 9.25	–	0ᵃ	–

Table 4. Comparison of muscle activation between two groups ($\bar{x}$ ± sd). Note: †means that the original data has already been logarithmically transformed. 0ᵃ means that this coefficient is a reference value, therefore set to zero. *VS Education Group. §p indicates the p-value for between-group differences post-intervention, calculated using a generalized linear mixed model (GLMM).

combined with Tai Chi's emphasis on controlled ankle dorsiflexion during semi-squats—likely explains the muscle's preferential adaptation[27].

Although changes in other lower limb muscles did not reach statistical significance, the observed trends are consistent with previous studies[31,32]. These non-significant changes may be attributed to the relatively short intervention duration and larger muscles (e.g., gluteus maximus) may require longer intervention periods to induce measurable hypertrophy, as their role in Tai Chi—maintaining hip stability during slow, controlled movements—may be less dynamically challenged compared to high-intensity exercises. Future studies could explore the effects of Tai Chi on strengthening major muscle groups more comprehensively by extending the intervention duration or increasing training intensity.

The slight increases in the activation levels of the gluteus maximus, gluteus medius, and rectus femoris may be associated with Tai Chi's use of semi-squat postures, while the slight decrease in biceps femoris activation may reflect optimized knee flexion-extension control[25,37]. Tai Chi's emphasis on fluid movement patterns and balanced load distribution reduces the over-reliance on compensatory muscle activation, thereby optimizing the overall muscle activation pattern. Previous studies have also indicated that Tai Chi may enhance synergistic activation of the rectus femoris and biceps femoris, promoting joint stability and reducing cartilage wear and pain[38]. The observed reduction in horizontal plane ROM and extension moments further supports this hypothesis.

These biomechanical and neuromuscular changes collectively enhance gait stability and lower limb coordination, effectively reducing joint stress and slowing KOA progression. They also provide strong support for restoring patients' daily activity capabilities.

Overall, this study systematically analyzed clinical outcomes, biomechanical characteristics, and muscle activation patterns, revealing the significant benefits of Tai Chi training for KOA patients. The results suggest that Tai Chi not only alleviates pain and improves joint function but also enhances gait mechanics and neuromuscular coordination, offering a comprehensive lower limb support system during walking. These multifaceted mechanisms underscore Tai Chi's great potential as a non-pharmacological intervention in KOA management.

Limitations and future directions

This pilot study has limitations, including a small sample size ($n = 24$) and a 14-week intervention duration insufficient to assess long-term effects or structural adaptations. Joint contact forces were not directly quantified, and confounding factors (e.g., daily activity levels, medication use) were not rigorously controlled. Future studies should expand sample sizes and extend intervention durations (≥ 6 months), complemented by long-term follow-ups to evaluate sustained therapeutic effects. Advanced biomechanical assessments, such as musculoskeletal modeling, are recommended to quantify joint loading dynamics. Integrating wearable devices for activity monitoring and standardizing medication tracking protocols will enhance methodological rigor, ultimately advancing personalized Tai Chi regimens for knee osteoarthritis management.

Conclusion

This study highlights the benefits of a 14-week Tai Chi program in improving clinical symptoms and biomechanics in elderly patients with KOA. Tai Chi effectively alleviated pain, stiffness, and functional limitations while improving joint ROM, joint loading, and muscle activation. These findings underscore Tai Chi's potential as an

effective, low-impact, and accessible therapeutic approach for managing KOA and improving overall quality of life.

Data availability

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Author contributions

J.P. was responsible for experimental design, manuscript drafting, and revisions. Z.X., S.Y., Z.H. and H.S. contributed to data collection, analysis, and interpretation. X.Z. and B.L. coordinated the research, supervised the project, and critically reviewed the manuscript. All authors approved the final manuscript and agreed to be accountable for their respective contributions.

Declarations

Competing interests

The authors declare no competing interests.

Resource availability

The datasets generated and/or analyzed during the current study are not publicly available due to privacy issues. However, data will be available upon formal request to the corresponding author.

Ethics declarations

The project was approved by the Chinese Clinical Trial Registry (Registration No. ChiCTR2300078229; Initial registration date: 01/12/2023). All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Additional information

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