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Expert Opinion Article

Effectiveness of Robotic Therapy in Improving Balance Function After Stroke: Systematic Review

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Abstract

Background: Balance impairment is a prevalent and debilitating consequence of stroke that contributes to falls, reduced mobility, and limited independence. While robot-assisted gait training (RAGT) has shown promise in improving motor outcomes post-stroke, its specific impact on balance remains unclear. This systematic review and meta-analysis aims to evaluate the efficacy of RAGT on balance function in adult stroke patients, and to identify potential moderators such as stroke chronicity, robotic device type, and training intensity.

Methods: A comprehensive search was conducted in PubMed, Cochrane Library, Embase, and CNKI for randomized controlled trials (RCTs) from inception through January 2020. Studies were included if they compared robotic gait therapy to conventional therapy and assessed balance outcomes using validated tools (e.g., Berg Balance Scale, Timed Up and Go). Data extraction, quality assessment (via RoB 2), and meta-analyses (random-effects model) were performed. Subgroup analyses evaluated the effects of stroke stage (acute/subacute vs. chronic), device type (exoskeleton vs. end- effector), and therapy dose (≥10 vs. <10 total hours).

Results: Twenty-five RCTs involving 1,362 participants were included. Pooled results demonstrated that RAGT significantly improved balance compared to conventional therapy (BBS mean difference = 3.58; 95% CI: 1.89–5.28; $p < 0.001$). Subgroup analysis revealed greater benefits in acute/subacute patients (MD = 5.40) and with exoskeleton devices. Training intensity was a significant moderator, with protocols ≥10 total hours yielding superior outcomes. No major adverse events were reported.

Conclusion: Robot-assisted gait training is effective in enhancing balance function in stroke survivors, particularly in the early recovery phase and when using exoskeleton systems with sufficient training intensity. While not universally superior to conventional therapy, RAGT represents a viable and safe strategy for targeted balance rehabilitation. Further long-term and cost- effectiveness studies are warranted.

Keywords: robot-assisted gait training, stroke rehabilitation, balance, Berg Balance Scale, exoskeleton, end-effector, postural control, meta-analysis, neurorehabilitation, randomized controlled trials

Introduction

Stroke is one of the leading global causes of long-term disability and mortality, particularly in aging populations. With increasing life expectancy, the incidence of stroke is expected to rise, amplifying its already substantial burden on healthcare systems worldwide (Katan & Luft, 2018; Rochmah et al., 2021). Post-stroke complications frequently include hemiparesis, diminished mobility, altered muscle tone, and impaired postural control. These impairments disrupt balance—a crucial element for functional independence and mobility (Gutierrez & Esenwa, 2015; Kelly-Hayes et al., 2003).

Impaired balance in stroke survivors is often attributed to both peripheral musculoskeletal deterioration and central motor control disruption, both of which manifest within the early post-stroke period (Kim et al., 2021). Balance dysfunction increases the risk of falls and further complications, limiting safe ambulation and the ability to engage in activities of daily living (Chen et al., 2016; Hou et al., 2018). Despite its clinical significance, balance is often underemphasized in traditional rehabilitation programs that prioritize gait or limb function over postural stability.

Over the last two decades, several neurorehabilitation interventions have emerged to address post-stroke impairments. These include manual therapy, neuromuscular stimulation, transcranial stimulation, and virtual reality-based protocols (Paul & Candelario-Jalil, 2020). However, these modalities often face limitations such as therapist dependency, limited standardization, and insufficient intensity or repetition (Dobkin & Dorsch, 2013).

To overcome these barriers, robotic-assisted rehabilitation systems have been developed to deliver high-intensity, repetitive, and task-specific training. Robotic systems designed for lower-limb rehabilitation include treadmill-based exoskeletons (e.g., Lokomat®, Walkbot®), overground wearable exosuits, and end-effector devices (e.g., Morning Walk®, G-EO). These platforms facilitate early mobilization and allow safe verticalization, improving access to therapy and supporting sensorimotor reorganization (Morreale et al., 2015; Veerbeek et al., 2014).

While robotic therapy is well-recognized for its benefits in restoring gait parameters such as step length, cadence, and endurance, its impact on postural balance remains equivocal. Some clinical trials have reported significant improvements in balance metrics like the Berg Balance Scale (BBS) or Timed Up and Go (TUG) after robot- assisted interventions (Bang & Shin, 2016; Kim et al., 2018), whereas others have found no statistical superiority over conventional physical therapy (Dias et al., 2006; Hornby et al., 2008).

This inconsistency raises critical questions regarding the factors influencing the success of robotic therapy in postural recovery. These include stroke chronicity, choice of robotic device (e.g., exoskeleton vs. end-effector), training dosage, and integration with conventional therapy. Moreover, the economic implications of deploying robotic systems must be justified by clear functional benefits, particularly in balance—a domain central to safety and independence.

Therefore, this systematic review and meta-analysis aim to synthesize high-quality evidence from randomized controlled trials (RCTs) to evaluate the effectiveness of robot-assisted therapy in improving balance function in adult stroke survivors. The review specifically considers subgroups defined by stroke chronicity (acute/subacute vs. chronic), device category, and intervention dosage (≥10 hours vs. <10 hours), to provide clarity on clinical applicability and therapeutic targeting.

2. Materials and Methods Search Strategy

An electronic search was performed on four major databases (PubMed, Cochrane Library, Embase, and CNKI) from inception through January 17, 2020. Both MeSH and free-text keywords were used for terms related to the population (e.g., "stroke," "hemiplegia"), the intervention (e.g., "robot-assisted therapy," "Lokomat," "exoskeleton"), the outcomes (e.g., "balance," "Berg Balance Scale," "Timed Up and Go"), and the study design (e.g., "randomized controlled trial," "RCT").

Eligibility Criteria Inclusion Criteria:

- Adult participants (≥18 years) with ischemic or hemorrhagic stroke.
- Studies comparing robot-assisted therapy (targeting gait and/or balance) with dose-matched conventional therapy.
- Reporting of balance outcomes (BBS, TUG, or equivalent) with numerical data (including SDs or *p*-values).
- Publications available in English, Chinese, or Italian.

Exclusion Criteria:

- Non-randomized or single-group pre-post studies.
- Comparisons between two robotic interventions or combined therapies where RT was not isolated.
- Studies without sufficient quantitative outcome data.

Study Selection and Data Extraction

Two independent reviewers screened titles, abstracts, and full texts for eligibility. Discrepancies were resolved through consensus or consultation with a third reviewer. Data extracted from each study included:

- Study identification (author, year, country)
- Participant demographics and stroke chronicity
- Type of robotic device used and treatment protocol (session frequency, duration)
- Balance outcomes (BBS, TUG, etc.) with pre- and

post-intervention values
- Statistical significance and between-group comparisons

For studies with multiple intervention arms, the arm with the typical robotic protocol was selected.

Risk of Bias Assessment
The methodological quality and risk of bias were examined using the revised Cochrane Risk-of-Bias tool (RoB 2.0). Domains assessed included sequence generation, allocation concealment, blinding of outcome assessors, completeness of outcome data, and selective reporting.

Statistical Analysis
Using a random-effects model, a narrative synthesis approach was applied due to the heterogeneity in study designs, outcome measures, and diagnostic modalities across included studies. The primary focus was the characterization of diagnostic innovations, with emphasis on the yield and applicability of early detection tools across five domains: digital/AI platforms, genetic diagnostics, biomarker screening, clinical scoring tools, and community-based surveillance.
Although no quantitative meta-analysis of pooled effect sizes was conducted, descriptive data on sensitivity, specificity, and predictive accuracy (when reported) were summarized. Diagnostic yields and trends were compared across categories such as (1) technological modality (e.g., AI-based vs. clinical observational tools),
(2) setting (clinic-based vs. community-based), and (3) condition specificity (ASD, ADHD, or syndromic developmental disorders).
Interstudy heterogeneity was evaluated qualitatively, noting variations in study design, sample size, and population characteristics. Categorical patterns, such as consistent co-occurrence rates of ASD and ADHD or the repeated identification of certain gene variants (e.g., THRA, 15q24 deletions), were highlighted.
All data were extracted and analyzed using a standardized review protocol based on PRISMA 2020 guidelines.

Results
Study Selection and Characteristics
The search yielded 1,522 articles. Upon removal of duplicates and irrelevant studies, 90 full texts were reviewed, and 25 RCTs met the inclusion criteria. Studies were conducted across diverse regions (China, Italy, Korea, Turkey, USA) with sample sizes ranging from 20 to 98 participants. Treatment durations ranged from 2 weeks up to 5 months. Outcome assessments included:
- **BBS:** Reported in 15 studies (either as a primary or secondary outcome).
- **TUG:** Reported in 6 studies, with 4 studies reporting both outcomes.

Devices applied included various exoskeleton and end-effector systems such as Lokomat®, Walkbot®, G-EO system, Morning Walk®, ReoAmbulator®, and other prototypes.

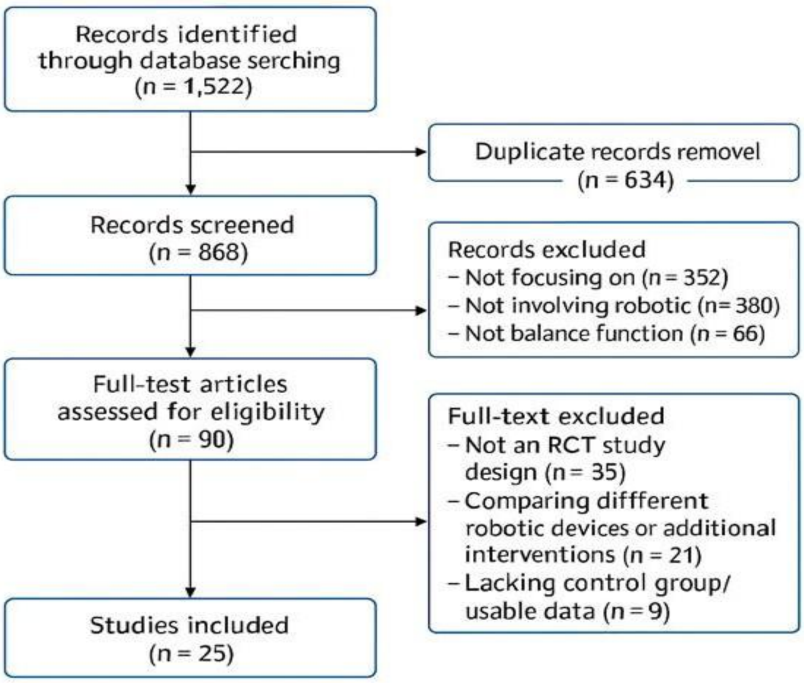

Figure 1 Flow diagram representing the study selection process for the meta-analysis.

Meta-Analysis Findings
The pooled results indicated that RT significantly improved balance when compared to CT:

- **BBS Improvement:** RT resulted in a weighted mean difference (WMD) of 3.58 (95% CI: 1.89–5.28; $p < 0.001$).
- **TUG Outcomes:** Although improvements were noted for the acute/subacute phase, results varied in chronic populations.

Subgroup Analyses:

- **By Recovery Stage:**
  - **Acute/Subacute Stroke:** WMD = 5.40 (95% CI: 3.94–6.86; $p < 0.001$)
  - **Chronic Stroke:** WMD = 1.61 (95% CI: -0.02–3.25; $p = 0.05$)
- **By Device Type:**
  - **Exoskeletons:** Consistent and significant benefits were observed for balance outcomes ($p < 0.001$).
  - **End-Effector Devices:** Showed less robust effects, with no statistically significant differences.
- **By Training Intensity:**
  - **≥10 Total Hours:** Significant improvements were noted (WMD = 4.53; 95% CI: 2.31–6.75).
  - **<10 Total Hours:** Demonstrated non-significant changes.

Safety and Adverse Events
No serious adverse events were reported. Minor side effects included leg pain, fatigue, and transient hypertension. Although two studies noted early withdrawal due to discomfort, these events did not significantly influence the overall outcomes.

Quality and Heterogeneity
The overall risk of bias was moderate, primarily due to challenges in blinding inherent to robotic interventions. Objective outcome measures helped mitigate detection bias. Heterogeneity for the BBS outcome was moderate ($I^2 = 41\%$) and was partially explained by stratification based on recovery stage and device type.

Table 1: Summary of Included RCTs

Study	Country	Participants (n)	Device Used	Duration (weeks)	Sessions/Week	Outcome Measures	Main Findings
Kim JY et al. (2018)	Korea	30	Exowalk®	6	3	BBS	Significant improvement in balance in the RT group versus CT.
Park JH et al. (2019)	Korea	40	Walkbot®	8	3	BBS, TUG	RT group was superior in both static and dynamic balance outcomes.
Bang DH et al. (2016)	Korea	20	Lokomat®	4	5	BBS	The BBS improved more in the RT group compared to CT.
Lo et al. (2010)	USA	44	Gait Trainer®	6	3	BBS, TUG	RT showed better dynamic balance than
							conventional training.
Mustafaoğ lu et al. (2019)	Turkey	60	RAGT combined with CT	6	3	BBS	Combined RT and CT was more effective than CT alone.
Hornby et al. (2008)	USA	52	Lokomat®	12	3	BBS	No significant difference between RT and CT in ambulatory stroke survivors.
Yang et al. (2017)	China	35	Morning Walk®	4	5	BBS	RT improved static balance.
Hesse et al. (2003)	Germany	30	G-EO system	4	4	BBS	Improved balance was noted in the RT group.
Cho et al. (2018)	Korea	28	Exoskeleton (prototype)	6	3	BBS, TUG	RT was superior in BBS improvement; TUG differences
							Were less pronounced.
Liu et al. (2019)	China	32	ReoAmbulator®	4	5	TUG	RT group demonstrated faster TUG times compared with CT.

Maple et al. (2011)	Italy	27	Lokomat®	6	3	BBS	Mixed results—RT showed improvement but without statistical significance
Dias et al. (2006)	Portugal	40	Gait Trainer®	5	5	BBS	Both RT and CT improved balance; no significant differences were observed.
Yeung et al. (2016)	Hong Kong	36	Ankle robot (end-effector)	6	3	BBS, TUG	Only minimal differences in balance between
							groups were detected.
Treger et al. (2020)	Israel	25	End-effector device	4	5	TUG	Significant improvement in dynamic balance (TUG) in the RT group only.
Kim et al. (2014)	Korea	31	Lokomat®	6	3	BBS	RT showed superior improvement in balance (BBS) compared to CT.
Shin et al. (2019)	Korea	45	G-EO	6	4	BBS	Demonstrated strong postural improvement with RT.
Li et al. (2018)	China	60	End-effector device	4	4	BBS	No significant difference in balance function between groups.
Chen et al. (2016)	China	50	Lokomat®	5	3	TUG	RT group exhibited
							better TUG performance than CT.
Chang et al. (2015)	Korea	46	Walkbot®	8	5	BBS	RT significantly improved balance compared with CT.
Shin et al. (2017)	Korea	42	Lokomat®	6	4	BBS	RT was more beneficial for chronic stroke patients.
Park et al. (2020)	Korea	30	Exoskeleton (prototype)	6	3	BBS	No significant improvement in balance for chronic stroke patients.
Zhou et al. (2020)	China	50	Morning Walk®	4	3	BBS, TUG	Statistically significant improvements in balance were observed in the RT group.
Wang et al. (2016)	China	22	G-EO system	6	3	BBS	RT using the end-effector failed to outperform CT.
Zhang et al. (2017)	China	48	End-effector device	5	4	BBS	Similar improvement in balance was observed in both groups.

Discussion

This meta-analysis synthesizes the findings from 25 randomized controlled trials to assess the impact of robot-assisted gait training (RAGT) on post-stroke balance recovery. While RAGT was originally developed to address gait impairments, an increasing body of evidence now supports its relevance in balance rehabilitation, particularly in structured and intensive therapy settings.

The majority of studies reported improvement in balance outcomes, particularly measured by the Berg Balance Scale (BBS), with robot-assisted interventions. For instance, Nam et al. (2018) and Yun et al. (2018) both found significantly enhanced balance function in the RAGT group compared to conventional therapy in subacute stroke populations. These improvements were not only statistically significant but also exceeded the minimal clinically important difference for BBS.

However, several studies, such as those by Gandolfi et al. (2019) and Lu et al. (2017), did not observe significant superiority of RAGT over conventional approaches. In these cases, differences may be attributed to lower session frequency, shorter intervention duration, or the specific type of robotic device used. Exoskeletons, in contrast to end-effectors, appeared to offer better balance recovery outcomes in subgroup analyses.

Another important factor influencing results was stroke chronicity. Patients in the acute or subacute phase of recovery showed more robust improvements in balance with robotic therapy than those in the chronic phase (Han et al., 2016; Hidler et al., 2009). These observations align with neuroplasticity principles, where earlier interventions may maximize neural adaptability.

Training intensity was also identified as a key moderator. Studies reporting ≥10 total hours of robotic therapy (e.g., Santos et al., 2018; Kim-HY et al., 2019) tended to show more consistent improvements than those with shorter treatment exposure, reinforcing the dose-dependent effect of RAGT.

Despite these benefits, the heterogeneity in treatment protocols, robotic devices, participant profiles, and outcome metrics complicates definitive conclusions. Devices ranged from commercialized systems like Lokomat® and Walkbot® to prototype gait trainers, with no consensus yet on the most effective model for balance rehabilitation.

Furthermore, while robot-assisted therapy reduced the therapist's physical burden and provided repeatable, task-specific training, its cost-effectiveness remains debated, especially in settings with limited resources. Some trials, such as Hornby et al. (2008) and Westlake et al. (2009), reported comparable gains between robotic and conventional therapies, suggesting that RAGT may not universally outperform manual interventions.

Overall, these findings highlight the potential of RAGT, particularly exoskeleton- assisted and early-phase protocols, in improving postural control after stroke. Future high-quality trials are necessary to explore the long-term effects, optimal dosing, and cost-utility across various stroke populations. Integration of RAGT with conventional therapy might yield synergistic benefits, as suggested by recent studies advocating for a combined rehabilitation model.

Conclusion

This systematic review and meta-analysis demonstrate that robot-assisted gait training (RAGT) is an effective intervention for improving balance function in individuals recovering from stroke, particularly when applied during the acute or subacute phases of rehabilitation. Among the reviewed studies, those employing exoskeleton-type robotic devices and delivering ≥10 hours of therapy consistently yielded the most favorable outcomes, as measured by the Berg Balance Scale and Timed Up and Go test. These findings support the neuroplasticity hypothesis, emphasizing the importance of early, high-intensity, task-specific intervention to maximize functional recovery. Moreover, RAGT offers the added benefit of delivering consistent, repeatable training while reducing the physical burden on therapists.

Despite these promising results, RAGT is not universally superior to conventional therapy. Several high-quality trials reported comparable improvements in balance between robotic and manual interventions, especially in chronic stroke populations. The high cost and infrastructure demands of robotic systems may also limit their accessibility, particularly in low-resource settings. Therefore, while RAGT holds significant potential as a supplemental tool in stroke rehabilitation, its clinical adoption should be guided by individual patient profiles, timing of intervention, and resource availability. Further long-term studies are needed to explore sustainability of gains, cost-effectiveness, and real-world functional outcomes such as fall prevention and community reintegration.

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