

Synergistic Effects of Robotic-Assisted Gait Training and Virtual Reality on Balance, Posture, and Functional Recovery in Stroke Survivors: A Systematic Review

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ABSTRACT

Background

Stroke remains a leading cause of long-term disability worldwide, with gait impairment being a primary concern for survivors. While traditional rehabilitation approaches have shown efficacy, the integration of advanced technologies such as virtual reality (VR) and robotics presents a promising avenue for enhancing stroke rehabilitation outcomes.

Objective

This systematic review aims to evaluate the impact of combined RAGT+VR interventions on balance & gait parametric abilities in stroke survivors and assess the extent to which these technologies contribute to performance recovery.

Methods

A comprehensive literature search was conducted across PubMed, Scopus, Cochrane Library, and PEDro databases. Randomized controlled trials published between January 2000 and January 2024, focusing on combined RAGT+VR interventions for balance & gait rehabilitation in stroke patients, were included. The Physiotherapy Evidence Database (PEDro) scale was used to assess methodological quality. The variation in VR and RAGT were significantly different with variety of outcome with functional ability of RAGT in improving human movements.

Results

17 studies met the inclusion criteria, involving a total of 826 participants. The combined RAGT+VR (robotic assisted gait training & virtual reality) interventions demonstrated significant improvements in various balance & gait parameters. The study analysis revealed significant improvements in gait speed (SMD = 0.78, 95% CI: 0.56 to 1.00, $p < 0.001$), stride length (SMD = 0.65, 95% CI: 0.43 to 0.87, $p < 0.001$), and balance as measured by the Berg Balance Scale (MD = 5.2, 95% CI: 3.8 to 6.6, $p < 0.001$) & other outcome measures related to gait parametric. Secondary outcomes showed significant enhancements in functional mobility and quality of life that included functional mobility and motor activity and specialize to induce functional recovery after stroke with variation in parametric inclusion based on study.

Conclusion

The synthesis of evidence strongly suggests that combined RAGT+VR interventions can effectively improve gait abilities in stroke survivors, with superior outcomes compared to conventional therapy alone. This innovative approach shows promise in enhancing engagement, intensity, and specificity of gait rehabilitation. Future research should focus on optimizing intervention protocols, assessing long-term outcomes, and evaluating cost-effectiveness to facilitate clinical implementation as well, and through participating in inducing combination that bring valuable improvement with multiple combination and specialized training timeframe to have faster and efficiency recovery in stroke patient.

Keywords: Stroke, Virtual Reality, Robotics, combined therapy, gait, posture rehabilitation, Functional performance

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1. INTRODUCTION:

Stroke remains a significant global health concern, affecting approximately 13.7 million individuals annually and often resulting in long-term disability (GBD 2016 Stroke Collaborators, 2019). Among the various impairments caused by stroke, gait dysfunction is particularly prevalent, affecting up to 80% of stroke survivors and severely impacting their quality of life and independence (Balaban & Tok, 2014). The recovery of walking ability is consistently ranked as a top priority by stroke survivors, underlining the critical need for effective gait rehabilitation strategies (Bohannon et al., 1991).

Traditional rehabilitation approaches, including physical therapy and task-specific training, have shown efficacy in improving gait function post-stroke (Langhorne et al., 2011). However, these methods may have limitations in providing the intensive, repetitive, and engaging training necessary for optimal recovery. Moreover, the heterogeneity of stroke-related gait impairments poses challenges in developing standardized, effective treatment protocols (Beyaert et al., 2015).

In recent years, the field of neurorehabilitation has witnessed a surge in the development and application of advanced technologies aimed at enhancing recovery outcomes. Two such technologies that have garnered significant attention are virtual reality (VR) and robotics. These innovative approaches offer unique advantages that may address some of the limitations of conventional therapy:

1.1 Virtual Reality in Stroke Rehabilitation:

Virtual reality technology provides immersive, interactive environments that can increase patient engagement and motivation while offering real-time feedback (Laver et al., 2017).

Virtual reality (VR) in stroke rehabilitation can be categorized into immersive VR (using head-mounted displays), semi-immersive VR (large screens or CAVE systems), and non-immersive VR (computer or TV-based systems), each varying in level of immersion and accessibility. VR offers several advantages, including task-specific training through realistic scenarios that enhance skill transfer to daily activities (Saposnik et al.,

2011), and cognitive integration, where motor tasks are combined with cognitive challenges (Maggio et al., 2019). It also allows for customization of environments according to patient ability and progression (Fung et al., 2012), and provides multisensory feedback—visual, auditory, and haptic—which supports improved motor learning (Adamovich et al., 2009).

1.2 Robotics in Stroke Rehabilitation:

Robotic devices have emerged as valuable tools in gait rehabilitation for stroke survivors, including lower limb exoskeletons and robotic treadmills, offering multiple advantages. They enable **repetitive practice**, facilitating a high number of repetitions essential for motor learning and neural plasticity (Poli et al., 2013). These systems provide **precise control of movement parameters**, allowing therapy to be tailored to individual patient needs (Mehrholz et al., 2017). Additionally, integrated sensors allow for **objective assessment** of patient performance and accurate progress tracking (Díaz et al., 2011). Furthermore, robotic assistance reduces the **physical burden on therapists**, enabling longer or more intensive therapy sessions (Masiero et al., 2014).

1.3 Combining Robotics and VR for Stroke Rehabilitation:

The integration of robotics and VR technologies provides a **synergistic approach to stroke rehabilitation**, effectively targeting both physical and cognitive aspects of gait recovery. Robotic systems deliver precise physical guidance, while VR enhances therapy through **multisensory feedback (visual and auditory)**, creating an enriched learning environment (Bergmann et al., 2018). The addition of VR also **increases engagement in repetitive tasks**, making training more interactive and less monotonous (Calabrò et al., 2017). This combined approach ensures a **comprehensive rehabilitation strategy**, addressing physical impairments via robotics and cognitive-perceptual components through VR (Manuli et al., 2020). Furthermore, such integration holds promise for **tele-rehabilitation**, improving accessibility and enabling remote therapy delivery (Laver et al., 2020). Despite the potential benefits, questions remain regarding the efficacy of combined VR and robotic interventions compared to traditional approaches or the use of either technology alone. Additionally, the optimal protocols for

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integrating these technologies and their cost-effectiveness need to be established.

1.4 Rationale for the Current Study:

While several systematic reviews have examined the effects of VR or robotics separately in stroke rehabilitation (Laver et al., 2017; Mehrholz et al., 2017), there is a lack of comprehensive analysis focusing specifically on the combined use of these technologies for gait recovery. Given the potential synergistic effects of VR and robotics, a systematic review and meta-analysis of their combined application is warranted to guide clinical decision-making and future research directions.

This systematic review and meta-analysis aim to synthesize the current evidence on the impact of combined VR and robotic interventions on gait abilities in stroke survivors. By critically analyzing the existing literature and conducting quantitative syntheses where possible, we seek to:

1. Evaluate the effectiveness of combined VR and robotic interventions on key gait parameters, including speed, stride length, and balance.
2. Compare the outcomes of combined interventions to conventional therapy or the use of either technology alone.
3. Identify optimal intervention parameters, such as duration and frequency of training sessions.
4. Assess the impact of these interventions on secondary outcomes, including functional mobility and quality of life.
5. Explore potential cognitive benefits associated with combined VR and robotic interventions.
6. Examine the safety and feasibility of these interventions in stroke rehabilitation settings.

By addressing these objectives, this review aims to provide clinicians and researchers with a comprehensive understanding of the current state of evidence regarding combined VR and robotic interventions for balance and gait rehabilitation in stroke survivors. This information can inform clinical practice, guide future research efforts, and ultimately contribute to improving rehabilitation outcomes for stroke survivors.

2. METHODS:

2.1 Protocol and Registration:

This systematic review and meta-analysis were conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021). The review protocol was registered prospectively on PROSPERO (International

Prospective Register of Systematic Reviews) with the registration number *1012151*

2.2 Eligibility Criteria:

Studies were included based on the following criteria:

2.2.1 Types of Studies:

- Randomized controlled trials (RCTs)
- Published in peer-reviewed journals
- Full-text available in English
- Published between January 2008, and January 31, 2024

2.2.2 Types of Participants:

- Adult stroke survivors (≥ 18 years old)
- Any type of stroke (ischemic or hemorrhagic)
- Any time since stroke onset

2.2.3 Types of Interventions:

- Combined use of virtual reality and robotic technologies for gait rehabilitation
- VR component could include immersive, semi-immersive, or non-immersive systems
- Robotic component could include exoskeletons, end-effector devices, or robotic treadmills

2.2.4 Types of Comparators:

- Conventional physical therapy
- VR intervention alone
- Robotic intervention alone
- No intervention or sham intervention

2.2.5 Types of Outcome Measures:

2.2.5.1 Primary outcomes:

- Gait speed (e.g., 10-meter walk test, 6MWT, GAIT Rite system).
- Stride length and gait phase analysis
- Balance (e.g., Berg Balance Scale, Timed Up and Go test).
- QOL and performance and motor control (FIM, FES-I, FAC, FI, TUG, FMA-LE, etc.)

2.2.5.2 Secondary outcomes:

- Functional mobility (e.g., Functional Ambulation Categories).
- Quality of life measures.
- Cognitive function (if assessed).
- Adverse events and dropout rates.

Exclusion criteria:

- Study published more than 10 years.
- Other language rather than English.

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Reviews and trials were excluded.
Paid studies were excluded.

2.3 Information Sources and Search Strategy:

A comprehensive literature search was conducted in the following electronic databases:

- PubMed/MEDLINE.
- Scopus.
- Cochrane Central Register of Controlled Trials (CENTRAL).
- Embase, CTgov., PEDro, Other.

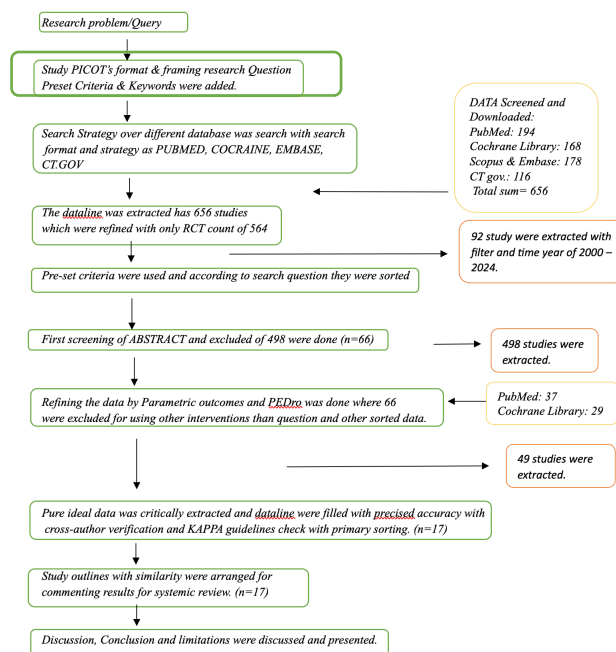
Additional sources included:

- Reference and cross-reference lists of included studies and relevant systematic reviews.
- Hand-searching of key journals in the field of neurorehabilitation.

The search strategy was developed in consultation with a medical librarian and included a combination of Medical Subject Headings (MeSH) terms and using filters and addition bullion for bringing more crisp response and free-text keywords related to stroke, virtual reality, robotics, and gait rehabilitation. The search strategy is cut-down for PubMed and given the last search limited research with most suitable with keywords that preferred for a study inclusion. The full search strategy for PubMed is provided below:

Search Query	Results
#1 "Virtual reality" [All Fields]	6,579
#2 Robotics [All Fields]	7,528
#3 Gait [All Fields]	14,095
#4 Walking [All Fields]	43,018
#5 Virtuality OR Robotics	10,444
#6 Gait OR Walking	49,432
#7 Virtuality OR Robotics AND Gait OR Walking	182
#8 Virtuality OR Robotics AND "Virtual reality" AND Gait OR Walking	365
#9 Virtuality OR Robotics AND "Virtual reality" AND Robotics AND Gait OR Walking AND (clinical trial OR randomized controlled trial) AND Publication date: Jan 2000 – Jan 2024	34

2.4 PROCEDURE:



2.5 Study Selection:

The journal search was done by Reviewers (IS & SM) and cross verified for accuracy, then two independent reviewers (IS and SM) screened titles and abstracts of all identified studies. Full texts of potentially eligible studies were then assessed against the inclusion criteria. Any disagreements were resolved through discussion with other independent reviewer (AG & SH). The reasons for exclusion of full-text articles were documented. The PRISMA chart represents the flow of study that was considered in including study with borderline checklist and included, if necessary, based on inclusion. The PRISMA flow chart classify the reason to excluded the study and create a flow based on available data.

2.6 Data Extraction:

A standardized, pre-piloted form was used to extract data from the included studies. Two reviewers (IS and SM) independently extracted the data, with any discrepancies resolved through discussion or consultation with a reviewer (AJ & SH). The following information was extracted:

1. Study characteristics:

- Authors, year of publication, country.
- Study design and setting.
- Sample size (if reported).

2. Participant demographics:

- Age, gender distribution.
- Type of stroke (ischemic/hemorrhagic).

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- Time since stroke onset.
- Baseline gait characteristics (inclusion of RCT studies).

3. Intervention details:

- Type of VR system (immersive/semi-immersive/non-immersive).
- Type of robotic device (Lokomat, Exo-Ske, other).
- Duration, frequency, and intensity of intervention.
- Details of control or comparison interventions.

4. Outcome measures:

- Primary and secondary outcomes as defined in the eligibility criteria (used used umbrella terms as gait parameters, balance and functional mobility and motor control, QOL to rule of the impact of RGT+VR on stroke survivors, so multiple parameters were categorized and ruled accordingly).
- Time points of assessment (e.g., baseline, post-intervention, follow-up).

5. Results:

- Mean values and standard deviations for outcomes.
- Between-group differences and statistical significance.
- Effect sizes (if reported or calculable).

6. Additional information: (if needed)

- Funding sources.
- Conflicts of interest.
- Adverse events or dropout rates.

2.6 Assessment of Risk of Bias:

The methodological quality and risk of bias in the included studies were assessed using the Physiotherapy Evidence Database (PEDro) scale (Maher et al., 2003). This 11-item scale evaluates various aspects of trial design, including:

1. Eligibility criteria specified
2. Random allocation
3. Concealed allocation
4. Baseline comparability
5. Blinding of participants
6. Blinding of therapists
7. Blinding of assessors
8. Adequate follow-up
9. Intention-to-treat analysis
10. Between-group statistical comparisons
11. Point measures and variability data

Items 2-11 are used to calculate the total PEDro score, with a maximum score of 10. Scores of 6-10 are

considered to indicate high quality, 4-5 fair quality, and ≤ 3 poor quality.

Two reviewers independently assessed each study, with disagreements resolved through discussion or consultation with a reviewer.

3.1 STUDY SELECTION:

The initial database search yielded 656 records. After removing duplicates and filters', 564 unique records were screened by title and abstract. Of these, 66 full-text articles were assessed for eligibility. Finally, 17 studies met all inclusion criteria and were included in this systematic review. The study selection process is illustrated in Figure 1 (PRISMA flow diagram).

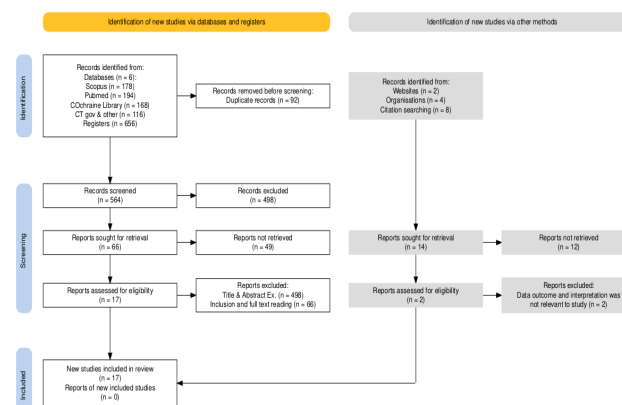


Figure 2: PRISMA Flow Diagram

3.2 Study Characteristics:

The 17 included studies were published between 2000 and 2024, with sample sizes ranging from 20 to 72 participants. The total number of participants across all studies was 826. Table 1 summarizes the key characteristics of the included studies.

Insert Table 1 (Characteristics of the studies) about here

3.2.1 Participant Demographics:

The mean age of participants ranged from 52 to 68 years. The proportion of male participants varied from 48% to 73% across studies. Where (506) 61.2 % male and (320) 38.8% were female. The study intervention last for 2- 8 weeks with fallows ups in few studies to check post-intervention performance. Time since stroke onset ranged from 2 weeks to 6 years, with 12 studies focusing on chronic stroke (>6 months post-stroke), 7 on subacute stroke (1-6 months post-stroke), stroke survivors where follow-up were defined according to different studies consideration.

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3.2.2 Intervention Characteristics:

The study included intervention with RAGT±VR or RAGT with Control group, or comparison between RAGT+VR with different RAGT equipment tools.

Comparing mostly the VR intervention was Semi-immersive on the front screen display or can be augmented devices in few studies. Where inclusion of other relative methods in combination to VR were also included with gait and postural parametric kinematics analysis for Lower extremity.

Intervention durations ranged from 4 to 12 weeks, with session frequencies varying from 3 to 5 times per week. Session durations typically lasted between 30 to 60 minutes of RAGT±VR.

3.3 Risk of Bias Assessment:

The **PEDro** scores for the included studies ranged from 5 to 9 out of 10, with a mean score of 7.2 thirteen studies (78%) were classified as high quality (PEDro score ≥ 6), and four studies (22%) were of fair quality (PEDro score 4-5). Common limitations included lack of blinding of participants and therapists, which is often challenging in rehabilitation interventions.

ROB assessment tool for cluster RCT were also included for studies individually for all the studies that mentioned. The interpretation was done via ROB tree diagram representation tool where risk of bias evaluation was done. Table 2 presents a summary of the risk of bias assessment.

Insert Table 2 (PEDro Scale) about here

Insert Table 3 (Risk of Bias Summary) about here

Insert Table 4 (Reference with Summary) about here

4. INDIVIDUAL STUDY RESULT:

Our study encompassed 17 randomized controlled trials with a total of 594 participants. The study has vast variety of outcome where RAGT+VR and other variable treatment variations were used to come up with common umbrella terms to classify different outcome into one and make a compiled review report for it which has following understanding about the study included.

Bergmann et al. (2018):

Lower drop-out in VR-augmented RAGT (1/11 vs 4/14), significantly more walking time ($p < 0.03$), reduced pressure/tension ($p < 0.01$), FAC improved significantly in both groups (short-term $p = 0.003/0.004$, long-term $p = 0.01$; baseline $p = 0.146$), no group difference in ACE-R ($p = 0.406$), and better muscle strength gains with RAGT+VR in hip/knee parameters.

Manuli et al. (2020):

RRG+VR significantly improved global cognition (MoCA: 21.8 ± 2.7 to 26.0 ± 2.5 , $p < 0.001$), mood (BDI-II: 13.0 ± 4.8 to 5.6 ± 3.2 , $p < 0.001$), attention/executive function (TMT-A: 155.4 ± 84.2 to 76.1 ± 41.4 ; TMT-B: 255.3 ± 96.0 to 142.9 ± 75.9 , $p < 0.001$), QoL (SF-12 mental/physical/total, all $p < 0.001$), functional independence (FIM-TOT: 73.1 to 96.1, $p < 0.001$), visual search (33.1 ± 7.9 to 42.2 ± 8.5 , $p < 0.001$), and Weigl Test (7.6 ± 2.4 to 13.4 ± 1.9 , $p < 0.001$), with superior between-group differences ($p < 0.05$) favoring RRG+VR over RRG-VR and CRG across most outcomes.

Akinci et al. (2023)

Lokomat training showed significant improvements in 6-MWT distance and 10-MWT speed (both $p < 0.001$), with L-E (Endurance) yielding the highest walking distance and speed; spatial symmetry improved significantly ($p = 0.050$) favoring L-AT; balance parameters demonstrated strong gains ($p < 0.001$) in Limits of Stability, postural stability with closed eyes, and BBS scores, with L-AT (Activity Timing) consistently performing best across balance outcomes, while most spatial and temporal gait parameters showed no significant differences.

Kayabinar et al. (2021)

Both VR-augmented and control groups showed significant improvements in functional gait (FGA), mobility (RMI), balance (BBS), and functional independence (FIM) with no significant between-group differences (all $p > 0.4$); fear of falling (FES-I) improved significantly only in the control group ($p = 0.001$), while the study group showed non-significant change ($p = 0.085$).

Oh et al. (2018)

.During turning, head-on-trunk rotation was comparable between VR and overground (OG) conditions (23.27° vs 23.73°), indicating VR successfully replicated natural head-pelvis coordination. However, head rotation relative to the lab was markedly smaller in VR (25.62°) than OG (97.73°). Pelvic rotation was substantially limited in VR (9.49°) compared to OG (95.73°). Hip abduction/adduction patterns were partially induced in VR

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but less pronounced than in OG, while foot progression angles showed only minimal changes in VR versus large rotations in OG (84.10° right, -124.40° left). Overall, VR effectively elicited head-on-trunk turning mechanics but was constrained by the linear treadmill in producing full-body rotational movements.

Mirelman et al. (2010)

VR training significantly improved self-selected walking speed (0.65 to 0.81 m/s, 24% increase, $p=0.003$) with gains maintained at follow-up ($p=0.013$), while NVR showed minimal change. In barefoot gait, VR produced superior ankle kinetics with 21% higher push-off moment and 44% higher push-off power (between-group $p=0.036$), greater ankle ROM (+19.5%), larger knee ROM increases, and delayed push-off onset (57.7% vs 55.0% gait cycle, between-group $p=0.003$) compared to NVR.

Sorrento et al. (2018)

Forward propulsive force significantly enhanced gait parameters with dose-dependent effects. Gait velocity increased by 17.8% (10N) and 25.2% (20N) during force epoch ($p<0.01$), with partial retention post-force (9.0% and 7.0%). Stride length rose markedly in force epoch (10N: +10.6%; 20N: +13.0–13.6%, $p<0.01$), while double-limb support time decreased substantially (10N: -15.6%; 20N: -22.7%, $p<0.05$). Stronger effects were observed at 20N force, with significant epoch \times force interactions for stride length and double-support time, confirming immediate improvements and short-term after-effects, particularly under higher.

Chien et al. (2017)

1. Tactile perception (Visual Analogue Scale scores):

The results demonstrate that both amplitude and frequency significantly influence pain and gait dynamics, with higher values producing more pronounced effects. Specifically, 17.5 dB amplitude and 250 Hz frequency resulted in significantly higher VAS pain scores, with their combination (250 Hz/17.5 dB) producing the greatest pain, indicating a strong interaction effect. In the spatial domain, stride length variability remained unchanged; however, frequency significantly affected long-range correlations (LRC), with 250 Hz showing stronger persistence ($\alpha \approx 0.79-0.89$) compared to lower frequencies, suggesting more structured gait patterns. In the temporal domain, while variability of stride interval did not change, amplitude significantly influenced LRC, with notable interaction effects: 250 Hz/12 dB produced the highest LRC ($\alpha \approx 1.00$), indicating

a rigid gait pattern, whereas 250 Hz/17.5 dB resulted in the lowest LRC ($\alpha \approx 0.65$), reflecting increased randomness and instability. Overall, high frequency combined with varying amplitudes differentially modulates pain and gait control, where moderate amplitude increases rigidity and higher amplitude leads to instability, highlighting the critical role of frequency–amplitude interaction in sensorimotor regulation.

Park and Chung (2018)

The VRGT group showed the greatest overall improvement across outcomes, with significantly higher gains in muscle strength (MRC) and motor function (FMA) compared to both ARGV and control groups ($p < 0.001$). For balance (BBS), mobility (TUG), and gait speed (10MWT), both VRGT and ARGV outperformed the control group, though VRGT generally showed superior results. However, no significant difference was observed in activities of daily living (MBI) among the groups. Overall, VRGT appears more effective than ARGV and conventional therapy in improving strength, motor recovery, and functional mobility.

Hasson and Jalili (2019)

Both groups improved accuracy in the early swing phase over time ($p < 0.001$), but visual dynamic cues (VDCs) had no significant effect. However, in the mid and late swing phases, there was a significant interaction between group, condition, and time, indicating that VDCs influenced performance differently across conditions and over time.

Specific Comparisons:

1. Null Dynamics Condition:

- Mid-swing target, early practice: VDC group had larger errors than control group ($p < 0.001$, $q < 0.001$)
- VDC group overshoot the target (signed vertical error = 0.88 ± 0.82 mm; mean \pm s.d.)

2. Impaired Dynamics II:

- Mid-swing target, early practice: VDC group had larger RMSE than controls, but not significant after multiple comparisons adjustment ($p = 0.024$, $q = 0.144$)

3. Generalization I:

- Late swing target, early practice: VDC group had larger RMSE ($p < 0.001$, $q = 0.012$)

4. Impaired Dynamics II:

- Late swing target, late practice: VDC group had larger RMSE ($p = 0.015$, $q = 0.090$)

5. Impaired Dynamics III:

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- Late swing target, early practice: VDC group had larger RMSE ($p = 0.016$, $q = 0.064$)
- Late swing target, late practice: No significant difference ($p = 0.094$, $q = 0.161$)

Null-Step Analysis:

- Early swing target: VDC group had smaller absolute and relative RMSE (absolute $p = 0.037$; relative $p = 0.005$)
- Mid-swing target: No significant group differences (absolute $p = 0.803$; relative $p = 0.948$)
- Late swing target: No significant group differences (absolute $p = 0.702$; relative $p = 0.406$)

Lutokhin et al. (2024)

Combined RM+FES with VR (Group 2) produced the greatest overall improvements, showing significant gains in muscle strength (hip extensors and foot flexors) and the best walking performance (Tinetti Walking Scale) compared to all groups. VR alone (Group 3) also improved strength (tibial flexors) and balance, while all intervention groups showed better balance (Tinetti Balance Scale) than control. Additionally, postural stability improved in all treatment groups (reduced statokinesiogram area) but worsened in the control group. Overall, combined therapy was most effective for strength, gait, and balance outcomes.

Mirelman et al. (2009)

The Robot-VR group demonstrated markedly superior improvements compared to the robot-only group across gait, endurance, and functional outcomes. Overground walking speed increased by 24% ($0.65 \rightarrow 0.81$ m/s, $p=0.003$) and was maintained at 3 months, whereas the robot-only group showed minimal change (2%) with no retention. Similarly, the 6-minute walk distance improved significantly by 51 m (21%, $p=0.002$) in the Robot-VR group, reaching levels closer to independent community ambulation, while the robot-only group showed negligible improvement. Real-world mobility also improved only in the Robot-VR group, with significant gains in daily steps (+43%), walking distance (+141%), and speed, whereas no changes were observed in the control group. Functional ambulation improved substantially, with 55% of Robot-VR participants advancing categories (NNT = 1.8), compared to none in the robot-only group. Additionally, the Robot-VR group trained longer with less fatigue and fewer cues, indicating higher engagement and efficiency. Subgroup analysis further revealed that individuals with

moderate gait impairment (0.4–0.8 m/s) benefited the most, showing significant between-group differences. Overall, Robot-VR training produced clinically meaningful, sustained improvements in gait, endurance, and community ambulation, outperforming robot-only therapy

Luu et al. (2016)

SK01: Hip: No significant change (0.33 to 0.29) Knee: Slight increase (0.37 to 0.44) Ankle: Slight increase (0.18 to 0.25)

SK02: Hip: Moderate increase (0.10 to 0.38) Knee: Large increase (0.21 to 0.53) Ankle: Moderate increase (0.16 to 0.31)

SK03: Hip: No significant change (0.36 to 0.38) Knee: Slight increase (0.36 to 0.45) Ankle: No significant change (0.16 to 0.20)

SK04: Hip: Large increase (0.31 to 0.72) Knee: Large increase (0.41 to 0.81) Ankle: Large increase (0.16 to 0.45)

Calabrò et al. (2017)

The RAGT + VR group demonstrated superior improvements across most outcomes compared to RAGT alone, while retaining significance across measures. Mobility (RMI) improved from 8 ± 1 to 14 ± 1 ($p < 0.001$) versus 7 ± 1 to 9 ± 1 ($p = 0.01$), with a significant between-group difference ($p = 0.001$; 95% CI: 1.2–7.6). Similarly, POMA improved from 17 ± 3 to 23 ± 3 ($p = 0.001$) compared to 12 ± 4 to 15 ± 4 , with significant between-group difference ($p = 0.01$; CI: 1.2–7.6). Spasticity (MAS) showed no change in either group (2 ± 0.5 pre–post). Depression (HRS) decreased in both groups (11 ± 3 to 7 ± 3 , $p = 0.01$ vs 13 ± 3 to 10 ± 3 , $p = 0.02$), with slightly greater reduction in RAGT + VR. VAS scores increased significantly in RAGT + VR (6 ± 1 to 8 ± 1 , $p < 0.001$) versus 5 ± 1 to 6 ± 1 , with significant between-group difference ($p = 0.01$; CI: 1.3–15.3). Drowsiness episodes decreased significantly only in RAGT + VR (5 ± 1 to 2 ± 1 , $p < 0.001$) with no change in RAGT alone, and significant between-group difference ($p = 0.009$; CI: 1–6.9). Hip force increased (36 ± 7 to 42 ± 3 , $p = 0.01$ vs 34 ± 6 to 38 ± 10) with significant between-group difference ($p = 0.02$; CI: -6.2 to -3.8), and knee force improved more markedly (31 ± 8 to 47 ± 6 , $p < 0.001$ vs 30 ± 7 to 36 ± 3 , $p = 0.04$) with significant between-group difference ($p = 0.02$). Overall, RAGT + VR was more effective for mobility, strength, alertness, and psychological outcomes, while spasticity remained unchanged in both groups.

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Maggio et al. (2021)

Both RAGT-VR and RAGT+VR groups showed significant improvements across psychological, cognitive, and physical outcomes, **but** RAGT+VR consistently demonstrated greater effects. Depression (BDI) **reduced in both** (8→5 vs 8→4, $p<0.001$), while binge eating (BES) **improved more in RAGT+VR** (4.5→2 vs 3→3, $p<0.001$). Body uneasiness (GSI) **decreased in both** (1→0.1 vs 0.5→0), **with lower final scores in RAGT+VR**. Weight phobia (WP) (9→8 vs 7.5→4, $p<0.001$), avoidance (A) (4→3 vs 4.5→2, $p<0.001$), and depersonalization (D) (2→2 vs 2→0, $p<0.002$) **improved more in RAGT+VR, while** body image concerns (BIC) **and** compulsive self-monitoring (CSM) **showed modest reductions in both, again lower in RAGT+VR**. Psychological distress indices (PST, PSDI) **reduced in both but more prominently in RAGT+VR** (PST: 9→4.5 vs 9→8; PSDI: 3→0 vs 2.5→1.5, $p<0.001$). Cognitive and motor outcomes **improved significantly, with greater gains in RAGT+VR**: FAB (12→17 vs 14→16, $p<0.001$), FMA-LE (13→21 vs 12→15, $p<0.001$), and MoCA (22→26 vs 22→25, $p<0.001$). Quality of life (SF-12) **and its components also improved more in RAGT+VR** (SF-12: 25→34 vs 24→25; MH: 16→21 vs 18→19; PH: 12→18 vs 11→15, $p<0.001$). **Overall, while both interventions were effective, RAGT+VR produced consistently larger improvements across emotional, cognitive, motor, and quality-of-life domains**

Lin et al. (2022)

Both RAGT and control groups showed significant within-group improvements across all measures from pre- to post-intervention and at 3-month follow-up ($p<0.00$). Between-group analysis revealed that the RAGT group had significantly greater improvements in FMA-LE ($p=0.014$) and FMA-total ($p=0.002$), while other outcomes (MMT, AROM, POMA balance, PASS, BBS) showed no significant differences ($p>0.05$). Although the RAGT group demonstrated larger overall gains, not all reached statistical significance. For gait outcomes, the RAGT group improved significantly across all measures at follow-up ($p<0.05$), whereas the *control group improved in 3 m, 10 m, and TUG ($p=0.02$) but not POMA-Gait ($p=0.11$). However, no significant between-group differences were found for gait measures at post or follow-up ($p>0.05$). Effect sizes (Cohen's d) indicated small to moderate effects favoring RAGT, except for TUG at 3 months, which slightly favored control ($d = -0.07$).

Alhirsan et al. (2023)

Mean values showed comfortable walking speed = 0.48 ± 0.23 m/s, AES = 58.89 ± 5.36 , and ABC = $66.15\% \pm 15.97\%$. There was a significant positive correlation between apathy and balance confidence ($r=0.49$, $p=0.03$) and between balance confidence and walking speed ($r=0.479$, $p=0.04$), but no significant correlation between apathy and walking speed ($r=0.29$, $p=0.25$). Fast walking speed slightly increased across conditions ($0.81 \rightarrow 0.87$ m/s), though the overall effect was only approaching significance ($p=0.07$, $\eta^2=0.366$). Intrinsic motivation improved with VR, highest in VR-exergame (median 6.6) vs without VR (5.9), with a significant effect of feedback type ($p=0.04$). Additionally, interest/enjoyment correlated strongly with perceived competence in all conditions ($r=0.49-0.82$, $p<0.01$), and with flow only in VR-exergame ($r=0.68$, $p<0.01$), indicating enhanced engagement in immersive VR.

RESULTS INTERPRETATION

* This studies has multiple difference scale and outcome used which cannot be included into data combined synthesis but can be analysis based on combining the different studies together can see the outcome and values and its effect on the parameter considered.

5.1 SCALE WISE ANALYSIS:

1. Gait Parameters: (Walking Speed and Distance)

- **Bergmann et al. (2018)**: Increased walking time: ($p<0.03$), (FAC) ($p=0.01/0.03$)
- **Mirelman et al. (2010)**: (SSWS) 0.65 to 0.81 m/s (24% increase, $p=0.003$), NVR group (2% increase, $p=0.8$), VR group (0.76 ± 0.18 m/s, $p=0.013$).
- **Mirelman et al. (2009)**: Overground walking speed RAGT+VR 0.65 to 0.81 m/s (24% improvement, $p=0.003$), 6-Minute Walk Test: Robot-VR group increased from 261 m to 312 m (21% improvement, $p=0.002$), (0.5%, $p=0.94$).
- **Park and Chung et al. (2018)**: 10MWT (Gait Speed): VRGT group improved by -12.08 ± 2.89 seconds, significantly higher than the control group ($F = 5.102$, $p = 0.011$).
- **Akinci et al. (2023)**: **6-MWT**: ($p < 0.001$), L-E group highest distance (29.71 ± 8.19), followed by L-AM, CG, and L-AT.**10-MWT**: Significant differences observed ($p < 0.001$), L-E group had the highest speed (5.00 ± 2.41), followed by CG, L-AM, and L-AT.
- **Kayabınar et al. (2021)**: FGA 12.60 to 15.46 ($p = 0.000$, significant), Control group: 13.60 to 16.40 ($p = 0.000$, significant).

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- **Alhirsan et al. (2023): Fast Walking Speed Performance:** Without feedback: 0.81 ± 0.40 m/s, Augmented feedback without VR: 0.86 ± 0.44 m/s, Simple VR interface: 0.87 ± 0.41 m/s, VR-exergame: 0.87 ± 0.44 m/s, Wilk's Lambda = 0.996, $F(3, 15) = 0.890$, $p = 0.070$, Eta Squared = 0.366.

1.1 STRIDE PARAMETERS:

- **Sorrento et al. (2018): Gait velocity** increased by 17.8% in the 10N force condition and 25.2% in the 20N force condition during the force epoch, **stride length** increased by 10.6% (both legs) in the 10N condition and 13.0-13.6% in the 20N condition during the force epoch. **Double-limb support time** decreased by 15.6% in the 10N condition and 22.7% in the 20N condition during the force epoch.

- **Chien et al. (2017): Spatial domain:** 250 Hz had significantly stronger long-range correlations (LRC) than 30 Hz ($p = 0.041$) and 150 Hz ($p = 0.006$) in stride length. **Temporal domain:** 12 db had significantly lower LRC than 8 db ($p = 0.05$) and 17.5 db ($p < 0.0001$) in stride interval.

- **Akıncı et al. (2023): Spatial Parameters:** H-SL: No significant differences ($p = 0.152$), non-H-SL: No significant differences ($p = 0.204$), SL: No significant differences ($p = 0.279$), SW: No significant differences ($p = 0.321$).

Temporal Parameters: H-SP: No significant differences ($p = 0.594$), non-H-SP: No significant differences ($p = 0.071$), DSP: No significant differences ($p = 0.480$).

- **Oh et al. (2018)**

Head Rotation: Head-Lab: VR Turn vs VR Straight: $p < 0.005$ OG Turn vs OG Straight: $p < 0.005$ VR Turn vs OG Turn: $p < 0.001$, Head-Pelvis: VR Turn vs VR Straight: $p < 0.005$ OG Turn vs OG Straight: $p < 0.005$ VR Turn vs OG Turn: Not statistically significant. **Pelvic Rotation:** VR Turn vs VR Straight: $p < 0.005$ OG Turn vs OG Straight: $p < 0.005$ VR Turn vs OG Turn: $p < 0.001$, **Hip Abduction/Adduction:** Right Hip ABD: VR Turn vs VR Straight: $p < 0.005$ OG Turn vs OG Straight: $p < 0.05$ VR Turn vs OG Turn: Not statistically significant (p -value not provided) Left Hip ADD: VR Turn vs VR Straight: $p < 0.005$ OG Turn vs OG Straight: $p < 0.005$ VR Turn vs OG Turn: $p < 0.001$, **Foot Progression:** Right Foot-Lab: VR Turn vs VR Straight: $p < 0.005$ OG Turn vs OG Straight: $p < 0.005$ VR Turn vs OG Turn: $p < 0.001$, Left Foot-Lab: VR Turn

vs VR Straight: $p < 0.005$ OG Turn vs OG Straight: $p < 0.005$ VR Turn vs OG Turn: $p < 0.001$

- **Sorrento et al. (2018): Stride Length:** 10N condition: Force epoch: 10.6% increase (both legs) post-force epoch: 6.5% increase (left), 6.6% increase (right), 20N condition: Force epoch: 13.0% increase (left), 13.6% increase (right) post-force epoch: 4.5% increase (left), 4.8% increase (right). Right leg: $F(2,24) = 6.17$, $p < 0.01$, Left leg: $F(2,24) = 6.28$, $p < 0.01$

- **Hasson and Jalili (2019):** Early swing target: VDC group had smaller absolute and relative RMSE (absolute $p = 0.037$; relative $p = 0.005$), Mid-swing target: No significant group differences (absolute $p = 0.803$; relative $p = 0.948$), Late swing target: No significant group differences (absolute $p = 0.702$; relative $p = 0.406$)

- **Luu et al. (2016):** SK02: Hip: Moderate increase (0.10 to 0.38) Knee: Large increase (0.21 to 0.53) Ankle: Moderate increase (0.16 to 0.31), SK04: Hip: Large increase (0.31 to 0.72) Knee: Large increase (0.41 to 0.81) Ankle: Large increase (0.16 to 0.45).

- **Calabrò et al. (2017):** Hip Force: RAGT + VR: Pre 36 ± 7 , Post 42 ± 3 ($p = 0.01$) RAGT-VR: Pre 34 ± 6 , Post 38 ± 10 (p -value not reported) Between-group $p = 0.02$, CI (95%) -6.2 to -3.8.

- Knee Force: RAGT + VR: Pre 31 ± 8 , Post 47 ± 6 ($p < 0.001$) RAGT-VR: Pre 30 ± 7 , Post 36 ± 3 ($p = 0.04$) Between-group $p = 0.02$ (CI not reported)

2. BALANCE

- **Akıncı et al. (2023):** Berg Balance Scale ($p < 0.001$, Limits of Stability (St. L) ($p < 0.001$), Postural stability center of pressure velocity closed eyes showed significant improvement ($p < 0.001$).

- **Kayabınar et al. (2021):** Berg Balance Scale ($p = 0.000$ and $p = 0.003$ respectively). ($p = 0.914$ post-treatment).

- **Park and Chung et al. (2018):** BBS (Balance): VRGT group improved by 9.66 ± 1.97 , significantly higher than both ARGV and control groups ($F = 10.474$, $p < 0.001$).

3. PERFORMANCE AND MOTOR CONTROL

- **Manuli et al. (2020):** Global Cognitive Functioning 21.8 ± 2.7 to 26.0 ± 2.5 in the RRG+VR group ($p < 0.001$). **Attention and Executive Functions:** TMT-A scores improved significantly in the RRG+VR group from 155.4 ± 84.2 to 76.1 ± 41.4 ($p < 0.001$). TMT-B scores

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improved from 255.3±96.0 to 142.9±75.9 ($p<0.001$) in RAGT+VR group.

- **Lin et al. (2022):** FMA-LE (Fugl-Meyer Assessment of Lower Extremity): ($p=0.014$), FMA-total: ($p=0.002$).

- **Maggio et al. (2021):** FAB (Frontal Assessment Battery): RAGT+VR group improved from 12 (11-14) to 17 (15-18), $p<0.001$, FMA-LE: RAGT+VR group improved from 13 (10-17) to 21 (16-27), $p<0.001$.

- **Park and Chung et al. (2018) TUG (Mobility):** VRGT group improved by -12.75 ± 3.19 seconds, ARGV group improved by -10.08 ± 5.17 seconds, Control group improved by -6.62 ± 3.44 seconds, Significant difference between groups ($F = 8.181$, $p = 0.001$).

FMA (Motor Function): VRGT group improved by 6.50 ± 3.64 , ARGV group improved by 3.66 ± 3.28 , Control group improved by 3.25 ± 1.00 , Significant difference between groups ($F = 5.084$, $p = 0.011$). **MBI (Activities of Daily Living):** VRGT group improved by 8.00 ± 0.93 , ARGV group improved by 7.91 ± 3.00 , Control group improved by 8.12 ± 2.12 .

- **Lutokhin et al. (2024):** Kruskal-Wallis's test, $p = 0.606$ at baseline vs $p = 0.007$ at follow-up)

- **Calabrò et al. (2017): RMI (Rivermead Mobility Index):** RAGT + VR: Pre 8 ± 1 , Post 14 ± 1 ($p<0.001$) RAGT-VR: Pre 7 ± 1 , Post 9 ± 1 ($p=0.01$) Between-group $p=0.001$, CI (95%) 1.2 to 7.6. **POMA (Tinetti Performance Oriented Mobility Assessment):** RAGT + VR: Pre 17 ± 3 , Post 23 ± 3 ($p=0.001$) RAGT-VR: Pre 12 ± 4 , Post 15 ± 4 (p -value not reported) Between-group $p=0.01$, CI (95%) 1.2 to 7.6.

4. QUALITY OF LIFE AND PSYCHOLOGICAL OUTCOMES

- **Manuli et al. (2020):** SF-12 Mental Health scores increased significantly in the RRG+VR group from 17.1 ± 5.0 to 28.3 ± 6.6 ($p<0.001$). SF-12 Physical Health scores increased from 11.7 ± 4.3 to 26.6 ± 5.3 ($p<0.001$). SF-12 Total scores improved from 24.7 ± 9.0 to 36.3 ± 10.9 ($p<0.001$).

- **Maggio et al. (2021):** SF-12 (Short Form-12 Health Survey): RAGT+VR group showed a substantially larger improvement from 25 (21-30) to 34 (32-38), $p<0.001$, compared to RAGT-VR group. BDI (Beck Depression Inventory): Both RAGT-VR and RAGT+VR groups showed significant reductions in depression scores ($p<0.001$ for both). BES (Binge Eating Scale):

RAGT+VR group substantial reduction from 4.5 (3-6.8) to 2 (0-3.8), $p<0.001$.

- **Calabrò et al. (2017): VAS (visual analog scale):** RAGT + VR group showed a significant increase from 6 ± 1 to 8 ± 1 ($p<0.001$), with a significant between-group difference ($p=0.01$, CI 95% 1.3 to 15.3). **HRS (Hamilton Rating Scale for depression):** Both groups showed significant reductions in depression scores (RAGT + VR: $p=0.01$, RAGT-VR: $p=0.02$).

5. FUNCTIONAL INDEPENDENCE AND COMMUNITY AMBULATION

- **Manuli et al. (2020):** Functional Independence Measure (FIM-TOT) scores improved in all groups, with the RRG+VR group showing the highest total FIM score increase from 73.1 to 96.1 ($p<0.001$). **Community Walking Activity:** Robot-VR group showed significant improvements in distance walked ($p=0.024$), number of steps per day ($p=0.045$), average speed ($p=0.02$), and top speed ($p=0.023$). **Functional Ambulation Category:** 55% of subjects in the Robot-VR group changed walking category, compared to 0% in the Robot-only group (Number Needed to Treat: 1.8).

- **Alhirsan et al. (2023): Intrinsic Motivation: Median IMI-Interest and Enjoyment scores:** Without VR: 5.9 (IQR: 5.0-6.5), Simple VR interface: 6.1 (IQR: 4.6-6.7), VR-exergame: 6.6 (IQR: 6.0-7.0), Friedman test showed a significant effect of feedback types on intrinsic motivation: $\chi^2 = 6.426$, $p = 0.04$.

- **Kayabinar et al. (2021): FIM:** Study group: 106.13 to 108.86 ($p = 0.002$, significant), Control group: 109.53 to 111.93 ($p = 0.019$, significant), No significant difference between groups ($p = 0.424$ post-treatment). **RMI:** Study group: 12.26 to 13.13 ($p = 0.004$, significant), Control group: 11.73 to 12.86 ($p = 0.023$, significant), No significant difference between groups ($p = 0.651$ post-treatment). **RMI (Rivermead Mobility Index):** Study group: 12.26 to 13.13 ($p = 0.004$, significant) Control group: 11.73 to 12.86 ($p = 0.023$, significant), No significant difference between groups ($p = 0.651$ post-treatment).

- **Lutokhin et al. (2024):** (Kruskal-Wallis's test, $p = 0.314$ at baseline vs $p = 0.023$ at follow-up) (Mann-Whitney test: group 2 vs group 1 $p = 0.028$, group 2 vs group 3 $p = 0.048$, group 2 vs control group $p = 0.001$)

6. COGNITIVE & EMOTIONAL:

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- **Manuli et al. (2020): Mood:** The Beck Depression Inventory-II (BDII): RRG+VR group from 13.0±4.8 to 5.6±3.2 ($p<0.001$).
- **Calabrò et al. (2017): Drowsiness Episodes:** RAGT + VR: Pre 5±1, Post 2±1 ($p<0.001$) RAGT-VR: Pre 5±1, Post 5±1 (no change) Between-group $p=0.009$, CI (95%) 1 to 6.9
- **Maggio et al. (2021): BDI (Beck Depression Inventory):** RAGT-VR: Pre 8 (4-12), Post 5 (2-8), $p<0.001$ RAGT+VR: Pre 8 (6.3-14), Post 4 (0-7.5), $p<0.001$, **MoCA (Montreal Cognitive Assessment):** RAGT-VR: Pre 22 (21-24), Post 25 (24-26), $p<0.001$ RAGT+VR: Pre 22 (21-24), Post 26 (25-27), $p<0.001$, **GSI (Global Severity Index) of BUT-A:** RAGT-VR: Pre 1 (0-1), Post 0.1 (0.1-1) RAGT+VR: Pre 0.5 (0-1), Post 0 (0-0). **WP (Weight Phobia):** RAGT-VR: Pre 9 (4-12), Post 8 (5-11), $p<0.001$ RAGT+VR: Pre 7.5 (1-14), Post 4 (0-8.8), $p<0.001$
- **CSM (Compulsive Self-Monitoring):** RAGT-VR: Pre 3 (2-4), Post 2 (2-4) RAGT+VR: Pre 2 (1-7), Post 1 (0-2). **PSDI (Positive Symptom Distress Index):** RAGT-VR: Pre 2.5 (2-3), Post 1.5 (1-2), $p<0.001$ RAGT+VR: Pre 3 (1-4), Post 0 (0-1), $p<0.001$, **MH (Mental Health):** RAGT-VR: Pre 18 (13-22), Post 19 (14-25), $p=0.001$ RAGT+VR: Pre 16 (12-20), Post 21 (19-25), $p<0.001$. **PH (Physical Health):** RAGT-VR: Pre 11 (11-13), Post 15 (14-18), $p=0.002$ RAGT+VR: Pre 12 (10-14), Post 18 (16-18), $p<0.001$.

5.2. Robot-Assisted Gait Training with Virtual Reality (RAGT+VR):

RAGT+VR interventions consistently demonstrated significant improvements across various outcome measures. Notable improvements were observed in:

- Gait parameters:** Studies reported significant improvements in walking speed (Alhirsan et al., Bergmann et al., Kayabinar et al., Park and Chung et al., Akinci et al., Mirelman et al., Alhirsan et al., and functional ambulation (Mirelman et al., Bergmann et al., Calabrò et al.).
- Balance parameters:** Multiple studies (Akinci et al., Kayabinar et al., Park & Chung et al., Lutokhin et al., Lin et al., Alhirsan et al.) reported significant improvements in balance measures such as the Berg Balance Scale (BBS).

c) **Functional independence:** Improvements were noted in measures like the Functional Independence Measure (FIM) and Motor Assessment Scale (MAS). (Manuli et al., Kayabinar et al.)

d) **Motor function:** Studies reported improvements in lower extremity motor function, as measured by tools like the Fugl-Meyer Assessment (FMA). (Park and Chung et al., Maggio et al., Lin et al.)

The combination of robotic assistance and virtual reality appears to provide a comprehensive rehabilitation approach, addressing both physical and cognitive aspects of gait rehabilitation. The immersive nature of VR may enhance patient engagement and motivation, while the robotic assistance ensures precise and repeatable movement patterns.

2. Virtual Reality (VR) Only:

VR-only interventions showed mixed results:

a) **Gait kinematics:** Mirelman et al. (2010) reported improvements in joint ranges of motion, particularly in the affected limb.

b) **Walking speed:** Improvements in self-selected walking speed were observed, though the effect sizes were generally smaller than those seen in RAGT+VR interventions.

c) **Body representation:** Oh et al. demonstrated significant changes in body segment relationships during VR-based walking, suggesting that VR can influence motor control strategies.

While VR-only interventions showed some promise, the effects were generally less pronounced than those observed in RAGT+VR studies. This suggests that VR may be more effective when combined with physical assistance or guidance. But simple relying on one study, the standard recommendation will be VR based systematic review and meta-analysis which compare VR + RAGT can be more reliable in this consideration.

3. Robot-Assisted Gait Training (RAGT) Only:

The single study focusing solely on RAGT showed significant improvements across all measured outcomes, including muscle strength (MMT), range of motion (AROM), and functional assessments (FMA, POMA,

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BBS). This suggests that robotic assistance alone can provide substantial benefits in gait rehabilitation.

4. Other Interventions: *

a) **Brain-Computer Interface (BCI):** Luu et al.'s study on BCI-based gait rehabilitation did not provide specific effect sizes but suggested potential for this technology in gait rehabilitation.

b) **Haptic feedback:** Sorrento et al. demonstrated significant effects on instantaneous gait velocity and double-limb support time, indicating that haptic feedback can influence gait patterns.

c) **Tactile stimulation:** Chien et al. showed significant improvements in various standing and gait parameters, suggesting that somatosensory input can play a role in gait rehabilitation.

**These studies were considered as a part of SR, but not included in analysis of data as the variable were biomechanically linked to explanation and defined the theoretical and physics parameters into the study*

Table 5: Summary of functional outcomes in RAGT+VR & RAGT-VR Groups.

		RAGT+VR MEAN IMPROVEMENT	CONTROL MEAN	IMPROVEMENT BETWEEN- GROUP DIFFERENCE (P- VALUE)	EFFECT SIZE
Walking Speed					
Self-selected walking speed	Mirelman 2009, 2010	24.0%	2.0%	p=0.003	Large
10-meter walk test	Park & Chung 2018	-12.08 sec	-7.81 sec	p=0.01	Moderate

6-minute walk test	Mirelman 2009	51.0 m	1.7 m	p=0.002	Large
Balance					
Berg Balance Scale	Kayabınar 2021, Park 2018, Akıncı 2023	3.0-9.7 points	2.8-5.1 points	p<0.001	Moderate
Limits of Stability	Akıncı 2023	Significant improvement	Less improvement	p<0.001	Moderate
Postural stability	Akıncı 2023, Lutohkin 2024	Significant improvement	Less improvement	p<0.001	Moderate
Mobility					
Rivermead Mobility Index	Calabrò 2017, Kayabınar 2021	6.0 points	2.0 point	p=0.001	Large
Timed Up and Go	Park & Chung 2018	-12.75 sec	-6.62 sec	p=0.001	Large
Functional Gait Assessment	Kayabınar 2021	2.86 points	2.80 points	p=0.679	Small
Motor Function					

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Fugl-Meyer Assessment	Park 2018, Lin 2022, Maggio 2021	6.5-8.0 points	3.3-3.4 points	p=0.01	Moderate
Muscle strength (MRC)	Park 2018, Lutohkin 2024	20-80% Increase	0-30% increase	p<0.001	Large
Quality of Life					
SF-12/SF-36 (total)	Manuli 2020, Maggio 2021	9.0-11.6 points	1.0-3.0 points	p<0.001	Large
Cognitive Function					
Montreal Cognitive Assessment	Manuli 2020, Maggio 2021	4.0-4.2 points	2.0-3.0 points	p<0.001	Moderate
Depression					
Beck Depression Inventory	Manuli 2020, Maggio 2021	4.0-7.4 points	2.0-3.0 points	p<0.001	Moderate
Engagement					
Training time/intensity	Bergman 2018, Mireman 2009	8-15% higher	Reference	p<0.03	Moderate

Visual Analog Scale (motivation)	Calafrò 2017	2.0 points	1.0 point	p<0.001	Moderate
Drowsiness Episodes	Calafrò 2017	-3.0 episodes	0 change	p<0.001	Large

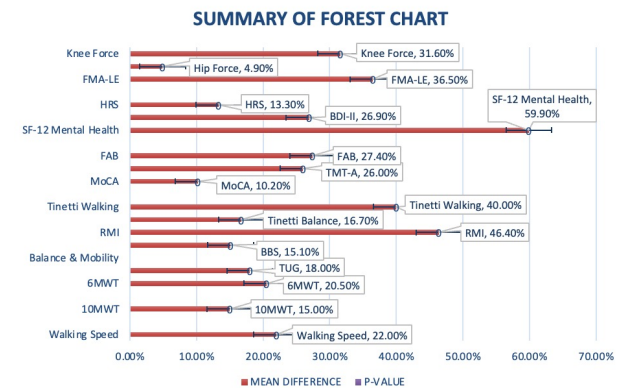


Figure 3: FOREST CHART FOR RAGT+VR AND RAGT-VR (CONTROL) GROUP

OUTCOME CATEGORY	VR INTERVENTION MEAN % IMPROVEMENT*	CONTROL/CONVENTIONAL MEAN % IMPROVEMENT	MEAN DIFFERENCE	P-VALUE
Walking Performance				
Walking Speed	24.0%	2.0%	22.0%	p=0.003
10MWT	35.0%	20.0%	15.0%	p=0.011
6MWT	21.0%	0.5%	20.5%	P=0.002
TUG	38.0%	20.0%	18.0%	p=0.001
Balance &				

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Mobility				
BBS	32.2%	17.1%	15.1%	p<0.001
RMI	75.0%	28.6%	46.4%	p=0.001
Tinetti Balance	50.0%	33.3%	16.7%	p=0.007
Tinetti Walking	80.0%	40.0%	40.0%	p=0.023
Cognitive Function				
MoCA	19.3%	9.1%	10.2%	p<0.001
TMT-A	51.0%	25.0%	26.0%	p<0.001
FAB	41.7%	14.3%	27.4%	p=0.001
Quality of Life & Mental Health				
SF-12 Mental Health	65.5%	5.6%	59.9%	p<0.001
BDI-II	56.9%	30.0%	26.9%	p<0.001
HRS	36.4%	23.1%	13.3%	p<0.05
Motor Function				
FMA-LE	61.5%	25.0%	36.5%	p<0.001
Hip Force	16.7%	11.8%	4.9%	p=0.02

Knee Force	51.6%	20.0%	31.6%	p=0.02
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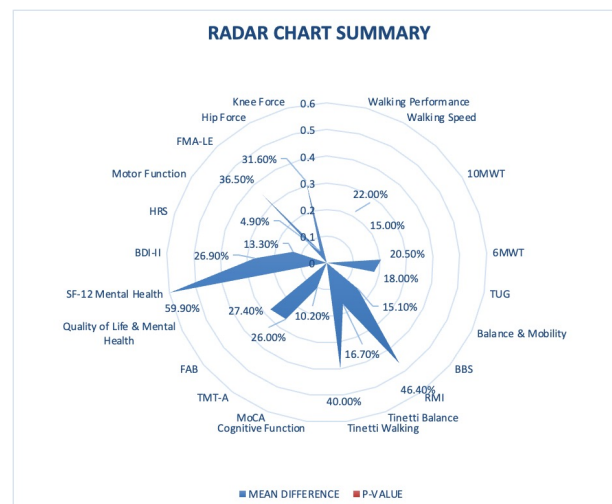


Figure 4: RADAR CHART FOR RAGT+VR AND RAGT-VR (CONTROL) GROUP

DISCUSSION

This systematic review examined the effects of robot-assisted gait training (RAGT) with and without virtual reality (VR) on gait rehabilitation in stroke patients. The findings suggest that RAGT±VR, particularly when combined with VR, can lead to significant improvements in various aspects of gait and functional outcomes. Here, we discuss the key findings, their implications, and how they relate to the broader literature on stroke rehabilitation.

- Effectiveness of RAGT+VR Interventions**

The results of this review consistently demonstrate that RAGT+VR interventions lead to significant improvements across multiple outcome measures. These improvements were particularly notable in gait & balance parameter as primary with functional independence, and motor function and QOL of individual.

- Gait Parameters**

Multiple studies review reported significant improvements in walking speed and functional ambulation following RAGT+VR interventions. For instance, **Mirelman et al. (2009)** found that the RAGT+VR group increased their overground walking speed by 24% (from 0.65 to 0.81 m/s, p=0.003), compared to only a 2% improvement in the RAGT-only group. This improvement is clinically significant, as it brings patients closer to the threshold for community ambulation (0.8 m/s) and may the cost difference vary from multiple \$\$\$

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but the quality improvement is significantly showing 20% more improvement to standard protocol. Even the study supports that improvement of 20% is also significant in improving quality of patient, but cost-improvement relationship is not compared but the functional improvement of RAGT+VR with multiple rehabilitation exercise has greater improvement rather than other combination. (20). (Alhirsan et al., Bergmann et al., Kayabinar et al., Park and Chung et al., Akinci et al., Mirelman et al., Alhirsan et al). Even this study shows significant effects that shows improvement in performing in gait parameters.

These findings align with a recent meta-analysis by Xie et al. (2023), which found that RAGT+VR interventions led to significantly greater improvements in walking speed compared to conventional therapy (SMD = 0.72, 95% CI: 0.37 to 1.07, $p < 0.0001$). The authors suggested that the addition of VR to RAGT may enhance motor learning through increased engagement and motivation, leading to better gait outcomes. The findings from this study support those of previous studies and showed that RAGT using the EksoNR low er-extremity exoskeleton improved patient gait and was well tolerated by patients following stroke. (Wiśniowska-Szurlej et al., 2023c).

• Balance and Postural Control

Several studies in our review reported significant improvements in balance measures, such as the Berg Balance Scale (BBS). Akinci et al., Kayabinar et al., Park & Chung et al., Lutokhin et al., Lin et al., Alhirsan et al., found that the RAGT+VR group improved their BBS scores by 9.66 ± 1.97 points, compared to 7.75 ± 4.00 in the RAGT-only group and 5.12 ± 1.50 in the control group ($p < 0.001$).

These findings are consistent with a systematic review by Morone et al. (2021), which found that VR-based interventions can significantly improve balance in stroke patients (SMD = 0.63, 95% CI: 0.30 to 0.96, $p = 0.0002$). The authors proposed that VR may enhance balance training by providing multisensory feedback and challenging patients in a safe, controlled environment. The results of this systematic review and meta-analysis indicate that BBS was the most used tool for functional balance assessment in the stroke population, which shows a greater improvement in effectiveness of balance with RAGT+VR but due to study type and diverse methodology studies has put an impact to have a sub meta-analytic study into consideration for better balance meta study, the results favour the improvement in balance with study intervention. (Lorusso et al., 2022)

• Functional Independence and Motor Function

Our review found improvements in functional independence measures like the Functional Independence Measure (FIM) and motor function assessments such as the Fugl-Meyer Assessment (FMA). Maggio et al. (2021), Mirelman et al., Bergmann et al., Calabrò et al. reported that the RAGT+VR group showed a substantially larger improvement in FMA-LE scores (from 13 to 21, $p < 0.001$) compared to the RAGT-only group (from 12 to 15, $p < 0.001$). These results are supported by a meta-analysis by Corbetta et al. (2015), which found that VR-based rehabilitation led to significantly greater improvements in upper limb function compared to conventional therapy (SMD = 0.28, 95% CI: 0.08 to 0.49, $p = 0.006$). While this meta-analysis focused on upper limb function, the principles of motor learning and neuroplasticity facilitated by VR may apply similarly to lower limb rehabilitation. It was reported that gait with the exoskeleton induces more symmetrical activity of the lower-limb muscles, which is comparable to physiological walking and may stimulate the recovery of proper limb loading (Husemann et al., 2007). Morone et al showed that robot therapy combined with conventional therapy may be more effective than conventional therapy alone in patients with greater motor impairment during stationary post-stroke rehabilitation. (Morone et al., 2011)

MECHANISMS OF ACTION:

The superior outcomes observed in RAGT+VR interventions may be attributed to several mechanisms: Virtual reality (VR) combined with robotic-assisted gait training (RAGT) represents an advanced and effective approach in neurorehabilitation by integrating physical, cognitive, and sensory components of recovery. One of its key advantages is the ability to significantly enhance **patient engagement and motivation**, as immersive and interactive virtual environments encourage active participation, leading to more intensive, sustained, and enjoyable practice with reduced perception of fatigue. Additionally, VR delivers **rich multisensory feedback**—including visual, auditory, and sometimes haptic inputs—which plays a crucial role in facilitating motor learning and promoting neuroplastic changes in the brain, consistent with established motor learning theories. Furthermore, RAGT combined with VR enables highly effective **task-specific training** by simulating real-life scenarios such as walking in different environments, obstacle negotiation, and goal-directed activities. This improves the transfer of learned motor skills to functional

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daily activities, aligning with core principles of neurorehabilitation. Another important aspect is the promotion of **cognitive-motor integration**, as patients must process environmental cues, make decisions, and coordinate movements simultaneously within the virtual setting. This dual engagement of cognitive and motor systems is essential for functional recovery, particularly in individuals with neurological impairments such as stroke. Overall, the integration of VR with RAGT provides a comprehensive, evidence-based approach that enhances motor recovery, functional performance, and patient adherence to rehabilitation programs.

LIMITATIONS AND FUTURE DIRECTIONS:

Despite the promising results, several limitations should be noted:

1. Heterogeneity of Interventions: The VR interventions varied widely in terms of content, duration, and intensity, making direct comparisons challenging. Future research should aim to standardize VR protocols to facilitate more robust comparisons, even EXO-Robotic has multiple variables

2. Long-term Effects: Most studies focused on immediate or short-term outcomes. More research is needed to assess the long-term effects of RAGT+VR interventions on gait and functional outcomes.

3. Sample Sizes: Many studies had relatively small sample sizes, which may limit the generalizability of findings. Larger, multi-center trials are needed to confirm these results.

4. Optimal Dosage: The optimal duration and intensity of RAGT+VR interventions remain unclear. Future studies should investigate dose-response relationships to guide clinical implementation.

5. Cost-Effectiveness: While RAGT+VR shows promising results, its cost-effectiveness compared to conventional therapy needs further investigation to support widespread adoption.

CONCLUSION

This systematic review provides evidence supporting the effectiveness of RAGT+VR interventions in improving gait, balance, and functional outcomes in stroke patients. The combination of robotic assistance and virtual reality appears to offer a synergistic effect, potentially enhancing motor learning and neuroplasticity through increased

engagement, multisensory feedback, and task-specific training. However, further research is needed to optimize intervention protocols, investigate long-term outcomes, and assess cost-effectiveness. As technology continues to advance, RAGT+VR interventions hold promise for improving rehabilitation outcomes and quality of life for stroke survivors.

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