

Article

Clinical Effects of Auditory Feedback Gait Training Using a Smart Walker on Gait Ability, Gait Symmetry and Balance Confidence in Individuals with Stroke: A Randomized Controlled Trial

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Abstract

Individuals with stroke commonly exhibit impaired gait ability, gait asymmetry, and reduced balance confidence, which limit functional mobility and participation in daily activities. This study aimed to investigate the effects of auditory feedback gait training using a smart walker on gait ability, symmetry, and balance confidence in individuals with stroke. Forty individuals with stroke were randomly assigned to either an experimental group ($n = 20$) or a control group ($n = 20$). The experimental group performed gait training using a smart walker equipped with an auditory feedback system, whereas the control group used an identical walker with the feedback function disabled. Both groups trained for 40 min per session, 5 times a week for 4 weeks. Outcomes were measured using the 10 m walk test, Timed Up and Go test, Dynamic Gait Index, Activities-specific Balance Confidence scale, and gait symmetry indices. The experimental group showed significant improvements in the Timed Up and Go test and Dynamic Gait Index compared to the control group ($p < 0.05$). Notably, step length asymmetry and double support asymmetry significantly decreased in the experimental group ($p < 0.05$), indicating improved gait quality. Auditory feedback-based smart gait training can aid in gait recovery and balance improvement through real-time self-regulation and may provide a differentiated active rehabilitation strategy for individuals with stroke.

Keywords: stroke rehabilitation; auditory feedback; gait disorders; gait training



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1. Introduction

Post-stroke gait impairment is a critical factor limiting activities of daily living and social participation, extending far beyond a simple reduction in mobility [1]. The decline in gait function significantly increases the risk of falls, where repeated fall experiences lead to a fear of walking and diminished self-confidence. This psychological burden, in turn, reduces motivation for rehabilitation and hinders functional recovery [2]. Consequently, modern stroke rehabilitation must shift its focus toward qualitative recovery, emphasizing the achievement of safe, stable, and independent walking.

Conventional gait training has primarily targeted quantitative performance indicators, such as walking speed and distance [3]. While useful for evaluation, this approach often overlooks the underlying control mechanisms—specifically, how patients perceive and regulate their physical state and environmental changes during ambulation [4]. As a result,

gait instability is frequently attributed solely to physical deficits like muscle weakness, while the cognitive and control-related aspects of walking remain under-researched [5].

Gait disorders in individuals with stroke are characterized not only by physical impairments, such as asymmetrical weight bearing [6], but also by maladaptive and habitual movement strategies that often develop without the patient's conscious awareness [7]. This deep-seated asymmetry compromises gait efficiency and stability, further increasing the risk of falls [8]. Therefore, restoring gait symmetry requires intervention strategies that enable patients to recognize and actively correct their postural imbalances in real time.

Although walkers are widely used in clinical practice to provide external stability [9], they often limit a user's opportunity to recognize and modify inefficient gait patterns [10]. To transition patients from passive recipients of assistance to "active agents" of self-regulation, it is essential to integrate real-time feedback into these assistive devices [11]. Given that individuals with stroke often exhibit high visual dependency, which can lead to cognitive overload during complex tasks [12], auditory feedback serves as a more effective alternative by providing essential information without interfering with visual attention [13].

In addition to reducing visual attentional demands, auditory feedback may enhance motor learning by providing external cues that help individuals detect gait errors in real time and adjust their movements accordingly [14]. Through auditory–motor coupling, individuals with stroke may become more aware of asymmetrical gait patterns and actively correct them during walking, which can contribute to improvements in gait symmetry and postural control [15]. Moreover, auditory feedback may strengthen sensorimotor integration and facilitate the development of more efficient and coordinated movement strategies [16]. Despite this potential, clinical evidence regarding integrated feedback—which simultaneously addresses physical and environmental factors—remains limited [17].

Accordingly, this study aimed to analyze the effects of integrated auditory feedback using a smart walker on gait ability, gait symmetry, and balance confidence in individuals with stroke. By comparing training with and without auditory feedback on weight-bearing asymmetry and environmental obstacles, this study seeks to provide clinical evidence for functional rehabilitation strategies that facilitate a safe return to daily life through improved motor control.

2. Materials and Methods

2.1. Ethical Approval

This study was conducted in accordance with the ethical principles of the Declaration of Helsinki and was approved by the Institutional Review Board (IRB) of Korea National University of Transportation (Approval No.: KNUT-2025-HR-33-53) on 23 December 2025. The study was also pre-registered with the Clinical Research Information Service (CRIS) (Registration No.: KCT0011380) on 26 December 2025. All participants provided written informed consent prior to participation after receiving a full explanation of the study purpose, procedures, and data confidentiality. The study was conducted and reported in accordance with CONSORT guidelines.

2.2. Subjects

This study was conducted in patients diagnosed with stroke who were receiving inpatient rehabilitation at S Nursing Hospital in Osan-si, Gyeonggi-do. Participants were recruited from patients who provided voluntary informed consent after receiving a full explanation of the study purpose and procedures.

The inclusion and exclusion criteria were as follows:

(1) Inclusion Criteria

- Adults aged ≥ 18 years who were at least 6 months post-stroke.

- Individuals able to understand and respond to feedback, with a score of ≥ 24 on the Korean version of the Mini-Mental State Examination (MMSE-K).
 - Individuals able to walk with a walker under therapist supervision (Functional Ambulation Category [FAC] ≥ 3).
 - Individuals with a score of ≥ 2 in the “Grip” item of the Manual Function Test (MFT).
 - Individuals with muscle tone of $\leq$ Grade 1 in the elbow flexors on the Modified Ashworth Scale (MAS).
 - Individuals without hearing impairment.
 - Individuals without significant visual field deficits affecting forward vision (corrected vision permitted).
 - Individuals without apraxia.
 - Individuals without a history of neurological diseases other than stroke.
- (2) Exclusion Criteria
- Individuals with a history of motor neuron diseases or psychiatric disorders.
 - Individuals with hemineglect.
 - Individuals scoring ≤ 3 on the “standing without support” item of the Berg Balance Scale (BBS).
 - Individuals who report persistent dizziness.

2.3. Research Procedure

This study was conducted as a randomized controlled trial to compare the effects of gait training based on the provision of integrated auditory feedback. A total of 40 participants were randomly allocated to either the experimental group or the control group ($n = 20$ per group) using a computer-generated randomization sequence. To minimize potential allocation bias, group assignment was conducted by an independent third party.

The sample size was calculated using G*Power version 3.1 (Heinrich Heine University Düsseldorf, Düsseldorf, Germany). An independent t -test was selected to compare changes between the two groups. Based on the findings of Kim et al. [18], an effect size (Cohen’s d) of 0.92 was assumed. With a significance level of $\alpha = 0.05$ and a statistical power of 0.80, the required sample size was estimated to be 20 participants per group (total $n = 40$). Considering an anticipated dropout rate of approximately 10%, a total of 44 participants were initially recruited. During the study period, three participants were discharged from the hospital and one participant withdrew consent, resulting in a final sample of 40 participants who completed the study.

All participants underwent pre-intervention assessments prior to the intervention, followed by a 4-week training program. Post-intervention assessments were conducted using the same outcome measures and in the same order as the pre-intervention assessments. All assessments were performed by evaluators who were blinded to group allocation.

During both pre- and post-intervention assessments, participants were evaluated under identical testing conditions. The auditory feedback function of the smart walker was disabled during all outcome measurements to ensure that the assessment reflected retained training effects rather than immediate assistance from the feedback system.

To ensure accurate perception of auditory feedback and minimize external distractions, all interventions were performed in an environment controlled by indoor noise levels of 30–50 dB, referencing Fidêncio et al. [19]. The participant flow throughout the study is presented in Figure 1.

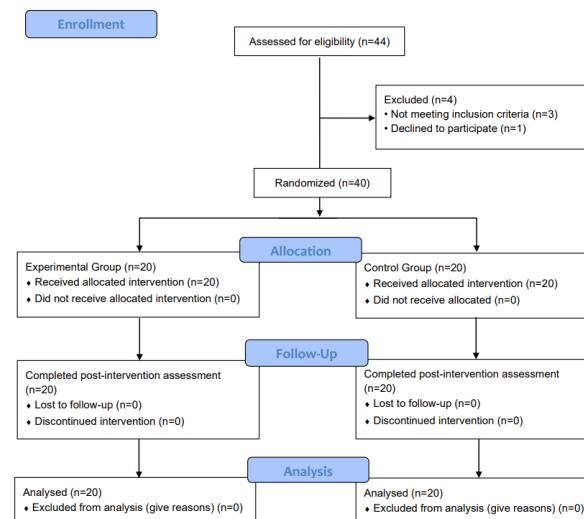


Figure 1. CONSORT flow diagram of participant recruitment, allocation, follow-up, and analysis.

2.4. Auditory Feedback Smart Walker System

The smart walker used in this study was developed to provide real-time auditory feedback by detecting weight-bearing asymmetry and frontal environmental conditions during gait. The system was equipped with load sensors mounted beneath both armrests to continuously monitor upper-limb weight-bearing during walking, while an ultrasonic distance sensor mounted at the front of the walker was used to detect frontal obstacles. Sensor signals were sampled at 50 Hz. Prior to data collection, all sensors were calibrated using known reference weights and zero-offset correction procedures to ensure measurement consistency.

Weight-bearing asymmetry was quantified as the difference in load between the left and right sides measured through the armrest-mounted sensors. The system was programmed to detect asymmetry when the difference exceeded a predefined threshold. In this study, the threshold for detecting asymmetrical weight bearing during gait was defined based on a relative load difference normalized to body weight. Weight-bearing asymmetry was calculated using the following equation:

$$\text{Asymmetry (\%BW)} = \frac{L - R}{BW} \times 100$$

Because no established criterion exists for upper-limb weight-bearing asymmetry during walker-assisted gait in individuals with stroke, a theoretical reference value was derived using a biomechanical moment equilibrium model. Normal mediolateral center of mass (COM) displacement during gait was assumed to be 2.5 cm (within the reported physiological range of 2–4 cm) based on previous studies [20–23], and the distance between walker armrests was set at 0.5 m. Upper-limb loading during walker-assisted gait has been reported to correspond to approximately 20% of body weight based on previous studies involving postoperative walker use [24]. Because quantitative data on upper-limb weight-bearing during walker-assisted gait in individuals with stroke are currently unavailable, this value was adopted as a pragmatic design parameter for biomechanical estimation rather than a stroke-specific reference.

Substituting these values into the moment equilibrium equation yielded an estimated left–right upper-limb loading difference of approximately 2% of body weight during normal gait. This value represents the predicted asymmetry associated with physiological mediolateral COM movement during walking and was therefore used as a theoretical reference for establishing the feedback threshold.

Individuals with stroke generally exhibit greater gait variability and increased reliance on upper-limb support during walker-assisted gait than healthy individuals. Therefore, rather than directly applying the theoretical value of 2% BW, the feedback threshold was pragmatically set at 3% body weight, taking these clinical characteristics into consideration. This 3% value was selected as a pragmatic feedback trigger rather than a pathological cutoff.

For implementation in the feedback system, the individualized threshold value was converted into an absolute load difference (kg) according to each participant's body weight. Raw load-cell data were used for threshold detection without additional smoothing or noise-reduction filtering. When the weight-bearing asymmetry exceeded the individualized threshold and persisted for more than 1 s, auditory feedback was delivered. Although no additional digital filtering was applied, the 1 s persistence criterion was used to minimize false feedback caused by transient sensor fluctuations. The feedback delay was programmed to approximately 1 s, although minor variations associated with microcontroller processing time may have occurred during operation. A prerecorded female voice message was used for all auditory feedback, consisting of the phrases "It tilted to the left" and "It tilted to the right." The feedback was provided intermittently and repeated at 2 s intervals if the asymmetry condition continued. The intensity of all auditory feedback was standardized to approximately 60–70 dB to ensure clear perception by the participants.

Frontal obstacle detection was achieved using the ultrasonic distance sensor mounted approximately 50 cm above the front of the walker. When an obstacle was detected within a distance of approximately 1 m, auditory feedback stating "An obstacle has been detected ahead" was provided.

2.5. Intervention Method

The experimental group performed gait training using a smart walker equipped with an auditory feedback system, whereas the control group used an identical walker with the feedback function disabled. All interventions were conducted five times per week for four weeks, with each session lasting 40 min. Training was safely carried out under the one-on-one supervision of a physical therapist.

The training was structured into obstacle-free and obstacle-laden environments, and the composition of sets and the increase in difficulty were gradually adjusted weekly.

Each session began with participants seated in a chair with armrests for safety. Upon the therapist's instruction, participants stood up and initiated gait training using the smart walker. The experimental group was instructed to use the auditory feedback provided during walking to recognize and regulate their gait patterns.

Each session included 15 min of straight-line walking in an obstacle-free environment and 15 min of walking in an obstacle-present environment, with a 10 min rest period between sets.

Participants were instructed to walk at a self-selected comfortable speed while maintaining safety and task completion within the allocated session time. The walking protocol was based on the low walking speed of individuals with stroke (approximately 0.20 m/s), as reported by Hosoi et al. [25]. The reference speed of 0.20 m/s was used solely to estimate minimum task duration and structure the training volume, rather than to constrain walking speed during training.

At this speed, walking 10 m takes about 50 s; based on this, one set was composed of a total of 20 m of walking task, consisting of a round trip over a 10 m straight path in an obstacle-free environment.

To adjust the intensity of the obstacle-free walking training, the number of sets was progressively increased. It consisted of 4 sets in Week 1, 5 sets in Weeks 2–3, and 6 sets in

Week 4. All sets were timed using a stopwatch, and participants completed the planned sets within 15 min during each session.

For obstacle walking training, the protocol described by Lee [26] was adapted for the present study. Obstacles were arranged along a 10 m straight path, and participants were instructed to avoid stepping on or over them.

Obstacle characteristics were progressively modified to increase task difficulty. During Weeks 1–2, three obstacles (60 × 60 × 20 cm) were used. In Week 3, four obstacles (50 × 50 × 15 cm) were introduced, and in Week 4, five obstacles (40 × 40 × 10 cm) were used. The spacing between obstacles was consistently maintained at approximately 80 cm, which corresponds to the minimum width required for walker passage.

Prior to the intervention, participants received standardized instructions regarding the meaning of each auditory cue and completed a brief familiarization session with the smart walker system. Because all participants met the inclusion criterion of MMSE-K ≥ 24 and the auditory feedback consisted of simple voice messages, no apparent difficulties in understanding the feedback were observed during training.

To minimize co-intervention bias, supervising therapists followed a standardized protocol and provided only safety-related verbal instructions and physical assistance when necessary. No additional feedback regarding gait symmetry, weight shifting, or task performance was provided during the intervention sessions.

2.6. Outcome Measure

2.6.1. Timed up and Go Test (TUG)

The Timed Up and Go test (TUG) was used to evaluate dynamic balance and functional gait ability. The TUG is a test that measures the time required to stand up from a seated position, walk 3 m, turn, return, and sit down; the time was recorded in seconds (sec) [27]. If a walking aid is used in daily life, its use is permitted during the evaluation, and the test was performed without assistance from others. The intra-rater reliability of the TUG is ICC = 0.97, and the inter-rater reliability is ICC = 0.96. In this study, the test was repeated three times, and the average of each measurement was used for analysis [28].

2.6.2. GAITRite® Gait System

An electronic gait analysis system (GAITRite®, CIR Systems Inc., Franklin, NJ, USA) was used to objectively assess spatiotemporal gait parameters. The system consists of a pressure-sensitive walkway that automatically records foot contact data as participants walk across the mat, and these data are processed into spatiotemporal variables using dedicated software [29].

To ensure steady-state walking, participants were instructed to begin walking approximately 2 m before reaching the measurement mat. The walkway was approximately 4.8 m in length, with an active sensing area of 3.6 m, allowing accurate capture of foot contact during gait.

The primary gait asymmetry variables analyzed in this study were step length asymmetry, step time asymmetry, and double support asymmetry. Each asymmetry index was calculated as the difference between paretic and non-paretic values divided by their sum and expressed as a percentage. Values closer to 0 indicated greater gait symmetry [30]. The theoretical reference value was calculated as follows:

$$\frac{\Delta F}{W} = 0.2 \times \frac{2 \times 0.025}{0.5} = 0.02$$

The GAITRite® system has demonstrated high reliability, with inter-rater reliability reported as ICC = 0.92 and intra-rater reliability ranging from ICC = 0.77 to 0.90, depending on the variable [31]. The gait asymmetry index was calculated as follows:

$$\text{Gait asymmetry index} = \frac{\text{Non-paretic side parameter} - \text{Paretic side parameter}}{\text{Non-paretic side parameter} + \text{Paretic side parameter}} \times 100$$

2.6.3. Dynamic Gait Index (DGI)

The Dynamic Gait Index (DGI) was used to assess dynamic gait ability. The DGI is an eight-item clinical measure designed to evaluate functional gait under various task demands, including changes in speed, head movements, turning, and obstacle negotiation.

The items include walking on a level surface, changing walking speed, walking with horizontal and vertical head turns, walking with a 180° turn, stepping over and around obstacles, and stair negotiation. Each item is scored on a 4-point scale (0–3), yielding a total score ranging from 0 to 24, with lower scores indicating greater impairment in functional mobility [32].

The DGI has demonstrated excellent reliability, with intra-rater and inter-rater reliability both reported as ICC = 0.96 [33].

2.6.4. 10Meter Walking Test (10MWT)

The 10Meter Walking Test (10MWT) was administered to assess walking speed during short-distance ambulation. Participants were asked to walk on a 14 m pathway at their preferred walking pace, using their regular assistive devices when necessary. To reduce the influence of acceleration and deceleration, only the time required to traverse the central 10 m segment was recorded, while the initial and final 2 m were excluded from measurement [34]. The assessment was repeated three times, and the mean of the three trials was used for statistical analysis. Walking time was recorded in seconds. The 10MWT has been reported to demonstrate excellent intra-rater reliability in individuals with stroke (ICC = 0.95–0.99) [35].

2.6.5. Activities-Specific Balance Confidence Scale (ABC Scale)

The Korean version of the Activities-Specific Balance Confidence Scale (ABC Scale) was used to assess balance confidence during daily activities. The ABC Scale is a self-administered questionnaire developed by Powell & Myers [36] to evaluate balance self-efficacy in older adults.

The scale consists of 16 items representing functional activities of varying difficulty, such as reaching, stair negotiation, indoor and outdoor walking, and walking on ramps or in crowded environments. Each item is rated from 0% (no confidence) to 100% (complete confidence), and the overall score is calculated as the mean of all items, with higher scores indicating greater balance confidence.

In this study, a Korean-adapted version of the ABC Scale was used. The intra-rater reliability of the Korean version has been reported as ICC = 0.96 [37].

2.7. Data Processing and Analysis

All data processing for this study was performed using SPSS 23.0 for Windows (SPSS Inc., Chicago, IL, USA).

The homogeneity of baseline characteristics between the Experimental Group (EG) and the Control Group (CG) was assessed using the chi-square test and the independent *t*-test. Normality of the change scores was evaluated using the Shapiro–Wilk test. For normally distributed variables, paired *t*-tests were used to compare pre- and post-intervention values within each group (EG and CG), and independent *t*-tests were applied to compare between-group differences in change scores. For non-normally distributed variables, the Wilcoxon

signed-rank test was used for within-group comparisons, and the Mann–Whitney U test was employed for between-group comparisons. All statistical significance levels were set at $\alpha = 0.05$.

3. Results

3.1. General Characteristics of Study Participants

No significant between-group differences were observed in baseline characteristics, including age, sex, time since onset, diagnosis type, paretic side, height, weight, and MMSE-K scores (Table 1). The groups were therefore considered comparable at baseline.

Table 1. General characteristics of the subjects ($N = 40$).

Variable	EG ^a ($n = 20$)	CG ^b ($n = 20$)	p
Age (year)	62.30 (12.32)	63.30 (9.85)	0.778
Gender (Male/Female)	8/12	10/10	0.376
Onset (months)	24.70 (8.65)	24.35 (8.39)	0.897
Diagnosis (Infarction/Hemorrhage)	17/3	16/4	0.500
Affected side (Left/Right)	9/11	13/7	0.170
Height (cm)	163.85 (8.67)	164.35 (9.37)	0.862
Weight (kg)	61.25 (9.17)	60.35 (8.53)	0.972
MMSE-K ^c (score)	25.45 (1.60)	26.40 (1.53)	0.920

a. EG: Experimental group, b. CG: Control group, c. MMSE-K: Korean Mini-Mental State Examination.

3.2. Shapiro–Wilk Normality Tests for Change Scores

The normality of the change scores was assessed using the Shapiro–Wilk test (Table 2). The ABC scale, SLA, and STA satisfied the normality assumption and were therefore analyzed using parametric methods. In contrast, TUG, 10MWT, DGI, and DSA violated the normality assumption and were analyzed using non-parametric methods.

Table 2. Results of the Shapiro–Wilk normality tests for change scores.

Variable	EG ^a p -Value	CG ^b p -Value
TUG ^c	0.340	0.006
10MWT ^d	0.004	0.021
DGI ^e	0.003	0.005
ABC scale ^f	0.443	0.570
SLA ^g	0.977	0.679
STA ^h	0.576	0.367
DSA ⁱ	0.027	0.696

a. EG: Experimental group, b. CG: Control group, c. TUG: Timed Up and Go test, d. 10MWT: 10 Meter Walk Test, e. DGI: Dynamic Gait Index, f. ABC scale: Activities-specific Balance Confidence scale, g. SLA: Step Length Asymmetry, h. STA: Step Time Asymmetry, i. DSA: Double Support Asymmetry.

3.3. Timed up and Go Test (TUG)

The experimental group demonstrated a significantly greater reduction in TUG time compared with the control group, with a between-group difference in change scores of 2.85 s (95% CI: 1.92 to 3.78) (Table 3).

Table 3. Comparison of the Timed Up and Go test before and after intervention ($N = 40$).

TUG ^c (Sec)	EG ^a ($n = 20$)		CG ^b ($n = 20$)		Z	p	d	Between-Group Difference (95% CI)
	Mean (SD)	95% CI	Mean (SD)	95% CI				
Pre	23.10 (3.91)	21.27 to 24.93	25.20 (3.00)	23.80 to 26.60	−1.902	0.065		
Post	16.55 (3.77)	14.79 to 18.31	21.50 (3.36)	19.93 to 23.07				

Table 3. Cont.

	EG ^a (n = 20)		CG ^b (n = 20)					
TUG ^c (Sec)	Mean (SD)	95% CI	Mean (SD)	95% CI	Z	p	d	Between-Group Difference (95% CI)
Difference value	6.55 (1.70)	5.75 to 7.35	3.70 (1.26)	3.11 to 4.29	−4.643	0.001 ***	1.91	2.85 (1.92 to 3.78)
Z	−3.934		−3.955					
p	0.001 ***		0.001 ***					

*** $p < 0.001$, a. EG: Experimental group, b. CG: Control group, c. TUG: Timed Up and Go test.

3.4. 10Meter Walking Test (10MWT)

The experimental group demonstrated a greater reduction in 10MWT time compared with the control group, but this difference was not statistically significant, with a between-group difference in change scores of 1.20 s (95% CI: −0.31 to 2.71) (Table 4).

Table 4. Comparison of the 10Meter Walking Test before and after intervention (N = 40).

	EG ^a (n = 20)		CG ^b (n = 20)					
10MWT ^c (Sec)	Mean (SD)	95% CI	Mean (SD)	95% CI	Z	p	d	Between-Group Difference (95% CI)
Pre	17.45 (2.58)	16.24 to 18.66	17.40 (1.93)	16.50 to 18.30	0.069	0.945		
Post	13.75 (1.97)	12.83 to 14.67	14.90 (1.55)	14.18 to 15.63				
Difference value	3.70 (2.47)	2.54 to 4.86	2.50 (2.25)	1.45 to 3.55	−1.769	0.081	0.51	1.20 (−0.31 to 2.71)
Z	−3.937		−3.531					
p	0.001 ***		0.001 ***					

*** $p < 0.001$, a. EG: Experimental group, b. CG: Control group, c. 10MWT: 10Meter Walking Test.

3.5. Dynamic Gait Index (DGI)

The experimental group showed greater improvement in DGI scores than the control group. A statistically significant between-group difference in change scores was observed, with a mean difference of 1.55 points (95% CI: 0.49–2.61) (Table 5).

Table 5. Comparison of the Dynamic Gait Index before and after intervention (N = 40).

	EG ^a (n = 20)		CG ^b (n = 20)					
DGI ^c (Score)	Mean (SD)	95% CI	Mean (SD)	95% CI	Z	p	d	Between-Group Difference (95% CI)
Pre	15.05 (2.68)	13.80 to 16.30	15.40 (1.95)	14.49 to 16.31	−0.471	0.640		
Post	17.15 (2.53)	15.97 to 18.33	15.95 (1.76)	15.13 to 16.77				
Difference value	2.10 (2.07)	1.13 to 3.07	0.55 (1.09)	0.04 to 1.06	−3.451	0.001 ***	0.94	1.55 (0.49 to 2.61)
Z	−3.061		−2.031					
p	0.002 ***		0.049 *					

* $p < 0.05$, *** $p < 0.001$, a. EG: Experimental group, b. CG: Control group, c. DGI: Dynamic Gait Index.

3.6. Activities-Specific Balance Confidence Scale (ABC Scale)

The experimental group demonstrated a greater increase in ABC scale score compared with the control group, but this difference was not statistically significant, with a between-group difference in change scores of 0.30 points (95% CI: −5.49 to 6.09) (Table 6).

Table 6. Comparison of the Activities-specific Balance Confidence Scale before and after intervention ($N = 40$).

ABC Scale ^c (Score)	EG ^a ($n = 20$)		CG ^b ($n = 20$)		t	p	d	Between-Group Difference (95% CI)
	Mean (SD)	95% CI	Mean (SD)	95% CI				
Pre	54.25 (13.05)	48.14 to 60.36	55.90 (5.65)	53.26 to 58.54	−0.519	0.607		
Post	65.70 (14.42)	58.95 to 72.45	66.15 (5.69)	53.49 to 68.81				
Difference value	11.45 (12.09)	5.79 to 17.11	11.15 (4.12)	9.22 to 13.08	0.11	0.091	0.03	0.30 (−5.49 to 6.09)
t	−4.234		−7.511					
p	0.001 ***		0.001 ***					

*** $p < 0.001$, a. EG: Experimental group, b. CG: Control group, c. ABC Scale: Activities-specific Balance Confidence Scale.

3.7. Gait Asymmetry

3.7.1. Step Length Asymmetry (SLA)

The experimental group demonstrated a greater reduction in SLA compared with the control group, and this difference was statistically significant, with a between-group difference in change scores of 7.77% (95% CI: 1.86 to 13.68) (Table 7).

Table 7. Comparison of gait asymmetry measured by the GAITRite system (version 4.0, CIR Systems Inc., Franklin, NJ, USA) before and after intervention ($N = 40$).

EG ^a (<i>n</i> = 20)			CG ^b (<i>n</i> = 20)					
	Mean (SD)	95% CI	Mean (SD)	95% CI	t/Z	<i>p</i>	d	Between-Group Differences (95% CI)
SLA ^c (%)								
Pre	18.72 (10.40)	13.85 to 23.59	14.78 (9.00)	10.57 to 18.99	−0.519(t)	0.607		
Post	9.54 (9.43)	5.13 to 13.95	13.38 (10.23)	8.59 to 18.17				
Difference value	9.18 (10.95)	4.06 to 14.30	1.41 (7.08)	−1.90 to 4.72	2.441(t)	0.019 *	0.03	7.77 (1.86 to 13.68)
t	3.749		0.885					
<i>p</i>	0.001 ***		0.387					
STA ^d (%)								
Pre	13.82 (12.95)	7.76 to 19.88	21.22 (15.29)	14.06 to 28.38	−1.652(t)	0.107		
Post	22.85 (13.20)	16.68 to 29.02	23.76 (21.11)	13.88 to 33.64				
Difference Value	9.03 (19.21)	0.04 to 18.02	2.54 (17.96)	−5.87 to 10.95	−1.103(t)	0.277	0.35	6.49 (−5.41 to 18.39)
T	−2.102		−0.633					
<i>P</i>	0.049 *		0.652					
DSA ^e (%)								
Pre	9.64 (7.43)	6.16 to 13.12	7.35 (8.91)	3.18 to 11.52	−1.731(Z)	0.086		
Post	2.98 (2.35)	1.88 to 4.08	7.74 (5.45)	5.19 to 10.29				
Difference value	6.66 (6.36)	3.68 to 9.64	0.39 (8.84)	−3.75 to 4.53	−2.840(Z)	0.004 *	0.81	6.27 (1.35 to 11.19)
Z	−3.696		−2.61					
<i>p</i>	0.001 ***		0.794					

* $p < 0.05$, *** $p < 0.001$, a. EG: Experimental group, b. CG: Control group, c. SLA: step length asymmetry, d. STA: step time asymmetry, e. DSA: double support asymmetry.

3.7.2. Step Time Asymmetry (STA)

The experimental group showed greater improvement in STA than the control group. However, no statistically significant between-group difference in change scores was observed, with a mean difference of 6.49% (95% CI: −5.41 to 18.39) (Table 7).

3.7.3. Double Support Asymmetry (DSA)

The experimental group showed a greater reduction in DSA than the control group. A statistically significant between-group difference in change scores was observed, with a mean difference of 6.27% (95% CI: 1.35 to 11.19) (Table 7).

4. Discussion

The purpose of this study was to examine the impact of smart walker-assisted gait training combined with auditory feedback on gait ability, gait symmetry and balance confidence in individuals with stroke. After the intervention period, significant improvements in gait-related measures were observed in both groups.

This may be attributed to the repetitive gait practice enabled by the stable support base provided by the walker [9]. However, the greater improvements observed in the experimental group across several key outcomes suggest that auditory feedback provided additional therapeutic benefits beyond repetitive training alone. To determine whether these improvements exceeded measurement error, the magnitude of change was compared with previously reported minimal detectable change (MDC) values. For the Timed Up and Go test in individuals with chronic stroke, the MDC has been reported to be approximately 3.2 s [38]. The mean improvement observed in the experimental group exceeded this threshold, suggesting that the change likely reflects a true functional improvement rather than measurement variability.

The significant improvement observed in the Timed Up and Go (TUG) test indicates enhanced functional mobility, including movements such as sit-to-stand, turning, and walking. These improvements reflect more stable weight shifting and postural transitions during functional tasks. Notably, the greater improvement in the experimental group implies that auditory feedback may have facilitated more active movement control rather than passive task repetition [39].

Similarly, the Dynamic Gait Index (DGI) showed significantly greater improvement in the experimental group, indicating enhanced adaptability of gait under complex task conditions. The DGI includes tasks such as speed changes, head movements, and obstacle negotiation, which require continuous interaction between the individual and the environment [40]. The provision of auditory feedback regarding armrest-load asymmetry and forward obstacles may have increased participants' awareness of gait performance and environmental demands during walking [41]. These findings are consistent with the view that gait is a functional task requiring continuous interaction with the environment rather than a simple repetitive movement [42].

In contrast, no significant between-group difference was observed in the 10Meter Walking Test (10MWT). This may be explained by the intervention primarily influencing qualitative aspects of gait rather than walking speed. Since walking speed is affected by multiple factors including muscle strength, endurance, and neuromuscular capacity, a longer intervention duration may be required to detect significant differences between groups [3].

Analysis of gait symmetry revealed variable-specific responses. Step length asymmetry (SLA) and double support asymmetry (DSA) significantly decreased in the experimental group, with greater improvements compared to the control group. These findings may suggest that auditory feedback facilitated correction of armrest-load asymmetry

during walking [8]. Rather than reflecting a simple increase in step length, these changes may indicate improved interlimb coordination and a reorganization of gait control [43]. However, these mechanisms remain hypothetical because kinematic variables were not directly measured.

In particular, the improvement in step length asymmetry may reflect improved spatial coordination between the lower limbs during walking. Similarly, the reduction in double support asymmetry may indicate improved temporal symmetry during the gait cycle.

In contrast, step time asymmetry (STA) showed an increase in the experimental group without a significant between-group difference. As participants attempted to improve spatial symmetry and postural control, temporal parameters may have been temporarily disrupted [44]. Increased neuromuscular demand associated with adapting to a new gait strategy may have contributed to transient increases in temporal asymmetry [45].

Furthermore, auditory feedback may have induced an external focus of attention, which has been shown to facilitate motor learning and improve movement efficiency [12]. Unlike conventional gait training that emphasizes internal focus on limb movement, this intervention encouraged participants to regulate gait based on externally provided cues.

Beyond statistical significance, the clinical relevance of the observed improvements warrants careful consideration. In the present study, the experimental group demonstrated greater reductions in TUG time and greater improvements in DGI scores compared with the control group, with between-group differences supported by 95% confidence intervals that did not cross zero. These findings strengthen the robustness of the intervention effect beyond *p*-value interpretation alone. The magnitude of the observed effect sizes provides additional insight into the clinical relevance of the intervention. According to Cohen's conventional criteria, the between-group effect sizes for TUG ($d = 1.91$), DGI ($d = 0.94$), and DSA ($d = 0.81$) can be interpreted as large effects. These findings suggest that the benefits of auditory feedback training were not only statistically significant but also potentially clinically meaningful. In particular, the large effect observed for TUG indicates meaningful improvements in functional mobility tasks commonly encountered in daily life, including standing up, turning, and walking. Similarly, the large effects observed for DGI and DSA suggest improved adaptability during walking and enhanced gait symmetry, both of which are important clinical factors associated with walking performance and mobility after stroke. To further evaluate whether the observed changes exceeded measurement error, the magnitude of improvement was interpreted in light of previously reported minimal detectable change (MDC) values for individuals with stroke. The mean reduction in TUG time observed in the experimental group exceeded commonly reported MDC95 thresholds, suggesting that the improvement likely reflects a true functional change rather than measurement variability.

In addition, minimal clinically important difference (MCID) values reported for gait-related outcomes indicate the degree of change perceived as meaningful in clinical practice. The magnitude of improvement observed in the experimental group approached or exceeded established MCID ranges for gait performance, supporting the potential clinical importance of the intervention.

Nevertheless, it should be acknowledged that MDC and MCID thresholds may vary depending on stroke chronicity, baseline functional level, and assessment protocols. Furthermore, established MCID values are not available for all outcome measures included in this study. Therefore, while the present findings support both statistical and potential clinical significance, the interpretation of clinical meaningfulness should be made with appropriate caution. Future research should continue to report between-group 95% confidence intervals and incorporate outcome-specific MDC and MCID benchmarks to enhance the interpretability and translational value of rehabilitation trials.

In summary, auditory feedback-based smart walker training improved gait symmetry and functional gait performance in individuals with stroke. The intervention showed clinically meaningful improvements in functional mobility and gait symmetry. However, because kinematic variables were not directly measured, the mechanisms underlying these improvements remain hypothetical and should be confirmed in future studies.

Limitations and Future Research

This study has several limitations that should be considered when interpreting the present findings. First, the sample size was relatively small and the intervention period was limited to four weeks, restricting conclusions regarding long-term retention and neuroplastic adaptation. Second, the integrated feedback design made it difficult to isolate the effects of individual feedback components. Third, the absence of kinematic analysis limited mechanistic interpretation of the observed improvements. Fourth, because only participants with relatively preserved cognitive function were included, the generalizability of the findings to the broader stroke population is limited. Additionally, participants could not be blinded to the auditory feedback intervention, which may have introduced expectancy effects, and individual differences in compliance, responsiveness, or prior familiarity with smart technologies were not formally assessed.

Finally, the 3% body-weight threshold used to trigger auditory feedback was adopted as a practical design parameter derived from a biomechanical model rather than an established stroke-specific clinical criterion. Because the pilot testing in three individuals aimed solely to assess system feasibility and usability, quantitative clinical indices—including sensitivity, specificity, and false-alarm rates—were not collected, nor was the clinical validity or optimality of the threshold formally evaluated.

Future studies should include larger and more diverse stroke populations with longer intervention and follow-up periods to determine long-term retention and neuroplastic adaptation. Kinematic and biomechanical analyses are also warranted to clarify the mechanisms underlying the observed improvements. In addition, clinically validated stroke-specific upper-limb weight-bearing thresholds should be established, and the independent contribution of individual feedback components should be evaluated to further validate and optimize the proposed auditory feedback system.

5. Conclusions

In conclusion, this study demonstrated that sensor-based feedback walker training improved functional mobility and gait symmetry in individuals with chronic stroke. In particular, improvements in spatial and temporal gait symmetry indices suggest that the intervention may facilitate qualitative gait recovery beyond gains in walking speed alone. Although the present findings should be interpreted with caution due to the small sample size and short intervention period, sensor-based feedback walker training may represent a promising adjunctive approach for improving gait symmetry and functional mobility in stroke rehabilitation. Further large-scale randomized controlled trials with long-term follow-up are warranted to confirm these findings.

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Data Availability Statement: The data presented in this study are available from the corresponding author upon reasonable request.

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