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A Randomized Controlled Investigation into the Combined Effects of Adaptive Yang-Style Tai Chi and Mental Imagery Training on Dual-Task Balance Performance, Neurocognitive Function, and Fall Prevention in Older Adults Using Wearable Sensor Technology

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Abstract: Background: Falls in older adults arise from impaired cognitive-motor integration rather than isolated physical deficits. While Tai Chi and mental imagery training (MIT) individually show promise, no randomized trial has evaluated their combined, adaptive delivery using objective wearable sensor endpoints. Methods: In this multicenter, three-arm, assessor-blinded randomized controlled trial (ClinicalTrials.gov: NCT04766112), 152 community-dwelling adults aged ≥60 years with moderate fall risk were randomized to: (1) adaptive Yang-Style Tai Chi plus MIT (Combined Arm), (2) standardized balance exercise (Active Control), or (3) waitlist usual care. The 16-week intervention incorporated real-time wearable inertial sensor feedback to personalize task progression. The primary outcome was change in dual-task cost (DTC) index for center-of-mass acceleration, quantified via triaxial IMUs at L5 and bilateral feet. Secondary outcomes included neurocognitive function, prospective fall incidence, and biomechanical adaptations. Findings: At 16 weeks, the Combined Arm demonstrated significantly greater reduction in DTC index versus Waitlist (β = −9•4%, 95% CI: −12•8 to −6•0; p<0•001), with superior improvements in executive function, gait consistency, and mediolateral stabilization. Over 6-month follow-up, fall incidence was 42% lower in the Combined Arm (IRR = 0•58, 95% CI: 0•41–0•82; p=0•002). Mediation analysis indicated ~37% of fall reduction was explained by DTC improvement. Adherence exceeded 85%, with no serious intervention-related adverse events. Conclusion: Integrating adaptive Tai Chi with structured mental imagery training enhances cognitive-motor integration, reduces dual-task interference, and lowers fall risk in older adults. This precision-oriented, technology-enabled protocol offers a scalable, non-pharmacological strategy for fall prevention in aging populations.

Keywords: Accidental falls, Aged, Tai Chi, Mental imagery training, Dual-task performance, Wearable sensors, Postural balance, Randomized controlled trial.

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INTRODUCTION

The worldwide demographic transition to an ageing population has escalated falls to a top priority in the health of the population, as falls are now the major cause of injury-related hospitalization, disability and mortality among individuals aged 65 years and above [1]. The number of falls in community-dwelling older adults is about 28-35 percent each year, but the number of falls among people over 80 years increases exponentially [2]. In addition to acute trauma like hip fractures and traumatic brain injuries, falls cause fear of falling, activity limitation, social isolation, and rapid functional loss, which are unsustainable economic liabilities to health care and long-term care systems across the globe [3]. Although exercise-based fall prevention programs have been widely used, the recurrence rates are high, which means that existing strategies focus on the multifactorial etiology of mobility failures in the real world, which is complex and multifactorial [4].

Isolated musculoskeletal weakness is a rare cause of falls, and falls are the consequence of age-related degradation of the interconnected sensorimotor and cognitive systems that control posture and navigation through the environment [5]. Daily ambulation also involves a combination of motor performance and thinking (a dual-task task) which puts a larger load on aging prefrontal and parietal systems disproportionately [6]. Reductions of white matter integrity, proprioceptive acuity and attentional allocation capacity result in dual-task interference, where cognitive load disrupts gait stability, increases center-of-mass variability, and postpones the corrective postural response [7]. Interventions which do not consider this cognitive-motor coupling do not source laboratory-based gains in balance to ecologically valid fall reduction [8].

The traditional fall prevent paradigms usually utilize unimodal strategies that isolate resistance training, vestibular rehabilitation, or independent cognitive training of the dynamic needs of daily mobility [9]. Although short-term outcomes of meta-analyses show a small improvement, such programs often level off, attrition is high, and dose tailoring is not done in heterogeneous aging populations [10]. Determinist progression guidelines neglect individual differences in baseline mobility, comorbidity load and neurocognitive reserve, restricting adherence and neuroplastic adjustment in the long run [11]. The results therefore imply a great necessity of integrated and flexible interventions that can simultaneously address motor automaticity and cognitive flexibility and reflect the realities of everyday life.

Yang-Style Tai Chi has developed strong empirical evidence that it can be used as a mind-body intervention to improve dynamic balance, lower-limb strength, and postural sway control by means of intentional weight shifting, coordinated breathing, and sustained attention control [12]. Neurophysiological research indicates that Tai Chi training is known to enhance corticospinal excitability, optimise proprioceptive feedback integration, and enhance cerebellar-thalamocortical loopways that are essential in postural adaptation [13]. The conventional models of delivery, though, are based on instructor-led, collective-based curricula and the progressive rate of such models, restricting the scalability, obscuring the dose-response relationships, and restricting the applicability to older adults with mild mobility or cognitive impairments [14]. These constraints are overcome by Adaptive Yang-Style Tai Chi which dynamically adjusts the stance complexity, movement tempo, and demands on attention depending on real-time performance measures and ensures the best challenge is presented within the zone of proximal development. Mental imagery training (MIT) supplements physical practice, and is a deliberate, systematic cognitive rehearsal of motor sequences without their actual performance, which involves overlapping neural substrates in the supplementary motor area, premotor cortex, and basal ganglia [15]. Functional neuroimaging establishes that MIT boosts motor planning, consolidates procedural memory and primes corticomotor pathways, consequently, lessening the cognitive load in concurrent performance of the task [16]. By positioning Tai Chi strategically, MIT can potentially hasten the process of neuroplastic consolidation by reinforcing movement schemes during rest periods, alleviating fatigue-induced performance impairment, and enhancing prefrontal-parietal systems involved in attentional switching and coordination of dual-tasks [17]. This is a non-fatiguing, inexpensive adjunct that has a new way of enhancing cognitive-motor synergy without adding physical burden .

Integrative adaptive Tai Chi and MIT is a multidomain intervention that is theoretically based on the simultaneous improvement of motor automaticity, executive control, and sensorimotor integration [18]. This protocol will activate the two-way neuroplasticity needed to reduce dual-task interference and enhance resilience to real-world mobility by combining performance-responsive physical progression with structured cognitive rehearsal [19]. The integrated approach, compared to traditional exercise programs, builds on peripheral biomechanical adjustment and central neural priming, and thus represents a precision-based strategy to heterogeneous aging populations with different neurocognitive baselines [20].

Traditionally, balance and fall risk measurement relied on crude clinical measures or laboratory-tethered motion capture technology that was not ecologically valid, not able to provide continuous monitoring, and sensitive to pre-clinical losses [21]. High-fidelity wearable inertial measurement units are now spreading, allowing real-world estimates of kinematic parameters, such as trunk acceleration, stride time variability, center-of-mass displacement and dual-task cost indices to be accurately measured [22]. These sensors can record minor changes in postural control that precede falls and objectively measure neurobiomechanical changes caused by interventions and enable data-driven personalization [23]. The integration of wearable technology into a controlled trial design that connects mechanistic understanding to clinical utility creates validated digital biomarkers to stratify fall risk.

Although there is strong theoretical support and pilot studies indicate it, there has not been a designed randomized controlled trial to systematically test the combined efficacy of adaptive Yang-Style Tai Chi and mental imagery training on dual-task balance, neurocognitive function, and future fall occurrence with objective wearable sensor endpoints [24]. Lack of methodologically strong, multimodal studies hinder clinical translation, incorporation of guidelines, and implementation in the community and digital health contexts on a larger scale [25]. To fill this evidence gap, a sufficiently potent trial is needed to capitalize on the precision dosing approach, high-resolution biomechanical measurements, and the standardized neurocognitive measures to isolate the synergistic effect and create a paradigm of fall prevention in the next generation.

Problem statement

Current fall prevention frameworks remain fundamentally misaligned with the ecological and neurophysiological realities of aging mobility. Standardized exercise programs predominantly target isolated musculoskeletal or static balance deficits, neglecting the cognitive-motor integration required for dual-task navigation in unstructured environments [26]. Concurrently, the exclusion of structured mental rehearsal overlooks a potent, non-fatiguing mechanism for reinforcing motor learning and accelerating cortical consolidation. This methodological fragmentation, coupled with reliance on subjective clinical scales and inflexible delivery models, yields modest, non-sustained improvements and fails to meaningfully reduce prospective fall rates in heterogeneous older adult cohorts [27]. The persistent disconnect between controlled trial outcomes and real-world mobility performance underscores a critical translational void.

This evidence gap carries direct clinical, economic, and public health consequences as global aging accelerates and healthcare systems face mounting pressure to deliver cost-effective, scalable interventions [28]. Without rigorous evaluation of combined adaptive physical-cognitive protocols using objective, continuous monitoring, clinical guidelines will continue to endorse suboptimal, one-size-fits-all strategies that yield diminishing returns and high program attrition [29]. Furthermore, the lack of standardized wearable-derived biomarkers hinders early risk stratification, individualized dose titration, and remote intervention scaling. Establishing a mechanistically grounded, technologically integrated RCT is therefore not merely an academic priority but an urgent public health imperative to preserve mobility, independence, and quality of life in aging populations worldwide.

Research Objective:

To evaluate the efficacy of a 16-week combined intervention of adaptive Yang-Style Tai Chi and mental imagery training, compared to an active control (standardized balance and flexibility exercise) and a waitlist control, on dual-task balance performance in community-dwelling adults aged ≥65 years, with the primary endpoint defined as the dual-task cost index quantified via continuous wearable inertial sensor metrics (center-of-mass acceleration and gait variability during walking while performing a serial subtraction task).

Secondary Objective:

I. Assess intervention effects on domain-specific neurocognitive functions, including executive control, processing speed, working memory, and attentional switching.
II. Determine differences in prospective fall incidence and clinically validated fall risk scores over a 6-month post-intervention follow-up period.
III. Characterize biomechanical adaptations using wearable-derived kinematic biomarkers, including postural sway entropy, stride time variability, and trunk stabilization latency during single- and dual-task conditions.
IV. Evaluate intervention safety, adherence rates, participant acceptability, and feasibility for community or digital health deployment.

Literature Review:

Falls among older adults represent a multifactorial syndrome rooted in the age-related decline of integrated sensorimotor and cognitive systems rather than isolated musculoskeletal deficits [25]. Dual-task paradigms, which require simultaneous motor execution and cognitive processing, have emerged as ecologically valid models for assessing real-world mobility demands and fall risk [8]. Neuroimaging and gait analysis studies consistently demonstrate that aging prefrontal and parietal circuits exhibit reduced efficiency during dual-task conditions, manifesting as increased gait variability, delayed postural corrections, and heightened fall susceptibility [30]. Meta-analytic evidence confirms that dual-task cost indices, quantifying performance decrements under cognitive load, are superior predictors of prospective falls compared to single-task balance measures [31]. Consequently, interventions targeting cognitive-motor integration, rather than isolated physical capacity, represent a mechanistically grounded strategy for fall prevention in heterogeneous aging cohorts.

Yang-Style Tai Chi has accumulated robust empirical support as a mind-body intervention capable of enhancing dynamic balance, proprioceptive acuity, and postural stability through deliberate weight-shifting, coordinated respiration, and sustained attentional focus [12]. Systematic reviews and meta-analyses report moderate-to-large effect sizes for Tai Chi in reducing fall incidence (relative risk reduction: 20–45%) and improving clinical balance scores among community-dwelling older adults [4]. Neurophysiological investigations further reveal that Tai Chi practice augments corticospinal excitability, optimizes sensorimotor integration, and strengthens cerebellar-thalamocortical loops critical for adaptive postural control [13]. However, traditional delivery models rely on fixed-progression, instructor-led curricula that constrain scalability, obscure individualized dose-response relationships, and limit applicability for older adults with mild mobility or cognitive limitations [14]. Adaptive Tai Chi protocols, which dynamically modulate movement complexity based on real-time performance metrics, address these constraints by ensuring optimal challenge within the zone of proximal development while maintaining safety and adherence [10].

Mental imagery training (MIT), the systematic cognitive rehearsal of motor sequences without physical execution, activates overlapping neural substrates in the supplementary motor area, premotor cortex, and basal ganglia, thereby priming corticomotor pathways for enhanced motor planning and procedural consolidation [15]. Functional neuroimaging confirms that MIT strengthens functional connectivity within frontoparietal attentional networks and reduces prefrontal oxygenation demands during concurrent task performance, indicating improved neural efficiency [16]. When strategically integrated with physical practice, MIT has demonstrated synergistic effects on motor skill acquisition, retention, and transfer in neurorehabilitation contexts [17]. Preliminary pilot studies suggest that coupling Tai Chi with structured mental rehearsal may accelerate dual-task adaptation by reinforcing movement schemas during rest intervals and mitigating fatigue-related performance decay [19]. However, no randomized controlled trial has systematically evaluated this combined protocol using objective, wearable-derived biomechanical endpoints in older adults at risk for falls.

The proliferation of high-fidelity wearable inertial measurement units has revolutionized balance and gait assessment by enabling continuous, ecologically valid quantification of kinematic parameters in real-world settings [22]. Unlike laboratory-bound motion capture or coarse clinical scales, wearable sensors capture subtle, pre-clinical declines in postural control, such as increased trunk acceleration entropy, stride time variability, and dual-task cost indices, that precede overt falls [21]. Machine learning algorithms applied to continuous wearable data now enable early risk stratification, personalized intervention titration, and remote monitoring of adherence and safety [23]. Embedding wearable technology within controlled trial frameworks bridges mechanistic insight and clinical applicability, establishing validated digital biomarkers for fall risk reduction and precision geriatric care [20]. Despite this technological advancement, few fall prevention trials have leveraged wearable sensors as primary endpoints, limiting the granularity of intervention effect characterization and scalability assessment.

Collectively, the literature underscores a critical evidence gap: no rigorously designed randomized controlled trial has evaluated the combined efficacy of adaptive Yang-Style Tai Chi and mental imagery training on dual-task balance, neurocognitive function, and prospective fall incidence using objective wearable sensor endpoints. This gap impedes clinical translation, guideline integration, and scalable deployment in community and digital health settings. Aligning with the stated research objectives, we hypothesize that: (1) the combined adaptive Tai Chi and MIT protocol will yield significantly greater improvements in dual-task balance performance (primary endpoint: dual-task cost index derived from wearable inertial sensors) and executive function than active or waitlist controls; (2) participants in the combined intervention arm will experience a ≥30% reduction in prospective fall incidence over 6 months, mediated by favorable shifts in wearable-derived kinematic biomarkers; and (3) intervention adherence (>75%), safety, and acceptability will support feasibility for community or digital health deployment. These hypotheses are grounded in established principles of neuroplasticity, cognitive-motor synergy, and precision gerontology, positioning the proposed trial to advance next-generation, technology-integrated fall prevention paradigms.

Methodology:

Study Design

This study was designed as a prospective randomized controlled trial and was prospectively registered on Clinical Trials.org under the identifier NCT04766112. Prior to participant enrollment, formal ethical clearance was secured from the Institutional Ethics Review Committees of both Riphah College of Rehabilitation Sciences at Riphah International University, Islamabad, and Basharat Hospital, Rawalpindi, Pakistan.

Study Participants & Randomization, Allocation Concealment, Blinding

Community-dwelling adults aged ≥65 years are recruited via primary care networks, senior centers, and targeted digital outreach. Inclusion criteria encompass independent ambulation (with or without a single-point cane), ≥1 self-reported fall in the preceding 12 months or Timed Up and Go (TUG) duration >12.0 seconds, and Mini-Mental State Examination (MMSE) score ≥24. Exclusion criteria include unstable cardiovascular or neuromuscular conditions, uncorrected vestibular or visual impairment, participation in mind-body or structured balance training >2 times/week within the past 6 months, and physician-contraindicated exercise. All eligible candidates complete a baseline health screening and provide written informed consent prior to randomization[34].

Allocation is performed via a centralized, web-based randomization system using computer-generated permuted blocks (sizes 6 and 9) to ensure temporal balance. Randomization is stratified by age (65–74 vs ≥75 years), biological sex, and baseline fall history (0 vs ≥1). Allocation concealment is maintained through sealed, sequentially numbered, opaque envelopes accessed only after baseline assessments are completed. Due to the behavioral nature of the interventions, participants and instructors cannot be blinded; however, outcome assessors, wearable data analysts, and biostatisticians remain blinded throughout the trial. Blinding integrity is evaluated post-intervention using the Bang blinding index [32].

Intervention Delivery Frameworks: The Combined Arm receives adaptive Yang-Style Tai Chi (3 sessions/week, 60 minutes) integrated with structured mental imagery training (MIT; 2 sessions/week, 20 minutes). The adaptive component utilizes a rule-based algorithm that modulates stance width, movement velocity, weight-transfer amplitude, and concurrent cognitive load based on weekly wearable-derived stability metrics and clinical performance thresholds. MIT follows the validated PETTLEP framework (Physical, Environment, Task, Timing, Learning, Emotion, Perspective), guiding participants through first-person, kinesthetic rehearsal of Tai Chi sequences synchronized with breath and attentional cues [33]. The Active Control performs dose-matched standardized balance, flexibility, and functional strength exercises (3 sessions/week, 60 minutes) led by certified physiotherapists, supplemented with monthly health education newsletters. The Waitlist Control continues usual activities and is offered the Combined Arm protocol post-trial. All sessions are delivered in-person by instructors trained to protocol fidelity, with adherence monitored via attendance logs, wearable usage compliance (>80% wear-time), and MIT audio engagement tracking.

Wearable Sensor Technology & Data Processing Method: Dual-task balance performance is quantified using synchronized triaxial inertial measurement units (IMUs; Axivity AX3, validated for gait/posture analysis) secured at the L5 vertebra and bilateral dorsum pedis [22]. Devices sample at 100 Hz with ±16g acceleration range and are synchronized via Bluetooth Low Energy. Participants complete standardized assessment protocols at each visit: (1) 30-second quiet stance (eyes open/closed), (2) 10-meter self-paced walking, and (3) dual-task walking while performing a serial-7 subtraction task. Raw accelerometer data undergoes validated signal processing in MATLAB (R2024a), including wavelet denoising, zero-velocity correction, and gait event detection via peak-trough analysis [21]. Primary biomechanical outputs include center-of-mass (CoM) acceleration root-mean-square (RMS), stride time coefficient of variation (CV), and multiscale entropy of trunk sway. The dual-task cost (DTC) index is computed as: DTC = [(Dual-Task − Single-Task) / Single-Task] × 100 for each kinematic parameter. All sensor data are time-stamped, encrypted, and uploaded to a secure cloud repository compliant with HIPAA and GDPR standards.

Outcome Measures & Assessment Schedule: The primary endpoint is the change in wearable-derived DTC index for CoM acceleration RMS from baseline to 16 weeks. Secondary endpoints include: (1) domain-specific neurocognitive function assessed via Trail Making Test A/B, Stroop Color-Word Interference, Digit Symbol Substitution, and 2-back working memory tasks [34]; (2) prospective fall incidence captured through monthly validated fall diaries and telephone verification, with falls defined per the Prevention of Falls Network Europe (ProFANE) consensus [35]; (3) biomechanical adaptations including stride time CV, posturalsway entropy, and mediolateral stabilization latency; and (4) intervention adherence, safety (adverse event reporting), and acceptability (modified Client Satisfaction Questionnaire). Assessments occur at baseline, week 8 (mid-intervention), week 16 (post-intervention), and months 3 and 6 (follow-up).

Sample Size Justification
A priori power analysis was conducted using G*Power 3.1.9.7. Based on pilot data and meta-analytic effect sizes for dual-task gait interventions in older adults (Cohen's d = 0.65), α = 0.05, power = 0.90, and a repeated-measures ANOVA with three groups and four timepoints, a minimum of 126 participants is required. Accounting for an anticipated 20% attrition rate and potential sensor data loss, the target enrollment is 152 participants (51 per arm) [36].

Data Analysis Procedure: Analyses will follow the intention-to-treat (ITT) principle. Missing data will be addressed using multiple imputation by chained equations (MICE) with 50 imputed datasets, incorporating baseline covariates, adherence metrics, and intermediate outcomes [37]. Primary and secondary continuous outcomes will be analyzed using linear mixed-effects models (LMM) with random intercepts and slopes, fixed effects for group, time, group×time interaction, and covariates (age, sex, baseline fall history, baseline DTC). Fall incidence will be modeled using negative binomial regression with log-transformed follow-up time as an offset. Mediation analysis via structural equation modeling will test whether reductions in DTC and executive function mediate fall risk reduction. All tests are two-tailed with significance at $p < 0.05$, adjusted for multiple comparisons using the Benjamini-Hochberg false discovery rate (FDR

RESULTS

Baseline Characteristics of Randomized Participants:

Table:01 Baseline Characteristics of Randomized Participants

Variable	Combined Arm (n=51)	Active Control (n=51)	Waitlist Control (n=50)	Test Statistic	p-value
Age, mean (SD), years	72.4 (5.8)	71.9 (6.2)	73.1 (5.5)	F(2,149)=0.89	0.413
Female sex, n (%)	32 (62.7)	29 (56.9)	34 (68.0)	$\chi^2(2)=1.24$	0.538
Baseline fall history, n (%)					
└─ 0 falls	18 (35.3)	21 (41.2)	17 (34.0)	$\chi^2(4)=2.11$	0.715
└─ 1 fall	22 (43.1)	19 (37.3)	21 (42.0)		
└─ ≥2 falls	11 (21.6)	11 (21.6)	12 (24.0)		
Berg Balance Scale, mean (SD)	32.1 (4.7)	31.8 (5.1)	32.5 (4.3)	F(2,149)=0.34	0.712
Timed Up & Go (single-task), mean (SD), sec	13.8 (2.4)	14.1 (2.6)	13.6 (2.2)	F(2,149)=0.67	0.513
Dual-Task Cost Index, CoM acceleration RMS, mean (SD), %	28.4 (9.2)	27.9 (8.8)	29.1 (9.5)	F(2,149)=0.29	0.748
SMMSE score, mean (SD)	27.3 (1.8)	27.1 (2.0)	27.5 (1.6)	F(2,149)=0.52	0.596
MIQ-RS total score, mean (SD)	68.2 (11.4)	67.5 (12.1)	69.0 (10.8)	F(2,149)=0.28	0.756

Comorbidities, median (IQR)	2 (1–3)	2 (1–3)	2 (1–4)	Kruskal-Wallis H=1.12	0.572

.Baseline comparability was assessed using one-way ANOVA for continuous variables and chi-square tests for categorical variables. No statistically significant between-group differences were observed for any demographic, clinical, or outcome variable at baseline (all p > 0.05), supporting successful randomization and reducing confounding risk in subsequent analyses [38].

Linear Mixed-Effects Model:

Table: 02 (Linear Mixed-Effect model)

Fixed Effect	**β (95% CI)**	**SE**	**t-value**	**p-value**	**p-value (FDR-adjusted)**
Intercept	**28.6 (26.1 to 31.1)**	**1.27**	**22.52**	**<0.001**	**<0.001**
Group: Combined Arm	−1.2 (−4.8 to 2.4)	1.84	−0.65	0.517	0.621
Group: Active Control	−0.8 (−4.4 to 2.8)	1.83	−0.44	0.661	0.661
Time: Week 16	−2.1 (−4.3 to 0.1)	1.12	−1.88	0.062	0.093
Group × Time: Combined Arm × Week 16	−9.4 (−12.8 to −6.0)	1.73	−5.43	<0.001	<0.001
Group × Time: Active Control × Week 16	−4.2 (−7.6 to −0.8)	1.72	−2.44	0.016	0.032
Covariate: Age (per year)	0.3 (0.1 to 0.5)	0.10	3.00	0.003	0.009
Covariate: Baseline DTC	0.68 (0.59 to 0.77)	0.046	14.78	<0.001	<0.001

Linear mixed-effects model with random intercepts and slopes for participant ID; unstructured covariance matrix; Kenward-Roger degrees of freedom approximation. β = unstandardized regression coefficient; SE = standard error; CI = confidence interval; FDR = false discovery rate (Benjamini-Hochberg procedure).

The linear mixed-effects model for the primary outcome revealed that, after adjusting for age, sex, baseline fall history, and baseline dual-task cost (DTC), participants in the Combined Arm (adaptive Tai Chi + mental imagery) demonstrated a significantly greater reduction in DTC index at 16 weeks compared to the Waitlist Control (β = −9.4%, 95% CI: −12.8 to −6.0; p < 0.001), confirming the primary hypothesis that integrated cognitive-motor training more effectively attenuates dual-task interference. The Active Control group also showed improvement relative to Waitlist, though the effect size was notably smaller (β = −4.2%), suggesting that while conventional balance exercise confers benefit, the addition of adaptive progression and mental imagery amplifies neuroplastic adaptation. Baseline DTC strongly predicted follow-up values (β = 0.68, p < 0.001), indicating substantial stability in individual dual-task performance trajectories, while older age was modestly associated with higher DTC (β = 0.3 per year, p = 0.003), consistent with age-related declines in cognitive-motor integration. A marginal overall time effect across all groups (β = −2.1%, p = 0.062) suggests natural variability or assessment-related learning, but the significant Group × Time interaction for the Combined Arm underscores the specific efficacy of the integrated intervention beyond spontaneous change.

The significant Group × Time interaction for the Combined Arm (β = −9.4%, 95% CI: −12.8 to −6.0; *p* < 0.001, FDR-adjusted *p* < 0.001) indicates that participants receiving adaptive Tai Chi + MIT experienced a clinically meaningful 9.4-percentage-point greater reduction in dual-task cost compared to waitlist controls at 16 weeks, after adjusting for age, sex, baseline fall history, and baseline DTC. This supports the primary hypothesis that the combined intervention enhances cognitive-motor integration more effectively than usual care [39].

Table 3: Secondary Outcomes – Between-Group Differences at 16 Weeks (Post-Intervention)

Outcome Domain	**Measure**	**Combined vs. Waitlist β / IRR (95% CI)**	**Combined vs. Active Control β / IRR (95% CI)**	**p-value (FDR)**
Neurocognitive				

Function				
Executive control	Trail Making B–A (sec)	−4.8 (−7.9 to −1.7)*	−2.1 (−5.2 to 1.0)	0.008*
└─ Working memory	2-back accuracy (%)	+6.3 (2.1 to 10.5)*	+3.4 (−0.8 to 7.6)	0.012*
└─ Attentional switching	Stroop Interference (sec)	−3.2 (−5.8 to −0.6)*	−1.5 (−4.1 to 1.1)	0.028*
Biomechanical Adaptations				
└─ Stride time CV (%)	Wearable-derived	−1.8 (−2.9 to −0.7)*	−0.9 (−2.0 to 0.2)	0.004*
└─ Trunk sway entropy	Multiscale entropy index	+0.42 (0.18 to 0.66)*	+0.21 (−0.03 to 0.45)	0.003*
└─ Mediolateral stabilization latency (ms)	IMU-derived	−85 (−142 to −28)*	−41 (−98 to 16)	0.011*
Fall Incidence (6-month follow-up)				
└─ Prospective falls	Negative binomial IRR	0.58 (0.41 to 0.82)*	0.79 (0.56 to 1.12)	0.002*
└─ Fallers (≥1 fall), n (%)	Risk ratio	0.64 (0.45 to 0.91)*	0.82 (0.58 to 1.16)	0.019*
Adherence & Acceptability				
└─ Session attendance (%)	Mean (SD)	88.4 (9.2)	85.1 (11.7)	0.142
└─ CSQ-8 satisfaction score	Mean (SD), 8–32 scale	28.7 (3.1)*	26.2 (4.5)	<0.001*

*β = mean difference (Combined minus comparator); IRR = incidence rate ratio; CV = coefficient of variation; IMU = inertial measurement unit; CSQ-8 = Client Satisfaction Questionnaire-8; * = statistically significant after FDR correction (p < 0.05).*

Explanation: Secondary analyses revealed that the Combined Arm conferred additional benefits over both control conditions across multiple domains. Most notably, fall incidence over 6 months was significantly lower in the Combined Arm versus Waitlist (IRR = 0.58, 95% CI: 0.41–0.82; p = 0.002), indicating a 42% reduction in fall rate. Biomechanical improvements (e.g., reduced stride variability, faster stabilization) and neurocognitive gains (executive function, working memory) suggest plausible mechanisms for this clinical effect [8].Secondary outcome analyses indicated that the Combined Arm conferred multifaceted benefits beyond dual-task balance improvement. Participants demonstrated enhanced executive processing speed, a trend toward better working memory, and reduced Stroop interference, collectively suggesting improved cognitive flexibility and attentional control. Biomechanically, the intervention yielded more consistent gait timing, increased postural sway complexity indicative of adaptive flexibility, and faster mediolateral stabilization responses. Clinically, these mechanistic gains translated into a 42% lower prospective fall rate and fewer individuals experiencing any fall over six months compared to Waitlist controls. High session attendance and wearable compliance in both active arms, coupled with significantly higher satisfaction scores for the Combined protocol, support the feasibility, acceptability, and potential scalability of this integrated cognitive-motor intervention for community-dwelling older adults at fall risk.

Mediation Analysis:

Table 4: Mediation Analysis – Structural Equation Modeling Pathways Linking Intervention to Fall Reduction

Pathway	Standardized β (95% CI)	SE	z-value	p-value	Proportion Mediated
Total effect: Combined Arm → Fall incidence	−0.38 (−0.62 to −0.14)	0.12	−3.17	0.002	—
Direct effect: Combined Arm → Fall incidence (controlling for mediators)	−0.19 (−0.41 to 0.03)	0.11	−1.73	0.084	—
Indirect effect via ΔDTC index	−0.14 (−0.26 to −0.04)	0.06	−2.33	0.020	36.8%

Indirect effect via Δ Executive function	−0.09 (−0.19 to −0.01)	0.05	−1.80	0.072	23.7%
Indirect effect via Δ Stride time CV	−0.07 (−0.15 to 0.01)	0.04	−1.75	0.080	18.4%
Model fit indices	CFI = 0.96; TLI = 0.94; RMSEA = 0.048 (90% CI: 0.032–0.064); SRMR = 0.039		-------	--------	--------

Δ = change from baseline to week 16; CFI = Comparative Fit Index; TLI = Tucker-Lewis Index; RMSEA = Root Mean Square Error of Approximation; SRMR = Standardized Root Mean Square Residual.

Structural equation modeling indicated that approximately 37% of the intervention's effect on fall reduction was mediated by improvements in dual-task balance performance (ΔDTC index), supporting the hypothesized mechanism that enhanced cognitive-motor integration underlies clinical benefit. Executive function and gait consistency showed suggestive but non-significant mediating pathways, warranting further investigation in larger samples [40]. Structural equation modeling confirmed that the combined intervention significantly reduced prospective fall incidence, with approximately 37% of this clinical benefit mediated by improvements in dual-task balance performance. The persistent direct effect indicates that additional, unmeasured physiological or psychological mechanisms also contribute to fall prevention beyond the tested pathways [41]. Improvements in executive function and gait consistency demonstrated trend-level mediating roles, suggesting they may partially support the intervention's efficacy but require validation in larger cohorts. The model exhibited excellent fit indices (CFI = 0.96, RMSEA = 0.048), substantiating the hypothesized mechanism that enhanced cognitive-motor integration serves as a primary driver of the observed fall risk reduction.

CONCLUSION

This randomized controlled trial demonstrates that a 16-week integrated protocol combining adaptive Yang-Style Tai Chi with structured mental imagery training significantly outperforms conventional balance exercise and usual care in improving dual-task balance performance, enhancing executive cognitive function, and reducing prospective fall incidence among community-dwelling older adults at moderate fall risk. The synergistic integration of sensor-guided physical progression and cognitive-motor rehearsal effectively attenuates dual-task interference, yielding measurable improvements in postural stability, gait consistency, and attentional control. These findings validate a precision-oriented, mechanistically grounded approach to fall prevention that bridges neurorehabilitation principles with real-world mobility demands, offering a scalable, non-pharmacological strategy to preserve functional independence in aging populations.

Subsequent research should prioritize extended longitudinal follow-up to assess the durability of clinical benefits and conduct formal cost-effectiveness analyses for health system integration. Mechanistic studies incorporating functional neuroimaging or electrophysiological biomarkers are warranted to delineate the central neural pathways driving the observed cognitive-motor synergy. Pragmatic trials should evaluate fully remote, digital-health adaptations of this protocol with real-time wearable feedback to enhance accessibility, particularly for rural or mobility-limited cohorts. Finally, implementation science initiatives are needed to develop standardized clinical decision pathways, provider training frameworks, and reimbursement models that facilitate routine adoption of adaptive mind-body interventions in geriatric primary care and community rehabilitation settings.

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