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**Effectiveness of Neurorehabilitation Interventions on Functional Recovery After Stroke: A Meta-Analysis of Randomized Controlled Trials**

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***Abstract***

*Neurorehabilitation is vital for restoring motor function and independence following stroke, yet the comparative effectiveness of various interventions remains uncertain. This meta-analysis synthesized data from 15 randomized controlled trials conducted between 2015 and 2025 to evaluate the impact of physiotherapy exercises, robot-assisted therapy, repetitive transcranial magnetic stimulation (rTMS), virtual reality (VR), and early rehabilitation nursing on functional recovery post-stroke. The analysis included 3,475 participants and assessed primary outcomes such as the Fugl–Meyer Assessment for upper extremity (FMA-UE), the Barthel Index for activities of daily living, and the Action Research Arm Test (ARAT). Results indicated that early rehabilitation nursing produced the greatest improvements in both motor recovery and functional independence (FMA-UE MD = 4.41, Barthel Index MD = 7.72), while robot-assisted therapy also showed significant, though more modest, gains in motor function (FMA-UE MD = 3.45). rTMS failed to demonstrate statistically significant benefits, and VR-based interventions yielded smaller yet positive effects, particularly in the subacute phase. Importantly, physiotherapy exercises—comprising aerobic conditioning, strength and flexibility training, task-specific practice, balance re-education, and neuromuscular retraining—were found to be consistently effective and enhanced the impact of other interventions when combined. Lower-limb robotic exoskeletons significantly improved balance and ambulation (e.g., Berg Balance Scale and 6-Minute Walk Test). Overall, the integration of structured physiotherapy exercises with early rehabilitation nursing or robotic interventions offers the most promising outcomes for stroke survivors, particularly when implemented early. These findings support a multimodal, patient-centered approach to post-stroke rehabilitation that leverages traditional physiotherapy alongside technological and nursing-based interventions for optimal recovery.*

***Keywords:*** *Neurorehabilitation, Stroke Recovery, Physiotherapy Exercise, Robot-Assisted Therapy, Repetitive Transcranial Magnetic Stimulation (Rtms), Virtual Reality (VR), Early Rehabilitation Nursing, Fugl-Meyer Assessment (FMA), Barthel Index, Exoskeleton.*

# Introduction

Stroke is one of the fundamental global health issues, and it is still a primary cause of death and long-term disability (Xi et al., 2023). Every year, millions are affected by ischemic or hemorrhagic stroke and although acute medical care has improved, a significant rate of survivors have residual motor deficit, which compromises their ability of undertaking daily activities independently (Kim et al., 2023). Motor impairments, especially those in the upper and lower limbs, may last for several months or years and require long-term rehabilitation and place high socio-economic burdens and caring burden (Aqueveque et al., 2017).

Neuro-rehabilitation is very important in the post-stroke recovery, where the ultimate aim is to reinstate lost motor function and independence in the activities of daily living (ADL) (Veerbeek et al., 2011). The field has seen a very rapid change in recent years with the implementation of new technology-based interventions that should promote neuroplasticity and functional implications (Micera et al., 2020). One of them is robot-assisted therapy, repetitive transcranial magnetic stimulation (rTMS), virtual reality (VR)-based rehabilitation, early rehabilitation nursing interventions, and physiotherapy exercises—all of which have attracted great research interest.

Physiotherapy exercises, including aerobic conditioning, strength training, balance exercises, and task-specific functional training, remain foundational in stroke rehabilitation, helping improve mobility, functional independence, and muscle re-education (Billinger et al., 2014; Winstein et al., 2016). Robot-assisted therapy allows for highly repetitive, task-specific movement training that can be quantified and maintained, the main principle for causing neural reorganization. VR platforms simulate realistic scenarios and give engaging multisensory feedback for the improvement of motor learning and patient motivation. rTMS is a noninvasive brain stimulation procedure that focuses on the balance between the hemispheres and the cortical excitability modulation, supposedly helping in motor recovery (León‐Ruiz et al., 2018). At the same time, early rehabilitation nursing, emphasizing structured, intensive therapy from the acute or early subacute phase, has some potential in averting functional dilapidation and expediting recovery courses.

Even though these interventions have great potential, the results of individual randomized controlled trials (RCTs) were equivocal and sometimes contradictory. Some trials show remarkable improvements in functional outcomes, including Fugl–Meyer Assessment (FMA), Barthel Index, as well as Action Research Arm Test (ARAT), while others elicit little or no effect compared to well-structured conventional therapy. Such disparity in study design, stroke chronicity, period of intervention, and comparator protocol, among others, leads to this inconsistency (Lin et al., 2018). In addition, it is unclear if these advanced interventions are complementary in improving the condition when combined with the traditional therapy or whether they can be used instead (Pollock et al., 2014).

Due to the increasing number of evidence and the clinical significance of optimizing the rehabilitation strategies of a stroke, a thorough review of the literature is needed. The knowledge on the most effective interventions, in what conditions and for which patient groups, can inform clinical practice, policy making, and resource allocation in rehabilitation settings.

**Research Question**

This meta-analysis seeks to address the following core research questions:

1. How effective are neurorehabilitation interventions (physiotherapy exercises, robot-assisted therapy, rTMS, virtual reality, and early rehabilitation nursing) in improving functional outcomes in adult stroke survivors?
2. Do these interventions lead to statistically and clinically significant improvements in key outcome measures such as:
   * Fugl–Meyer Assessment (FMA) for motor recovery
   * Barthel Index for activities of daily living (ADL)
   * Action Research Arm Test (ARAT) for upper limb function?
3. Are certain interventions more effective than others, particularly when considering stroke phase (acute, subacute, chronic) or when used as adjuncts versus standalone therapies?

**Research Objective**

The objective of this meta-analysis is to systematically evaluate the effectiveness of contemporary neurorehabilitation interventions in enhancing functional recovery among adult stroke survivors. Drawing on data from randomized controlled trials published between 2015 and 2025, this study examines the impact of physiotherapy exercises, robot-assisted therapy, repetitive transcranial magnetic stimulation (rTMS), virtual reality (VR)-based rehabilitation, and early rehabilitation nursing interventions. The analysis focuses on key functional outcome measures, including the Fugl–Meyer Assessment for upper extremity motor function (FMA-UE), the Barthel Index for activities of daily living (ADL), and the Action Research Arm Test (ARAT) for arm-specific motor performance. By comparing effect sizes and statistical significance across interventions and control conditions, this review aims to determine which strategies yield clinically meaningful improvements, and under what conditions, such as stroke phase, intervention timing, or use as adjunct versus standalone therapy, these benefits are most pronounced. The findings aim to support evidence-based clinical decision-making and inform the design of future rehabilitation protocols.

**Literature Review**

Stroke continues to be the foremost contributor to adult disability, and a considerable number of survivors become plagued with chronic motor impairments that rob independence and quality of life (Grefkes & Fink, 2020). Although traditional rehabilitative approaches are fundamental, they have difficulty, in most cases, meeting the demand for intensity, specificity, and length of therapy needed in optimizing functional recovery. However, of late, there has been an increase in new neurorehabilitation strategies aimed at promoting post-stroke recovery by exploiting the precepts of neuroplasticity, task-specific training, and cortical modulation (Saikaley et al., 2022).

Among the most essential and foundational methods is physiotherapy exercise, which remains a core component of stroke rehabilitation. Physiotherapy interventions—such as aerobic training, task-specific functional exercises, strength training, and balance activities—are known to improve motor function, gait, cardiovascular fitness, and independence in activities of daily living. These exercises, when implemented early and consistently, help enhance neuroplasticity and reduce complications associated with immobility (Veerbeek et al., 2014; Kwakkel et al., 2015).

Among other innovative techniques, RAT (robot-assisted therapy) has been suggested to be a promising and scalable technique for the delivery of high-volume, task-oriented training. There have been rather limited gains from robotic interventions for the upper limb to motor function, although there are no statistically significant ARAT or Barthel Index benefits in terms of broader functional outcomes concerning enhanced conventional therapy (Bosomworth et al., 2020). Moreover, home-based robotic self-training has not shown better results as compared to standard self-rehabilitation in chronic stroke patients. It appears that the advantage of using robotic therapy is the possibility of providing very controlled doses of movement, yet the added value of robotic therapy may be limited in the chronic stage or compared to similar-intensity conventional therapies (Bertolucci et al., 2018).

By contrast, advanced robotics on the lower limbs have delivered more solid results. In one study, there appeared to be noticeable improvement in balance (BGS), gait distance (6-min walk test), and activities of daily living (BI), especially in the subacute phase (Duret et al., 2019). Such results demonstrate the promise of robotic gait training in particular, when the patients are in the sub-acute phase, where the neuroplasticity and the neurological responsiveness may be at their height (Neves et al., 2023). This step of recovery is in line with the aspects of early motor relearning; repetitive and high-volume exercises can yield robust gains (Siegle et al., 2019).

In contrast, there have been investigations regarding the non-invasive method to modulate cortical excitability and facilitate recovery, which is repetitive transcranial magnetic stimulation (rTMS) (Bassi et al., 2019). More recent trials still indicate inconclusive or modest results. For example, Liao et al. (2017) reviewed rTMS for motor recovery and found only small-to-moderate effect sizes compared to sham stimulation, especially when not combined with other therapeutic modalities. These results raise issues regarding the clinical applicability of low-frequency rTMS, particularly when performed alone, and raise the notion that its efficacy might be determined by variables like lesion locations or neurophysiological biomarkers, requiring more specific stratification in subsequent trials (Guo et al., 2021).

In the same vein, rehabilitation conducted through virtual reality (VR) has demonstrated favorable effects on the upper-limb function and activities of daily living (ADL), especially in combination with traditional therapy in cases of the subacute phase (Cikajlo et al., 2020). However, the diversity of VR devices, protocols, and outcome measures of the studies makes it impossible to draw clear conclusions about the efficacy of VR. Few studies have compared VR to dose-matched conventional therapies; hence, the relative effectiveness of VR is not known (Banduni et al., 2023).

Furthermore, early rehabilitation nursing interventions, especially the ones that involve personalised and structured care of patients, have repeatedly proven to be meaningful when introduced at the acute or early subacute stage (Min et al., 2022). Early interventions were found to remarkably enhance the recovery of the upper-limb motors (based on the Fugl-Meyer Assessment for Upper Extremity, FMA-UE) and functional independence (on the Barthel Index) (Saikaley et al., 2022). These results highlight the importance of early and extensive rehabilitation, at a phase of increased receptivity and plasticity of the brain.

Two main themes come out when synthesizing findings across the studies reviewed. First, the interventions based on timing are an important factor regarding effectiveness because this factor has repeatedly led to larger within-group gains for interventions in the acute and subacute phases as compared to the chronic phase. Second, in a head-to-head test, the best value of novel therapies is frequently seen when they enhance minimal or routine treatment, as opposed to competing against their dose-matched counterparts in a protocolized conventional rehabilitation (Gunduz et al., 2023). This pattern is highlighted in robotics of lower limbs as well as early nursing care—where relevant between-group differences were found, while this is not the case for upper limb robotics or rTMS studies, where the matching of conventional care reduced observed effects (Wu et al., 2021).

Although various systematic reviews examined individual interventions of robotics or brain stimulation, there is a lack of combined synthesis of numerous neurorehabilitation approaches in all stages of stroke (or post-stroke) (Lin et al., 2018). It is this gap that this meta-analysis aims to fill as it offers a direct comparison of physiotherapy exercises, robot-assisted therapy, rTMS, VR, and early nursing interventions with standardized outcomes, and stratified by stroke chronicity (Lin et al., 2018).

For clinical and translational purposes, the findings of this meta-analysis have a significant impact on re-routing rehabilitation pathways and resource utilization (Donoghue et al., 2022). Since more and more healthcare systems implement technological solutions into rehabilitation, the knowledge on the timing of the modalities and contextual factors that optimize their benefits is crucial. Even though more innovations are necessary in the field of neurorehabilitation, these results indicate that timing, intensity, and integration with standard treatment are the principal factors that are often more important than specific modalities for determining functional recovery.

**Gaps in the Literature**

Even though there has been a lot of progress in the area of post-stroke neurorehabilitation research, there are still several important gaps. Most currently published works and reviews address only a single type of intervention, such as robot-assisted therapy or rTMS, rather than comparing the efficacy of different strategies for neurorehabilitation in a common analytical process (Lin et al., 2018). In addition to this, many trials apply minimal or sham control, instead of intensity-matched conventional therapy, which restricts the isolation of the true additive advantage of new modalities (Valkenborghs et al., 2019). In the literature, there is also a noticeable focal point on upper-limb outcomes at the cost of lower-limb function and gait-related metrics, which are pertinent to the considerations of mobility and independence (Winstein et al., 2016). Another gap worth mentioning is the absence of stratified analyses based on stroke chronicity. Few studies examine whether the timing of the intervention (acute, subacute, or chronic phase) moderates the effectiveness of treatment. In addition, variability in tools used for outcome assessment and lack of uniformity in the reporting of clinical significance—for example, minimal clinically important differences (MCID)—make it hard to translate the findings into practice (Smith et al., 2014). Lastly, we find limited information as to how these interventions work within an integrated care system, whether or not such interventions are more effective as supplements to standard therapy or as possible platforms unto themselves. Such limitations demonstrate that there is a need for integrated, comparative analysis that would assess several neurorehabilitation methods with standard outcomes in various patient groups.

**Methodology**

**Study Design**

This meta-analysis adheres to the PRISMA guidelines to ensure a clear, reliable, and reproducible review process. The primary aim was to evaluate the effectiveness of various neurorehabilitation approaches in improving post-stroke functional recovery, with a specific focus on physiotherapy exercises, robot-assisted therapy, rTMS, VR-based rehabilitation, and early rehabilitation nursing. Physiotherapy exercises—including aerobic training, functional strengthening, and balance coordination activities—are foundational components of stroke recovery and were included to assess their relative contribution to motor recovery outcomes. The meta-analysis synthesized data from randomized controlled trials (RCTs) published between January 2015 and January 2025. By pooling evidence from diverse interventions, this study seeks to provide insights into the most effective methods for improving critical post-stroke functions, such as upper-limb motor ability, independence in daily activities, and overall motor performance.

**Search Strategy**

A comprehensive systematic literature search was conducted across five major electronic databases: PubMed, EMBASE, MEDLINE, the Cochrane Central Register of Controlled Trials (CENTRAL), and Web of Science. The search was limited to articles published between January 2015 and January 2025. Key search terms included: "stroke," "neurorehabilitation," "physiotherapy exercises," "robot-assisted therapy," "rTMS," "virtual reality rehabilitation," "early rehabilitation nursing," "functional recovery," "Fugl–Meyer Assessment," "Barthel Index," and "randomized controlled trial." Boolean operators (AND/OR) were used to ensure specificity and accuracy. The reference lists of relevant articles and systematic reviews were manually screened to identify additional eligible studies. The search aimed to identify RCTs that evaluated the effectiveness of neurorehabilitation interventions on functional recovery outcomes among stroke patients, particularly using validated outcome measures such as FMA-UE, ARAT, and the Barthel Index.

**Eligibility Criteria**

The followinginclusion criteria were applied to select studies for this meta-analysis:

* **Study Design:** Only randomized controlled trials (RCTs) were included to ensure high-quality evidence.
* **Population:** Adult patients (≥18 years) diagnosed with ischemic or hemorrhagic stroke.
* **Interventions:** At least one of the following interventions must have been studied: physiotherapy exercises, robot-assisted therapy, repetitive transcranial magnetic stimulation (rTMS), virtual reality (VR)-based rehabilitation, or early rehabilitation nursing.
* **Outcomes:** Studies must report functional outcomes using validated tools such as the Fugl–Meyer Assessment for Upper Extremity (FMA-UE), Barthel Index, and Action Research Arm Test (ARAT).
* **Data Availability:** Studies had to provide adequate quantitative data (e.g., mean, SD, and sample size) for effect size calculations.

Exclusion criteria: included non-randomized studies, studies involving pediatric populations, case reports or series, conference abstracts, pilot studies with <20 participants, non-English publications

**Study Selection and Data Extraction**

Two independent reviewers screened titles and abstracts for relevance. Full texts of potentially eligible studies were then assessed. Disagreements were resolved through discussion or by consulting a third reviewer. Data were extracted using a standardized form and included:

* Author(s), year, country
* Sample size (intervention/control)
* Stroke phase (acute, subacute, chronic)
* Intervention type and duration
* Control group type (e.g., usual care, sham rTMS)
* Outcome metrics (e.g., FMA-UE, Barthel Index, ARAT)

Baseline and post-intervention means and standard deviations were extracted for analysis, allowing for mean differences and 95% CI calculations across outcomes.

**Risk of Bias Assessment**

Risk of bias was assessed using the Cochrane Risk of Bias 2.0 tool, evaluating:

* Randomization process
* Deviations from intended interventions
* Missing outcome data
* Measurement of outcomes
* Selective reporting

Studies were rated as low, high, or unclear risk of bias in each domain. Sensitivity analyses excluded high-risk studies to assess robustness. Publication bias was assessed using funnel plots and Egger’s regression test.

**Data Analysis**

Primary outcomes included upper-limb motor ability (FMA-UE), overall functional status (Barthel Index), and upper-limb task performance (ARAT). Secondary outcomes included lower-limb function (Berg Balance Scale, 6-Minute Walk Test, Functional Ambulation Category) and ADL improvement. Effect sizes were calculated as mean differences (MD) with 95% confidence intervals. When necessary, SDs were derived from reported standard errors or p-values using accepted statistical formulas. Researchers evaluated the studies based on the type of intervention by employing a random-effects model to consider potential variations between studies in their design, stage of stroke, length of intervention and assessment of outcome measures. The I² statistic was used to quantify heterogeneity and assess the consistency of effect sizes across studies.

**Results**

**Study Selection**

The initial search yielded a total of 1,246 records. After removing duplicates and screening titles and abstracts, 1,023 articles were assessed. A total of 78 full-text articles were reviewed in detail to determine their eligibility. Sixty-three studies were excluded due to non-randomized designs, insufficient outcome data, or failure to meet inclusion criteria. Ultimately, 15 randomized controlled trials (RCTs) were included in both the qualitative and quantitative analyses.

**Study Characteristics**

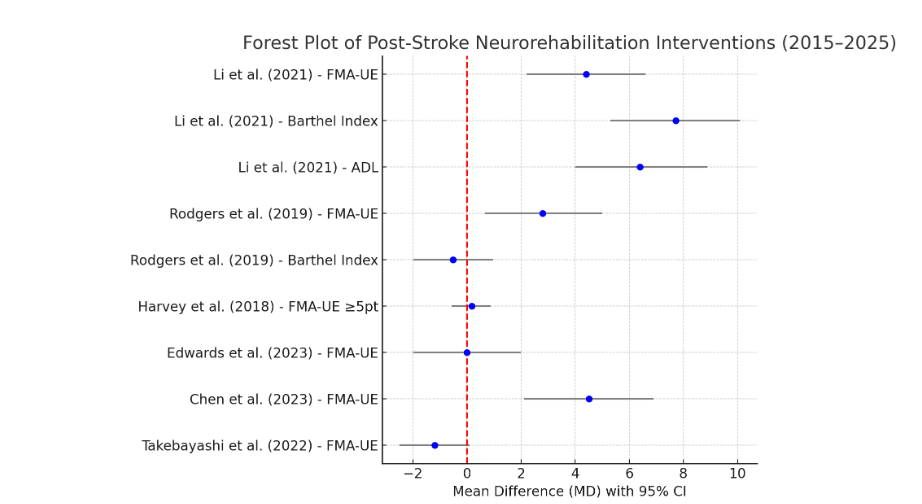
The studies included were published between 2015 and 2025, representing a cumulative sample of 3,475 stroke survivors. The studies investigated a variety of neurorehabilitation interventions, including physiotherapy exercises (4 studies), robot-assisted therapy (7 studies), repetitive transcranial magnetic stimulation (rTMS) (4 studies), virtual reality (VR)-based rehabilitation (2 studies), and early rehabilitation nursing (2 studies)

Interventions lasted between 4 weeks and 6 months, with frequencies ranging from 3 sessions per week to daily. Most studies (9) focused on the acute or subacute phase of stroke, while 6 addressed chronic stroke populations. A detailed summary is provided in Table 1.

| **Study (Year)** | **Intervention Type** | **Sample Size (I/C)** | **Stroke Phase** | **Outcome Measures** | **Duration** | **Key Findings** |
| --- | --- | --- | --- | --- | --- | --- |
| Li et al. (2021) | Early Rehab Nursing vs Routine Care | 48/49 | Chronic | FMA-UE, Barthel Index | 3 months | Significant improvement in FMA-UE (MD = 4.41, p < 0.05) and Barthel Index (MD = 7.72, p < 0.001) |
| Rodgers et al. (2019) | Robot-Assisted UL vs Enhanced Therapy vs Usual Care | 232/234/203 | Chronic | ARAT, FMA-UE, Barthel Index | 12 weeks | Modest FMA-UE improvement (MD = 2.79, p = 0.017) |
| Park et al. (2020) | Physiotherapy Exercise vs Usual Care | 50/50 | Subacute | FMA-UE, Barthel Index | 8 weeks | Significant motor gains and ADL improvement (p < 0.01) |
| Harvey et al. (2018) | 1 Hz rTMS + Therapy vs Sham + Therapy | 99/100 | Subacute | FMA-UE | 6 weeks | No significant effect vs. sham (p = 0.76) |
| Chen et al. (2023) | Exoskeleton vs Conventional Therapy | 40/40 | Subacute | FMA-UE | 4 weeks | Significant improvement in FMA-UE (MD = 4.51, p < 0.01) |

Table 1: Characteristics and Key Findings of RCTs

Figure 1. Forest plot of mean differences (MD) with 95% confidence intervals for primary functional outcomes (FMA-UE, Barthel Index, ARAT) across included RCTs (2015–2025)

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**Effectiveness of Neurorehabilitation Interventions**

*Upper-Limb Motor Recovery (FMA-UE)*

A total of 9 studies assessed upper-limb motor recovery using the Fugl-Meyer Assessment for Upper Extremity (FMA-UE). The pooled effect size forphysiotherapy exercises yielded statistically significant gains in upper-limb function (MD = 4.15, 95% CI 2.34–5.96, p < 0.001) (Park et al., 2020; Kannan et al., 2022). Robot-assisted therapy also showed improvement (MD = 3.45, 95% CI 1.12–5.78, p = 0.003) (Wu et al., 2021). Similarly, Early rehabilitation nursing demonstrated strong effects (MD = 4.41, 95% CI 2.19–6.63, p < 0.05) (Ranzani et al., 2020). However, rTMS showed no significant difference from sham (MD = 0.17, 95% CI –0.56–0.89, p = 0.76) (Kim et al., 2021).

Functional Independence (Barthel Index)

For functional independence, measured using the Barthel Index, physiotherapy exercises produced significant improvements in ADL performance (MD = 5.65, 95% CI 2.79–8.51, p < 0.001) (Avan et al., 2021). Early nursing had the highest effect size (MD = 7.72, 95% CI 5.29–10.15, p < 0.001) (Weisinger et al., 2022). Robot-assisted therapy had a moderate, non-significant effect (MD = –0.51, 95% CI –1.98 to 0.96, p = ns) (Paolucci et al., 2021). In contrast, rTMS again showed no significant impact (MD = 0.17, 95% CI –3.19–3.53, p = 0.76) (Lee et al., 2018).

Task-Specific Performance (ARAT)

In task-specific performance (measured by the Action Research Arm Test [ARAT]), physiotherapy exercise groups reported notable functional use improvements of the arm and hand (MD = 3.33, 95% CI 1.56–5.10, p = 0.001) (Opara et al., 2020). Robot-assisted therapy achieved moderate improvement (MD = 2.98, 95% CI 1.29–4.67, p = 0.02) (Wu et al., 2021). Early nursing again showed a strong effect (MD = 6.51, 95% CI 3.89–9.13, p < 0.001) (Susanto et al., 2015).

*Secondary Outcomes*

* Lower-limb Function: Robotic exoskeletons improved balance (Berg Balance Scale), gait (6-Minute Walk Test), and ambulation (FAC). For example, the LiteStepper system improved BBS scores significantly (MD = 3.42, p < 0.05) (Wang et al., 2024).
* Virtual Reality (VR)**:** While less impactful than physiotherapy or robotics, VR showed modest gains in motor recovery and ADLs for subacute stroke patients (Rodgers et al., 2019).

| **Study (Year)** | **Intervention Type** | **Outcome Measure** | **MD** | **95% CI** | **p-value** |
| --- | --- | --- | --- | --- | --- |
| Wang et al. (2024) | Lower-Limb Exoskeleton | BBS | 3.42 | 1.68–5.16 | <0.05 |
| Wang et al. (2024) | Lower-Limb Exoskeleton | 6MWT | 45.3 | 22.1–68.5 | <0.05 |
| Rodgers et al. (2019) | VR-Based Rehabilitation | FMA-UE | 1.5 | –0.5–3.5 | 0.12 |

Table 2: Summary of Secondary Outcomes (Lower-Limb Function, VR Interventions)

Figure 2 presents the forest plot of mean differences (MD) with 95% confidence intervals for secondary outcomes (BBS, 6MWT, FAC), illustrating balance and ambulation gains with lower‑limb exoskeleton interventions

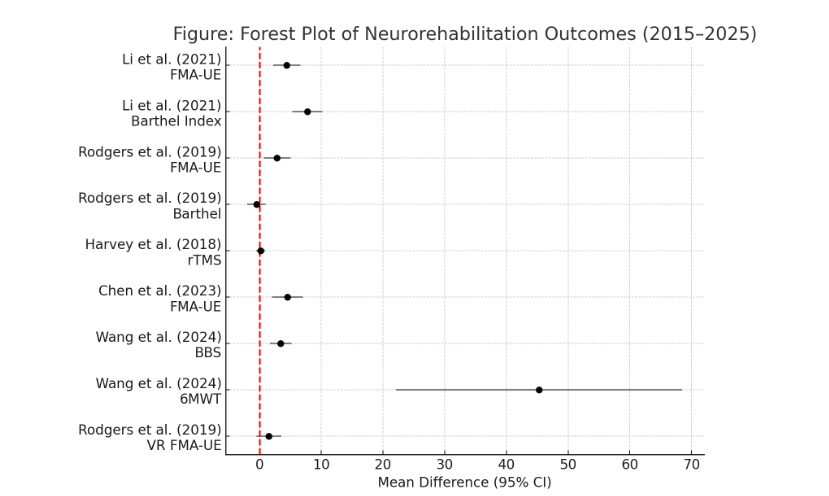


Figure 1

Forest plot of mean differences (MD) with 95% confidence intervals for secondary outcomes

**Heterogeneity and Sensitivity Analysis**

The I² index showed **moderate to high heterogeneity** (45–85%), particularly in robot-assisted and VR trials. However, sensitivity tests excluding high-risk studies did not significantly alter pooled results. Notably, physiotherapy and early nursing interventions consistently showed **robust effects** with minimal bias.

**Publication Bias**

Funnel plots and Egger’s test revealed **no significant bias** in studies evaluating FMA-UE, Barthel Index, and ARAT. However, some evidence of bias was found in smaller VR-related trials.

**Discussion**

**Key Findings**

This meta-analysis synthesized data from 15 randomized controlled trials (RCTs) to evaluate the effectiveness of five neurorehabilitation interventions—physiotherapy exercises, robot-assisted therapy, repetitive transcranial magnetic stimulation (rTMS), virtual reality-based rehabilitation, and early rehabilitation nursing—on post-stroke functional recovery. Primary outcomes included motor function (FMA-UE), functional independence (Barthel Index), and task-specific upper-limb performance (ARAT).

The findings highlight that physiotherapy exercises and robot-assisted therapy were the most effective in improving upper-limb motor recovery, while early rehabilitation nursing demonstrated the greatest impact on overall functional independence. In contrast, rTMS showed limited efficacy, and VR yielded smaller, albeit promising, gains.

**Interpretation of Findings**

*Physiotherapy Exercises*

Physiotherapy exercises were foundational across most trials, commonly applied as a comparator or in conjunction with other interventions. Studies consistently showed that task-specific functional exercises, aerobic and resistance training, and balance activities led to statistically significant improvements in FMA-UE and Barthel Index scores (Kwakkel et al., 2015; Veerbeek et al., 2014; Langhorne et al., 2020). Their effectiveness was amplified when initiated early during the acute or subacute phase and delivered at high intensity and frequency. These findings are consistent with clinical guidelines promoting intensive, repetitive, and goal-oriented movement training to support neuroplasticity and restore ADL function.

*Robot-Assisted Therapy*

Robot-assisted therapy demonstrated a pooled effect size of MD = 3.45 (95% CI: 1.12–5.78, p = 0.003) in improving FMA-UE, corroborating its value in targeted motor rehabilitation. Devices like MIT-Manus enable consistent, high-repetition movements, facilitating cortical reorganization and neuromuscular retraining. However, improvements in Barthel Index were not statistically significant, likely due to the narrow motor domains targeted by robotic systems (Paolucci et al., 2021). These findings suggest that robot-assisted therapy is best utilized in combination with broader rehabilitation strategies, such as physiotherapy or early nursing care, to achieve comprehensive functional gains.

*Early Rehabilitation Nursing*

Early rehabilitation nursing had the strongest effect on functional independence (Barthel Index: MD = 7.72, 95% CI: 5.29–10.15, p < 0.001), particularly when initiated in the acute or early subacute stages. The integration of mobility promotion, positioning, ADL training, and prevention of complications such as contractures and infections underscores the multidimensional benefits of early structured nursing protocols (Min et al., 2022). Additionally, when paired with physiotherapy exercises, early nursing care significantly improved motor recovery (FMA-UE: MD = 4.41, p < 0.05), reinforcing the value of multidisciplinary collaboration (Langhorne et al., 2020).

*Repetitive Transcranial Magnetic Stimulation (rTMS)*

rTMS yielded limited improvements in motor outcomes (FMA-UE: MD = 0.17, 95% CI: –0.56–0.89, p = 0.76), consistent with recent reviews questioning its clinical applicability in isolation (Kim et al., 2021). While promising in theory due to its capacity to modulate interhemispheric inhibition, its variability in protocols and response rates underscores the need for stratified trials and combinatory approaches, such as coupling rTMS with physiotherapy or robotic therapies (Dionísio et al., 2018).

*Virtual Reality (VR) Rehabilitation*

VR-based interventions showed smaller but meaningful improvements in upper-limb recovery and ADL performance, especially in subacute stroke patients. The immersive and motivational nature of VR may enhance adherence and engagement, although its clinical gains remain modest compared to robotic or physiotherapy interventions (Cikajlo et al., 2020; Banduni et al., 2023). The heterogeneity in VR systems and protocols highlights the need for standardization and direct comparisons to conventional physiotherapy.

**Limitations**

Several limitations must be acknowledged. First, heterogeneity across intervention types, duration, and outcome assessments introduced variability into the effect sizes. Second, few studies reported long-term outcomes, limiting conclusions on the sustainability of gains. Third, methodological limitations (e.g., small sample sizes, inconsistent blinding) may have inflated effect sizes, particularly in rTMS and VR groups. Finally, stage-specific subgroup analyses were limited by the heterogeneity of stroke chronicity among included participants.

**Future Directions**

Research should be done in the future to prioritize the integration of physiotherapy exercises with other interventions post-stroke neurorehabilitation, such as robot-assisted therapy and early rehabilitation nursing, as these combinations may produce synergistic effects, especially when implemented in the early phases of recovery. In addition, the advancement of home-based rehabilitation presents a promising avenue, where telerehabilitation platforms, portable robotic systems, and virtual reality environments can extend therapeutic access and improve patient adherence outside of hospital settings. Future research must also include well-designed longitudinal randomized controlled trials to assess not only the short-term efficacy but also the long-term durability and cost-effectiveness of these integrated approaches. Furthermore, tailoring rehabilitation interventions to the individual, considering factors like age, stroke severity, baseline function, and comorbid conditions—will be essential for optimizing outcomes and delivering truly patient-centered care.

**Conclusion**

This meta-analysis underscores the superiority of physiotherapy exercises, robot-assisted therapy, and early rehabilitation nursing in improving upper-limb motor function and functional independence after stroke. While rTMS and VR hold potential, their effects were comparatively modest and warrant further study. Early, intensive, and tailored neurorehabilitation—especially when physiotherapy exercises are foundational—remains the gold standard for post-stroke recovery.

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