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Original Article

Long-term impact of robot-assisted training on walking pattern reconstruction in chronic stroke survivors: insights from multiparametric gait analysis

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Abstract: Aims: To determine whether robot-assisted lower-limb training promotes superior walking pattern reconstruction in chronic stroke survivors, as quantified by multiparametric gait analysis and supported by concurrent improvements in motor, balance, and functional outcomes. Methods: In this retrospective observational study, 80 patients with chronic stroke sequelae treated between January 2024 and January 2026 were allocated according to routine rehabilitation exposure to a control group (n = 45) or an observation group (n = 35); the primary endpoint was post-intervention gait remodeling, defined by change in gait speed and multiparametric spatiotemporal gait indices, while secondary endpoints included lower-limb motor recovery, spasticity, balance, functional independence, clinically meaningful responder status, and multivariable analysis of determinants of gait-speed change as the principal marker of walking pattern reconstruction. Results: After 10 weeks, the observation group showed significantly greater improvement than the control group in lower-limb motor function, including Fugl Meyer Assessment of the Lower Extremity total, proximal, and distal subscores, Timed Up and Go performance, and 10-m walking speed (all $P < 0.001$). Spasticity was also more effectively reduced, with lower Modified Ashworth Scale composite and segment-specific scores ($P = 0.002$ to < 0.001). In addition, balance, spatiotemporal gait parameters, and motor-related functional independence improved more markedly in the observation group (all $P < 0.001$ for key outcomes). Conclusion: Robot-assisted lower-limb rehabilitation, when added to conventional therapy, significantly enhanced gait remodeling, motor recovery, spasticity reduction, balance performance, and locomotion-related independence in chronic stroke survivors, supporting its value as an effective strategy for promoting more physiological and clinically meaningful walking restoration after stroke.

Keywords: Chronic stroke, robot-assisted training, gait pattern remodeling, multiparametric gait analysis, neurorehabilitation

Introduction

Stroke is one of the major causes of lifelong disability in the world, and poor walking has been one of the most chronic and debilitating sequelae [1, 2]. There are still several people with chronic stroke who have undergone traditional rehabilitation, and who retain lower gait velocity, lower endurance, interlimb asymmetry, disturbed joint kinematics, inadequate dynamic balance and lower adaptability to environmental requests. Such gait deficits are not just biomechanical abnormalities but they severely limit the amount of ambulation in the community, the degree of participation, and are reasons behind falls, deconditioning, and loss of independence [3, 4]. Innovations in stroke rehabilitation guidelines thus are putting substantial weight on the principles of recovery by means of task-specific, intensive, and patient-centered therapy as well as by noting that recovery at the chronic stage is almost always incomplete and widely variable.

One strategy that is starting to be promising in overcoming these limitations is robot-assisted gait training to provide high dose, repetitive, and reproducible locomotor training with controllable task difficulty and therapist assistance [5, 6]. Ideally, robotic technologies can be use-

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ful in gait recovery, improving the intensity of steps, facilitating more periodic gait cycle training, and helping them practice gait cycles individually, on the ground or on a treadmill [7]. Nevertheless, the clinical evidence is subtle as opposed to being null and cut-and-dried. Recent literature reviews indicate electromechanical- and robot-assisted gait training with physiotherapy has the potential to increase the probability of independent walking and potentially enhance gait-related outcomes, although the level and duration of effect increases with chronicity of stroke, initial ambulatory status, device type, training dose, and may increase when compared to other interventions [8, 9]. Notably, there are nonetheless guideline panels which consider evidence on the overall efficacy of robot-assisted therapy to be too fragile to make a blanket recommendation to use or avoid robot-assisted therapy in practice, and more mechanistically informed and phase-specific studies are required.

One of the main factors contributing to such uncertainty is that most previous studies have assessed robotic interventions in terms of global clinical outcome, i.e. walking speed, functional ambulation category, balance scales, or activities of daily living. These measures though clinically meaningful, do not tell much about how walking is altered, following training. Post stroke gait is a multidimensional construct that is influenced by the ability of spatiotemporal organization, segmental coordination, joint excursions, compensatory strategies, symmetry and variability throughout the gait cycle [10]. The highly subjective observational gait assessment is still used in clinical practice and might not identify the delicate but significant locomotor control change. In comparison, quantitative multiparametric gait analysis permits a more specific description of walking performance and motor strategy such that investigators can go beyond the query of whether patients walk faster to the more clinically related question of whether they walk better [11].

This difference is especially noteworthy in survivors of a chronic stroke, whereby the supposed functional improvements can be accompanied by the presence of a compensatory gait pattern instead of its true reconstruction. Based on this, assessment of the effect of robot-assisted training in the long term is more than short term functional test; it entails a whole analysis of whether training causes long term reorganization of the gait mechanism and intersegmental coordination. The multiparametric framework is highly appropriate to achieve that purpose as it can concurrently record the variations across spatiotemporal performance, symmetry, kinematic quality and entire walking pattern. It is in this context that the current research examined how robot-assisted training affects walking pattern reconstruction in survivors of chronic stroke on multiparametric gait analysis. Our hypothesis was that, although robot-assisted training would be related to the increase in traditional walking performance, it would also result in lasting remodeling of the gait patterns that displayed signs of more efficient and less compensatory locomotor control.

Materials and methods

Study design

This retrospective observational study included 80 patients with chronic stroke sequelae who received rehabilitation at Nantong Haimen People's Hospital between January 2024 and January 2026. According to the rehabilitation program received during routine clinical practice, patients were assigned to a control group (n = 45) or an observation group (n = 35). Eligible patients were aged over 18 years, had a first-ever ischemic or hemorrhagic stroke confirmed by computed tomography or magnetic resonance imaging, were in the chronic phase with unilateral hemiplegia and persistent gait impairment, had stable vital signs and a stable medical condition, and had complete pre- and post-intervention clinical and gait assessment data. Exclusion criteria were recurrent stroke within the previous 6 months, severe cognitive impairment, aphasia or psychiatric disorders precluding cooperation, severe cardiac, hepatic, or renal dysfunction, serious musculoskeletal disorders, joint deformities, fractures, and incomplete treatment records. The control group received conventional rehabilitation and physical therapy, including neurofacilitation, balance training, isotonic muscle strengthening, bridging, weight-shift training, gait training, and coordination/motor-control training, for 45 min per session, 6 days per week, for 10 weeks, together with guideline-based pharmacologic

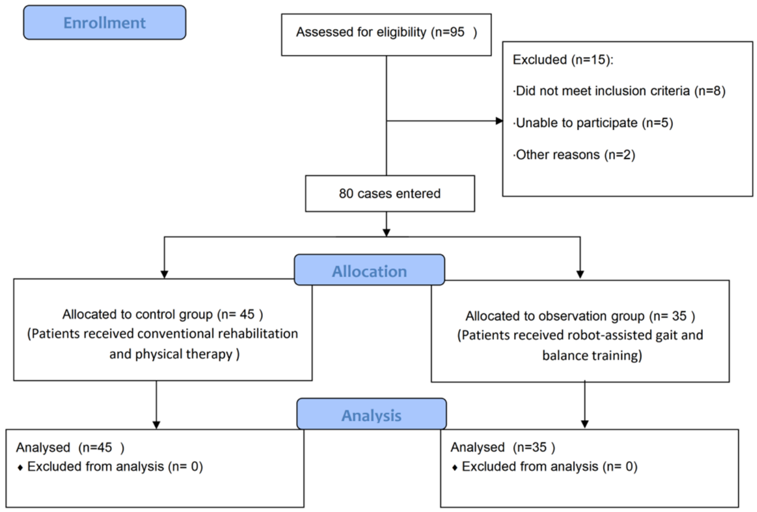

Figure 1. Flow diagram of patient enrollment, allocation, follow-up, and analysis.

secondary stroke prevention and management of underlying comorbidities. In addition to this, the observation group received robot-assisted gait and balance training using the ZEPU-AI1 lower-limb rehabilitation robot in a speed-regulated simulated gait mode. Patients were secured with a body-weight-support harness, with initial body-weight unloading set at up to 50% and robotic guidance set at up to 100%, followed by individualized adjustment according to motor status, exercise tolerance, and safety. Bilateral leg length settings were calibrated to each patient's hip and knee alignment, and both feet were positioned symmetrically. The visual-feedback scene, walking speed, and assistance parameters were individualized and adjusted during treatment by the supervising therapist. Each robotic session lasted 20 min and was delivered 3 times per week for 10 consecutive weeks. The device was equipped with an automatic emergency-braking system that immediately stopped the device in the event of discomfort or equipment malfunction. In the observation group, spatiotemporal gait parameters, including gait speed, step length, and cadence, as well as robot-derived hip and knee torque feedback data across the gait cycle, were recorded for analysis (**Figure 1**).

Ethics statement

This study was reviewed and approved by the Ethics Committee of Nantong Haimen People's Hospital. Given the retrospective design of the study and the use of de-identified clinical data collected during routine rehabilitation practice, the requirement for written informed consent was waived by the institutional ethics committee in accordance with relevant national regulations and institutional policies. All study procedures were conducted in compliance with the ethical principles of the Declaration of Helsinki, and strict measures were taken to protect patient privacy and data confidentiality throughout data collection, processing, and analysis.

Data collection

Clinical data were retrospectively retrieved from the electronic medical records and standardized rehabilitation assessment data of Nantong Haimen People's Hospital by trained investigators through a predetermined data-collection form. Baseline variables were demographic variables (age, sex, and body mass index), stroke variables (stroke subtype, hemiplegic side, and time since onset of the stroke), major vascular risk variables and comorbidities (hypertension, diabetes mellitus, dyslipidemia, smoking history), and baseline neurological and functional condition. The National Institutes of Health Stroke Scale (NIHSS) and the Fugl-Meyer Assessment of the Lower Extremity (FMA-LE) were used to assess neurological severity and motor impairment, respectively, and ambulatory capacity, balance, and activities of daily living were evaluated using the Functional Ambulation Category, Berg Balance Scale (BBS), and Modified Barthel Index, respectively. The outcome data were collected at two prespecified time points, namely, preintervention and postintervention. The FMA-LE total score and subscores of the proximal and distal extremities, Timed Up and Go test (TUG), and 10-m walking speed were used to assess lower-limb motor function. The muscle tone of the affected lower limb was assessed using the Modified Ashworth Scale (MAS) and the composite score as well as the individual scores of the hip adductors, knee extensors, knee flexors, ankle plantar flexors, and ankle invertors. Balance function was assessed using the BBS, Postural Assessment Scale for Stroke (PASS), Functional Reach Test, Activities-specific Balance

Confidence Scale, one-leg stance test on the affected side, and based on the performance of TUG. Gait parameters were measured using spatiotemporal parameters such as gait speed, cadence, affected-side and unaffected-side step length, stride length, duration of the gait cycle, double-support time and swing time of the affected limb. The level of functional independence was evaluated using the Functional Independence Measure (FIM) which includes total, motor, and cognitive scores, as well as the self-care, sphincter control, transfer, locomotion, communication, and social cognition subscores. Moreover, the a priori criteria of clinically meaningful responder outcomes were a 0.16 m/s increase in gait speed, a 6-point increase in the FMA-LE total score, a 5-point increase in the BBS score, a 2-point increase in locomotion-related FIM, and a 20% decrease in the MAS composite score. In analyses of the determinants of gait remodeling, gait speed was assessed at baseline and 10 weeks, and changes in predictor variables were entered into three multivariable models, including treatment allocation, change in MAS composite score, change in BBS score, baseline NIHSS score, time since stroke onset, and age. All evaluations were based on routine clinical rehabilitation records completed by senior therapists who were not involved in the current data analysis.

Outcome measures

The main intervention outcome was gait remodeling, measured by change in gait speed and supported by spatiotemporal gait parameters, including cadence, step length of the unaffected and affected sides, stride length, gait cycle duration, double-support time, and swing phase. The secondary outcomes were lower-limb motor recovery, muscle tone, balance function, functional independence and clinically meaningful response. The FMA-LE, consisting of total, proximal, and distal subscores, and the TUG and walking speed over 10 m, was the basis of lower-limb motor recovery assessment. The scale of spasticity was evaluated by the use of the MAS which is a scale comprising of a composite score and segment rating. The BBS, PASS, Functional Reach Test, Activities-specific Balance Confidence Scale, one-leg stance time on the affected leg and TUG performance were used to measure the balance function. Functional independence was assessed by the FIM, which includes total, motor, and cognitive scores and domain-specific subscores. In addition, responder analysis was used to evaluate clinically meaningful improvement according to prespecified thresholds for gait speed, FMA-LE, BBS, locomotion-related FIM, and MAS composite score. Multivariate analysis further used change in gait speed as the primary measure of gait remodeling.

Sample size calculation

Because this was a retrospective observational study based on routinely collected clinical data, no a priori sample size calculation was performed before patient inclusion. Instead, all eligible patients who met the predefined inclusion and exclusion criteria during the study period were consecutively included in the analysis. To evaluate whether the final sample was adequate for detecting a clinically relevant between-group difference, a post hoc power analysis was performed using the primary gait-remodeling indicator, namely, postintervention 10-m walking speed. Based on the observed between-group difference at 10 weeks, with 45 patients in the control group and 35 patients in the observation group, a two-sided significance level of 0.05 yielded an estimated statistical power of > 99%, indicating that the available sample size was sufficient to detect the observed treatment effect.

Statistical analysis

Statistical analyses were performed using standard statistical software packages. Continuous variables were presented as mean ± standard deviation, and categorical variables as number (percentage). The independent-samples t test was used to compare variables that are normally distributed and continuous, and the chi-square test or Fisher's exact test, depending on the variable type, were used to compare categorical variables between groups. Between-group differences at baseline and post-intervention (10 weeks) were assessed using independent-samples t tests, whereas within-group changes over the same period were assessed using paired t tests. Binary logistic regression was used to compute odds ratios (ORs) and 95% confidence intervals (CIs) for the responder analysis. Multivariate linear regression anal-

Table 1. Comparison of baseline clinical characteristics between the two groups

Variable	Control group (n = 45)	Observation group (n = 35)	Statistic	*P* value
Age (years)	63.4 ± 8.7	61.9 ± 9.1	t = 0.75	0.457
Male sex, n (%)	28 (62.2)	20 (57.1)	χ^2 = 0.21	0.647
Body mass index (kg/m^2)	24.8 ± 2.9	24.3 ± 3.1	t = 0.74	0.463
Time since stroke onset (months)	9.7 ± 3.8	10.2 ± 4.1	t = -0.56	0.579
Ischemic stroke, n (%)	34 (75.6)	27 (77.1)	χ^2 = 0.02	0.879
Right hemiplegia, n (%)	23 (51.1)	17 (48.6)	χ^2 = 0.05	0.824
Hypertension, n (%)	31 (68.9)	23 (65.7)	χ^2 = 0.09	0.761
Diabetes mellitus, n (%)	14 (31.1)	10 (28.6)	χ^2 = 0.06	0.803
Dyslipidemia, n (%)	18 (40.0)	13 (37.1)	χ^2 = 0.07	0.796
Current or former smoking, n (%)	16 (35.6)	11 (31.4)	χ^2 = 0.16	0.690
NIHSS score	5.8 ± 1.9	5.5 ± 1.7	t = 0.73	0.467
FMA-LE score	21.7 ± 4.6	22.4 ± 4.2	t = -0.70	0.487
Functional Ambulation Category	2.9 ± 0.8	3.1 ± 0.7	Z = -1.12	0.264
Berg Balance Scale	33.6 ± 6.5	34.8 ± 6.1	t = -0.84	0.402
Modified Barthel Index	58.4 ± 10.7	60.9 ± 11.2	t = -1.01	0.316

Note: Data are presented as mean ± SD or n (%). NIHSS, National Institutes of Health Stroke Scale; FMA-LE, Fugl-Meyer Assessment of the Lower Extremity; SD, standard deviation.

ysis was conducted to identify independent predictors of gait remodeling, with change in gait speed as the dependent variable and change in time since stroke onset, age, change in MAS composite score, change in BBS score, treatment allocation, and baseline NIHSS score as candidate covariates. Standardized regression coefficients were reported to compare the relative contribution of each predictor. All tests were two-sided, and a *P* value < 0.05 was considered statistically significant.

Results

Comparison of baseline clinical characteristics between the two groups

No significant between-group differences were observed in core demographic variables, including age, sex, and body mass index, nor in stroke chronicity, as reflected by the time since stroke onset (all P > 0.05). The distribution of stroke subtype and hemiplegic side was also similar, suggesting that the underlying neurological profile was broadly comparable between groups. Likewise, major vascular risk factors and comorbid conditions, including hypertension, diabetes mellitus, dyslipidemia, and smoking history, were evenly represented, reducing the likelihood that systemic baseline differences confounded subsequent outcome comparisons. Importantly, the two groups were also well matched with respect to baseline neurological severity and locomotor function. Specifically, no significant differences were found in NIHSS score, lower-extremity motor impairment as measured by the FMA-LE, ambulatory capacity assessed by the Functional Ambulation Category, balance performance assessed by the BBS, or activities of daily living assessed by the Modified Barthel Index (all P > 0.05) (**Table 1**).

Comparison of lower-limb motor function between the two groups

At baseline, lower-limb motor impairment and gait-related functional performance were comparable between the two groups, with no significant between-group differences in FMA-LE total score, proximal subscore, distal subscore, TUG, or 10-m walking speed (all P > 0.05). After 10 weeks, both groups showed improvement; however, the observation group demonstrated significantly greater improvements than the control group across all lower-limb motor outcomes. Specifically, significant between-group differences were observed in FMA-LE total score (P < 0.001), FMA-LE proximal subscore (P < 0.001), FMA-LE distal subscore (P < 0.001), TUG performance (P < 0.001), and 10-m walking speed (P < 0.001) (**Table 2**).

Table 2. Comparison of lower-limb motor function between the two groups

Variable	Time point	Control group (n = 45)	Observation group (n = 35)	*t*/Z value	*P* value
FMA-LE total score	Before intervention	21.7 ± 4.6	22.4 ± 4.2	-0.70	0.487
	After 10 weeks	25.9 ± 4.8	30.8 ± 4.5	-4.63	< 0.001
FMA-LE proximal subscore	Before intervention	13.4 ± 2.9	13.8 ± 2.7	-0.63	0.532
	After 10 weeks	16.1 ± 2.8	18.9 ± 2.6	-4.56	< 0.001
FMA-LE distal subscore	Before intervention	8.3 ± 2.1	8.6 ± 1.9	-0.66	0.511
	After 10 weeks	9.8 ± 2.0	11.9 ± 1.8	-4.84	< 0.001
Timed Up and Go test (s)	Before intervention	27.8 ± 6.4	26.9 ± 6.1	0.63	0.529
	After 10 weeks	22.4 ± 5.7	17.8 ± 4.9	3.84	< 0.001
10-m walking speed (m/s)	Before intervention	0.42 ± 0.11	0.44 ± 0.12	-0.78	0.439
	After 10 weeks	0.51 ± 0.12	0.68 ± 0.14	-5.84	< 0.001

Note: Data are presented as mean ± SD. FMA-LE, Fugl-Meyer Assessment of the Lower Extremity; SD, standard deviation.

Table 3. Comparison of MAS scores between the two groups

Variable	Time point	Control group (n = 45)	Observation group (n = 35)	Statistic	*P* value
MAS composite score (affected lower limb)	Before intervention	1.92 ± 0.43	1.88 ± 0.40	*t* = 0.43	0.669
	After 10 weeks	1.54 ± 0.38	1.17 ± 0.31	*t* = 4.67	< 0.001
MAS of hip adductors	Before intervention	1.71 ± 0.39	1.68 ± 0.36	*t* = 0.35	0.726
	After 10 weeks	1.39 ± 0.34	1.16 ± 0.29	*t* = 3.19	0.002
MAS of knee extensors	Before intervention	1.86 ± 0.41	1.82 ± 0.38	*t* = 0.45	0.653
	After 10 weeks	1.51 ± 0.36	1.15 ± 0.30	*t* = 4.78	< 0.001
MAS of knee flexors	Before intervention	1.63 ± 0.37	1.59 ± 0.35	*t* = 0.49	0.628
	After 10 weeks	1.34 ± 0.31	1.12 ± 0.27	*t* = 3.32	0.001
MAS of ankle plantar flexors	Before intervention	2.14 ± 0.46	2.09 ± 0.44	*t* = 0.49	0.623
	After 10 weeks	1.72 ± 0.40	1.29 ± 0.33	*t* = 5.19	< 0.001
MAS of ankle invertors	Before intervention	1.95 ± 0.42	1.90 ± 0.39	*t* = 0.54	0.593
	After 10 weeks	1.58 ± 0.37	1.21 ± 0.30	*t* = 4.85	< 0.001

Note: Data are presented as mean ± SD. MAS, Modified Ashworth Scale; SD, standard deviation.

Comparison of MAS between the two groups

At baseline, muscle tone of the affected lower limb was comparable between the two groups, with no significant between-group differences in the MAS composite score or in individual muscle-group scores, including the hip adductors, knee extensors, knee flexors, ankle plantar flexors, and ankle invertors (all P > 0.05). After 10 weeks of intervention, both groups exhibited reductions in spasticity; however, the reduction in spasticity was significantly greater in the observation group than in the control group. Significant between-group differences were observed in the MAS composite score of the affected lower limb (P < 0.001), as well as in the MAS of hip adductors (P = 0.002), knee extensors (P < 0.001), knee flexors (P = 0.001), ankle plantar flexors (P < 0.001), and ankle invertors (P < 0.001) (**Table 3**).

Comparison of balance function between the two groups

At baseline, balance-related outcomes were broadly comparable between the control group and the observation group, with no significant between-group differences across the evaluated domains (P > 0.05 for all). After 10 weeks of intervention, both groups showed improvement in balance performance; however, the magnitude of change was consistently greater in the observation group. Specifically, the observation group achieved significantly better outcomes in the BBS (P < 0.001), PASS (P < 0.001), Functional Reach Test (P < 0.001), Activities-spe-

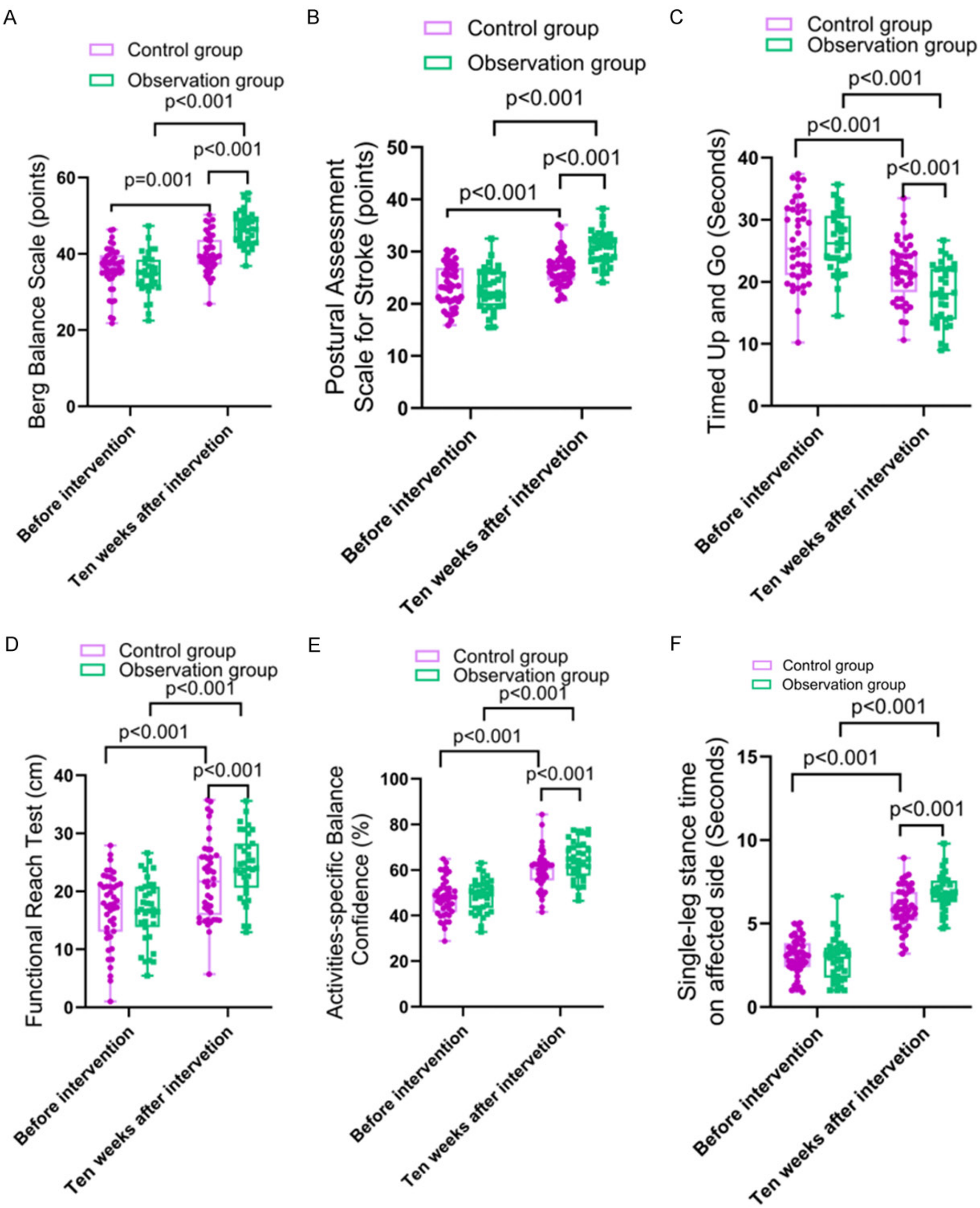

Figure 2. Comparison of balance function between the two groups. (A) Berg Balance Scale score; (B) Postural Assessment Scale for Stroke score; (C) Timed Up and Go test; (D) Functional Reach Test; (E) Activities-specific Balance Confidence Scale; and (F) Single-leg stance time on the affected side.

cific Balance Confidence Scale ($P < 0.001$), and single-leg stance time on the affected side ($P < 0.001$), together with a significantly shorter TUG time ($P < 0.001$), compared with the control group after 10 weeks of intervention (**Figure 2**).

Comparison of spatiotemporal gait parameters between the two groups

At baseline, the two groups were comparable across all evaluated spatiotemporal gait parameters, with no significant between-group differences observed in gait speed, cadence, affected-side step length, unaffected-side step length, stride length, gait cycle duration, double-support phase, or swing phase of the affected limb (all P > 0.05). After 10 weeks of intervention, both groups showed improvement in gait performance; however, the observation group demonstrated significantly greater improvement than the control group across all major spatiotemporal domains. Specifically, significantly better outcomes were observed in gait speed (P < 0.001), cadence (P < 0.001), affected-side step length (P < 0.001), unaffected-side step length (P < 0.001), and stride length (P < 0.001) in the observation group. In parallel, temporal gait organization was also more favorably modulated, as reflected by a shorter gait cycle duration (P < 0.001), a lower proportion of double-support phase (P < 0.001), and a higher swing-phase proportion of the affected limb (P < 0.001) compared with the control group (**Figure 3**). Overall, these findings indicate that robot-assisted rehabilitation conferred additional benefits in improving walking efficiency, step generation, and temporal coordination, thereby promoting a more physiological gait pattern in chronic stroke survivors.

Comparison of FIM between the two groups

At baseline, overall functional independence was comparable between the two groups, with no significant between-group differences in total FIM score, motor FIM score, cognitive FIM score, or any domain-specific subscores, including self-care, sphincter control, transfer, locomotion, communication, and social cognition (all P > 0.05). After 10 weeks of intervention, both groups showed improvement in functional status; however, the observation group demonstrated significantly greater improvements in domains closely related to motor recovery and mobility. Specifically, significant between-group differences were observed in total FIM score (P < 0.001), motor FIM score (P < 0.001), self-care subscore (P < 0.001), sphincter control subscore (P = 0.004), transfer subscore (P < 0.001), and locomotion subscore (P < 0.001). In contrast, no significant between-group differences were identified in cognitive FIM score (P = 0.065), communication subscore (P = 0.108), or social cognition subscore (P = 0.053) after treatment (**Table 4**). Taken together, these findings indicate that robot-assisted rehabilitation produced additional benefits in activity-level independence, particularly in motor-dependent functional domains, while its effect on cognitive and communication-related dimensions appeared limited over the 10-week intervention period.

Responder analysis for clinically meaningful improvement

The observation group showed higher response rates for a ≥ 0.16 m/s increase in gait speed (P = 0.003; OR, 4.12; 95% CI, 1.58-10.76), a ≥ 6-point increase in FMA-LE total score (P = 0.002; OR, 4.37; 95% CI, 1.69-11.28), a ≥ 5-point increase in BBS score (P = 0.001; OR, 5.05; 95% CI, 1.85-13.77), a ≥ 2-point increase in locomotion-related FIM (P = 0.002; OR, 4.52; 95% CI, 1.75-11.68), and a ≥ 20% reduction in MAS composite score (P = 0.003; OR, 4.25; 95% CI, 1.63-11.06) (**Table 5**). Taken together, these findings indicate that the superiority of robot-assisted rehabilitation was not limited to statistical differences in group means, but was also reflected in a substantially higher likelihood of achieving clinically meaningful improvements in motor recovery, spasticity reduction, balance restoration, gait performance, and locomotion-related independence.

Multivariable predictors of gait remodeling after intervention

To identify independent determinants of gait remodeling, a multivariable linear regression model was constructed with change in gait speed as the dependent variable. After adjustment for relevant clinical covariates, robot-assisted training remained an independent positive predictor of gait improvement (P < 0.001), with the largest standardized effect in the model (standardized β = 0.46). In parallel, greater reduction in lower-limb spasticity, as reflected by the decrease in MAS composite score, was independently associated with greater improvement in gait speed (P = 0.001; standardized β = -0.28), whereas improvement in balance function, measured by the change in BBS score, was also a significant favorable predictor (P = 0.004; standardized β = 0.25). By contrast, higher baseline neurological impairment was independently associated with less pronounced gait remodeling (P = 0.009; standardized β = -0.21). Neither time since stroke

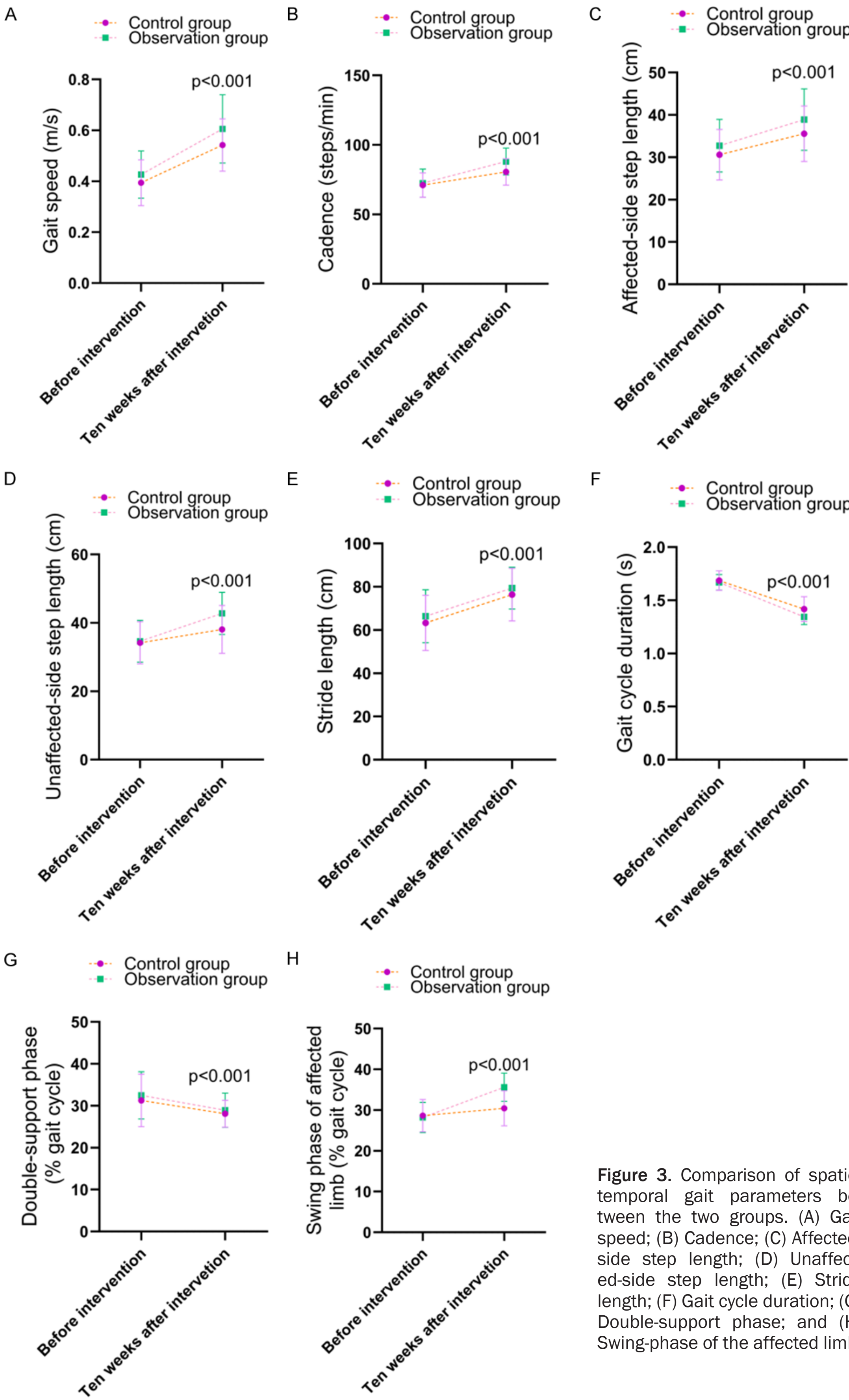

Figure 3. Comparison of spatio-temporal gait parameters between the two groups. (A) Gait speed; (B) Cadence; (C) Affected-side step length; (D) Unaffected-side step length; (E) Stride length; (F) Gait cycle duration; (G) Double-support phase; and (H) Swing-phase of the affected limb.

Table 4. Comparison of FIM scores between the two groups

Variable	Time point	Control group (n = 45)	Observation group (n = 35)	Statistic	*P* value
FIM total score	Before intervention	82.6 ± 11.4	84.1 ± 10.9	*t* = -0.59	0.557
	After 10 weeks	93.8 ± 10.7	104.9 ± 9.8	*t* = -4.76	< 0.001
Motor FIM score	Before intervention	55.4 ± 8.6	56.7 ± 8.2	*t* = -0.68	0.501
	After 10 weeks	64.2 ± 8.1	73.8 ± 7.5	*t* = -5.39	< 0.001
Cognitive FIM score	Before intervention	27.2 ± 4.1	27.4 ± 3.8	*t* = -0.22	0.824
	After 10 weeks	29.6 ± 3.7	31.1 ± 3.3	*t* = -1.87	0.065
Self-care subscore	Before intervention	23.8 ± 4.3	24.1 ± 4.0	*t* = -0.32	0.751
	After 10 weeks	27.1 ± 4.0	30.6 ± 3.7	*t* = -4.01	< 0.001
Sphincter control subscore	Before intervention	10.4 ± 2.1	10.7 ± 2.0	*t* = -0.64	0.525
	After 10 weeks	11.3 ± 1.9	12.5 ± 1.6	*t* = -2.99	0.004
Transfer subscore	Before intervention	13.2 ± 2.7	13.6 ± 2.5	*t* = -0.67	0.504
	After 10 weeks	15.6 ± 2.4	18.1 ± 2.1	*t* = -4.86	< 0.001
Locomotion subscore	Before intervention	7.8 ± 1.9	8.1 ± 1.8	*t* = -0.71	0.481
	After 10 weeks	9.3 ± 1.8	11.8 ± 1.6	*t* = -6.43	< 0.001
Communication subscore	Before intervention	12.9 ± 2.0	13.1 ± 1.8	*t* = -0.46	0.647
	After 10 weeks	13.8 ± 1.7	14.4 ± 1.5	*t* = -1.63	0.108
Social cognition subscore	Before intervention	14.3 ± 2.4	14.3 ± 2.3	*t* = 0.00	0.999
	After 10 weeks	15.8 ± 2.1	16.7 ± 1.9	*t* = -1.97	0.053

Note: Data are presented as mean ± SD. FIM, Functional Independence Measure; SD, standard deviation.

Table 5. Responder analysis for clinically meaningful improvement

Responder definition	Control group, n (%)	Observation group, n (%)	OR (95% CI)	*P* value
≥ 0.16 m/s increase in gait speed	12 (26.7)	21 (60.0)	4.12 (1.58-10.76)	0.003
≥ 6-point increase in FMA-LE total score	15 (33.3)	24 (68.6)	4.37 (1.69-11.28)	0.002
≥ 5-point increase in BBS score	18 (40.0)	27 (77.1)	5.05 (1.85-13.77)	0.001
≥ 2-point increase in locomotion-related FIM	16 (35.6)	25 (71.4)	4.52 (1.75-11.68)	0.002
≥ 20% reduction in MAS composite score	14 (31.1)	23 (65.7)	4.25 (1.63-11.06)	0.003

Note: OR, odds ratio; CI, confidence interval; FMA-LE, Fugl-Meyer Assessment of the Lower Extremity; BBS, Berg Balance Scale; FIM, Functional Independence Measure; MAS, Modified Ashworth Scale.

onset (P = 0.117) nor age (P = 0.214) showed a significant independent association with gait-speed change in the fully adjusted model (**Table 6**). Taken together, these findings indicate that the beneficial effect of robot-assisted rehabilitation on walking reconstruction was robust after multivariable adjustment and was closely linked to concurrent improvements in spasticity control and balance restoration.

Sensitivity analyses for the effect of robot-assisted rehabilitation on gait remodeling

Sensitivity analyses showed that the association between robot-assisted rehabilitation and improvement in gait speed was robust across multiple model specifications. As shown in the forest plot (**Figure 4**), the unadjusted model yielded an estimated treatment effect of 0.150 m/s (95% CI, 0.101-0.199; P < 0.001). The effect remained significant after adjustment for age, sex, baseline NIHSS score, and time since stroke onset (β = 0.143, 95% CI, 0.095-0.191; P < 0.001), and after further adjustment for baseline gait speed, MAS composite score, and BBS score (β = 0.136, 95% CI, 0.087-0.185; P < 0.001). Consistent results were also observed in the per-protocol analysis (β = 0.147, 95% CI, 0.097-0.197; P < 0.001) and after excluding the upper and lower 5% of extreme responders (β = 0.139, 95% CI, 0.091-0.187; P < 0.001), indicating that the beneficial effect of robot-assist-

Table 6. Multivariable predictors of gait remodeling after intervention

Predictor	β	SE	Standardized β	95% CI	Tolerance	VIF	*P* value
Robot-assisted training (yes vs. no)	0.118	0.023	0.46	0.073 to 0.163	0.84	1.19	< 0.001
ΔMAS composite score	-0.067	0.019	-0.28	-0.104 to -0.030	0.61	1.64	0.001
ΔBBS score	0.009	0.003	0.25	0.003 to 0.015	0.63	1.58	0.004
Baseline NIHSS score	-0.014	0.005	-0.21	-0.024 to -0.004	0.79	1.27	0.009
Time since stroke onset	-0.003	0.002	-0.11	-0.007 to 0.001	0.90	1.11	0.117
Age	-0.001	0.001	-0.08	-0.003 to 0.001	0.86	1.16	0.214

Note: β, regression coefficient; SE, standard error; CI, confidence interval; VIF, variance inflation factor; MAS, Modified Ashworth Scale; BBS, Berg Balance Scale; NIHSS, National Institutes of Health Stroke Scale; Δ, change from baseline to 10 weeks.

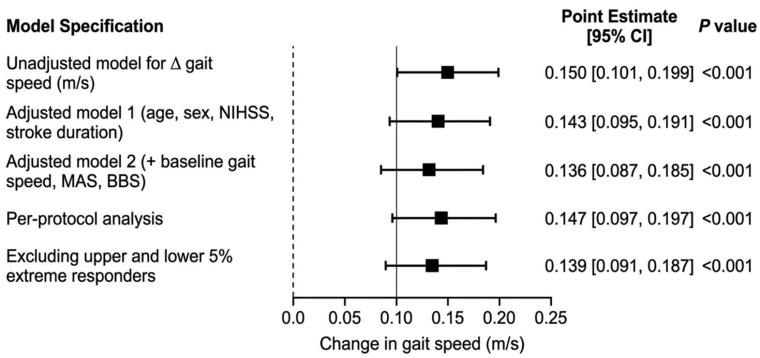

Figure 4. Sensitivity analyses for the robustness of the treatment effect. Note: CI, confidence interval; NIHSS, National Institutes of Health Stroke Scale; MAS, Modified Ashworth Scale; BBS, Berg Balance Scale; Δ, change.

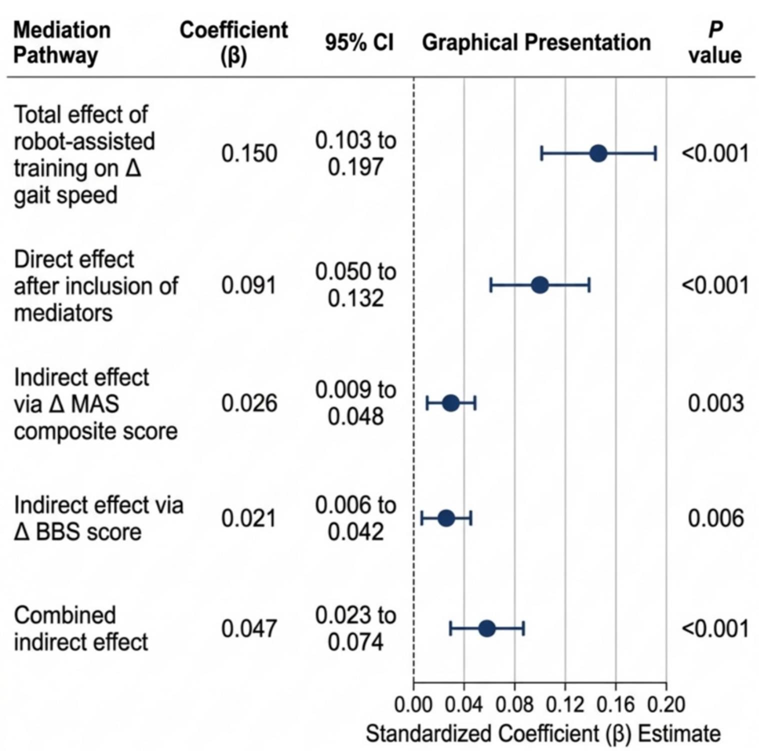

Figure 5. Parallel mediation analysis for treatment effect on gait-speed change. Note: CI, confidence interval; MAS, Modified Ashworth Scale; BBS, Berg Balance Scale; Δ, change; β, standardized coefficient.

ed rehabilitation on gait-speed change was stable and not materially influenced by model specification or extreme observations.

Parallel mediation analysis for treatment effect on gait-speed change

Parallel mediation analysis was performed to examine whether changes in spasticity and balance contributed to the treatment effect on change in gait speed. As shown in **Figure 5**, robot-assisted training had a significant total effect on change in gait speed (β = 0.150, 95% CI, 0.103-0.197; P < 0.001). After simultaneous inclusion of change in MAS composite score and change in BBS score as mediators, the direct effect remained statistically significant but was attenuated (β = 0.091, 95% CI, 0.050-0.132; P < 0.001), indicating partial mediation. Significant indirect effects were identified through both pathways, including a reduction in the MAS composite score (β = 0.026, 95% CI, 0.009-0.048; P = 0.003) and an improvement in the BBS score (β = 0.021, 95% CI, 0.006-0.042; P = 0.006). The combined indirect effect was also significant (β = 0.047, 95% CI, 0.023-0.074; P < 0.001), suggesting that part of the treatment benefit on gait-speed improvement was mediated through concurrent reductions in spasticity and improvements in balance function.

Discussion

The current analysis shows that robot-assisted lower-limb training in combination with conventional rehabilitation provided greater recovery benefits compared with conventional rehabilitation alone in chronic stroke survivors. In addition to enhancing impairment-level results, the intervention was accompanied by uniform improvements in lower-limb motor control, spasticity, balance, spatiotemporal gait organization, and activity-level independence. Of particular importance, the superiority of the robot-assisted program was also supported by significant between-group differences in mean changes, responder analyses indicating a greater likelihood of achieving clinically meaningful improvement, and multivariate modelling showing that robot-assisted training remained a predictor of gait remodeling after adjustment for relevant covariates. Taken together, these results indicate that the positive effect of robot-assisted rehabilitation was not limited to performance improvement but reflected a more comprehensive restoration of post-stroke walking patterns.

Compared with conventional therapy alone, robot-assisted rehabilitation showed greater improvement in lower-limb motor recovery. This agrees with the broader stroke rehabilitation literature, which indicates that repetitive, task-specific, and high-dose locomotor practice can promote motor relearning and enhance lower-extremity function, especially when the training is intensive and goal-directed [12]. In the current study, the observation group showed greater improvements in FMA-LE total, proximal, and distal subscores, indicating global motor recovery rather than improvement limited to a single part of the limb. The first plausible reason is that robotic assistance may increase movement repetition, regularity, and repeatability, reducing therapist-dependent variability in training delivery. This kind of training can enhance sensorimotor integration and selective motor control and inhibit maladaptive compensatory mechanisms [13]. Clinically, this indicates that robot-assisted training can be particularly useful when the treatment objective is not only to intensify the volume of exercise but also to provide a higher degree of standardized and biologically significant locomotor practice.

The robot-assisted program was associated with greater reduction in lower-limb spasticity. Other researchers have shown contradictory findings on whether robotic gait training has a significant effect on muscle tone, probably because spasticity is influenced by reflex hyperexcitability and secondary biomechanical adaptation [14]. The observation group showed greater reductions in the MAS composite score and individual muscle-group scores, especially around the knee and ankle, in the current cohort. Mechanically guided repetitive stepping can reduce abnormal stretch-related reflex activity by enhancing more physiological joint excursion, more appropriate timing of muscle activation, and reciprocal inhibition during gait cycles. Meanwhile, better positioning and gradual loading of the paretic limb can contribute to minimizing the stiffness of the soft tissues and abnormal co-contraction. This finding has clinical significance because persistent spasticity is not merely a sign of motor dysfunction but may also prevent effective stepping, balance recovery, and community-level ambulation. It also suggests that studies that evaluate only locomotor outcomes but do not measure spasticity risk underestimating a significant mediator of gait improvement.

Robot-assisted rehabilitation provided significant benefits for balance recovery. The observation group demonstrated greater improvements in static and dynamic balance measures, such as BBS, PASS, functional reach, balance confidence, single-leg stance time, and TUG. This trend is consistent with the idea that post-stroke balance and gait recovery are closely related processes [15]. The published stroke neurorehabilitation literature has repeatedly indicated that postural control is closely connected to walking capacity; nevertheless, many interventions have not provided the opportunity to enhance both processes in a single intervention [16]. The simultaneous improvement in balance and gait in our study indicates that robot-assisted stepping might have enhanced postural control through repeated weight shifting, symmetrical training, and safer loading of the paretic limb under guided conditions. These adaptations may have facilitated anticipatory and reactive postural responses, thereby improving effective gait performance. Translationally, this provides further support for considering robot-assisted gait training not only as a walking intervention but also as a balance-oriented rehabilitation strategy that may reduce fall risk and improve mobility confidence.

The intervention improved gait organization, not only walking speed. The changes observed in the observation group were predominantly reflected in cadence, step length, stride length, gait cycle duration, double-support phase, and swing-phase proportion of the affected limb, indicating a shift toward a more physiological spatiotemporal pattern. This fact is critical as gait improvement after stroke is commonly misinterpreted when speed is used as the sole outcome measure. Patients may walk faster through compensatory trunk movements, increased reliance on the nonparetic limb, or altered timing, which can overstate apparent functional improvement without providing any indication of locomotor recovery. In contrast, the current findings suggest that robot-assisted rehabilitation led to improved step generation and enhanced temporal organization of the gait cycle [17]. These mechanisms may be partly explained by repeated exposure to near-normal kinematic paths, more stable interlimb timing, and constrained practice that restricts maladaptive movement solutions. The larger implication is that future stroke rehabilitation research should shift toward greater reliance on multidimensional gait assessment when the scientific objective is to assess actual gait remodeling.

Robot-assisted rehabilitation improved activity-level independence, although this effect was more evident in motor activities. The observation group demonstrated greater improvements in total FIM, motor FIM, self-care, sphincter control, transfer, and locomotion subscores, whereas cognitive and communication-related FIM dimensions were not significantly different between groups. This trend is consistent with existing rehabilitation theory: interventions designed to improve locomotor and lower-extremity motor recovery primarily transfer to mobility-dependent activities of daily living and have minimal direct effects on cognition or language [18]. The practical value of this finding has two aspects. First, this suggests that the observed biomechanical and motor gains were functional and not limited to laboratory results [7, 19, 20]. Second, it cautions against extrapolating the future value of the anticipated positive effect of robot-assisted gait training to areas where such a positive effect is unlikely to be achieved without targeted cognitive, communicative, or psychosocial interventions [11]. It has therefore been recommended that robot-assisted therapy be placed as part of a multidimensional rehabilitation program and not as a holistic treatment for all post-stroke disabilities.

Several limitations of this research should be acknowledged. To begin with, this was a single-center retrospective study with a relatively small sample, which limits causal inference and generalizability. Second, treatment allocation was not randomized. Although baseline characteristics were similar and multivariable adjustment was performed, residual confounding cannot be excluded. Third, the observation period was only 10 weeks; therefore, it remains unclear whether the observed gains would persist in the long term despite the emphasis on gait remodeling. Fourth, despite the relative richness of clinical and spatiotemporal outcomes used in the study, a deeper mechanistic interpretation would have been supported by more specific biomechanical, electromyographic, and neurophysiological outcome measures. Fifth, some outcomes were based on routine clinical practice, which could introduce assessor-related variation. Lastly, this study included patients with chronic stroke, and thus the results are not directly applicable to patients in the acute or subacute phase of recovery.

In conclusion, the addition of robot-assisted lower-limb rehabilitation to conventional therapy showed better results in lower-limb motor recovery, spasticity reduction, balance, spatiotemporal gait organization, and motor-related functional independence among chronic stroke survivors. The benefit was supported not only by mean between-group differences but also by higher rates of clinically meaningful response and multivariate evidence that robot-assisted training was an independent predictor of gait remodeling. These results indicate that robot-assisted rehabilitation may facilitate a more physiological and functionally relevant restoration of post-stroke walking and could provide a strong rationale for future multicenter randomized studies with extended follow-up and more intensive mechanistic evaluations.

Disclosure of conflict of interest

None.

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