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Molecular & Cellular Biomechanics 2024, 21(3), 541.
https://doi.org/10.62617/mcb541

Article

Biomechanical analysis of balance control in the elderly By Ba Duan Jin

Ye Cheng[1], Yan Song[2], Feilong Wu[3,*]

[1] Department of Physical Education, Hebei University of Economics and Business, Shijiazhuang 050061, China
[2] School of Foreign Languages, Hebei University of Economics and Business, Shijiazhuang 050061, China
[3] College School of Sports Science, Shenyang Normal University, Shenyang 110034, China
*** Corresponding author:** Feilong Wu, mrwyatt123@126.com

CITATION

Cheng Y, Song Y, Wu F. Biomechanical analysis of balance control in the elderly By Ba Duan Jin. Molecular & Cellular Biomechanics. 2024; 21(3): 541. https://doi.org/10.62617/mcb541

ARTICLE INFO

Received: 15 October 2024
Accepted: 5 November 2024
Available online: 19 November 2024

Abstract: This study aims to evaluate the biomechanical effects of Ba Duan Jin on balance control in the elderly, seeking effective fitness methods to enhance their balance capabilities and reduce the risk of falls. Methods: Participants were randomly assigned to an experimental group (EG) and a control group (CG), with 25 individuals in each. The Berg Balance Scale (BBS) and mechanical measurements were utilized to evaluate the participants' balance abilities and biomechanical performance. Statistical analyses were performed to compare the outcomes between the EG and CG, ensuring a comprehensive assessment of the differences. Results: The experimental group demonstrated a significant improvement in the Berg Balance Scale (BBS) scores ($p < 0.01$), with a notable increase in the eyes-closed standing task (BBS6), which reached significance ($p < 0.05$), indicating a consistent advantage for the experimental group in this area. Biomechanical measurements revealed that the experimental group exhibited significantly higher parameters compared to the control group, including stability index (EG: 0.7 ± 0.1/2.2 ± 0.4, CG: 0.6 ± 0.1/1.9 ± 0.3), power (EG: 3.2 ± 0.5/3.8 ± 0.6, CG: 2.9 ± 0.4/3.5 ± 0.5), energy expenditure (EG: 20.1 ± 3.8/25.0 ± 4.3, CG: 16.5 ± 3.2/20.3 ± 3.8), and step frequency (EG: 95.0 ± 5.5/105.0 ± 6.0, CG: 85.0 ± 5.0/100.0 ± 5.5). Additionally, peak force (EG: 345.2 ± 30.1/412.6 ± 35.8, CG: 310.4 ± 28.5/310.4 ± 28.5), impact force (EG: 68.3 ± 7.2/85.7 ± 8.9, CG: 55.8 ± 6.7/72.4 ± 8.1), average force (EG: 280.5 ± 25.6/320.7 ± 30.2, CG: 245.3 ± 22.8/280.1 ± 26.4), and direction of force (EG: 10.0 ± 2.0/15.0 ± 2.5, CG: 8.5 ± 1.5/12.0 ± 2.0) also exhibited significant differences ($p < 0.05$). Notably, the static single-leg stance (EG: 3.38 ± 0.39, CG: 2.38 ± 0.50), dynamic sit-to-stand (EG: 3.77 ± 0.34, CG: 2.85 ± 0.37), turning movements (EG: 3.88 ± 0.27, CG: 2.58 ± 0.56), and double-leg step-ups (EG: 4.00 ± 0.02, CG: 2.69 ± 0.49) displayed extremely significant differences ($p < 0.01$). These results indicate that Ba Duan Jin training effectively enhances balance control and reduces the risk of falls among the elderly. Conclusion: As a traditional form of physical exercise, Ba Duan Jin effectively enhances balance control and reduces the risk of falls among older adults, providing valuable practical evidence for health management in this population. Future research should focus on conducting more long-term studies with larger sample sizes to verify the applicability and long-term effects of Ba Duan Jin across various age groups and health conditions in older individuals.

Keywords: Baduanjin; elderly; risk of falling; balance control; biomechanical analysis

1. Introduction

As the aging population grows, the decline in balance and the prevalence of unsteady gait among older adults have led to a rising incidence of falls, significantly impacting their health and increasing the burden on families and society [1–3]. Research indicates that more than one-third of community-dwelling individuals aged 65 and older experience at least one fall each year [4]. Moreover, 5%–20% of these falls result in severe head injuries, lacerations, or fractures, further elevating the risks of restricted mobility and mortality [5]. The consequences of falls become increasingly severe with age, substantially increasing the likelihood that older adults will require admission to nursing homes [6].

Body balance control refers to an individual's ability to maintain stability, coordination, and adaptability to environmental changes in both static and dynamic states [7–9]. Effective balance control is essential for daily activities, athletic performance, and fall prevention [10,11]. Notably, older adults experience a gradual decline in the functional components of body balance control, which is positively correlated with an increased risk of falls [12–14]. Research has established a strong relationship between limb muscle thickness and functional capacity, balance, and fall incidents [15–18]. Additionally, neuromuscular control mechanisms in older adults are typically diminished, exhibiting significant degeneration that further heightens fall risk [19]. Consequently, postural control is crucial for maintaining balance in older adults, relying on the precise timing of inputs from the vestibular, visual, proprioceptive, and somatosensory systems to implement adaptive strategies for orientation and stability [11,20]. Findings suggest that the execution of dual tasks can adversely affect postural control in older adults, increasing the burden on working memory [21]. The declines in visual, proprioceptive, and vestibular sensitivity among older individuals necessitate heightened attention to maintaining postural stability while standing and walking [22]. In this context, performing dual tasks may further compromise the stability of physical activities in older adults [23]. Some scholars have examined biomechanical factors such as center of gravity shifts, muscle strength, and neuromuscular regulation, highlighting that exercise can enhance these factors to improve balance ability [24]. In particular, lower limb muscle strength and balance control play crucial roles [25,26]. Additionally, research has explored the relationship between aging anxiety and physical activity among middle-aged and older African Americans, finding that reducing anxiety can promote a more active lifestyle [27]. Furthermore, the importance of a positive psychological state in facilitating physical activity among older adults has also been emphasized [28].

Currently, an increasing number of studies are focusing on traditional forms of exercise, such as Tai Chi and yoga, and their effects on balance and fall prevention among older adults. Research has shown that these activities significantly enhance balance by improving lower limb muscle strength, postural control, and proprioception [29,30]. Among these traditional exercises, Ba Duan Jin—a Chinese health regimen with a history spanning over a thousand years—has also attracted the attention of scholars both domestically and internationally. Ba Duan Jin comprises eight movements that integrate breath regulation, gentle motion, and mental focus, with the aim of harmonizing energy flow, strengthening musculoskeletal function, and enhancing psychological well-being [31]. Its slow and gentle movements render it particularly suitable for individuals of varying fitness levels, especially older adults [32,33].

From the perspective of exercise biomechanics, the movements of Ba Duan Jin emphasize balance and coordination, notably through exercises such as "Two Hands to Tuotian Regulates Three Burners" and "Left and Right Bow Like Archers." These activities enhance limb stability and flexibility through repeated practice [34–36], positioning Ba Duan Jin as a promising option for balance training in older adults. The slow, continuous movements of Ba Duan Jin significantly strengthen the core and lower limb muscles, aiding in the maintenance of good posture and enhancing balance control through weight transfer and postural adjustment training [37]. Research indicates that regular practice of Ba Duan Jin improves physical posture, stability, and overall health in older individuals, thereby enhancing their quality of life [38]. Randomized controlled trials and systematic reviews have shown that Ba Duan Jin effectively enhances physical function, muscle strength, balance, and flexibility in older adults, making it a safe and effective exercise method that can help mitigate physiological decline [39,40]. Despite the existing studies that confirm its beneficial effects, there is still a lack of sufficient randomized controlled trials and long-term observations, resulting in an inadequate scientific evidence base. Therefore, investigating the role of Ba Duan Jin in balance control among older adults is of significant practical importance, as it offers additional options for physical activity and contributes to their health and well-being.

2. Materials and methods

2.1. Participants and group requirements

This study recruited a total of 46 participants, all aged 65 to 75, from an elderly healthcare and wellness hospital in Shijiazhuang, Hebei Province. After discussions with the participants and their families, 26 older adults met the study's criteria, with 13 assigned to the experimental group (EG) and 13 to the control group (CG). This study assessed both groups on various indicators, including age, gender, education level, fall history, BMI, health status, and daily activity levels. A standard health questionnaire was employed for a comprehensive evaluation of all participants to ensure they had no significant illnesses or physical disabilities. Additionally, daily step counts were recorded using wearable devices (smart wristbands) to confirm levels of daily activity, thereby effectively controlling for individual differences that could influence the study outcomes. The EG participated in traditional Ba Duan Jin health and wellness training, engaging in sessions five times a week, each lasting 1.5 hours. In contrast, the CG maintained their usual daily activities without participating in this training. The study aimed to assess the practical effects of Ba Duan Jin on balance control in older adults by comparing the differences in biomechanical parameters of balance between the two groups. The experiment was conducted from July 8 to 8 October 2024, lasting a total of 84 days. Prior to the intervention, participants were informed about the requirements and precautions associated with Ba Duan Jin training. In accordance with the Declaration of Helsinki, 26 informed consent forms and 26 declarations of informed consent from family members were signed, and the study received approval from the Academic Ethics Committee of Hebei University of Economics and Business (Approval Number: HBJMDX20240706).

2.2. Inclusion and exclusion criteria

(1) Inclusion Criteria: (1) This study will recruit older adults aged 60 years and above who are in generally good health, without serious cardiovascular, respiratory, visual, auditory, or central nervous system disorders. (2) Participants must be capable of independently performing basic daily activities. (3) Participants should not have a history of severe injuries affecting balance (such as hip fractures or ankle sprains) within the past year.

(2) Exclusion Criteria: (1) Individuals with significant health issues that severely impact balance, including recent heart disease, severe visual or auditory impairments, central nervous system disorders, or cognitive impairments, will be excluded. (2) Individuals with musculoskeletal disorders or those currently taking medications that affect balance will also be excluded. (3) Participants who have engaged in other balance training or physical therapy within the past year, who cannot complete necessary balance assessments due to health reasons, or who have mental health issues affecting their willingness to participate will be excluded from the study.

2.3. Berg balance scale (BBS)

This study employed the Berg Balance Scale (BBS) to evaluate the balance abilities of older adults. The BBS consists of 14 tasks that assess participants' balance performance under both static and dynamic conditions. These tasks encompass common daily activities, such as standing with eyes closed, standing on one leg, stepping over obstacles, changing pace, and climbing stairs [41,42]. Each task is scored according to the participant's performance, with scores ranging from 0 (unable to complete) to 4 (completely independent). The maximum possible total score is 56 points. Based on these scores, participants' balance abilities are classified, with scores below 45 typically indicating a higher risk of falls, thereby suggesting that these individuals may face an increased danger of falling in their daily lives.

2.4. Force plate analysis (FPA)

To assess the biomechanical effects of Eight-Section Brocade on balance control in older adults, a series of precise mechanical measurement tools and equipment were utilized. First, force sensors manufactured by Kistler Instruments Ltd (Model: Kistler 9257A; Accuracy: ± 0.2% of reading; Data Acquisition Frequency: 1000 Hz) were employed to measure peak force, impact force, and average force in real time as participants performed various tasks [43,44]. This approach facilitated a detailed analysis of force variations and stability during both static and dynamic tasks [45,46]. Second, a high-precision motion capture system developed by Vicon Motion Systems Ltd (Model: Vicon Vero 2.2; Accuracy: ± 0.1 mm; Data Acquisition Frequency: 100 Hz) was used to record participants' movement trajectory parameters, including gait cycle time, stride length, and cadence[47]. This process is essential for understanding the movement behaviors and gait characteristics of older adults [48]. Additionally, a high-precision timer from Time Instruments Inc (Model: Stopwatch Pro Model 3000; Accuracy: ± 0.01 s) measured the duration of force exertion and the time taken by participants to complete tasks, thereby ensuring data accuracy [49]. A power meter from InBody Co., Ltd. (Model: T3 InBody Analyzer; Accuracy: ± 0.5% of reading; Data Acquisition Frequency: 50 Hz) was utilized to measure the power output and energy expenditure of participants during task execution, thereby assessing the efficiency and intensity of the exercises [50]. Additionally, the balance control ability of participants was evaluated using an AMTI platform (Model: AMTI OR6-7 Platform; Accuracy: ± 0.1% of reading; Data Acquisition Frequency: 100 Hz), which calculated stability indices to provide a comprehensive understanding of their balance capabilities [51]. During the experiment, all participants underwent standardized training prior to the study to ensure they were fully acquainted with the experimental procedures. The study was structured in two phases: in the static task phase, participants were required to maintain a standing position at a designated spot while the force sensors recorded various mechanical parameters for 60 s; in the dynamic task phase, participants walked along a predetermined path, with data collected using both the motion capture system and force sensors. The combination of these measurement tools provided comprehensive and detailed biomechanical data to evaluate the impact of Eight-Section Brocade on balance control in older adults.

2.5. Statistical analysis

Data analysis was conducted using SPSS statistical software (Version 25.0). Descriptive statistics and paired sample t-tests were employed to assess changes in balance ability, as measured by the Berg Balance Scale scores, between the experimental group and the control group. For mechanical measurements, ANOVA was utilized to compare the mechanical parameters of participants during both static standing and dynamic walking, allowing for the determination of significant differences between the two groups. A significance level of $p < 0.05$ was established, with a highly significant threshold set at $p < 0.01$. Data visualization was achieved using GraphPad Prism 8.0.1.

3. Results

3.1. Baseline data of participants

By comparing the baseline data of the EG and the CG, we assessed various parameters, including age (EG: 71.31 ± 3.22; CG: 69.08 ± 2.21), gender distribution (EG: 9 females [69.23%], 4 males [30.76%]; CG: 8 females [61.53%], 5 males [38.46%]), education level (EG: 4 elementary [30.8%], 5 middle school [38.5%], 4 high school [30.8%]; CG: 9 elementary [22.5%], 3 middle school [23.1%], 1 high school [7.7%]), fall history (EG: 3.69 ± 1.46; CG: 3.54 ± 1.33), health status (EG: 72.3 ± 5.8; CG: 71.9 ± 5.5), daily activity levels (EG: 3200 ± 150; CG: 3250 ± 130), and BMI (EG: 25.12 ± 2.68; CG: 24.10 ± 1.89). The assessment results indicated no statistically significant differences between the two groups ($P > 0.05$), confirming their comparability and ruling out any initial conditions that could affect the study outcomes. This allows for an accurate evaluation of the intervention effects (see **Table 1** for details).

Table 1. Baseline data.

Index		EG (N = 13)	CG (N = 13)	*P*
Age (year)		71.31 ± 3.22	69.08 ± 2.21	0.08
Gender (N,%)	Male	9/69.23	8/61.53	0.10
	Female	4/30.76	9/69.2	
Educational level (N,%)	Primary school	4/30.8	9/22.5	1.00
	Junior high school	5/38.5	3/23.1	
	High school	4/30.8	1/7.7	
Number of falls (within 3 months)		3.69 ± 1.46	3.54 ± 1.33	0.25
Health status		72.3 ± 5.8	71.9 ± 5.5	0.75
Daily activity levels(day)		3100 ± 150	3150 ± 130	0.78
BMI		25.12 ± 2.68	24.10 ± 1.89	0.56

3.2. Analysis of BBS results

The results presented in **Table 2** indicate that the experimental group outperformed the control group across all 14 assessment items. Specifically, in tasks such as “Sit to Stand” (EG: 3.77 ± 0.34; CG: 2.85 ± 0.37; BBS1), “Independent Standing” (EG: 3.78 ± 0.354; CG: 2.62 ± 0.49; BBS2), “Independent Sitting” (EG: 3.92 ± 0.27; CG: 2.85 ± 0.37; BBS3), “Stand to Sit” (EG: 4.08 ± 0.27; CG: 2.85 ± 0.37; BBS4), “Bed-Chair Transfer” (EG: 4.00 ± 0.10; CG: 2.84 ± 0.36; BBS5), “Eyes Closed Standing” (EG: 2.38 ± 0.50; CG: 2.00 ± 0.01; BBS6), “Feet Together Standing” (EG: 3.85 ± 0.39; CG: 2.54 ± 0.51; BBS7), “Forward Reaching in Standing” (EG: 3.85 ± 0.39; CG: 2.62 ±0.49; BBS8), “Picking Up an Object from the Floor” (EG: 3.69 ± 0.49; CG: 2.54 ± 0.50; BBS9), “Turning to Look Behind” (EG: 3.68 ± 0.47; CG: 2.54 ± 0.51; BBS10), “Turning Around” (EG: 3.88 ± 0.27; CG: 2.58 ± 0.56; BBS11), “Alternating Foot Stairs” (EG: 4.00 ± 0.02; CG: 2.69 ± 0.49; BBS12), “Feet Forward and Backward Standing” (EG: 3.77 ± 0.35; CG: 2.61 ± 0.31; BBS13), and “Single-Leg Standing” (EG: 3.38 ± 0.39; CG: 2.38 ± 0.50; BBS14), the experimental group’s mean scores were significantly higher than those of the control group ($P < 0.01$). These data suggest a remarkable improvement in balance and coordination abilities within the experimental group. Notably, in the “Eyes Closed Standing” (BBS6) task, the experimental group exhibited a slight advantage over the control group, achieving statistical significance ($P < 0.05$), which indicates a certain level of superiority in this specific task (**Figure 1**).

Table 2. Berg balance scale: Experimental group v. control group.

Item	Group	M ± SD (P^2)	*P*
BBS 1	EG	3.77 ± 0.34 (*)	0.01
	CG	2.85 ± 0.37	
BBS 2	EG	3.78 ± 0.35 (*)	
	CG	2.62 ± 0.49	
BBS 3	EG	3.92 ± 0.27 (*)	
	CG	2.85 ± 0.37	

Table 2. (*Continued*).

Item	**Group**	**M ± SD (P^2)**	***P***
BBS 4	EG	4.08 ± 0.27 (*)	0.01
	CG	2.85 ± 0.37	
BBS 5	EG	4.00 ± 0.10 (*)	
	CG	2.84 ± 0.36	
BBS 6	EG	2.38 ± 0.50	0.05
	CG	2.00 ± 0.01	
BBS 7	EG	3.85 ± 0.39 (*)	0.01
	CG	2.54 ± 0.51	
BBS 8	EG	3.85 ± 0.39 (*)	
	CG	2.62 ± 0.49	
BBS 9	EG	3.69 ± 0.49 (*)	
	CG	2.54 ± 0.50	
BBS 10	EG	3.68 ± 0.47 (*)	
	CG	2.54 ± 0.51	
BBS 11	EG	3.88 ± 0.27*	
	CG	2.58 ± 0.56	
BBS 12	EG	4.00 ± 0.02	
	CG	2.69 ± 0.49	
BBS 13	EG	3.77 ± 0.35*	
	CG	2.61 ± 0.31	
BBS 14	EG	3.38 ± 0.39*	
	CG	2.38 ±0.50	

Notes: [1] *P*-value: between-group difference; [2] *P*-value: within-group difference. [3] $P < 0.05$, *$P < 0.01$.

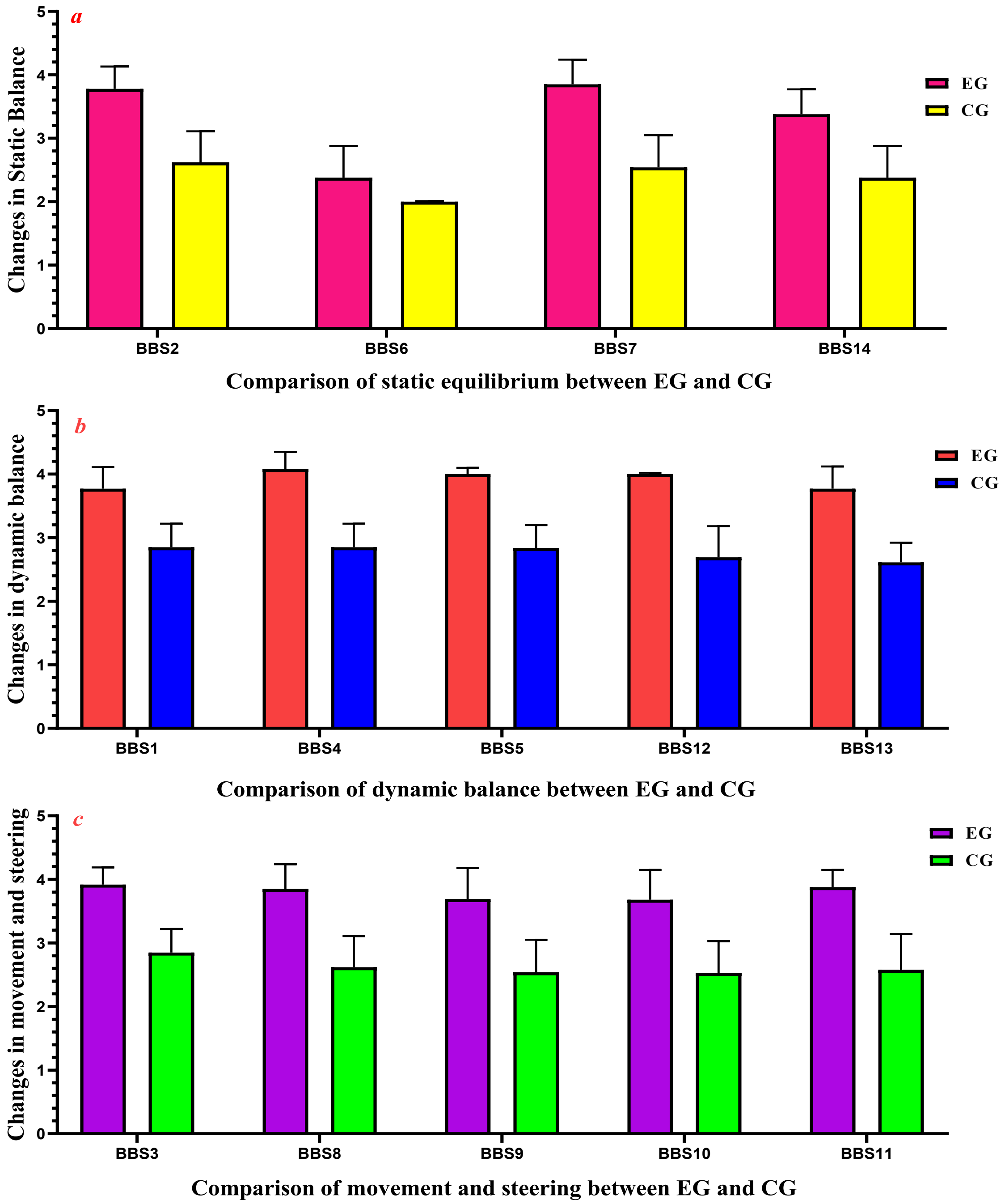

Figure 1. Changes in berg balance scale ratings: EG v. CG.

3.3. Analysis of FAP results

ANOVA analysis of the performance of both groups during static and dynamic tasks (**Table 3**) revealed significant differences across multiple biomechanical parameters ($p < 0.05$). Specifically, the results showed notable differences in the following metrics: stability index (EG: 0.7 ± 0.1/2.2 ± 0.4; CG: 0.6 ± 0.1/1.9 ± 0.3), power (EG: 3.2 ± 0.5/3.8 ± 0.6; CG: 2.9 ± 0.4/3.5 ± 0.5), energy expenditure (EG: 20.1 ± 3.8/25.0 ± 4.3; CG: 16.5 ± 3.2/20.3 ± 3.8), cadence (EG: 95.0 ± 5.5/105.0 ± 6.0; CG: 85.0 ± 5.0/100.0 ± 5.5), peak force (EG: 345.2 ± 30.1/412.6 ± 35.8; CG:

310.4 ± 28.5/310.4 ± 28.5), impact force (EG: 68.3 ± 7.2/85.7 ± 8.9; CG: 55.8± 6.7/72.4 ± 8.1), average force (EG: 280.5 ± 25.6/320.7 ± 30.2; CG: 245.3 ± 22.8/280.1 ± 26.4), force direction (EG: 10.0 ± 2.0/15.0 ± 2.5; CG: 8.5 ± 1.5/12.0 ± 2.0), rate of change (EG: 21.3 ± 3.4/34.2 ± 4.1; CG: 19.8 ± 3.0/30.5 ± 3.8), gait cycle time (EG: 45.2 ± 5.0/50.5 ± 6.0; CG: 40.0 ± 4.5/45.5 ± 5.5), stride length (EG: 0.5 ± 0.1/0.7 ± 0.1; CG: 0.4 ± 0.1/0.6 ± 0.1), and duration of static balance (EG: 3.2 ± 0.4; CG: 2.8 ± 0.3). Compared to the CG, Ba Duan Jin training demonstrated a significant effect in enhancing static balance control among older adults ($p < 0.05$).

In dynamic tasks, although the "duration" (EG: 2.5 ± 0.5; CG: 2.3 ± 0.4) did not show a statistically significant difference ($p > 0.05$), this finding aligns with expectations and reflects the complexity and adaptability of dynamic balance control. Factors such as gait, turning, and various movement styles may collectively influence the "duration." Compared to static balance, the intricacy and adaptability of dynamic balance may account for the relatively close performance levels between the experimental and control groups, resulting in no significant differences observed. Future research could further investigate the impact of varying intervention durations and methods on dynamic balance to achieve a deeper understanding. Nevertheless, the EG exhibited a significant increase in the rate of force change, indicating improved response speed and force control during dynamic tasks. Notably, the EG also demonstrated significant increases in stride length and cadence ($p < 0.05$), suggesting enhanced movement efficiency in dynamic tasks. The force direction parameter revealed that the EG displayed a more concentrated and effective distribution of force during dynamic activities. In summary, although no significant difference was found in duration, the EG showed marked improvements in response speed, force control, and movement efficiency during dynamic tasks (**Figure 2**).

Table 3. Comparison of mechanical parameters in static and dynamic tasks among elderly individuals aged 65–75.

Parameter	Task type	EG (M ± SD)	CG (M ± SD)	SMD	SE	P
Peak force (PF)	static state	345.2 ± 30.1	310.4 ± 28.5	24.8	6.7	0.002
	dynamic	412.6 ± 35.8	370.5 ± 32.7	42.1	7.3	0.001
Impact force (IF)	static state	68.3 ± 7.2	55.8 ± 6.7	12.5	3.0	0.001
	dynamic	85.7 ± 8.9	72.4 ± 8.1	13.3	3.2	0.003
Average force (AF)	static state	280.5 ± 25.6	245.3 ± 22.8	35.2	6.3	0.012
	dynamic	320.7 ± 30.2	280.1 ± 26.4	40.6	6.8	0.011
Duration (s)	static state	3.2 ± 0.4	2.8 ± 0.3	0.4	0.2	0.048
	dynamic	2.5 ± 0.5	2.3 ± 0.4	0.2	0.1	0.105
Change rate (N/s)	static state	21.3 ± 3.4	19.8 ± 3.0	1.5	0.8	0.035
	dynamic	34.2 ± 4.1	30.5 ± 3.8	3.7	0.9	0.009
Stability index	static state	0.7 ± 0.1	0.6 ± 0.1	0.2	0.1	0.038
	dynamic	2.2 ± 0.4	1.9 ± 0.3	0.3	0.1	0.021
Gait cycle time (s)	static state	45.2 ± 5.0	40.0 ± 4.5	5.2	0.9	0.014
	dynamic	50.5 ± 6.0	45.5 ± 5.5	5.0	1.0	0.019
Power (W)	static state	3.2 ± 0.5	2.9 ± 0.4	0.3	0.1	0.042
	dynamic	3.8 ± 0.6	3.5 ± 0.5	0.3	0.1	0.035

Table 3. (*Continued*).

Parameter	Task type	EG (M ± SD)	CG (M ± SD)	SMD	SE	P
Energy consumption (J)	static state	20.1 ± 3.8	16.5 ± 3.2	3.6	0.7	0.011
	dynamic	25.0 ± 4.3	20.3 ± 3.8	4.7	0.9	0.012
Step length (m)	static state	0.5 ± 0.1	0.4 ± 0.1	0.1	0.05	0.025
	dynamic	0.7 ± 0.1	0.6 ± 0.1	0.1	0.05	0.030
Step frequency (steps/min)	static state	95.0 ± 5.5	85.0 ± 5.0	10.0	1.5	0.022
	dynamic	105.0 ± 6.0	100.0 ± 5.5	5.0	1.0	0.040
Direction of force (degrees)	static state	10.0 ± 2.0	8.5 ± 1.5	1.5	0.5	0.040
	dynamic	15.0 ± 2.5	12.0 ± 2.0	3.0	0.6	0.035

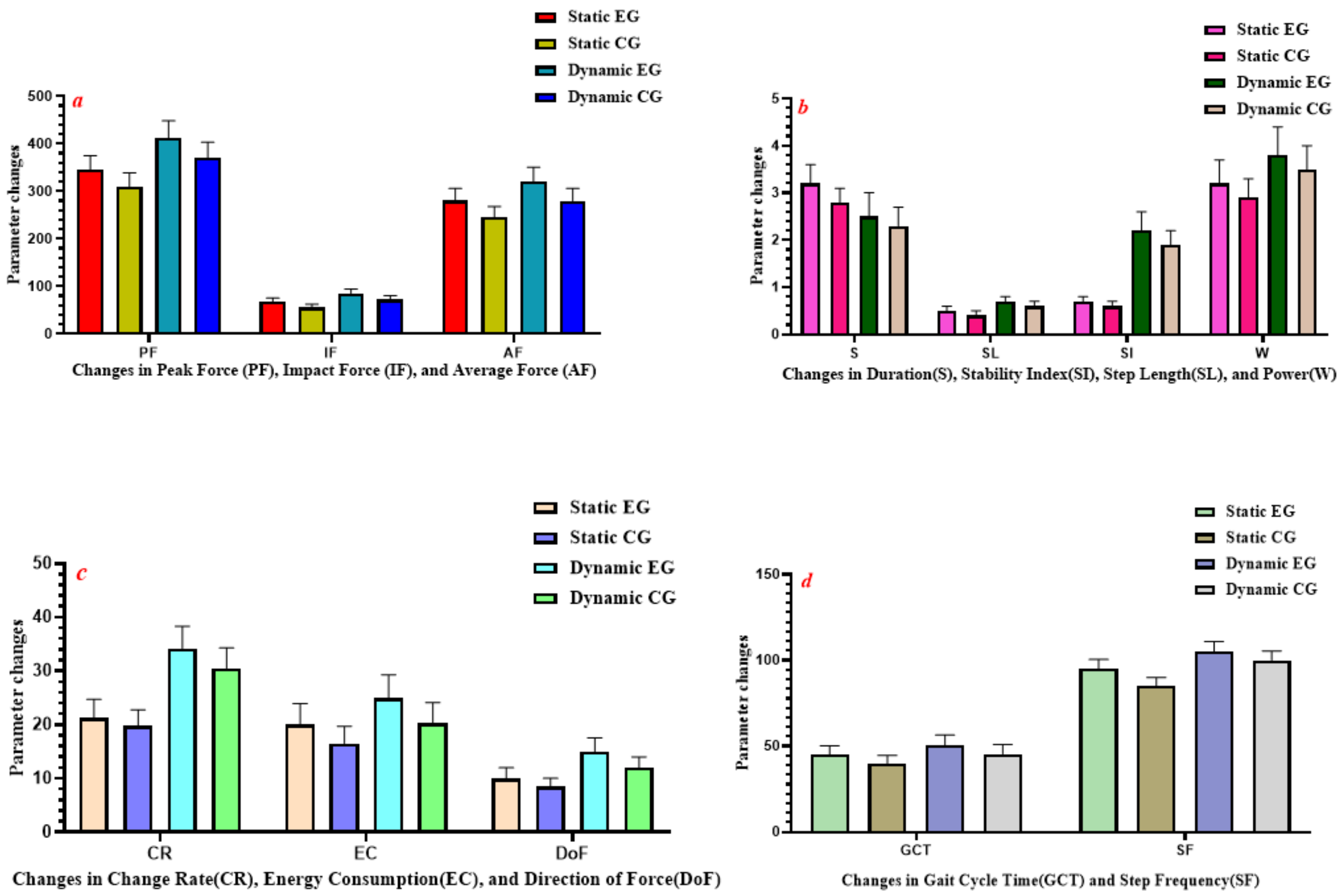

Figure 2. Static and dynamic changes in balance control of elderly people: EG v. CG.

4. Discussion

This study analyzed the biomechanical effects of Ba Duan Jin on balance control in older adults, integrating experimental results from both static and dynamic balance tasks to explore its specific mechanisms of action. As a traditional Chinese health exercise, Ba Duan Jin has been widely utilized to enhance balance capabilities among the elderly. Data analysis from the Berg Balance Scale and mechanical measurements provides biomechanical support for the role of Ba Duan Jin in improving balance control. The findings not only corroborate previous research but also offer new perspectives and deeper insights, thereby enriching our understanding of the effects of Ba Duan Jin.

Firstly, the EG exhibited significant improvements in balance control, indicating that long-term practice of Ba Duan Jin effectively enhances older adults' ability to maintain stability in various postures. This finding aligns with previous research on traditional exercises, such as Tai Chi and Qigong, which have shown that these practices significantly improve static balance by emphasizing control of the center of gravity, lower limb strength, and core stability [48–50]. The enhancement in static balance is primarily attributed to the slow and deliberate postural transitions characteristic of Ba Duan Jin, which require a high level of proprioceptive engagement and fine muscle control, thereby increasing participants' postural stability. This improvement not only enhances balance capabilities but also reduces the risk of falls, ultimately contributing to a better quality of life for older adults. Existing literature has also demonstrated that Ba Duan Jin training significantly increases scores on the Berg Balance Scale assessments, consistent with the outcomes of this study. Notably, improvements were observed in tasks such as standing with eyes closed, turning to look backward, and single-leg standing, reflecting an enhancement in balance control [51–54]. This not only improved balance abilities but also reduced the risk of falls, thereby enhancing the quality of life for older adults [55,56]. Previous studies have demonstrated that Ba Duan Jin training significantly increases scores on the BBS assessments [57], consistent with the findings of this study. Notable improvements were observed in tasks such as standing with eyes closed, turning to look backward, and single-leg standing, all of which reflect enhanced balance control. Moreover, Ba Duan Jin training directly reduces fall risk by enhancing vestibular function, improving proprioception, and optimizing neuromuscular control. Further quantitative analyses confirmed a significant negative correlation between scores on the eyes-closed standing task and fall risk. However, no significant differences were observed in the duration of dynamic balance tasks, suggesting new avenues for future research to explore potential mechanisms of improvement and long-term effects. It is noteworthy that our study differed from previous research in terms of training duration and biomechanical measurement methods. We implemented a longer training period (three months) and utilized more precise biomechanical measurement devices during data collection [53,54], thereby increasing the reliability and accuracy of our results. Furthermore, the randomized controlled trial (RCT) design of this study bolstered the scientific rigor and credibility of our findings, contrasting with earlier studies that primarily focused on theoretical explanations and lacked practical measurement indicators [55,56].

Furthermore, although the difference in duration for dynamic balance tasks between the two groups was not statistically significant, this may be attributed to the inherent complexity of dynamic balance. Dynamic balance relies not only on muscle strength and proprioception but also integrates vestibular function, visual feedback, and the central nervous system [57,58]. However, the significant improvement observed in the eyes-closed standing test among the experimental group offers further insights. The increase in scores for this task indicates that participants have enhanced their ability to rely on the vestibular system and proprioception in the absence of visual feedback [59]. This directly reflects the multidimensional impact of Ba Duan Jin on balance control.

Finally, biomechanical analysis indicates that repeated practice of Ba Duan Jin significantly enhances balance coordination and center of gravity transfer, improving the sensitivity and response speed of vestibular function. This allows older adults to maintain effective balance control even with reduced visual information. This further underscores the significant impact of Ba Duan Jin training on strengthening leg muscle power and enhancing dynamic stability in older adults [60,61]. Increased leg muscle strength is a key factor in fall prevention, while improved dynamic stability aids older individuals in maintaining better balance during daily activities, consistent with previous research findings. While Ba Duan Jin training has been shown to enhance muscle strength and balance in older adults, this study provides further validation of these effects through more detailed mechanical measurements, revealing that the impact of Ba Duan Jin on improving dynamic stability is particularly pronounced. This finding offers stronger scientific support for the practical application and promotion of Ba Duan Jin [62]. By integrating data from the Berg Balance Scale (BBS) and mechanical measurements, this study demonstrates that Ba Duan Jin training not only improves functional balance capabilities but also enhances biomechanical stability in older adults. These findings advocate for Ba Duan Jin as an effective exercise modality for preventing and intervening in fall risks among the elderly [63]. Although prior studies have indicated that Ba Duan Jin can improve balance in older adults, research on its underlying biomechanical mechanisms remains limited. This study combines BBS and mechanical measurement data to elucidate the comprehensive impact of Ba Duan Jin training on balance control in older adults, encompassing both functional and biomechanical dimensions. This discovery not only deepens our understanding of the effects of Ba Duan Jin but also provides new directions and foundations for future research and practical applications.

5. Conclusions and research limitations

The decline in balance control among older adults is closely associated with their quality of life, mobility, and risk of falls. As a traditional exercise method, Baduanjin is recognized for its gentle and progressive nature, which is believed to effectively enhance these capabilities. This study evaluates the impact of Baduanjin on balance control in older adults from a biomechanical perspective. The findings reveal significant changes in static and dynamic balance parameters, as assessed by the BBS and biomechanical measurements. For instance, movements such as "Two Hands to Tuotian Regulates Three Burners", "Left and Right Bow Like Archers." "shake the head and tail to go to the heart fire" "two hands to climb the feet to strengthen the kidney and waist" and "the back of the seven ups and downs" demonstrated marked differences in change rate, stability index, stride length, cadence, and force direction. This indicates that Baduanjin enhances vestibular function, proprioception, and muscle control in older adults, collectively contributing to improved balance ability and a reduced risk of falls, which aligns with the objectives of this study. This finding not only offers a non-pharmacological intervention method for balance control in older adults but also provides new insights for future research and practical applications.

However, this study has certain limitations. Firstly, the small sample size may affect the generalizability of the results, limiting their applicability to larger and more diverse older adult populations. Secondly, the focus on short-term biomechanical changes lacks a long-term follow-up assessment of effects. In light of these limitations, this study will continue to address these issues and aim for further optimization in future research, thereby enhancing the reliability and applicability of the findings, and ultimately promoting the well-being of older adults' physical and mental health.

Author contributions: Study conception and design, YC, YS and FW; data collection, YC, YS and FW; analysis and interpretation of results, YC, YS and FW; draft manuscript preparation, YC, YS and FW. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by Hebei Natural Science Foundation (H2023207002).

Availability of data and materials: We need to seek approval from the project approval unit. If the unit agrees, the author can provide data and materials.

Ethical approval: In accordance with the Declaration of Helsinki, 26 informed consent forms and 26 declarations of informed consent from family members were signed, and the study received approval from the Academic Ethics Committee of Hebei University of Economics and Business (Approval Number: HBJMDX20240706; Approval Date: 7 July 2024).

Conflict of interest: The authors declare no conflict of interest.

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