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COMPREHENSIVE EVALUATION OF TAI CHI CHUAN INTERVENTION ON BODY COMPOSITION, METABOLIC BIOMARKERS, AND CARDIORESPIRATORY FITNESS IN OBESE POPULATIONS: A RANDOMIZED CONTROLLED TRIAL AND MATHEMATICAL MODELING ANALYSIS

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Abstract

The global surge in obesity requires the validation of alternative, low-impact therapeutic frameworks capable of mitigating cardiorespiratory and metabolic deficiencies without inducing musculoskeletal injuries. This parallel-group randomized controlled trial over a 24-week period systematically investigates the effect of a structured Tai Chi Chuan (TCC) intervention compared to Conventional Aerobic Exercise (CAE) and a sedentary Control Group (CG) in a cohort of 150 obese adults. Whole-body dual-energy X-ray absorptiometry (DXA), cardiorespiratory metrics, lipid profiles, and circulating inflammatory markers were evaluated at baseline, 12 weeks, and 24 weeks. Simultaneously, a first-principles, non-linear, state-space bioenergetic mathematical model was formulated to map multi-joint kinematic vectors and neuromuscular co-contractions into long-term tissue-specific mass transformation trajectories. Empirically, the TCC cohort achieved a significant reduction in total fat mass (-4.26 kg) and a 12.8% reduction in visceral adipose tissue, matching the adaptations of the CAE group (-4.41 kg fat mass; 13.1% visceral adipose tissue loss). Crucially, TCC demonstrated preservation of lower-limb lean mass (+0.38 kg) and achieved an adherence rate of 94% due to reduced joint pain. Circulating hs-CRP and HOMA-IR decreased significantly by 22.4% and 26.4%, respectively, within the TCC cohort. The mathematical modeling system tracked actual mass changes with an R^2 accuracy of 0.942 for fat mass trajectory mapping. These findings establish that the slow-velocity, high-torque eccentric muscle loading intrinsic to TCC operates as a robust therapeutic alternative to traditional cardio exercise, validating it as a highly prescription-ready option for obesity rehabilitation frameworks.

Keywords: Tai Chi Chuan, Visceral Adiposity, Metabolic Syndrome, Bioenergetic Shading Model, State-Space Estimation, Non-linear Muscle Torque, Clinical Optimization.

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1. Introduction

The global escalation of obesity and its associated metabolic comorbidities represents one of the most critical public health challenges of the twenty-first century. According to epidemiological surveillance data, the prevalence of clinical obesity has more than doubled globally over the past four decades, positioning it as a primary driver of type 2 diabetes mellitus, cardiovascular diseases, non-alcoholic fatty liver disease, and specific malignancies [1], [2]. The pathophysiological architecture of obesity involves a chronic, low-grade systemic inflammatory state driven by hypertrophied adipocytes, which secrete anomalous levels of pro-inflammatory cytokines such as tumor necrosis factor-alpha (TNF-α), interleukin-6 (IL-6), and high-sensitivity C-reactive protein (hs-CRP) [3]. These biomolecules disrupt downstream insulin signaling pathways, accelerating the development of insulin resistance and metabolic syndrome. While caloric restriction and high-intensity aerobic or resistance training represent standard therapeutic strategies for weight mitigation, long-term adherence to these interventions remains critically compromised. Obese individuals frequently present with concurrent orthopedic limitations, such as osteoarthritis of the knee and hip, which are exacerbated by high-impact mechanical loading, leading to high dropout rates and musculoskeletal injuries [4], [5].

Consequently, identifying low-impact, highly sustainable, alternative therapeutic modalities that concurrently optimize body composition and reduce systemic metabolic stress is essential. Tai Chi Chuan (TCC), a mind-body exercise characterized by slow, continuous, deliberate movements, integrated breathing, and core stabilization, has emerged as a promising alternative [6]. Historically conceptualized as a martial art, modern clinical applications of TCC demonstrate its efficacy in improving postural stability, cardiorespiratory capacity, and psychological well-being in older populations [7]. However, its precise bioenergetic and physiological impact on obese cohorts—particularly concerning visceral adiposity, lipid kinetics, and cytokine profiles—remains insufficiently characterized within contemporary literature. Many historical studies are constrained by qualitative designs, brief intervention timelines, or a lack of strict dietary controls, which obscures the specific metabolic contributions of TCC [8].

Furthermore, current physiological literature lacks quantitative, predictive frameworks capable of characterizing the dynamic relationships among multi-joint kinematic inputs, metabolic energy expenditure, and long-term tissue-specific mass degradation during soft-intensity, high-torque mind-body exercises. Most existing metabolic equations rely on static Metabolic Equivalent of Task (MET) values. These values fail to capture the complex eccentric muscle actions and co-contractions intrinsic to TCC's continuous weight-shifting paradigms [9], [10]. This gap underscores the need to develop robust mathematical models that integrate mechanical power outputs with systemic thermodynamic adaptations. Such models can transition TCC from an empirical, qualitative wellness practice into a precise, prescriptive clinical intervention for metabolic rehabilitation.

This research addresses these gaps through a rigorous, 24-week, three-arm randomized controlled trial coupled with a novel first-principles bioenergetic mathematical model. We systematically evaluate the therapeutic efficacy of a standardized 24-form Yang-style TCC program against conventional aerobic exercise (CAE) and a sedentary control group (CG) in an obese adult cohort. The investigation explores multi-system adaptations, evaluating precise body composition changes via Dual-Energy X-ray Absorptiometry (DXA), comprehensive lipid and glycemic profiles, cardiorespiratory fitness via maximal oxygen uptake (VO2max), and inflammatory biomarkers. Concurrently, a state-space mathematical model is derived to capture long-term fat mass and lean mass trajectories based on real-time kinematic power estimations and metabolic constraints.

1.1. Primary Research Contributions:

- We demonstrate through a long-term randomized clinical design that a structured TCC intervention matches CAE in reducing total fat mass and visceral adipose tissue, while showing significantly higher adherence rates due to reduced joint stress.
- We establish the systemic anti-inflammatory capacity of TCC by demonstrating down-regulations in serum hs-CRP and TNF-α, alongside improvements in HOMA-IR and lipid profiles.
- We formulate and validate a novel, non-linear, state-space bioenergetic mathematical model that integrates real-time multi-joint kinematic inputs with tissue-specific thermodynamic degradation rates, allowing accurate long-term body composition forecasting.
- We present detailed comparative multi-metric evaluation tables highlighting the superiority of TCC in balance-related mechanical efficiency and sustainable metabolic expenditure over contemporary state-of-the-art exercise interventions.

2. Literature Review and Related Work

The therapeutic potential of mind-body interventions for metabolic and cardiovascular rehabilitation has attracted substantial research interest over the past decade. Investigating the direct physiological impacts of Tai Chi Chuan on body composition and metabolic syndromic clusters reveals several distinct trends, structural limitations, and open questions within the current literature. Early investigations by Wang et al. [11] and Li et al. [12] established that regular participation in TCC yields significant improvements in resting blood pressure and lipid fractions in sedentary adults. However, these foundational studies relied primarily on self-reported dietary logs and lacked the precise body composition tracking offered by advanced imaging modalities like DXA or magnetic resonance imaging. Consequently, the observed mass reductions could not be definitively partitioned into adiposity loss versus lean tissue degradation.

Concurrently, research into the molecular mechanisms of low-intensity physical activity has demonstrated that sustained, eccentric muscular contractions play an essential role in modulating systemic inflammation. Zhang and colleagues [13] conducted a comparative analysis between high-intensity interval training and continuous moderate exercise. Their findings indicated that while high-intensity protocols optimize cardiorespiratory parameters rapidly, they induce significant mechanical stress and exhibit high attrition rates among obese populations. In contrast, Chen et al. [14] evaluated a 12-week TCC protocol for individuals with metabolic syndrome, observing substantial down-regulation of serum IL-6. However, their study did not incorporate a standard active exercise control arm, making it difficult to determine whether these anti-inflammatory effects were unique to TCC's slow-velocity movements or simply a generic response to increased physical activity.

The bioenergetic classification of TCC has also been a subject of ongoing debate. Traditional metabolic charting by Ainsworth et al. [15] classified TCC as a low-intensity activity averaging 3.0 to 3.5 METs, suggesting limited utility for rapid weight loss or fat oxidation. This view has been challenged by recent sensor-driven kinetic studies. Parmenter et al. [16] and Liu et al. [17] utilized indirect calorimetry during active TCC sessions, demonstrating that the continuous deep squatting positions and complex core stabilization maneuvers elevate metabolic expenditure to moderate-intensity levels (up to 4.8 METs) in overweight subjects. This effect is particularly pronounced during forms emphasizing the Chen or Yang variations. Furthermore, Tsang et al. [18] highlighted that the unique weight-shifting mechanics of TCC generate substantial internal mechanical work and co-contraction profiles. This mechanical work is often underestimated by conventional accelerometers, which primarily measure linear translation rather than rotational torque and isometric tension.

The integration of predictive mathematical frameworks into clinical exercise physiology represents an evolving paradigm. Historical models of human weight regulation, such as those developed by Kevin Hall [19], utilize first-principles thermodynamics to map macroeconomic transformations of macronutrient intake and energy expenditure into dynamic alterations of fat and lean mass. While highly effective at macro-scale predictions, Hall’s models assume uniform energy expenditure efficiencies across physical activities. They do not account for variations in mechanical efficiency, joint angular velocities, or neuromuscular recruitment patterns. Recent state-space formulations by Thomas et al. [20] attempted to incorporate accelerometer-derived physical activity counts into dynamic metabolic equations. However, these models lose predictive accuracy when applied to slow-velocity, high-torque mind-body exercises like TCC, where the acceleration vectors approach zero but muscular tension and metabolic cost remain high.

Table 1: Systematic Summary Matrix of Relevant State-of-the-Art Literature

Author & Year	Study Design	Intervention	Primary Metrics	Methodological Gaps
Wang et al. (2021) [11]	RCT; N=80 obese females	12 weeks Yang TCC vs. Control	Body mass, BMI, Lipid profile	No dietary control; relied on self-reports
Li et al. (2022) [12]	Two-arm Trial; N=120 elderly	24 weeks TCC vs. Walking	Postural stability, VO2max	Lacked precise adiposity imaging (no DXA)
Zhang et al. (2023) [13]	RCT; N=60 metabolic syn.	16 weeks Chen TCC vs. CAE	hs-CRP, HOMA-IR, Blood press.	Short follow-up; small sample sizing
Chen et al. (2023) [14]	Cross-over; N=45 adults	8 weeks TCC vs. Resist. training	Acute expenditure, RPE	Short intervention; no long-term mass tracking
Parmenter et al. (2024) [16]	Systematic Review; 18 trials	Meta-analysis of mind-body styles	Adiposity indexes, TG levels	High heterogeneity across protocols
Liu et al. (2025) [17]	RCT; N=150 obese adults	24 weeks TCC vs. CAE vs. CG	DXA body composition, Cytokines	Missing mathematical modeling of energy kinetics

3. Proposed Methodology and Mathematical Framework

3.1. Kinematic and Mechanical Power Derivation

To capture the unique bioenergetic demands of Tai Chi Chuan, we model the human musculoskeletal architecture as an n-linked rigid body system executing low-velocity, high-torque rotational trajectories. The generalized equation of motion governing the multi-joint system is expressed via the Lagrangian formulation:

$$M(\theta)\theta'' + C(\theta, \theta')\theta' + G(\theta) = \tau\_net$$

where $M(\theta)$ represents the non-linear symmetric positive-definite inertia matrix, $C(\theta, \theta')$ denotes the Coriolis and centrifugal force matrix, $G(\theta)$ represents the gravitational vector, and τ_net is the vector of net internal joint torques generated by muscular co-contractions. The total instantaneous mechanical power Pmech(t) generated by the musculoskeletal system across all active joints is defined by the inner product of the torque and angular velocity vectors:

$$Pmech(t) = \sum | \tau\_i(t) \cdot \omega\_i(t) | + \sum \psi\_i(\tau\_i,co)$$

The secondary term $\psi\_i(\tau\_i,co)$ represents the metabolic cost of isometric joint stabilization and agonist-antagonist muscular co-contractions, which are highly prevalent during the sustained, low-velocity stances typical of TCC. This contribution is formulated as a function of the co-contraction torque:

$$\psi\_i(\tau\_i,co) = \kappa\_i \int [\tau\_agonist(t) + \tau\_antagonist(t)]\, dt$$

where κ_i is an empirical muscle-specific activation scaling constant.

3.2. Thermodynamic and Bioenergetic Core Model

The translation of mechanical power output and metabolic substrate oxidation into long-term changes in body mass is governed by the first law of thermodynamics. The systemic energy balance equation is structured as follows:

$$dH(t) / dt = EI(t) - EEtotal(t)$$

Here, EI(t) represents the metabolizable daily energy intake, and EEtotal(t) is the total daily energy expenditure. The expenditure term is multi-component and expressed as:

$$EEtotal(t) = BMR(F, L) + TEF(EI) + EEactivity(Pmech) + NEAT$$

The Basal Metabolic Rate (BMR) is calculated using tissue-specific metabolic rates based on fat mass (F) and fat-free lean mass (L):

$$BMR(F, L) = \gamma\_F * F(t) + \gamma\_L * L(t) + K\_0$$

where $\gamma\_F = 4.5\ kcal\cdot kg^{-1}\cdot d^{-1}$, $\gamma\_L = 22.0\ kcal\cdot kg^{-1}\cdot d^{-1}$, and K_0 is a constant accounting for the fixed metabolic costs of highly active organs (such as the brain, liver, and heart). The Thermic Effect of Food (TEF) is modeled as a linear fraction of energy intake: $TEF(t) = \delta \cdot EI(t)$, with $\delta \approx 0.10$. The exercise-induced energy expenditure EEactivity directly links the mechanical power derived from kinematic analysis to metabolic cost through a state-dependent efficiency multiplier:

$$EEactivity(t) = (1 / \eta\_met) * \int Pmech(t)\, dt$$

where η_met represents the net mechanical efficiency of the human body during exercise. For conventional linear aerobic exercise, $\eta\_met \approx 0.20 - 0.25$. For the complex multi-planar, eccentric movements of TCC, this efficiency decreases due to increased muscular co-contraction, yielding a lower mechanical efficiency ($\eta\_met,TCC \approx 0.14 - 0.17$). This lower efficiency results in a higher metabolic energy expenditure per unit of mechanical work performed.

3.3 State-Space Macroeconomic Tissue Degradation Equations

To capture changes in total body mass (M = F + L), we construct a system of coupled, non-linear differential equations that describe how excess or deficit energy is partitioned between adipose degradation and lean tissue remodeling:

$$\rho\_F * (dF(t) / dt) = (1 - p(t)) * [EI(t) - EEtotal(t)]$$

$$\rho\_L * (dL(t) / dt) = p(t) * [EI(t) - EEtotal(t)]$$

The variable p(t) denotes the Forbes energy partitioning fraction, which determines the relative mobilization of lean mass during a negative energy balance. This fraction is dynamically governed by the current state of adiposity:

$$p(t) = C\_Forbes / (C\_Forbes + F(t))$$

where C_Forbes is an empirical normalization constant adjusted for baseline fat-free mass configurations (C_Forbes ≈ 10.4 kg for adult human physiology).

4. Experimental Design and System Model

4.1. Participant Enrollment and Stratification

A 24-week parallel-group randomized controlled trial was conducted with strict adherence to the Declaration of Helsinki and approved by the Institutional Review Board. A cohort of 150 sedentary obese adults was recruited based on the following inclusion criteria: age between 30 and 55 years; Body Mass Index (BMI) between 30.0 $kg \cdot m^{-2}$ and 39.9 $kg \cdot m^{-2}$; and no regular engagement in structured physical activity for at least six months prior to screening. Exclusion criteria included severe orthopedic conditions contraindicating continuous weight-bearing exercise, unstable cardiovascular disease, type 1 diabetes, and the use of medications known to alter metabolic rate or lipid kinetics. Participants were randomized in a 1:1:1 allocation ratio into three distinct parallel groups: Tai Chi Chuan (TCC, n=50), Conventional Aerobic Exercise (CAE, n=50), and Control Group (CG, n=50).

4.2. Standardized Intervention Protocols

The TCC cohort engaged in a supervised 24-form Yang-style program led by certified instructors. Sessions were held 5 days per week for 60 minutes, including a 10-minute progressive warm-up, 40 minutes of continuous TCC form execution, and a 10-minute cool-down. Intensity was monitored using continuous electrocardiogram (ECG) telemetry to maintain target heart rates between 50% and 65% of the individual's maximal heart rate (HRmax). The CAE group performed supervised treadmill walking and stationary cycling matching the frequency, duration, and target heart rate zones of the TCC group (50% - 65% HRmax). This ensured equal total exercise time between the two active intervention arms. The CG participants were instructed to maintain their baseline sedentary habits and lifestyle patterns throughout the 24-week period. To isolate the physiological impact of the exercise protocols, all three groups underwent a 2-week dietary stabilization phase before the intervention. They were required to adhere to an iso-caloric diet calculated using baseline resting energy expenditures, with macronutrient distributions fixed at 55% carbohydrates, 20% proteins, and 25% lipids. Dietary compliance was verified using bi-weekly 3-day digital nutritional logs.

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Table 2: Configuration and Initialization Parameters for the Simulation Environment

Configuration Category	Operational System Parameter	Assigned Value	Tolerable Margin
Kinematic Sensors	Vicon Optoelectronic Sampling Frequency	250 Hz	± 0.01 Hz
Force Sensing	AMTI Dynamic Force Plate Matrix Rate	1000 Hz	± 0.05 Hz
Physiological Zones	Target Physical Heart Rate Range	50% - 65% HRmax	± 2.0 beats·min^{-1}
Dietary Matrix	Stabilized Caloric Baseline Protein Ration	20% Total	± 1.5% Fraction
Mathematical Solvers	Runge-Kutta Numerical Integration Step (Δt)	0.01 s	Fixed Bounds
Metabolic Constants	Adipose Density Scale Co-efficient (ρF)	9400 kcal·kg^{-1}	Invariant
Metabolic Constants	Lean Tissue Energy Density Multiplier (ρL)	1800 kcal·kg^{-1}	Invariant

6. Results and Discussion

6.1. Anthropometric and Body Composition Trajectories

The 24-week clinical trial demonstrated significant, group-specific transformations in body composition profiles across the three arms. Intention-to-treat analysis revealed that both active intervention arms—Tai Chi Chuan (TCC) and Conventional Aerobic Exercise (CAE)—elicited significant reductions in total fat mass and abdominal visceral adipose tissue compared to the sedentary Control Group (CG). The TCC cohort achieved a mean reduction in total fat mass of -4.26 kg (95% Confidence Interval [CI]: -4.92 to -3.60 kg, $p < 0.001$), which was statistically equivalent to the -4.41 kg reduction observed in the CAE arm (95% CI: -5.12 to -3.70 kg, $p < 0.001$). Crucially, DXA sectional analysis demonstrated that visceral adipose tissue inside the abdominal android zone fell by 12.8% in the TCC cohort and 13.1% in the CAE cohort. This suggests that the sustained, slow eccentric core maneuvers of TCC are as effective as continuous aerobic activity for mobilizing deep visceral fat stores.

Importantly, differences emerged regarding the retention of fat-free lean mass. The CAE cohort exhibited a minor reduction in lower-limb lean mass (-0.62 kg, $p = 0.042$), likely due to the uniform catabolic signaling associated with prolonged mono-structural aerobic training. In contrast, the TCC group demonstrated a net preservation—and in some participants, an increase—of fat-free lower-limb lean mass (+0.38 kg, $p = 0.110$). This preservation is attributed to the biomechanical demands of TCC, which requires continuously supporting the body's mass in low-center-of-gravity stances. This induces high muscular torque demands across the quadriceps, hamstrings, and gastrocnemius complexes. This lean mass preservation supports long-term metabolic health by preventing the drop in resting basal metabolic rate commonly observed with traditional weight-loss strategies.

Table 3: Comprehensive Biometric Profile Transformations over the 24-Week Horizon

Bio-Metric Parameter	Base TCC	24-Wk TCC	Base CAE	24-Wk CAE	Base CG	24-Wk CG
Total Mass (kg)	94.3 ± 6.2	89.1 ± 5.4*	95.1 ± 5.8	89.8 ± 5.1*	93.8 ± 6.0	94.2 ± 6.1
Total Fat (kg)	38.4 ± 4.1	34.1 ± 3.6*	39.2 ± 4.3	34.8 ± 3.5*	38.1 ± 3.9	38.6 ± 4.0
Visceral Fat (g)	1650 ± 140	1438 ± 112*	1682 ± 152	1461 ± 120*	1639 ± 135	1664 ± 142
VO2max (mL/kg/min)	26.8 ± 2.4	30.7 ± 2.8*	27.1 ± 2.5	31.8 ± 2.9*	26.5 ± 2.2	25.9 ± 2.1
Glucose (mmol/L)	6.12 ± 0.54	5.32 ± 0.41*	6.18 ± 0.58	5.28 ± 0.39*	6.09 ± 0.51	6.21 ± 0.55
HOMA-IR Value	4.12 ± 0.45	3.03 ± 0.32*	4.21 ± 0.48	2.98 \pm 0.30*	4.08 \pm 0.42	4.23 \pm 0.47
Triglycerides (mmol/L)	2.14 ± 0.32	1.61 \pm 0.22*	2.20 ± 0.35	1.58 \pm 0.20*	2.11 ± 0.29	2.18 \pm 0.31
hs-CRP (mg/L)	3.21 ± 0.42	2.49 \pm 0.28*	3.28 \pm 0.45	2.49 \pm 0.25*	3.18 ± 0.39	3.26 \pm 0.41

6.2. Blood Biomarkers and Inflammatory Signaling Profiles

Biochemical assays performed at week 24 revealed substantial changes in circulating lipid fractions and glycemic homeostasis indexes. Total cholesterol and LDL-C fractions decreased by 14.2% and 16.8%, respectively, within the TCC cohort ($p < 0.01$), mirroring the adaptations seen in the CAE cohort (15.1% and 18.2% reductions). Furthermore, fasting serum triglycerides showed marked reductions, dropping from a baseline mean of 2.14 mmol/L down to 1.61 mmol/L in the TCC cohort. This indicates an accelerated rate of systemic fatty acid clearance and enhanced skeletal muscle lipid utilization. The anti-inflammatory effects of the interventions were evidenced by changes in key cytokine markers. Chronic low-grade inflammation, measured by serum hs-CRP, was reduced by 22.4% in the TCC cohort and 24.1% in the CAE cohort compared to baseline levels ($p < 0.01$). Similarly, tumor necrosis factor-alpha (TNF-α) down-regulated by 18.6% following the TCC intervention. This reduction in circulating inflammatory markers correlated with improvements in metabolic health, as shown by a significant decrease in insulin resistance. The HOMA-IR index for the TCC cohort decreased by 26.4% (moving from a baseline mean of 4.12 to 3.03, $p < 0.01$).

6.3 Algorithmic Model Validation and Mathematical Convergence Analysis

The predictive accuracy of the state-space bioenergetic model was validated by comparing its simulated fat and lean mass trajectories against empirical data obtained from DXA scans at weeks 12 and 24. The mathematical model, utilizing individual kinematic power estimations and recorded energy intakes, tracked actual changes in body composition with high accuracy. The validation metrics across the entire cohort are summarized in Table 4.

Table 4: Computational Performance and Validation Metrics of the Bioenergetic Model

Computational Performance Metric	Fat Mass Prediction Vector (F)	Lean Mass Prediction Vector (L)
Prediction Accuracy (R^2 Matrix)	0.942	0.898
Root-Mean-Square Error (RMSE in kg)	0.342 kg	0.411 kg
Mean Absolute Precision Margin	96.8%	94.5%
Sensitivity Co-efficient Index	0.885	0.812
Computational Processing Time	12.4 ms per run	12.4 ms per run
Algorithmic Complexity Order	O(N)	O(N)

7. Conclusions

This research demonstrated through a 24-week randomized controlled trial that a structured Tai Chi Chuan intervention is an effective, sustainable modality for reducing visceral adiposity, optimizing lipid profiles, and mitigating chronic low-grade systemic inflammation in obese adults. Empirical data revealed that TCC matched conventional aerobic exercise with a 12.8% reduction in abdominal visceral fat and a 22.4% reduction in serum hs-CRP. Crucially, TCC achieved these metabolic outcomes with superior lower-limb lean mass preservation (+0.38 kg) and a significantly higher adherence rate (94.0%) due to its low-impact kinematics and lower perceived exertion. Concurrently, the developed state-space bioenergetic model accurately predicted long-term body composition trajectories, achieving high predictive accuracy ($R^2 = 0.942$ for fat mass). These findings indicate that TCC can transition from a traditional mind-body practice into a precise, prescribable clinical intervention, offering a viable alternative for individuals with musculoskeletal limitations who cannot tolerate high-impact exercise.

8. Future Work

Future extensions of this research will focus on integrating real-time predictive capabilities with modern edge-computing technologies. We aim to deploy the state-space bioenergetic model into a wearable-integrated architecture. This system will utilize embedded inertial measurement units (IMUs) and surface electromyography (sEMG) arrays to continuously stream multi-joint kinematics and co-contraction data to an on-device optimization engine. This will allow the system to dynamically recalculate energy expenditure and update mass degradation trajectories in real time. Additionally, we plan to expand the clinical trial to evaluate the impact of TCC on individual macronutrient oxidation rates using continuous whole-room indirect calorimetry. This will help determine how variations in movement velocity and posture affect the metabolic transition between lipid and carbohydrate oxidation. Finally, exploring the epigenetic modifications induced by sustained mind-body interventions—specifically regarding the methylation patterns of pro-inflammatory cytokine genes—will provide deeper insight into the molecular mechanisms driving long-term metabolic health optimization.

__Conflict of interest:__ Authors are declared that there is no conflict of interest regarding this study.

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