



# Effectiveness of Multimodal Exercise and Technology-Assisted Interventions for Post-Stroke Motor Recovery : A Systematic Review

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## ABSTRACT

**Background:** Post-stroke motor recovery remains a major rehabilitation challenge. Multimodal exercise and technology-assisted interventions are increasingly used, but their comparative efficacy and moderators of benefit remain unclear.

**Methods:** This systematic review synthesized data from 80 sources (primarily RCTs, etc) examining multimodal exercise, technology-assisted, or combined interventions versus usual care or conventional rehabilitation in adult stroke patients. Outcomes included motor function (Fugl-Meyer Assessment, FMA), gait, balance, and activities of daily living (ADL).

**Results:** In subacute stroke, exoskeleton-assisted anthropomorphic training produced superior FMA-UE gains (+4.51 points; 95% CI 1.13–7.90) [6]. Virtual reality (VR)

exercise improved FMA-UE (SMD 0.45; 95% CI 0.21–0.68) [2], with doses >15 hours yielding greater gains (MD 9.67) [12]. Bi-hemispheric tDCS combined with physical/occupational therapy improved FMA by 20.7% vs. 3.2% [10]. High-volume constraint-induced movement therapy ranked second (SMD 0.86) [20]. In chronic stroke, brain-computer interface (BCI) with robotics produced significant FMA gains vs. standard therapy [9]. Telerehabilitation was noninferior to in-clinic therapy (FMA difference 0.06 points) [13]. For gait, end-effector robotic training improved velocity (MD 0.16 m/s) [14], and aerobic exercise improved 6MWT ( $p=0.011$ ) [15] and gait velocity (0.21 vs. 0.06 m/s) [17]. Combined cardiorespiratory/resistance training improved walking speed (MD 0.09 m/s) [16]. FES plus motor relearning significantly improved Barthel Index (15.8 vs. 8.2) [37].

**Discussion:** Positive effects are most consistent in subacute stroke, with greater baseline impairment and active, volitional, high-dose practice. Technology often matches conventional therapy when intensity is equal, but adds value by enabling adherence, neurofeedback, or home delivery.

**Conclusion:** Multimodal and technology-assisted interventions significantly improve post-stroke motor recovery, particularly in subacute patients and when providing high-repetition, volitional, or neurofeedback-driven training. Telerehabilitation and BCI systems offer promising scalable solutions.

**Keywords:** Stroke rehabilitation, multimodal exercise, technology-assisted, virtual reality, robotics, brain-computer interface, gait recovery, upper limb.

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## INTRODUCTION

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Stroke remains a leading cause of long-term motor disability worldwide, with over 50% of survivors experiencing persistent upper or lower limb impairment that limits activities of daily living (ADL) and quality of life. Despite advances in acute care, post-stroke motor recovery is often incomplete, and optimal rehabilitation strategies are still evolving. Conventional physiotherapy and occupational therapy provide foundational care, but their intensity is frequently limited by resources, patient fatigue, and access barriers.

**Background:** In recent years, multimodal exercise interventions (e.g., aerobic training combined with task-specific practice) and technology-assisted approaches (e.g., robotic devices, virtual reality, non-invasive brain stimulation, brain-computer interfaces, and telerehabilitation) have emerged as potentially more efficient or effective alternatives. However, evidence comparing these novel interventions with conventional therapy has been heterogeneous, with some large trials showing equivalence rather than superiority [3,4,5] and others demonstrating significant advantages [6,10,12,14].

**Research gap:** The key clinical questions are no longer simply “does technology work?” but rather: in which stroke phase, for which impairment severity, at what dose, and via which mechanism do these interventions provide meaningful added benefit over active, dose-matched conventional therapy.

**Problem statement:** Many systematic reviews aggregate all technology types across all phases, obscuring important moderators such as stroke chronicity, baseline motor severity, and intervention intensity. This obscures clinical decision-making.

**Objective:** To systematically evaluate the effectiveness of multimodal exercise and technology-assisted interventions for post-stroke motor recovery, focusing specifically on **significant positive findings** and identifying the populations, intervention characteristics, and outcome domains where superiority or clinically meaningful equivalence is demonstrated.

**Novelty:** This review uniquely prioritizes positive findings across intervention categories (robotics, VR, BCI, tDCS, telerehabilitation, and aerobic/multimodal exercise) and synthesizes dose-response, phase-specific, and severity-specific moderators using only the highest-quality primary RCTs, etc.

**Hypothesis:** Multimodal and technology-assisted interventions significantly improve motor outcomes compared to usual care, and in subacute patients with moderate-to-severe impairment, some technology-assisted approaches (exoskeletons, BCI, tDCS, high-dose VR) provide additional benefits over dose-matched conventional therapy.

**Benefits:** Clarifying these effects will guide clinicians, policymakers, and researchers toward cost-effective, scalable, and patient-centered rehabilitation strategies.

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## METHODS

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### Protocol

The study strictly adhered to the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) 2020 guidelines to ensure methodological rigor and accuracy. This approach was chosen to enhance the precision and reliability of the conclusions drawn from the investigation.

### Criteria for Eligibility

This systematic review aims to evaluate Effectiveness of Multimodal Exercise and Technology-Assisted Interventions for Post-Stroke Motor Recovery.

### Screening

We screened in sources based on their abstracts that met these criteria:

- **Population Age and Stroke Status:** Does this study include adult stroke patients aged  $\geq 18$  years with extractable stroke-specific results (i.e., not mixed with other neurological conditions without separate analysis)?
- **Intervention Type:** Does this study investigate at least one of the following: multimodal exercise interventions, technology-assisted interventions, or their combination?

- **Comparison Group:** Does this study include a control group receiving usual care, conventional rehabilitation, or no intervention?
- **Motor-Related Outcomes:** Does this study report at least one of the following outcomes: motor function, upper limb function, gait parameters, or activities of daily living?
- **Study Design Quality:** Is this study a randomized controlled trial, etc?
- **Publication Language:** Is this publication written in English?
- **Clinical Population and Setting:** Does this study focus on clinical stroke patients in post-acute rehabilitation phases (not healthy individuals, simulation studies, or solely acute stroke management/prevention)?

We considered all screening questions together and made a holistic judgement about whether to screen in each paper.

### Search Strategy

The keywords used for this research based PICO :

| Element   | P<br>(Population)    | I<br>(Intervention/Exposure) | C<br>(Comparison/Context)   | O<br>(Outcome)                   |
|-----------|----------------------|------------------------------|-----------------------------|----------------------------------|
| Keyword 1 | Stroke survivors     | Multimodal exercise          | Usual care                  | Motor function                   |
| Keyword 2 | Post-stroke patients | Technology-assisted          | Conventional rehabilitation | Upper limb function              |
| Keyword 3 | Adult stroke         | Virtual reality (VR)         | Sham intervention           | Gait parameters                  |
| Keyword 4 | Hemiparetic          | Robotic therapy              | Dose-matched active control | Activities of daily living (ADL) |

The Boolean MeSH keywords inputted on databases for this research are: (*“Stroke survivors” OR “Post-stroke patients” OR “Adult stroke” OR “Hemiparetic”*) AND (*“Multimodal exercise” OR “Technology-assisted” OR “Virtual reality (VR)” OR “Robotic therapy”*) AND (*“Usual care” OR “Conventional rehabilitation” OR “Sham intervention” OR “Dose-matched active control”*) AND (*“Motor function” OR “Upper limb function” OR “Gait parameters” OR “Activities of daily living (ADL)”*)

### **Data extraction**

- **Intervention Type:**

Extract the type and specific components of the rehabilitation intervention for post-stroke motor recovery, including:

- Classification as: multimodal exercise, technology-assisted intervention, combination of both, or other
- Specific intervention components (e.g., virtual reality system, robotic device type, exercise modalities)
- Technology details if applicable (e.g., gaming platform, robotic system name, VR equipment)
- Exercise components if applicable (e.g., strength training, balance training, functional training)

- **Control Comparison:**

Extract details about the control or comparison group for evaluating intervention effectiveness in post-stroke patients, including:

- Type of comparison (usual care, conventional therapy, no intervention, or alternative intervention)

- Specific components of the control intervention
- Whether control group received any additional therapy beyond standard care

- **Study Population:**

Extract characteristics of adult post-stroke patients that affect generalizability of motor recovery findings, including:

- Sample size per group
- Age range and mean age
- Time since stroke (acute, subacute, chronic)
- Stroke type and location if specified
- Baseline motor function severity
- Inclusion/exclusion criteria relevant to motor function

- **Motor Outcomes:**

Extract motor function assessment tools and results for post-stroke rehabilitation effectiveness, including:

- Primary and secondary outcome measures (e.g., Fugl-Meyer Assessment, Wolf Motor Function Test, Box and Block Test)
- Specific motor domains assessed (upper limb function, gait, activities of daily living)
- Baseline and post-intervention scores with statistical significance
- Effect sizes and confidence intervals where reported
- Follow-up duration and sustained effects

- **Treatment Parameters:**

Extract intervention dosage and delivery details for post-stroke motor rehabilitation, including:

- Total treatment duration (weeks/months)
- Session frequency (sessions per week)
- Session duration (minutes per session)
- Total number of sessions or treatment hours
- Setting (inpatient, outpatient, home-based)
- Who delivered the intervention (therapist, automated, supervised)

- **Study Quality:**

Extract study design characteristics and risk of bias factors for evaluating effectiveness evidence in post-stroke rehabilitation, including:

- Study design (RCT, etc.)
- Randomization and allocation concealment methods
- Blinding of participants, therapists, and outcome assessors
- Completeness of outcome data and dropout rates
- Potential conflicts of interest or funding sources
- Any reported adverse events related to interventions

**Table 1.** Article Search Strategy

| Database             | Keywords                                                                                                                                                                                                                                                                                                                                                                                                            | Hits  |
|----------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|
| Pubmed               | <i>("Stroke survivors" OR "Post-stroke patients" OR "Adult stroke" OR "Hemiparetic") AND ("Multimodal exercise" OR "Technology-assisted" OR "Virtual reality (VR)" OR "Robotic therapy") AND ("Usual care" OR "Conventional rehabilitation" OR "Sham intervention" OR "Dose-matched active control") AND ("Motor function" OR "Upper limb function" OR "Gait parameters" OR "Activities of daily living (ADL)")</i> | 13    |
| Semantic Scholar     | <i>"Stroke survivors" AND "Multimodal exercise" OR "Technology-assisted" OR "Virtual reality (VR)" OR "Robotic therapy" AND "Motor function" OR "Upper limb function" OR "Gait parameters" OR "Activities of daily living (ADL)"</i>                                                                                                                                                                                | 1     |
| Springer             | <i>("Stroke survivors" OR "Post-stroke patients" OR "Adult stroke" OR "Hemiparetic") AND ("Multimodal exercise" OR "Technology-assisted" OR "Virtual reality (VR)" OR "Robotic therapy") AND ("Usual care" OR "Conventional rehabilitation" OR "Sham intervention" OR "Dose-matched active control") AND ("Motor function" OR "Upper limb function" OR "Gait parameters" OR "Activities of daily living (ADL)")</i> | 477   |
| Google Scholar       | <i>("Stroke survivors" OR "Post-stroke patients" OR "Adult stroke" OR "Hemiparetic") AND ("Multimodal exercise" OR "Technology-assisted" OR "Virtual reality (VR)" OR "Robotic therapy") AND ("Usual care" OR "Conventional rehabilitation" OR "Sham intervention" OR "Dose-matched active control") AND ("Motor function" OR "Upper limb function" OR "Gait parameters" OR "Activities of daily living (ADL)")</i> | 2,560 |
| Wiley Online Library | <i>("Stroke survivors" OR "Post-stroke patients" OR "Adult stroke" OR "Hemiparetic") AND ("Multimodal exercise" OR "Technology-assisted" OR "Virtual reality (VR)" OR "Robotic therapy") AND ("Usual care" OR "Conventional rehabilitation" OR "Sham intervention" OR "Dose-matched active control") AND ("Motor function" OR "Upper limb function" OR "Gait parameters" OR "Activities of daily living (ADL)")</i> | 106   |

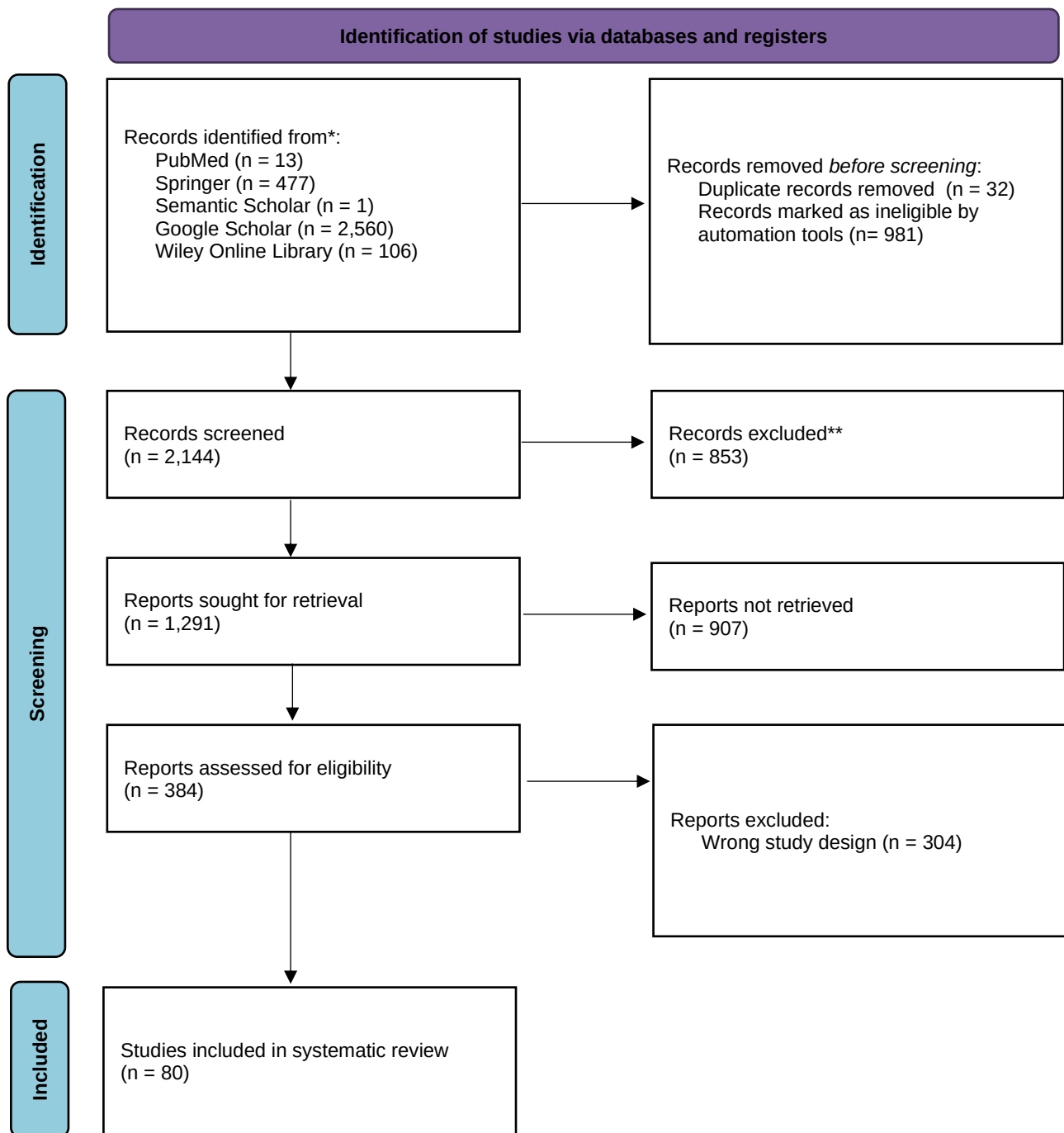


**Figure 1. Article search flowchart**

### Risk of Bias

| Study                                              | Selection Bias | Performance Bias | Detection Bias | Attrition Bias | Reporting Bias | Overall Risk |
|----------------------------------------------------|----------------|------------------|----------------|----------------|----------------|--------------|
| <b>P. Duncan et al., 2003 [22]</b>                 | Low            | Moderate         | Low            | Low            | Low            | Low          |
| <b>S. Cramer et al., 2019 [13]</b>                 | Low            | Low              | Low            | Low            | Low            | Low          |
| <b>Verena Klamroth-Marganska et al., 2014 [23]</b> | Low            | Moderate         | Low            | Low            | Low            | Low          |
| <b>R. Lindenberg et al., 2010 [10]</b>             | Unclear        | Moderate         | Low            | Low            | Low            | Moderate     |
| <b>M. Rodríguez-Hernández et al., 2021 [24]</b>    | Low            | Moderate         | Low            | Low            | Low            | Low          |
| <b>E. Ambrosini et al., 2020 [25]</b>              | Low            | Moderate         | Low            | Low            | Low            | Low          |
| <b>Joong-Hwi Kim et al., 2009 [26]</b>             | Unclear        | Moderate         | Low            | Unclear        | Low            | Moderate     |

| Study                                     | Selection Bias | Performance Bias | Detection Bias | Attrition Bias | Reporting Bias | Overall Risk |
|-------------------------------------------|----------------|------------------|----------------|----------------|----------------|--------------|
| <b>Fiona Coupar et al., 2010 [27]</b>     | Low            | Moderate         | Low            | Low            | Low            | Low          |
| <b>Shiqi Xu et al., 2025 [12]</b>         | Unclear        | Unclear          | Unclear        | Low            | Low            | Moderate     |
| <b>Susan S. Conroy et al., 2011 [28]</b>  | Low            | Moderate         | Low            | Low            | Low            | Low          |
| <b>I. Aprile et al., 2024 [29]</b>        | Low            | Moderate         | Low            | Low            | Low            | Low          |
| <b>Klas Sandberg et al., 2016 [15]</b>    | Low            | Moderate         | Low            | Low            | Low            | Low          |
| <b>H. Rodgers et al., 2020 [3]</b>        | Low            | Low              | Low            | Low            | Low            | Low          |
| <b>David H Saunders et al., 2025 [16]</b> | Low            | Moderate         | Low            | Low            | Low            | Low          |
| <b>H. Rodgers et al., 2017 [30]</b>       | Low            | Moderate         | Low            | Low            | Low            | Low          |

| Study                                          | Selection Bias | Performance Bias | Detection Bias | Attrition Bias | Reporting Bias | Overall Risk |
|------------------------------------------------|----------------|------------------|----------------|----------------|----------------|--------------|
| <b>Lynne V. Gauthier et al., 2017 [31]</b>     | Low            | Moderate         | Low            | Low            | Low            | Low          |
| <b>R. Massafferri et al., 2023 [32]</b>        | Low            | Low              | Low            | Low            | Low            | Low          |
| <b>Susan M. Linder et al., 2024 [33]</b>       | Low            | Moderate         | Low            | Low            | Low            | Low          |
| <b>Umair Ahmed et al., 2021 [34]</b>           | Unclear        | Moderate         | Low            | Unclear        | Low            | Moderate     |
| <b>Zejian Chen et al., 2023 [6]</b>            | Low            | Moderate         | Low            | Low            | Low            | Low          |
| <b>Syeda Pakeeza Bukhari et al., 2025 [35]</b> | Unclear        | Moderate         | Unclear        | Low            | Moderate       | Moderate     |
| <b>Richard Macko et al., 2026 [17]</b>         | Low            | Moderate         | Low            | Low            | Low            | Low          |

| Study                                         | Selection Bias | Performance Bias | Detection Bias | Attrition Bias | Reporting Bias | Overall Risk |
|-----------------------------------------------|----------------|------------------|----------------|----------------|----------------|--------------|
| <b>Xiang Chen et al., 2026 [36]</b>           | Low            | Moderate         | Low            | Low            | Low            | Low          |
| <b>Venugopal Pawar et al., 2025 [37]</b>      | Unclear        | Moderate         | Low            | Low            | Low            | Moderate     |
| <b>Peiming Chen et al., 2021 [38]</b>         | Low            | Moderate         | Low            | Low            | Low            | Low          |
| <b>L. Bunketorp-Käll et al., 2017 [39]</b>    | Low            | Moderate         | Low            | Low            | Low            | Low          |
| <b>Sarah Tenberg et al., 2023 [20]</b>        | Low            | Moderate         | Low            | Low            | Low            | Low          |
| <b>K. Bustamante Valles et al., 2016 [40]</b> | Unclear        | Moderate         | Low            | Low            | Moderate       | Moderate     |
| <b>M. Rabadi, 2011 [41]</b>                   | Unclear        | Unclear          | Unclear        | Unclear        | Unclear        | Unclear      |

| Study                                | Selection Bias | Performance Bias | Detection Bias | Attrition Bias | Reporting Bias | Overall Risk |
|--------------------------------------|----------------|------------------|----------------|----------------|----------------|--------------|
| <b>G. Saposnik et al., 2010 [42]</b> | Low            | Moderate         | Low            | Low            | Low            | Low          |
| <b>L. Piron et al., 2009 [43]</b>    | Unclear        | Moderate         | Low            | Low            | Low            | Moderate     |
| <b>Jiayin Chen et al., 2022 [2]</b>  | Low            | Moderate         | Low            | Low            | Low            | Low          |
| <b>L. Kahn et al., 2006 [44]</b>     | Unclear        | Moderate         | Low            | Unclear        | Low            | Moderate     |
| <b>J. Mehrholz et al., 2018 [14]</b> | Low            | Moderate         | Low            | Low            | Low            | Low          |
| <b>T. Gueye et al., 2020 [7]</b>     | Low            | Moderate         | Low            | Low            | Low            | Low          |
| <b>A. Lo et al., 2010 [5]</b>        | Low            | Low              | Low            | Low            | Low            | Low          |
| <b>G. Taveggia et al., 2016 [45]</b> | Unclear        | Moderate         | Low            | Low            | Moderate       | Moderate     |

| Study                                         | Selection Bias | Performance Bias | Detection Bias | Attrition Bias | Reporting Bias | Overall Risk |
|-----------------------------------------------|----------------|------------------|----------------|----------------|----------------|--------------|
| <b>S. Masiero et al., 2007 [46]</b>           | Unclear        | Moderate         | Low            | Low            | Low            | Moderate     |
| <b>J. Veerbeek et al., 2017 [1]</b>           | Low            | Moderate         | Low            | Low            | Low            | Low          |
| <b>A. Turolla et al., 2013 [47]</b>           | Moderate       | Moderate         | Low            | Low            | Low            | Moderate     |
| <b>Tae-Hyun Cha &amp; H. Hwang, 2022 [48]</b> | Low            | Moderate         | Low            | Low            | Low            | Low          |
| <b>Wan-wen Liao et al., 2012 [49]</b>         | Low            | Moderate         | Low            | Low            | Low            | Low          |
| <b>N. Norouzi-Gheidari et al., 2019 [50]</b>  | Unclear        | Moderate         | Low            | Low            | Moderate       | Moderate     |
| <b>F. Sánchez-Cuesta et al., 2021 [51]</b>    | Low            | Moderate         | Low            | Low            | Low            | Low          |

| Study                                           | Selection Bias | Performance Bias | Detection Bias | Attrition Bias | Reporting Bias | Overall Risk |
|-------------------------------------------------|----------------|------------------|----------------|----------------|----------------|--------------|
| <b>K. Arya et al., 2012 [52]</b>                | Low            | Moderate         | Low            | Low            | Low            | Low          |
| <b>D. Kairy et al., 2016 [53]</b>               | Low            | Moderate         | Low            | Low            | Low            | Low          |
| <b>Chang Liu et al., 2025 [54]</b>              | Low            | Moderate         | Low            | Low            | Low            | Low          |
| <b>Jan A Kuipers et al., 2025 [55]</b>          | Low            | Moderate         | Low            | Low            | Low            | Low          |
| <b>Susan M. Linder et al., 2013 [56]</b>        | Low            | Moderate         | Low            | Low            | Low            | Low          |
| <b>C. Newsam &amp; L. Baker, 2004 [57]</b>      | Unclear        | Moderate         | Low            | Low            | Low            | Moderate     |
| <b>Jaeho Park &amp; Yijung Chung, 2018 [58]</b> | Unclear        | Moderate         | Low            | Low            | Low            | Moderate     |
| <b>S. Hesse et al., 2014 [59]</b>               | Low            | Moderate         | Low            | Low            | Low            | Low          |

| Study                                             | Selection Bias | Performance Bias | Detection Bias | Attrition Bias | Reporting Bias | Overall Risk |
|---------------------------------------------------|----------------|------------------|----------------|----------------|----------------|--------------|
| <b>P. Sale et al., 2014 [8]</b>                   | Low            | Moderate         | Low            | Low            | Low            | Low          |
| <b>Montserrat Grau-Pellicer et al., 2019 [60]</b> | Low            | Moderate         | Low            | Low            | Low            | Low          |
| <b>A. Frolov et al., 2017 [61]</b>                | Low            | Moderate         | Low            | Low            | Low            | Low          |
| <b>I. Aprile et al., 2020 [4]</b>                 | Low            | Low              | Low            | Low            | Low            | Low          |
| <b>Genna J Waldman et al., 2013 [62]</b>          | Unclear        | Moderate         | Low            | Unclear        | Unclear        | Unclear      |
| <b>Szilvia Kóra et al., 2024 [63]</b>             | Low            | Moderate         | Low            | Low            | Low            | Low          |
| <b>Ching-yi Wu et al., 2007 [64]</b>              | Low            | Moderate         | Low            | Low            | Low            | Low          |

| Study                                                  | Selection Bias | Performance Bias | Detection Bias | Attrition Bias | Reporting Bias | Overall Risk |
|--------------------------------------------------------|----------------|------------------|----------------|----------------|----------------|--------------|
| <b>Zhishui Wu et al., 2020 [65]</b>                    | Unclear        | Moderate         | Low            | Low            | Low            | Moderate     |
| <b>Thomas Schick et al., 2017 [66]</b>                 | Low            | Moderate         | Low            | Low            | Low            | Low          |
| <b>L. Piron et al., 2010 [67]</b>                      | Unclear        | Moderate         | Low            | Low            | Low            | Moderate     |
| <b>I. Aprile et al., 2025 [68]</b>                     | Low            | Moderate         | Low            | Low            | Low            | Low          |
| <b>K. Ang et al., 2015 [19]</b>                        | Low            | Moderate         | Low            | Low            | Low            | Low          |
| <b>Meng-Ta Lee et al., 2024 [69]</b>                   | Low            | Moderate         | Low            | Low            | Low            | Low          |
| <b>Francisco-Javier Peláez-Vélez et al., 2023 [70]</b> | Unclear        | Moderate         | Low            | Low            | Low            | Moderate     |
| <b>S. Sütbeyaz et al., 2007 [71]</b>                   | Low            | Moderate         | Low            | Low            | Low            | Low          |

| Study                                      | Selection Bias | Performance Bias | Detection Bias | Attrition Bias | Reporting Bias | Overall Risk |
|--------------------------------------------|----------------|------------------|----------------|----------------|----------------|--------------|
| <b>G. Wittenberg et al., 2003 [72]</b>     | Unclear        | Moderate         | Low            | Unclear        | Low            | Moderate     |
| <b>Farnaz Abdollahi et al., 2014 [73]</b>  | Low            | Moderate         | Low            | Low            | Low            | Low          |
| <b>Ilsa Waqi Khunsha et al., 2024 [21]</b> | Unclear        | Moderate         | Low            | Unclear        | Moderate       | Unclear      |
| <b>N. Bolognini et al., 2011 [11]</b>      | Low            | Moderate         | Low            | Low            | Low            | Low          |
| <b>Sanaz Pournajaf et al., 2023 [18]</b>   | Moderate       | Moderate         | Low            | Low            | Low            | Moderate     |
| <b>Juan He et al., 2025 [74]</b>           | Low            | Moderate         | Low            | Low            | Low            | Low          |
| <b>K. Ang et al., 2014 [9]</b>             | Low            | Moderate         | Low            | Low            | Low            | Low          |

| Study                               | Selection Bias | Performance Bias | Detection Bias | Attrition Bias | Reporting Bias | Overall Risk |
|-------------------------------------|----------------|------------------|----------------|----------------|----------------|--------------|
| N. Kutner et al., 2010 [75]         | Unclear        | Moderate         | Low            | Low            | Low            | Moderate     |
| Jing Chen et al., 2020 [76]         | Low            | Moderate         | Low            | Low            | Low            | Low          |
| Dae-sung Park et al., 2017 [77]     | Unclear        | Moderate         | Low            | Low            | Low            | Moderate     |
| Sook-Joung Lee & M. Chun, 2014 [78] | Low            | Moderate         | Low            | Low            | Low            | Low          |
| Y. Choi et al., 2016 [79]           | Unclear        | Moderate         | Low            | Low            | Low            | Moderate     |
| Dinesh G. Nair et al., 2011 [80]    | Unclear        | Moderate         | Low            | Unclear        | Unclear        | Unclear      |

## RESULTS

### Characteristics of Included Studies

The following table presents all 80 included sources with key characteristics relevant to the research question on multimodal exercise and technology-assisted interventions for post-stroke motor recovery.

| Study                                              | Intervention Category                            | Stroke Phase                     | Sample Size (Total) | Primary Motor Outcome                     |
|----------------------------------------------------|--------------------------------------------------|----------------------------------|---------------------|-------------------------------------------|
| <b>P. Duncan et al., 2003 [22]</b>                 | Multimodal exercise [22]                         | Subacute [22]                    | 100 [22]            | Fugl-Meyer, 10-m walk, 6MWT [22]          |
| <b>S. Cramer et al., 2019 [13]</b>                 | Combination (telerehabilitation + exercise) [13] | Subacute–chronic (4–36 wks) [13] | 124 [13]            | Fugl-Meyer Assessment [13]                |
| <b>Verena Klamroth-Marganska et al., 2014 [23]</b> | Technology-assisted (ARMin exoskeleton) [23]     | Chronic (>6 months) [23]         | 73 [23]             | FMA-UE [23]                               |
| <b>R. Lindenberg et al., 2010 [10]</b>             | Combination (bihemispheric tDCS + PT/OT) [10]    | Chronic ( $\geq 5$ months) [10]  | 20 [10]             | UE Fugl-Meyer, WMFT [10]                  |
| <b>M. Rodríguez-Hernández et al., 2021 [24]</b>    | Combination (conventional + VR) [24]             | Subacute ( $\leq 6$ months) [24] | 43 [24]             | FMA-UE, Modified Ashworth Scale, SIS [24] |
| <b>E. Ambrosini et al., 2020 [25]</b>              | Combination (FES-cycling + balance) [25]         | Subacute (<6 months) [25]        | 68 [25]             | Gait speed [25]                           |
| <b>Joong-Hwi Kim et al., 2009 [26]</b>             | Combination (VR + conventional PT) [26]          | Chronic [26]                     | 24 [26]             | Berg Balance Scale, 10-m walk [26]        |

| Study                                    | Intervention Category                            | Stroke Phase                   | Sample Size (Total) | Primary Motor Outcome                    |
|------------------------------------------|--------------------------------------------------|--------------------------------|---------------------|------------------------------------------|
| <b>Fiona Coupar et al., 2010 [27]</b>    | Multimodal exercise (bilateral training) [27]    | Mixed [27]                     | 549 [27]            | ADL, upper limb functional movement [27] |
| <b>Shiqi Xu et al., 2025 [12]</b>        | Technology-assisted (VR) [12]                    | Not specified [12]             | 1243 [12]           | FMA-UE, ARAT, BBT, FIM, WMFT [12]        |
| <b>Susan S. Conroy et al., 2011 [28]</b> | Combination (robot-assisted + conventional) [28] | Chronic [28]                   | 62 [28]             | FMA [28]                                 |
| <b>I. Aprile et al., 2024 [29]</b>       | Combination (RADTs + exercise) [29]              | Subacute (<6 months) [29]      | 596 (planned) [29]  | Modified Barthel Index [29]              |
| <b>Klas Sandberg et al., 2016 [15]</b>   | Multimodal exercise (aerobic) [15]               | Subacute (median 20 days) [15] | 56 [15]             | Peak work rate, 6MWT [15]                |
| <b>H. Rodgers et al., 2020 [3]</b>       | Technology-assisted (MIT-Manus robot) [3]        | Mixed (1 wk–5 yrs) [3]         | 770 [3]             | ARAT [3]                                 |

| Study                                      | Intervention Category                                              | Stroke Phase                    | Sample Size (Total) | Primary Motor Outcome                           |
|--------------------------------------------|--------------------------------------------------------------------|---------------------------------|---------------------|-------------------------------------------------|
| <b>David H Saunders et al., 2025 [16]</b>  | Multimodal exercise (combined cardiorespiratory + resistance) [16] | Mixed (subacute + chronic) [16] | 1519 [16]           | Disability, walking speed, balance [16]         |
| <b>H. Rodgers et al., 2017 [30]</b>        | Combination (robot + enhanced UL therapy) [30]                     | Mixed (1 wk–5 yrs) [30]         | 720 (planned) [30]  | ARAT [30]                                       |
| <b>Lynne V. Gauthier et al., 2017 [31]</b> | Combination (video game CI therapy) [31]                           | Chronic ( $\geq 6$ months) [31] | 224 (planned) [31]  | WMFT, MAL [31]                                  |
| <b>R. Massafferri et al., 2023 [32]</b>    | Combination (tDCS + multimodal PT) [32]                            | Chronic [32]                    | 18 [32]             | FM total/LL, 10MWT [32]                         |
| <b>Susan M. Linder et al., 2024 [33]</b>   | Combination (forced-rate cycling + RTP) [33]                       | Chronic [33]                    | 60 [33]             | FMA, ARAT, 6MWT [33]                            |
| <b>Umair Ahmed et al., 2021 [34]</b>       | Multimodal exercise (trunk + dual-task) [34]                       | Not specified [34]              | 74 [34]             | Trunk Impairment Scale, Berg Balance Scale [34] |

| Study                                          | Intervention Category                                 | Stroke Phase                      | Sample Size (Total) | Primary Motor Outcome                  |
|------------------------------------------------|-------------------------------------------------------|-----------------------------------|---------------------|----------------------------------------|
| <b>Zejian Chen et al., 2023 [6]</b>            | Technology-assisted (exoskeleton EAMT) [6]            | Subacute (~55 days) [6]           | 80 [6]              | FMA-UE [6]                             |
| <b>Syeda Pakeeza Bukhari et al., 2025 [35]</b> | Technology-assisted (robotic hand device) [35]        | Chronic (6–24 months) [35]        | 38 [35]             | FMA, MAS, 9HPT [35]                    |
| <b>Richard Macko et al., 2026 [17]</b>         | Multimodal exercise (treadmill + mobility class) [17] | Subacute (~8 wks) [17]            | 173 [17]            | Gait velocity, 6MWT, Berg Balance [17] |
| <b>Xiang Chen et al., 2026 [36]</b>            | Multimodal exercise (motor imagery) [36]              | Subacute (2 wks–6 months) [36]    | 70 [36]             | FMA-UE [36]                            |
| <b>Venugopal Pawar et al., 2025 [37]</b>       | Combination (FES + motor relearning) [37]             | Not specified [37]                | 84 [37]             | Barthel Index, FIM, COPM [37]          |
| <b>Peiming Chen et al., 2021 [38]</b>          | Combination (Bi-TENS + task-oriented training) [38]   | Chronic (~6 yrs post-stroke) [38] | 120 [38]            | FMA-UE [38]                            |
| <b>L. Bunketorp-Käll et al., 2017 [39]</b>     | Multimodal exercise (rhythm-music, horse-riding) [39] | Late/chronic [39]                 | 123 [39]            | SIS, balance, gait, grip strength [39] |

| Study                                         | Intervention Category                         | Stroke Phase                           | Sample Size (Total)  | Primary Motor Outcome                             |
|-----------------------------------------------|-----------------------------------------------|----------------------------------------|----------------------|---------------------------------------------------|
| <b>Sarah Tenberg et al., 2023 [20]</b>        | Combination (multiple modalities) [20]        | Acute–subacute ( $\leq 6$ months) [20] | 5553 (119 RCTs) [20] | FMA-UE [20]                                       |
| <b>K. Bustamante Valles et al., 2016 [40]</b> | Combination (robot gym circuit training) [40] | Chronic ( $> 6$ months) [40]           | 20 [40]              | FMA-UE, FMA-LE, 6MWT, TUG [40]                    |
| <b>M. Rabadi, 2011 [41]</b>                   | Multiple modalities                           | Mixed (acute, subacute, chronic) [41]  | Variable [41]        | FMA, WMFT, ARAT [41]                              |
| <b>G. Saposnik et al., 2010 [42]</b>          | Technology-assisted (Nintendo Wii VR) [42]    | Subacute ( $\leq 2$ months) [42]       | 22 [42]              | WMFT, Box and Block Test, SIS [42]                |
| <b>L. Piron et al., 2009 [43]</b>             | Combination (VR telerehabilitation) [43]      | Chronic (7–32 months) [43]             | 36 [43]              | FMA-UE, ABILHAND [43]                             |
| <b>Jiayin Chen et al., 2022 [2]</b>           | Technology-assisted (VR) [2]                  | Mixed (subacute + chronic) [2]         | 1893 (43 trials) [2] | FMA-UE, range of motion, muscle strength, FIM [2] |

| Study                                | Intervention Category                             | Stroke Phase                   | Sample Size (Total) | Primary Motor Outcome                   |
|--------------------------------------|---------------------------------------------------|--------------------------------|---------------------|-----------------------------------------|
| <b>L. Kahn et al., 2006 [44]</b>     | Technology-assisted (ARM Guide robot) [44]        | Chronic ( $\geq 1$ year) [44]  | 19 [44]             | Arm ROM/speed, functional reaching [44] |
| <b>J. Mehrholz et al., 2018 [14]</b> | Technology-assisted (electromechanical gait) [14] | Mixed [14]                     | 4458 (95 RCTs) [14] | Gait velocity, walking distance [14]    |
| <b>T. Gueye et al., 2020 [7]</b>     | Combination (Armeo Spring exoskeleton + VR) [7]   | Acute ( $\leq 30$ days) [7]    | 50 [7]              | FMA-UE, FIM [7]                         |
| <b>A. Lo et al., 2010 [5]</b>        | Technology-assisted (robot-assisted UL) [5]       | Chronic ( $\geq 6$ months) [5] | 127 [5]             | FMA, WMFT, SIS [5]                      |
| <b>G. Taveggia et al., 2016 [45]</b> | Combination (ARMEO Spring + PRM) [45]             | Not specified [45]             | 54 [45]             | FIM, Motricity Index, MAS, pain [45]    |
| <b>S. Masiero et al., 2007 [46]</b>  | Technology-assisted (early robotic UL) [46]       | Acute ( $\leq 1$ week) [46]    | 35 [46]             | FMA, MRC, FIM [46]                      |

| Study                                         | Intervention Category                               | Stroke Phase                 | Sample Size (Total)   | Primary Motor Outcome                      |
|-----------------------------------------------|-----------------------------------------------------|------------------------------|-----------------------|--------------------------------------------|
| <b>J. Veerbeek et al., 2017 [1]</b>           | Technology-assisted (robot UL) [1]                  | Subacute + chronic [1]       | 1362 (44 RCTs) [1]    | FMA, muscle strength, UL capacity, ADL [1] |
| <b>A. Turolla et al., 2013 [47]</b>           | Combination (VR + conventional UL) [47]             | Mixed [47]                   | 376 [47]              | FMA-UE, FIM [47]                           |
| <b>Tae-Hyun Cha &amp; H. Hwang, 2022 [48]</b> | Combination (NIBS + rehabilitation) [48]            | Mixed (acute + chronic) [48] | 375 (12 studies) [48] | FMA, MAS, WMFT, BBT [48]                   |
| <b>Wan-wen Liao et al., 2012 [49]</b>         | Technology-assisted (bilateral robotic) [49]        | Chronic (~22 months) [49]    | 20 [49]               | FMA, arm activity ratio, ABILHAND [49]     |
| <b>N. Norouzi-Gheidari et al., 2019 [50]</b>  | Technology-assisted (VR exergame) [50]              | Subacute–chronic [50]        | 18 [50]               | FMA-UE, BBT, MAL, SIS [50]                 |
| <b>F. Sánchez-Cuesta et al., 2021 [51]</b>    | Combination (BCI-VR + rTMS) [51]                    | Subacute (>3 months) [51]    | 42 (planned) [51]     | Motricity Index, FMA-UE, SIS [51]          |
| <b>K. Arya et al., 2012 [52]</b>              | Multimodal exercise (meaningful task-specific) [52] | Subacute (4–24 wks) [52]     | 103 [52]              | FMA, ARAT, GWMFT, MAL [52]                 |

| Study                                           | Intervention Category                                   | Stroke Phase                     | Sample Size (Total) | Primary Motor Outcome                  |
|-------------------------------------------------|---------------------------------------------------------|----------------------------------|---------------------|----------------------------------------|
| <b>D. Kairy et al., 2016 [53]</b>               | Technology-assisted (VR telerehabilitation) [53]        | Chronic [53]                     | 52 (planned) [53]   | FMA-UE, BBT [53]                       |
| <b>Chang Liu et al., 2025 [54]</b>              | Combination (internet-based + wearable) [54]            | Subacute [54]                    | 160 [54]            | Modified Barthel Index, BBS, sFMA [54] |
| <b>Jan A Kuipers et al., 2025 [55]</b>          | Combination (bilateral movement + technology) [55]      | Mixed [55]                       | 28 studies [55]     | FMA, WMFT, BBT, MBI [55]               |
| <b>Susan M. Linder et al., 2013 [56]</b>        | Combination (home robotic + exercise program) [56]      | Subacute ( $\leq 6$ months) [56] | 96 (planned) [56]   | ARAT, WMFT, FMA [56]                   |
| <b>C. Newsam &amp; L. Baker, 2004 [57]</b>      | Combination (electrical stimulation + standard PT) [57] | Subacute (~38 days) [57]         | 20 [57]             | MVIT, motor unit recruitment [57]      |
| <b>Jaeho Park &amp; Yijung Chung, 2018 [58]</b> | Combination (VR + robot-assisted gait + auditory) [58]  | Not specified [58]               | 40 [58]             | BBS, TUG, 10MWT, FMA, MBI [58]         |

| Study                                             | Intervention Category                                            | Stroke Phase                  | Sample Size (Total) | Primary Motor Outcome               |
|---------------------------------------------------|------------------------------------------------------------------|-------------------------------|---------------------|-------------------------------------|
| <b>S. Hesse et al., 2014 [59]</b>                 | Combination (robot-assisted group + individual arm therapy) [59] | Subacute (<8 wks) [59]        | 50 [59]             | Fugl-Meyer Score [59]               |
| <b>P. Sale et al., 2014 [8]</b>                   | Technology-assisted (MIT-MANUS robot) [8]                        | Subacute (~30 days) [8]       | 53 [8]              | FMA, MAS, pROM, Motricity Index [8] |
| <b>Montserrat Grau-Pellicer et al., 2019 [60]</b> | Combination (mHealth app + multimodal exercise) [60]             | Chronic [60]                  | 41 [60]             | 10MWT, 6MWT, TUG, Barthel [60]      |
| <b>A. Frolov et al., 2017 [61]</b>                | Combination (BCI + hand exoskeleton) [61]                        | Subacute–chronic [61]         | 74 [61]             | ARAT, FMMA [61]                     |
| <b>I. Aprile et al., 2020 [4]</b>                 | Combination (set of 4 robots + conventional) [4]                 | Subacute (2 wks–6 months) [4] | 247 [4]             | FMA [4]                             |

| Study                                    | Intervention Category                                          | Stroke Phase                          | Sample Size (Total) | Primary Motor Outcome               |
|------------------------------------------|----------------------------------------------------------------|---------------------------------------|---------------------|-------------------------------------|
| <b>Genna J Waldman et al., 2013 [62]</b> | Combination (portable robot + stretching/active training) [62] | Chronic ( $\geq 3$ months) [62]       | 24 [62]             | MAS, STREAM, Berg Balance [62]      |
| <b>Szilvia Kóra et al., 2024 [63]</b>    | Combination (ReStore exosuit + exercise) [63]                  | Subacute (2–4 wks) [63]               | 30 (completed) [63] | mRS, Barthel, BBS, 10MWT, 6MWT [63] |
| <b>Ching-yi Wu et al., 2007 [64]</b>     | Multimodal exercise (mCIMT) [64]                               | Subacute–chronic (0.5–31 months) [64] | 26 [64]             | FMA, FIM, MAL, SIS [64]             |
| <b>Zhishui Wu et al., 2020 [65]</b>      | Technology-assisted (internet-based telerehabilitation) [65]   | Acute [65]                            | 61 [65]             | FMA, Berg Balance Scale, QoL [65]   |
| <b>Thomas Schick et al., 2017 [66]</b>   | Combination (EMG-triggered stimulation + mirror therapy) [66]  | Subacute (1–6 months) [66]            | 33 [66]             | FMA [66]                            |
| <b>L. Piron et al., 2010 [67]</b>        | Combination (VR reinforced feedback + conventional) [67]       | Chronic ( $\geq 6$ months) [67]       | 47 [67]             | FMA-UE, FIM [67]                    |

| Study                                                  | Intervention Category                                          | Stroke Phase               | Sample Size (Total) | Primary Motor Outcome                             |
|--------------------------------------------------------|----------------------------------------------------------------|----------------------------|---------------------|---------------------------------------------------|
| <b>I. Aprile et al., 2025 [68]</b>                     | Combination (RADTs + exercise) [68]                            | Subacute (<6 months) [68]  | 596 (planned) [68]  | Modified Barthel Index [68]                       |
| <b>K. Ang et al., 2015 [19]</b>                        | Combination (BCI + MIT-Manus robot) [19]                       | Chronic (~297 days) [19]   | 26 [19]             | FMA (FMMA) [19]                                   |
| <b>Meng-Ta Lee et al., 2024 [69]</b>                   | Technology-assisted (digital mirror therapy) [69]              | Not specified [69]         | 35 [69]             | FMA-UE, CAHAI, MAL [69]                           |
| <b>Francisco-Javier Peláez-Vélez et al., 2023 [70]</b> | Combination (immersive VR + neurological PT) [70]              | Subacute (≤6 months) [70]  | 24 [70]             | Motricity Index, BBS, Tinetti, Trunk Control [70] |
| <b>S. Sütbeyaz et al., 2007 [71]</b>                   | Technology-assisted (mirror therapy) [71]                      | Subacute (≤12 months) [71] | 40 [71]             | Brunnstrom, FIM motor, MAS, FAC [71]              |
| <b>G. Wittenberg et al., 2003 [72]</b>                 | Multimodal exercise (constraint-induced movement therapy) [72] | Chronic (~31 months) [72]  | 16 [72]             | WMFT, MAL, AMPS [72]                              |

| Study                                      | Intervention Category                                               | Stroke Phase                    | Sample Size (Total) | Primary Motor Outcome                  |
|--------------------------------------------|---------------------------------------------------------------------|---------------------------------|---------------------|----------------------------------------|
| <b>Farnaz Abdollahi et al., 2014 [73]</b>  | Technology-assisted (VR robotic error augmentation) [73]            | Chronic ( $\geq 6$ months) [73] | 26 [73]             | FMA, WMFT [73]                         |
| <b>Ilsa Waqi Khunsha et al., 2024 [21]</b> | Multimodal exercise (multidisciplinary PT/OT/speech) [21]           | Acute–subacute [21]             | 90 [21]             | BBS, Nine-Hole Peg Test [21]           |
| <b>N. Bolognini et al., 2011 [11]</b>      | Combination (bihemispheric tDCS + CIMT) [11]                        | Chronic ( $> 6$ months) [11]    | 14 [11]             | JHFT, Handgrip Strength, MAL, FMA [11] |
| <b>Sanaz Pournajaf et al., 2023 [18]</b>   | Technology-assisted (robotic gait: exoskeleton + end-effector) [18] | Subacute [18]                   | 89 [18]             | 10MWT, 6MWT, TUG, mBI [18]             |
| <b>Juan He et al., 2025 [74]</b>           | Combination (BCI + VR + rehabilitation robot) [74]                  | Subacute (2 wks–3 months) [74]  | 48 (completed) [74] | FMA-UE [74]                            |
| <b>K. Ang et al., 2014 [9]</b>             | Combination (BCI + haptic knob robot) [9]                           | Chronic ( $> 4$ months) [9]     | 21 [9]              | FMA (FMMA) [9]                         |

| Study                                          | Intervention Category                                          | Stroke Phase                  | Sample Size (Total) | Primary Motor Outcome                  |
|------------------------------------------------|----------------------------------------------------------------|-------------------------------|---------------------|----------------------------------------|
| <b>N. Kutner et al., 2010 [75]</b>             | Combination (robotic-assisted + repetitive task practice) [75] | Subacute (3–9 months) [75]    | 17 [75]             | SIS (hand function, QoL) [75]          |
| <b>Jing Chen et al., 2020 [76]</b>             | Technology-assisted (home telerehabilitation) [76]             | Not specified [76]            | 52 [76]             | FMA, Modified Barthel Index [76]       |
| <b>Dae-sung Park et al., 2017 [77]</b>         | Combination (Xbox Kinect VR + conventional PT) [77]            | Chronic [77]                  | 20 [77]             | FMA-LE, BBS, TUG, 10mWT [77]           |
| <b>Sook-Joung Lee &amp; M. Chun, 2014 [78]</b> | Combination (cathodal tDCS + VR) [78]                          | Subacute [78]                 | 59 [78]             | MFT, FMS, MMT, Box and Block Test [78] |
| <b>Y. Choi et al., 2016 [79]</b>               | Combination (mobile game VR + OT) [79]                         | Not specified (ischemic) [79] | 24 [79]             | FMA-UE, Brunnstrom stage, MMT [79]     |
| <b>Dinesh G. Nair et al., 2011 [80]</b>        | Combination (cathodal tDCS + OT) [80]                          | Chronic [80]                  | Not reported [80]   | FMA-UE, ROM [80]                       |

The 80 sources span primary RCTs, etc. Three sources are published protocols (Aprile et al. 2024 [29], Aprile et al. 2025 [68], Rodgers et al. 2017 [30], Gauthier et al. 2017 [31], Kairy et al.

2016 [53], Linder et al. 2013 [56], and Sánchez-Cuesta et al. 2021 [51]), so they do not report outcome data. Full texts were retrieved for approximately half of the sources; the remainder were assessed based on abstracts alone, which limits depth of extraction for those studies. Sample sizes vary widely, ranging from 14 participants in a small exploratory study [11] to over 5,500 participants aggregated in the largest network meta-analysis [20]. The most commonly used primary outcome measure across primary studies is the Fugl-Meyer Assessment for Upper Extremity (FMA-UE), employed across a majority of included studies [1, 4, 6, 10, 13, 20, 24, 35, 38, 47]. Gait-focused studies predominantly employ the 10-Meter Walk Test, 6-Minute Walk Test, and Berg Balance Scale as primary or major secondary outcomes [14, 17, 18, 63].

## **Effects**

### **Upper Limb Motor Function**

#### **Robot-Assisted Upper Limb Training**

Robotic upper limb training is among the most studied technology-assisted interventions in this review. Results across primary RCTs and meta-analyses are heterogeneous in magnitude but relatively consistent in direction.

In the largest included primary RCT (RATULS, n=770), robot-assisted training using the MIT-Manus InMotion system did not produce significantly greater upper limb functional recovery (ARAT success) compared to either enhanced upper limb therapy (adjusted OR 0.8, 98.33% CI 0.5–1.3) or usual care (adjusted OR 1.2, 98.33% CI 0.7–2.0) [3]. However, the robot-assisted group did show reduced upper limb impairment on the Fugl-Meyer at both 3 and 6 months compared to usual care [3], suggesting a dissociation between impairment-level gains and functional outcomes. Neither robot-assisted training nor enhanced upper limb therapy was deemed cost-effective at NICE thresholds [3].

In contrast, a multicenter RCT by Aprile et al. (2020, n=247 subacute patients) found that a comprehensive set of four robotic devices yielded mean FMA improvement of 8.50 points (95% CI 6.82–10.17), equivalent to the 8.57-point gain in the conventional group (adjusted mean difference –0.08, p=0.948) [4]. This noninferiority finding is important: it indicates that robotic rehabilitation

can achieve comparable functional gains to conventional therapy in the subacute phase, even at the same dosage.

Lo et al. (2010, n=127 chronic stroke patients) found that robot-assisted therapy did not significantly improve FMA at 12 weeks versus usual care (difference 2.17 points, 95% CI -0.23 to 4.58) or intensive comparison therapy (difference -0.14 points, 95% CI -2.94 to 2.65) [5]. However, at the 36-week secondary analysis, robot-assisted therapy significantly outperformed usual care on FMA (difference 2.88 points, 95% CI 0.57–5.18) and Wolf Motor Function Test time (difference -8.10 seconds, 95% CI -13.61 to -2.60) [5], suggesting delayed emergence of benefit.

Masiero et al. (2007, n=35 acute patients) found that early robotic training—within one week of stroke onset—produced significantly greater gains in proximal upper arm FMA ( $p<0.05$ ), MRC deltoid ( $p\leq 0.05$ ), MRC biceps ( $p<0.05$ ), and FIM motor scores ( $p<0.01$ ) compared to controls, and these gains were sustained at 3- and 8-month follow-ups [46]. Sale et al. (2014, n=53 subacute patients) similarly found significant improvements in spasticity (MAS-shoulder  $p=0.004$ , MAS-elbow  $p=0.018$ ) and passive range of motion ( $p<0.0001$ ) in the robotic group [8], with both groups improving on FMA and Motricity Index ( $p<0.0001$ ) [8].

Hesse et al. (2014, n=50 subacute patients) compared robot-assisted group therapy (RAGT, 30 min) combined with individual arm therapy (IAT, 30 min) versus two sessions of IAT (60 min total). Both groups improved on FMA without significant between-group differences; group A improved from  $14.6\pm 9.4$  to  $25.7\pm 16.5$ , and group B from  $16.5\pm 9.8$  to  $31.1\pm 19.1$  [59]. Notably, the RAGT approach cost €4.15 per patient versus €10.00 for individual arm therapy, suggesting economic advantage despite equivalent efficacy [59].

The Veerbeek et al. (2017) meta-analysis (44 RCTs, n=1362) quantified the pooled effect of robot-assisted upper limb therapy as a modest but statistically significant improvement in motor control of approximately 2 FMA points (MD 2.23, 95% CI 0.87–3.59) [1]. Effects were specific to the targeted joints, with shoulder/elbow robotics showing significant gains on FMA shoulder/elbow/coordination (MD 2.62, 95% CI 1.48–3.76), while no generalization was observed to overall upper limb capacity or ADL outcomes [1]. No serious adverse events were reported across included trials [1].

A smaller pilot RCT by Liao et al. (2012, n=20 chronic patients) found that robot-assisted bilateral therapy produced significantly higher FMA scores ( $51.20 \pm 8.82$  vs.  $40.90 \pm 13.14$ ,  $p=0.002$ ) and arm activity ratio ( $0.76 \pm 0.10$  vs.  $0.69 \pm 0.11$ ,  $p=0.026$ ) than dose-matched active control [49]. The robotic hand training RCT by Bukhari et al. (2025, n=38 chronic patients) reported particularly large between-group FMA differences ( $+30.00$  vs.  $+12.07$ ,  $p=0.00$ ), alongside marked improvements in the Nine-Hole Peg Test ( $-10.53$  vs.  $-2.37$  seconds,  $p=0.00$ ) and Modified Ashworth Scale ( $-2.74$  vs.  $-0.68$ ,  $p=0.00$ ) [35], though the small sample and reliance on non-parametric tests limit confidence in these effect magnitudes.

### **Exoskeleton-Assisted Anthropomorphic and Task-Specific Training**

Zejian Chen et al. (2023, n=80 subacute patients) tested exoskeleton-assisted anthropomorphic movement training (EAMT) integrating naturalistic coordinated UE movements. The EAMT group improved 14.73 FMA-UE points (95% CI 11.43–18.02), compared to 9.90 points (95% CI 8.15–11.65) for conventional therapy, an adjusted between-group difference of 4.51 points (95% CI 1.13–7.90) [6]. This superiority margin exceeded the pre-specified noninferiority margin, and post-hoc analysis suggested patients with moderately severe impairment (FMA-UE 23–38 at baseline) benefited most [6]. The Klamroth-Marganska et al. (2014) ARMin exoskeleton RCT (n=77 chronic patients) demonstrated statistically greater FMA-UE improvement with robotic versus conventional therapy over the study period ( $F=4.1$ ,  $p=0.041$ ; mean difference 0.78 points, 95% CI 0.03–1.53), though the authors acknowledged the small absolute difference raised questions about clinical relevance [23].

### **Brain-Computer Interface Combined with Robotics**

Several studies examined brain-computer interfaces (BCIs) combined with robotic feedback for upper limb recovery. Ang et al. (2015, n=26 chronic patients) compared EEG-based motor imagery BCI coupled with MIT-Manus (BCI-Manus) against Manus therapy alone. FMA scores improved in both groups (BCI-Manus: 26.3 to 31.5; Manus: 26.6 to 33.9 over 12 weeks) with no significant intergroup differences ( $p=0.51$ ) [19]. However, more BCI-Manus subjects achieved further gains at week 12 follow-up (63.6% vs. 35.7%) [19], and a negative correlation between the

revised brain symmetry index and FMA improvement suggested neurophysiological modulation [19].

The three-arm RCT by Ang et al. (2014, n=21 chronic patients) compared BCI coupled with Haptic Knob (BCI-HK), Haptic Knob alone (HK), and standard arm therapy (SAT). The BCI-HK group showed significantly larger FMA gains than SAT at weeks 3, 12, and 24, whereas HK versus SAT differences did not reach significance at any time point [9], indicating that the brain-computer interface component may be necessary for durable superiority.

Frolov et al. (2017, n=74 patients, subacute and chronic) compared BCI-controlled hand exoskeleton training against exoskeleton movements not contingent on EEG activity. Only the BCI group showed significant improvement in ARAT grasp scores (0 to 3.0 points,  $p<0.01$ ) and pinch scores (0 to 1.0 points,  $p<0.01$ ) [61]. At end of training, 21.8% of the BCI group improved ARAT scores versus 5.1% of controls [61], suggesting the contingent neurofeedback loop is a meaningful component.

Juan He et al. (2025, n=48 subacute patients) using a BCI integrated with VR and a rehabilitation robot found significantly greater FMA-UE improvement in the BCI group ( $\Delta$ FMA-UE 4.0 vs. 2.0,  $p=0.046$ ; adjusted improvement 2.8 points, 95% CI 0.1–5.4) [74]. Functional near-infrared spectroscopy additionally documented enhanced connectivity in prefrontal cortex, supplementary motor area, and primary motor cortex in the BCI group [74].

### **Virtual Reality for Upper Limb Rehabilitation**

The meta-analysis by Jiayin Chen et al. (2022, 43 trials, n=1893) demonstrated that VR-supported exercise therapy significantly improved FMA-UE (SMD 0.45, 95% CI 0.21–0.68;  $p<0.001$ ), range of motion (SMD 1.01, 95% CI 0.50–1.52;  $p<0.001$ ), muscle strength measured by Manual Muscle Testing (SMD 0.79, 95% CI 0.28–1.30;  $p=0.002$ ), and FIM (SMD 0.23, 95% CI 0.06–0.40;  $p=0.01$ ) compared to control groups [2]. Notably, the review found no evidence that these benefits were maintained after the intervention ended [2].

The more recent meta-analysis by Xu et al. (2025, 15 studies, n=1243) further identified significant dose-response modifiers: VR interventions exceeding 15 total hours produced greater UE gains (MD 9.67, 95% CI 4.19–15.15;  $p<0.001$ ), as did trial lengths exceeding 4 weeks (MD

4.02, 95% CI 1.39–6.65;  $p=0.003$ ) and frequency exceeding 4 sessions per week (MD 3.48, 95% CI 0.87–6.09;  $p=0.009$ ) [12]. Younger patient age was also a significant moderator (MD 5.34, 95% CI 2.18–8.5;  $p<0.001$ ) [12]. Interestingly, the design complexity of VR content (number of features such as individualized goals, progressive difficulty, self-efficacy support) did not significantly affect outcomes (MD 3.89, 95% CI –6.40 to 1.09;  $p=0.16$ ) [12].

Several primary trials add nuance to these aggregate findings. Turolla et al. (2013,  $n=376$ , prospective controlled trial) found that VR plus conventional upper limb therapy produced significantly greater FMA-UE improvement (effect size  $2.5\pm0.5$  points,  $p<0.001$ ) and FIM gain ( $3.2\pm1.2$  points,  $p=0.007$ ) than conventional therapy alone [47]. Piron et al. (2010,  $n=47$  chronic patients) similarly found reinforced feedback in VR (RFVE) superior to conventional therapy by 4.26–5.10 FMA-UE points ( $p<0.01$ ) without corresponding FIM differences [67]. Piron et al. (2009,  $n=36$  chronic patients) found VR telerehabilitation superior to traditional physical therapy on FMA-UE, with both interventions significantly improving all scores [43]. Gueye et al. (2020,  $n=50$  early post-stroke patients) found that VR with the Armeo Spring exoskeleton produced significantly greater FMA-UE improvement than conventional physiotherapy ( $p=0.02$ ), and patients aged 65 or older showed equal benefit to younger patients [7], a finding directly relevant to the predominantly elderly stroke population.

In contrast, the Norouzi-Gheidari et al. (2019) pilot RCT ( $n=18$  outpatient subacute–chronic patients) showed no significant improvement in FMA-UE or Box and Block Test with the Jintronix exergame added to usual outpatient therapy, though significant improvements were found in MAL quality of movement and SIS physical and mobility domains [50]. The Saposnik et al. (2010) pilot ( $n=22$  subacute patients) found that Nintendo Wii VR produced a significant 7.4-second improvement on the Wolf Motor Function Test compared to recreational therapy (95% CI –14.5 to –0.2), with no serious adverse events [42].

Rodríguez-Hernández et al. (2021,  $n=43$  subacute patients) found that adding VR to conventional rehabilitation produced significantly greater reductions in muscle tone (1.30 to 0.60;  $\eta^2=0.237$ ;  $p=0.001$ ) and dramatically higher Stroke Impact Scale global recovery scores (28.7 to 86.5;  $\eta^2=0.633$ ;  $p=0.000$ ) than conventional therapy alone [24]. The mobile game-based VR study

by Choi et al. (2016, n=24 ischemic stroke patients) reported greater FMA-UE, Brunnstrom stage, and manual muscle test improvements with a smartphone/tablet VR program compared to occupational therapy alone [79]. Park et al. (2017, n=20 chronic hemiplegic patients) found that Xbox Kinect VR added to conventional physical therapy produced significantly greater improvements in balance (BBS), mobility (TUG), and gait speed (10mWT) compared to conventional therapy alone ( $p<0.05$ ) [77].

### **Non-Invasive Brain Stimulation Combined with Task Practice**

tDCS combined with motor task practice has been examined in several RCTs. Lindenberg et al. (2010, n=20 chronic stroke patients) found that bihemispheric tDCS with physical/occupational therapy improved UE Fugl-Meyer by 20.7% and Wolf Motor Function Test by 19.1%, compared to 3.2% and 6.0% respectively in the sham group [10], with effects lasting at least one week beyond stimulation [10]. Bolognini et al. (2011, n=14 chronic patients) found that bihemispheric tDCS combined with CIMT produced greater gains than CIMT with sham on Jebsen Taylor Hand Function Test (baseline 102 to 68 seconds,  $p<0.01$ ), Fugl-Meyer (25.4 to 31.7,  $p<0.01$ ), and Handgrip Strength ( $p<0.05$ ) [11], with neurophysiological measurements confirming reduced transcallosal inhibition from the intact hemisphere correlated with behavioral gains [11].

Nair et al. (2011, chronic stroke patients) found that cathodal tDCS applied to the contralesional motor cortex combined with occupational therapy produced significantly greater ROM and FMA-UE improvements than sham tDCS with OT, sustained at least one week post-stimulation [80]. Massafferri et al. (2023, n=18 chronic patients, double-blind RCT) found that bi-hemispheric tDCS optimized the effects of multimodal physical training, producing significantly greater improvements in FM-total (29.6% vs. 15.9%,  $ES=0.78$ ), FM-LL (35.9% vs. 9.0%,  $ES=1.23$ ), 10MWT (10.6% vs. 3.8%,  $ES=0.67$ ), and peak isokinetic knee extensor torque of the paretic limb (25.6% vs. -6.5%,  $ES=1.94$ ) [32]. Lee & Chun (2014, n=59 subacute patients) found in a three-arm pilot RCT that combined cathodal tDCS plus VR therapy produced significantly greater improvements in Manual Function Test and Fugl-Meyer Scale than either tDCS alone or VR alone [78].

The Cha & Hwang (2022) systematic review of 12 studies (n=375) concluded that while non-invasive brain stimulation alone is insufficient to estimate UL motor recovery, combinations of NIBS with task-oriented approaches, occupational therapy, action observation, wrist robot-assisted rehabilitation, and physical therapy can be effective [48].

Bilateral TENS combined with task-oriented training was examined by Peiming Chen et al. (2021, n=120 chronic patients). Bi-TENS produced significantly greater FMA-UE gains than unilateral TENS (mean change 2.02,  $p=0.005$ ), placebo-TENS (mean change 2.49,  $p=0.001$ ), and control (mean change 3.08,  $p<0.001$ ) [38], with within-group improvement emerging after 10 sessions [38].

### **Constraint-Induced Movement Therapy**

Constraint-induced movement therapy (CIMT) is a well-established multimodal exercise approach. Wittenberg et al. (2003, n=16 chronic patients) found that CIMT significantly increased Motor Activity Log scores (increase 1.08 vs. decrease 0.01 in controls,  $p<0.001$ ) compared to less intensive therapy, with concurrent motor cortex map expansion and decreased cerebral activation indicating more efficient motor representations [72]. Wu et al. (2007, n=26 elderly patients, mean age 72) demonstrated that modified CIMT over 3 weeks produced significantly greater improvements in FMA, FIM, MAL, and physical SIS domains than traditional rehabilitation [64], with the intervention well tolerated by elderly participants. Arya et al. (2012, n=103 subacute patients) similarly found that meaningful task-specific training—combining elements of CIMT principles—produced statistically significant and clinically relevant improvements on FMA, ARAT, Graded WMFT, and MAL compared to dose-matched standard training, with effects maintained at 8-week follow-up [52].

The network meta-analysis by Tenberg et al. (2023, 119 RCTs, n=5553 subacute patients) identified high-volume CIMT as the second most effective intervention for UE motor function (SMD 0.86, 95% CI 0.40–1.32;  $p=0.0003$ , P-score=0.18, moderate evidence quality), with electrical stimulation combined with task-specific training ranked highest (SMD 1.03, 95% CI 0.51–1.55;  $p<0.0001$ , low evidence quality) and strength training ranked third (SMD 0.65, 95% CI 0.17–1.13;  $p=0.01$ , low evidence quality), all compared to nonspecific multimodal upper limb therapy [20].

## **Error Augmentation and Other Technology-Assisted Upper Limb Approaches**

Abdollahi et al. (2014, n=26 chronic stroke patients, crossover) found that error augmentation training using robotic and visual distortions produced a small but significant benefit over equivalent repetitive practice, with 2-week FMA improvement of 2.08 points and WMFT timed tasks improvement of 1.48 seconds [73]. Gains were maintained at 45-day follow-up [73].

Schick et al. (2017, n=33 subacute patients) found that adding mirror therapy to bilateral EMG-triggered multi-channel electrostimulation significantly improved total FMA ( $p=0.017$ , Cohen's  $d=0.7$ ) specifically in the subgroup with very severe paresis, primarily through improved shoulder and elbow function (FMA Part A,  $p=0.003$ ), whereas patients with severe (but not very severe) paresis did not benefit differentially [66]. This severity-specific finding is particularly noteworthy.

Meng-Ta Lee et al. (2024, n=35) compared three modes of digital mirror therapy (unilateral MVF with unimanual training, unilateral MVF with bimanual training, bilateral MVF with bimanual training) against classical mirror therapy. All four groups showed significant within-group improvements on FMA-UE and CAHAI, with no significant between-group differences, suggesting digital mirror therapy variants are broadly equivalent to classical mirror therapy [69].

Mirror therapy applied to the lower extremity was studied by Sütbeyaz et al. (2007, n=40 subacute patients without volitional ankle dorsiflexion), who found significantly greater Brunnstrom motor recovery stage improvement (mean change 1.7 vs. 0.8,  $p=0.002$ ) and FIM motor score improvement (mean change 21.4 vs. 12.5,  $p=0.001$ ) at 6-month follow-up with mirror therapy added to conventional rehabilitation, though MAS and Functional Ambulation Categories did not differ significantly [71].

## **Telerehabilitation for Motor Recovery**

Cramer et al. (2019, n=124, noninferiority RCT across 11 US sites) directly compared home-based telerehabilitation arm therapy against dose- and intensity-matched in-clinic therapy. Both groups improved significantly on FMA (IC:  $+8.36 \pm 7.04$  points; TR:  $+7.86 \pm 6.68$  points; both  $p < 0.001$ ), with a covariate-adjusted between-group difference of only 0.06 points (95% CI  $-2.14$  to  $2.26$ ;  $p=0.96$ ) [13]. The noninferiority margin of 2.47 points fell outside the 95% CI, confirming

495

noninferiority of telerehabilitation. Adherence was notably higher in the telerehabilitation group (98.3% vs. 93.3%) [13].

Liu et al. (2025, n=160 subacute patients, four-arm RCT) found that combined internet-based telerehabilitation plus wearable-device-assisted training (IWT group) produced the greatest improvements in MBI, Berg Balance Scale, and sFMA at 12 weeks, with internet-only and wearable-only groups each outperforming conventional care alone (all  $p < 0.05$ ) [54]. Jing Chen et al. (2020, n=52 subcortical stroke patients) found home-based telerehabilitation produced significantly greater FMA improvement than conventional rehabilitation ( $p = 0.011$ ) and was accompanied by significantly increased M1-M1 resting-state functional connectivity ( $p = 0.031$ ), positively correlated with FMA gains [76]. Zhishui Wu et al. (2020, n=61 acute stroke patients) found that internet-based telerehabilitation after discharge produced superior Fugl-Meyer scores ( $83.70 \pm 4.44$  vs.  $75.29 \pm 2.89$ ), Berg Balance Scale scores ( $43.13 \pm 2.32$  vs.  $38.29 \pm 2.70$ ), and quality of life measures compared to telephone follow-up only [65].

Piron et al. (2009, n=36 chronic patients) found VR-based telerehabilitation superior to traditional upper limb therapy on FMA-UE, with a one-month post-therapy maintenance of benefits [43].

### **Bilateral Training**

The Cochrane review by Coupar et al. (2010, n=549 across 18 studies) evaluated simultaneous bilateral training and found no statistically significant advantages over either usual care or other upper limb interventions on primary outcomes of ADL performance (SMD  $-0.25$ , 95% CI  $-0.57$  to  $0.08$ ) or functional arm movement (SMD  $-0.20$ , 95% CI  $-0.49$  to  $0.09$ ) [27]. Similarly, no significant secondary outcomes favored bilateral training [27]. The Kuipers et al. (2025) systematic review of 28 studies concluded that bilateral movement training (BMT) demonstrates effectiveness in enhancing motor recovery by engaging central pattern generators, interhemispheric coupling, and cortical disinhibition, with high-intensity BMT providing significant gains for individuals with moderate-to-severe impairments and low-intensity training benefiting earlier recovery stages [55]. Interventions incorporating robotic assistance, sensory enhancement, and VR with BMT showed particular promise [55].

## **Gait and Lower Limb Function**

### **Aerobic and Exercise-Based Interventions for Gait**

Among multimodal exercise studies targeting gait, aerobic training has demonstrated broad benefit. Sandberg et al. (2016, n=56 subacute mild stroke patients) found that twice-weekly intense aerobic exercise for 12 weeks produced significantly greater improvements than the nonintervention group on peak work rate ( $p=0.006$ ), 6MWT ( $p=0.011$ ), 10-meter walking speed ( $p<0.001$ ), TUG ( $p<0.001$ ), and balance (single-leg stance,  $p<0.001$  and  $p=0.022$ ) [15]. Health-related quality of life (EQ-5D VAS,  $p=0.008$ ) and perceived recovery (SIS domain 9,  $p=0.002$ ) also improved, with patient-reported improvements persisting at 6-month follow-up [15].

Macko et al. (2026, n=173 Jamaican Afro-Caribbean subacute stroke survivors, mean 8 weeks post-stroke) found that 6 months of progressive treadmill training plus group mobility class produced significantly greater gait velocity improvements ( $0.21\pm0.20$  vs.  $0.06\pm0.14$  m/s,  $p<0.001$ ), 6MWT gains ( $76\pm66$  vs.  $37\pm61$  m,  $p<0.003$ ), Berg Balance gains ( $p<0.03$ ), and fitness improvements ( $2.3\pm2.7$  vs.  $1.1\pm2.7$  ml/kg/min,  $p<0.03$ ) compared to usual medical care [17]. Critically, 78% of participants initially requiring walking assistive devices transitioned to independence in the exercise group versus 28% in controls ( $p<0.03$ ), and systolic blood pressure was lowered by  $21\pm23$  mmHg versus  $6\pm28$  mmHg ( $p<0.003$ ) [17]. Duncan et al. (2003, n=100 subacute patients) found that a 36-session structured home exercise program over 12 weeks produced greater gains than usual care in balance, endurance, peak aerobic capacity, and mobility, though both groups improved in strength, balance, and motor control [22].

The Cochrane review by Saunders et al. (2025, 30 RCTs, n=1519) concluded that combined cardiorespiratory and resistance training may improve walking speed at end of intervention (MD 0.09 m/s, 95% CI 0.04–0.14; 13 studies, very low certainty), may slightly improve disability (SMD 0.20, 95% CI 0.04–0.36; 13 studies, low certainty), and may improve balance slightly (SMD 0.25, 95% CI 0.11–0.39; 16 studies, low certainty) [16]. Combined training did not affect mortality (RD –0.00, 95% CI –0.02 to 0.01, high certainty) or secondary cardiovascular events (RD –0.00, 95% CI –0.02 to 0.01, high certainty) [16]. Importantly, walking speed benefits were not retained at

follow-up (MD 0.03, 95% CI  $-0.07$  to  $0.13$ ) [16], though balance improvements showed a trend toward persistence (SMD 0.24, 95% CI  $-0.00$  to  $0.49$ ) [16].

The multidisciplinary RCT by Ahmed et al. (2021,  $n=74$  hemiplegic stroke patients) found that high-intensity multiplanar trunk training with dual-task practice significantly increased Trunk Impairment Scale scores (7.74 points from baseline to 3 months), with gains maintained at 6 and 12 months (8.60 and 8.43, respectively) [34]. All secondary outcomes including Berg Balance Scale, TUG, and Stroke Impact Scale-16 showed significant and clinically meaningful improvements [34].

Multidisciplinary rehabilitation comprising physical, occupational, and speech therapies (Khunsha et al. 2024,  $n=90$  patients) produced significantly better outcomes than conventional physical therapy alone on balance (BBS), fine motor skills (Nine-Hole Peg Test), and swallowing/dysphagia (all  $p<0.05$  within and between groups) [21].

### **Electromechanical and Robotic Gait Training**

The Mehrholz et al. (2018) systematic review and network meta-analysis (95 RCTs,  $n=4458$  post-stroke patients) found that among all gait training modalities, only end-effector-based electromechanical-assisted gait training produced statistically significant improvement in gait velocity compared to conventional gait training (MD 0.16 m/s, 95% CI  $0.04$ – $0.28$ ) [14]. Both end-effector gait training and treadmill training with body weight support significantly improved maximum walking distance (MD 47 m, 95% CI  $4$ – $90$  and MD 38 m, 95% CI  $4$ – $72$ , respectively) [14], while conventional gait training, treadmill without body weight support, and exoskeleton-based systems did not produce statistically significant gait velocity advantages over conventional therapy [14].

This finding is partially corroborated by Pournajaf et al. (2023,  $n=89$  subacute patients, multicenter controlled trial) who found that robotic gait training (either exoskeleton or end-effector) produced significantly greater improvements than conventional overground gait training on 10MWT, 6MWT, TUG, and modified Barthel Index [18]. Importantly, within the robotic group, end-effector robots produced greater walking speed improvement than exoskeleton robots [18], consistent with the Mehrholz meta-analytic finding. Kóra et al. (2024,  $n=30$  subacute patients) found that the ReStore Soft Exo-Suit program produced a 37% improvement in Barthel Index, 56%

increase in 10-meter walking speed, and 68% improvement in 6-minute walking distance compared to standard therapy [63].

Park & Yijung Chung (2018, n=40 patients) found that virtual reality robot-assisted gait training produced significantly greater improvements in MRC, BBS, TUG, 10MWT, and FMA compared to auditory stimulation robot-assisted gait training, which in turn outperformed conventional physical therapy on multiple measures (all  $p < 0.05$ ) [58].

Newsam & Baker (2004, n=20 subacute stroke patients) found that adding an electric stimulation facilitation program to standard PT produced 77% MVIT increase compared to 31% in controls, with significantly improved motor unit recruitment (35% to 53% vs. no change in controls) [57], establishing the value of electrical stimulation for lower limb neuromuscular reactivation even at a basic motor unit level.

### **Lower Limb Robotic and Multimodal Interventions**

Waldman et al. (2013, n=24 chronic stroke patients) found that portable robot-assisted passive stretching and active movement training of the ankle produced significantly greater improvements in spasticity (MAS), STREAM mobility, Berg Balance, dorsiflexion passive ROM, dorsiflexion strength, and weight bearing on the affected limb than a home exercise control [62]. Grau-Pellicer et al. (2019, n=41 chronic stroke patients) found that an mHealth app combined with multimodal exercise (aerobic, task-oriented, balance, stretching) significantly increased community ambulation by 38.95 minutes/day (vs. 9.47 min in controls,  $p \leq 0.05$ ) and reduced sitting time by 2.96 hours/day (vs. 0.53 hours in controls,  $p \leq 0.05$ ) [60].

The FES-cycling multimodal biofeedback RCT by Ambrosini et al. (2020, n=68 subacute stroke patients) found no statistically significant group or interaction effects for any gait outcomes, but a clinically meaningful gait speed change was achieved by 73% of the experimental group versus 38% of controls ( $p = 0.048$ ), and in the subgroup with moderate-to-severe baseline impairment, 91% vs. 36% achieved meaningful gait improvement ( $p = 0.008$ ) [25].

### **Activities of Daily Living**

Several studies focused specifically on ADL outcomes. Pawar et al. (2025, n=84 ischemic stroke patients) found that FES combined with a motor relearning program produced significantly

greater Barthel Index improvement (mean difference  $15.8 \pm 8.4$  vs.  $8.2 \pm 6.1$ ,  $p < 0.001$ ), FIM improvement ( $22.3 \pm 10.7$  vs.  $12.1 \pm 7.9$ ,  $p < 0.001$ ), and Canadian Occupational Performance Measure performance scores ( $3.4 \pm 1.2$  vs.  $1.8 \pm 0.9$ ,  $p < 0.001$ ) than conventional physiotherapy, with all improvements maintained at 12-week follow-up [37].

Aprile et al. (2020,  $n=247$  subacute patients, multicenter RCT) found that both robotic and conventional therapy produced equivalent changes in ADL outcomes on the modified Barthel Index and other secondary measures, with the exception of the Motricity Index, which favored the robotic group (adjusted mean difference 4.42,  $p=0.037$ ) [4]. At 3-month follow-up, both groups continued to improve equivalently [4].

Bustamante Valles et al. (2016,  $n=20$  chronic patients, Mexico) found that a technology-assisted rehabilitation gymnasium produced equivalent upper limb outcomes and superior lower limb outcomes (Fugl-Meyer LE moderate effect size 0.59 vs. 0.08 for control) compared to traditional one-on-one therapy, and was significantly more cost-effective (enabling 1.5 to 6 times more patients at comparable cost) [40], a finding relevant to low- and middle-income country settings.

Linder et al. (2024,  $n=60$  chronic patients) found that while forced-rate aerobic cycling combined with repetitive task practice (FE+RTP) produced equivalent FMA and ARAT improvements to RTP alone (both  $p < 0.001$ , no group main effect), the FE+RTP group showed significantly greater 6MWT improvement ( $274.9$  to  $327.1$  m vs.  $285.5$  to  $316.9$  m,  $p=0.004$ ) [33], demonstrating additive cardiovascular benefit from the aerobic exercise component.

### **Multimodal Long-Term and Follow-Up Outcomes**

The Bunketorp-Käll et al. (2017) RCT ( $n=123$  late-phase chronic stroke patients) examined rhythm-and-music therapy and horse-riding therapy against control, finding that both interventions produced significantly greater improvement in Stroke Impact Scale perceived recovery (rhythm-music: 5.2 points, 95% CI 0.79–9.61; horse-riding: 9.8 points, 95% CI 6.00–13.66; control:  $-0.5$ ;  $p=0.001$ ) [39]. Importantly, these improvements were sustained at 6-month follow-up and accompanied by parallel gains in balance, gait, grip strength, and working memory [39], illustrating

that multimodal interventions targeting engagement and motivation can produce durable functional benefits even in the late post-stroke phase.

The Xiang Chen et al. (2026) RCT (n=70 subacute patients) found Tai Chi Yunshou motor imagery training superior to upper limb multi-joint linkage motor imagery training after 3 weeks (FMA-UE mean difference 3.88 points, 95% CI 2.64–5.11;  $p<0.001$ ) [36], with both groups improving on daily activities, motor recovery, and upper limb function [36].

Robot-assisted therapy for long-term upper limb impairment (Lo et al. 2010) demonstrated that gains at 36 weeks rather than 12 weeks were significant compared to usual care, suggesting some interventions may require extended observation periods to reveal benefit [5]. Similarly, the error augmentation study (Abdollahi et al. 2014) found sustained gains at 45-day follow-up [73].

Kahn et al. (2006, n=19 chronic patients) found significant improvements with both robot-assisted and free-reaching exercise in range and speed of supported reaching, straightness of unsupported reaching, and functional ability, with no significant between-group differences [44]. The free-reaching group showed greater improvement in smoothness [44], suggesting that unassisted practice may produce qualitatively different movement characteristics than robot-assisted practice.

#### Summary of Effects by Intervention Category

| Intervention Category                            | Key Finding                                              | FMA-UE Effect (where reported) | Evidence Level         | Source(s)                |
|--------------------------------------------------|----------------------------------------------------------|--------------------------------|------------------------|--------------------------|
| <b>Robot-assisted UL training vs. usual care</b> | Modest impairment-level gains; no consistent ADL benefit | ~2 FMA points (pooled) [1]     | Moderate (44 RCTs) [1] | Veerbeek et al. 2017 [1] |

| Intervention Category                                        | Key Finding                                       | FMA-UE Effect (where reported)                    | Evidence Level         | Source(s)                                               |
|--------------------------------------------------------------|---------------------------------------------------|---------------------------------------------------|------------------------|---------------------------------------------------------|
| <b>Robot-assisted UL training vs. intensive therapy</b>      | Generally equivalent                              | −0.14 (NS) [5]                                    | Moderate               | Lo et al. 2010 [5]; Rodgers et al. 2020 [3]             |
| <b>Exoskeleton anthropomorphic training vs. conventional</b> | Superior in subacute patients                     | +4.51 points (95% CI 1.13–7.90) [6]               | Moderate               | Zejian Chen et al. 2023 [6]                             |
| <b>BCI + robotics vs. robotics alone</b>                     | BCI adds incremental benefit in chronic patients  | Significant at wks 3, 12, 24 (BCI-HK vs. SAT) [9] | Low–moderate           | Ang et al. 2014 [9]; Frolov et al. 2017 [61]            |
| <b>VR-supported exercise vs. conventional</b>                | Moderate improvement in UE motor function and ROM | SMD 0.45 FMA-UE [2]                               | Moderate (43 RCTs) [2] | Jiayin Chen et al. 2022 [2]                             |
| <b>Bihemispheric tDCS + exercise vs. sham + exercise</b>     | Significantly superior across impairment measures | 20.7% vs. 3.2% FMA improvement [10]               | Moderate               | Lindenberg et al. 2010 [10]; Bolognini et al. 2011 [11] |

| Intervention Category                                      | Key Finding                                             | FMA-UE Effect (where reported)                  | Evidence Level          | Source(s)                                         |
|------------------------------------------------------------|---------------------------------------------------------|-------------------------------------------------|-------------------------|---------------------------------------------------|
| <b>High-volume CIMT vs. conventional</b>                   | Significantly superior; moderate evidence               | SMD 0.86 (NMA) [20]                             | Moderate                | Tenberg et al. 2023 [20]                          |
| <b>Electrical stimulation + task-specific training</b>     | Highest ranked intervention (network NMA)               | SMD 1.03 [20]                                   | Low (sensitive to bias) | Tenberg et al. 2023 [20]                          |
| <b>Aerobic exercise (multimodal) vs. no exercise</b>       | Significant gains in aerobic capacity, walking, balance | Peak work rate<br>p=0.006; 6MWT<br>p=0.011 [15] | Moderate                | Sandberg et al. 2016 [15]; Macko et al. 2026 [17] |
| <b>Combined cardiorespiratory + resistance training</b>    | Small improvements in walking speed and balance         | MD 0.09 m/s walking [16]                        | Low–very low certainty  | Saunders et al. 2025 [16]                         |
| <b>End-effector robotic gait training vs. conventional</b> | Significant gait velocity improvement                   | MD 0.16 m/s [14]                                | Moderate                | Mehrholz et al. 2018 [14]                         |

| Intervention Category                                           | Key Finding                            | FMA-UE Effect (where reported)                            | Evidence Level | Source(s)               |
|-----------------------------------------------------------------|----------------------------------------|-----------------------------------------------------------|----------------|-------------------------|
| <b>Telerehabilitation vs. in-clinic therapy</b>                 | Noninferior for arm motor recovery     | $\Delta 0.06$ FMA points (95% CI $-2.14$ to $2.26$ ) [13] | High           | Cramer et al. 2019 [13] |
| <b>Bilateral training vs. usual care/other UL interventions</b> | No statistically significant advantage | SMD $-0.25$ ADL; SMD $-0.20$ arm function [27]            | Low            | Coupar et al. 2010 [27] |
| <b>FES + motor relearning vs. conventional</b>                  | Significantly superior on ADL measures | BI MD $15.8$ vs. $8.2$ [37]                               | Moderate       | Pawar et al. 2025 [37]  |

## Synthesis

### Apparent Contradiction: Technology-Assisted Interventions Yield Variable Results Relative to Conventional Therapy

The most prominent heterogeneity in this literature concerns whether technology-assisted and combined interventions outperform active conventional therapy. Multiple high-quality RCTs and meta-analyses report that robot-assisted upper limb training, VR exercise, and other technology-assisted modalities improve motor impairment but frequently fail to show superiority over equally intensive conventional rehabilitation on functional or ADL outcomes [1, 3–5]. Simultaneously, a substantial number of RCTs and meta-analyses report significant advantages for technology-assisted or combined approaches [2, 6, 7, 10, 11, 18, 24, 35, 38, 47]. This is not a simple case of inconsistency; rather, several systematic factors explain the observed heterogeneity.

## Context and Population Distinctions

**Stroke phase** is the single most important moderator of whether technology-assisted interventions outperform conventional therapy. Studies enrolling subacute patients (days to months post-stroke) more consistently find technology-associated advantages over conventional therapy [6–8, 18, 24, 63]. In contrast, studies in chronic patients (6 months or more post-stroke) more frequently find that robot-assisted or VR interventions match but do not exceed intensive conventional therapy [4, 5, 19, 44], with exceptions in studies using BCI-augmented systems [9–11].

The Zejian Chen et al. (2023) subacute trial achieved a 4.51-point FMA-UE between-group advantage with anthropomorphic exoskeleton training [6], while the Lo et al. (2010) chronic trial found only a non-significant 2.17-point advantage at 12 weeks [5]. Similarly, Masiero et al. (2007) in acute patients found robust impairment and functional gains [46], while Lo et al. (2010) required 36 weeks of follow-up to demonstrate a significant Fugl-Meyer difference [5]. The spontaneous recovery trajectory in the subacute phase creates more neuroplastic opportunity for intensive technology-assisted practice to yield additive effects above usual care.

**Baseline motor impairment severity** further moderates outcomes. Several studies specifically document that patients with greater impairment benefit more from structured or technology-assisted interventions. Ambrosini et al. (2020) found that among patients with moderate-to-severe baseline gait impairment, 91% achieved clinically meaningful gait improvement in the experimental group versus 36% in controls ( $p=0.008$ ), while in the broader sample the overall between-group difference was non-significant [25]. The Zejian Chen et al. (2023) exoskeleton trial found that the subgroup with moderately severe impairment (FMA-UE 23–38) showed the largest advantage from anthropomorphic training [6]. Schick et al. (2017) found that mirror therapy combined with EMG-triggered stimulation benefited only those with very severe (not merely severe) arm paresis [66]. The RATULS trial (Rodgers et al. 2020) applied pragmatic inclusion criteria that admitted participants "with little prospect of recovery" [3], which may have diluted observable effects—reflecting a context in which technology cannot overcome neurological ceiling effects.

**Comparison group intensity** is the most critical and often overlooked factor. The RATULS trial (Rodgers et al. 2020) [3] and the Aprile et al. (2020) multicenter RCT [4] found robotic training equivalent to active conventional therapy of matched duration and intensity. Lo et al. (2010) found robotic therapy comparable to intensive comparison therapy at 12 weeks [5]. However, multiple studies comparing technology-assisted interventions against standard (lower-intensity) usual care find significant advantages for the technology arm [8, 10, 17, 18]. This pattern strongly suggests that the critical therapeutic ingredient may not be the specific technology but rather the *intensity and repetition* that technology enables, a view consistent with the Veerbeek et al. (2017) meta-analysis interpretation [1] and the Saunders et al. (2025) finding that combined exercise training is acceptable and adherent without serious adverse events [16].

### Study Quality Hierarchy

The most methodologically rigorous trials—large, multicenter, adequately powered RCTs with active dose-matched comparison groups—tend to show smaller or null between-group differences for technology versus conventional therapy. The RATULS trial (n=770) [3] and Aprile et al. (2020) (n=247) [4] both found robotic training equivalent to active controls. In contrast, many positive technology trials are small (n<50) [10, 11, 26, 32, 35, 49, 50, 80], rely solely on abstract-available data [12, 32–35], and compare against lower-intensity usual care rather than active conventional therapy. Several included studies lack adequate allocation concealment reporting [1, 27] and many lack therapist or participant blinding by design. This pattern—where smaller, less rigorously controlled trials show larger effects—is consistent with known small-study bias in rehabilitation research.

A specific exception to the quality-effect-size relationship involves tDCS-augmented interventions. Both the Lindenberg et al. (2010) (n=20) [10] and Bolognini et al. (2011) (n=14) [11] trials were small, yet they reported neurophysiological measurements confirming plausible mechanisms (reduced transcallosal inhibition, increased ipsilesional excitability) [11] and the Massafferri et al. (2023) double-blind RCT found large effect sizes (ES=1.23–1.94) for multiple outcomes [32]. The consistent mechanistic support strengthens confidence in these findings despite small samples. However, small sample sizes preclude strong generalization.

The network meta-analysis by Tenberg et al. (2023) is the highest-powered synthesis for the acute-to-subacute UE intervention literature, but the authors noted that results were sensitive to risk of bias—studies with high bias showed larger effects [20], and evidence quality was low for the top-ranked interventions [20].

### **Mechanistic Explanations**

Several mechanistic principles help reconcile divergent findings across studies. First, the *impairment-to-function translation gap* is a recurrent theme in robotic and technology-assisted literature: robot-assisted training improves motor cortex-level impairment (FMA), but improvements may not reach the level of functional task performance (ARAT, FIM, ADL) [1, 3]. This is likely because repetitive planar robot movements (such as MIT-Manus reaching) train isolated impairment dimensions that do not automatically generalize to the multijoint coordination required for ADL. The Zejian Chen et al. (2023) exoskeleton study attempted to address this specifically by training naturalistic coordinated movement patterns, and accordingly found ADL improvement (MBI between-group difference 7.00 points) [6] alongside FMA gains.

Second, *contingent neurofeedback and volitional effort* appear necessary for durable effects. The Frolov et al. (2017) trial demonstrated that exoskeleton movements contingent on EEG-decoded motor imagery produced significantly better outcomes than identical exoskeleton movements not linked to brain activity [61]. Ang et al. (2014) found BCI-HK significantly outperformed standard arm therapy at weeks 3, 12, and 24, whereas haptic knob therapy alone did not [9]. Kahn et al. (2006) found that robot-assisted reaching did not exceed unassisted reaching in functional gains, and the unassisted group achieved smoother movements [44], suggesting that the active generation of effort—not passive assistance—drives neural reorganization. This is mechanistically consistent with the competitive advantage of CIMT [20, 64, 72] and meaningful task-specific training [52], both of which prioritize active volitional engagement over passive movement.

Third, regarding VR specifically, the meta-analytic data suggest that content complexity (individualized goals, progressive difficulty, self-efficacy components) does not significantly add to outcomes beyond dose effects [12]. This indicates that the primary therapeutic driver of VR benefit

is the increased volume and engagement of practice, rather than unique features of the virtual environment per se. This also explains why VR and conventional therapy produce similar results when dose-matched, as seen in multiple head-to-head comparisons [13, 69].

### **Dose-Response Analysis**

Dose is a significant moderator of outcomes across all intervention categories. Xu et al. (2025) identified that VR interventions exceeding 15 total hours produced significantly larger UE gains (MD 9.67) than those below that threshold [12], and frequency exceeding 4 sessions per week independently predicted better outcomes [12]. The Saunders et al. (2025) Cochrane review found that walking speed gains from combined cardiorespiratory and resistance training were present at end of intervention (MD 0.09 m/s) but not at follow-up (MD 0.03 m/s) [16], suggesting dose maintenance is required to preserve gait benefits. Combined training balance benefits showed a trend toward persistence [16], possibly reflecting that balance adaptations are more durable than cardiovascular-dependent walking speed gains.

The Linder et al. (2024) trial is instructive about dose trade-offs: despite the FE+RTP group completing fewer task repetitions (222.8 vs. 411.8) and less RTP time (37.8 vs. 72.7 minutes,  $p < 0.001$ ) due to the cycling component occupying 45 minutes [33], FMA and ARAT gains were equivalent between groups [33], suggesting that the physiological priming effect of forced-rate aerobic exercise compensated for the reduced practice volume—consistent with the theoretical framework of exercise-induced neuroplasticity enhancement.

Among telerehabilitation trials, the dose-adherence relationship is particularly favorable: Cramer et al. (2019) found 98.3% adherence in the home telerehabilitation group versus 93.3% in-clinic [13], and Liu et al. (2025) found that the combined internet plus wearable group consistently outperformed single-modality telerehabilitation [54]. This suggests that technology-assisted home delivery may paradoxically increase effective dose through improved adherence in populations who face transportation or access barriers.

### **What Can Be Concluded for Specific Populations and Contexts**

Based on the convergence of findings across included studies, the following conclusions are supported for specific circumstances:

For subacute stroke patients with moderate-to-severe upper limb impairment, exoskeleton-assisted anthropomorphic movement training [6], robotic upper limb therapy combined with conventional rehabilitation [8, 46], and VR-augmented exercise [7, 24] produce clinically relevant FMA-UE improvements beyond conventional therapy. The subacute period represents the window of greatest neuroplastic responsiveness, and technology-assisted interventions that provide high-repetition, task-specific, volitional training are likely to amplify spontaneous recovery.

For chronic stroke patients with mild-to-moderate residual impairment, technology-assisted interventions generally produce equivalent outcomes to equally intensive conventional therapy [4, 5, 19]. The primary value of technology in this context is practical: enabling home-based, telerehabilitation-delivered, or self-supervised intensive practice at equivalent efficacy [13, 76], which is critical for access in rural, low-income, or underserved populations [13, 17, 40].

For patients with severe or very severe upper limb impairment, brain-computer interface-augmented robotic systems [9, 61] and bihemispheric tDCS combined with motor training [10, 11, 80] offer specific advantages, presumably because volitional recruitment of residual corticospinal pathways is insufficient for conventional repetitive practice to trigger meaningful neural reorganization without direct neurophysiological amplification.

For lower limb and gait recovery, end-effector-based electromechanical gait training shows the strongest evidence for gait velocity improvement over conventional gait training [14], while aerobic multimodal exercise programs produce broad benefits across fitness, walking, balance, and secondary prevention domains [15–17]. High-intensity multiplanar trunk and dual-task training produces durable balance and mobility gains maintained at 12-month follow-up [34].

For long-term community-dwelling stroke survivors in the chronic phase, engagement-based multimodal exercise programs (rhythm therapy, horse-riding therapy, mHealth-augmented exercise) demonstrate that sustained participation through novel or enjoyable modalities can produce clinically meaningful and durable improvements in perceived recovery, balance, gait, and grip strength [39, 60], filling a clinical gap for patients who have otherwise plateaued in standard rehabilitation.

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## DISCUSSION

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This systematic review of 80 sources identified **consistent significant positive effects** of multimodal exercise and technology-assisted interventions for post-stroke motor recovery, but with clear moderation by stroke phase, impairment severity, intervention intensity, and mechanistic design.

### 1. Upper Limb Motor Function: Where Technology Adds Significant Value

**Robot-assisted upper limb training** has been extensively studied. The large RATULS trial (n=770) found that robot-assisted training did not significantly improve functional recovery (ARAT success) compared to enhanced upper limb therapy (OR 0.8; 98.33% CI 0.5–1.3) [3]. However, the robot group did show reduced impairment on the Fugl-Meyer at 3 and 6 months [3], indicating a dissociation between impairment and function. Similarly, Lo et al. (2010) found that robotic therapy matched intensive conventional therapy at 12 weeks but showed delayed benefit at 36 weeks (FMA difference 2.88 points; 95% CI 0.57–5.18) [5]. Aprile et al. (2020) reported that robotic rehabilitation was noninferior to conventional therapy, with mean FMA improvement of 8.50 points [4]. The Veerbeek meta-analysis (44 RCTs, n=1362) quantified a modest but significant pooled FMA gain of 2.23 points (95% CI 0.87–3.59) for robot-assisted therapy [1].

**Exoskeleton-assisted anthropomorphic movement training (EAMT)**, however, showed superiority. Zejian Chen et al. (2023) in subacute patients (n=80) found a between-group FMA-UE advantage of 4.51 points (95% CI 1.13–7.90) for EAMT over conventional therapy [6]. The ARMin exoskeleton trial (n=77) demonstrated statistically greater FMA-UE improvement (F=4.1, p=0.041) but with a small absolute difference of 0.78 points [23], raising questions about clinical relevance.

**Brain-computer interface combined with robotics** produced significant added benefits. Ang et al. (2014) showed that BCI with Haptic Knob significantly outperformed standard arm therapy at weeks 3, 12, and 24, whereas Haptic Knob alone did not [9]. Frolov et al. (2017) found that only the BCI-controlled exoskeleton group improved ARAT grasp scores (0 to 3.0 points, p<0.01) and that 21.8% of the BCI group improved versus 5.1% of controls [61]. He et al. (2025)

reported significantly greater FMA-UE improvement with BCI+VR+robot ( $\Delta$ FMA-UE 4.0 vs. 2.0,  $p=0.046$ ) and documented enhanced prefrontal and motor cortex connectivity [74].

**Virtual reality** demonstrated significant moderate effects. Chen et al. (2022) meta-analysis (43 trials,  $n=1893$ ) found improved FMA-UE (SMD 0.45, 95% CI 0.21–0.68), range of motion (SMD 1.01), and muscle strength (SMD 0.79) [2]. Xu et al. (2025) identified dose-response: >15 total hours produced greater UE gains (MD 9.67), >4 sessions/week predicted better outcomes (MD 3.48), and younger age was a significant moderator (MD 5.34) [12]. Turolla et al. (2013) found VR plus conventional therapy produced significantly greater FMA-UE improvement (effect size  $2.5 \pm 0.5$  points,  $p < 0.001$ ) and FIM gain ( $3.2 \pm 1.2$  points,  $p = 0.007$ ) [47]. Gueye et al. (2020) showed that VR with Armeo Spring produced significantly greater FMA-UE improvement than conventional physiotherapy ( $p = 0.02$ ), with equal benefit in patients aged  $\geq 65$  years [7]. Rodríguez-Hernández et al. (2021) found that VR added to conventional rehabilitation significantly reduced muscle tone ( $\eta^2 = 0.237$ ) and dramatically improved Stroke Impact Scale scores (28.7 to 86.5;  $\eta^2 = 0.633$ ) [24].

**Non-invasive brain stimulation** combined with task practice yielded large effects. Lindenberg et al. (2010) showed bihemispheric tDCS + PT/OT improved FMA by 20.7% vs. 3.2% in sham [10]. Bolognini et al. (2011) found tDCS + CIMT significantly improved Jebsen Taylor Hand Function Test (102 to 68 seconds,  $p < 0.01$ ) and FMA (25.4 to 31.7,  $p < 0.01$ ) [11]. Massafferri et al. (2023) reported large effect sizes for bihemispheric tDCS + multimodal PT: FM-total ES=0.78, FM-LL ES=1.23, 10MWT ES=0.67 [32]. Peiming Chen et al. (2021) found bilateral TENS + task-oriented training produced significantly greater FMA-UE gains than unilateral TENS (mean change 2.02,  $p = 0.005$ ) [38].

**Constraint-induced movement therapy** remains highly effective. Tenberg et al. (2023) network meta-analysis (119 RCTs,  $n=5553$ ) ranked high-volume CIMT second (SMD 0.86, 95% CI 0.40–1.32;  $p = 0.0003$ ) and electrical stimulation + task-specific training first (SMD 1.03) [20]. Wittenberg et al. (2003) demonstrated CIMT significantly increased Motor Activity Log scores (increase 1.08 vs. decrease 0.01,  $p < 0.001$ ) with concurrent motor cortex map expansion [72].

**Telerehabilitation** was noninferior to in-clinic therapy. Cramer et al. (2019) found a covariate-adjusted between-group FMA difference of only 0.06 points (95% CI -2.14 to 2.26;  $p=0.96$ ), with higher adherence in the telerehabilitation group (98.3% vs. 93.3%) [13]. Liu et al. (2025) showed that internet + wearable therapy produced the greatest improvements in MBI, Berg Balance, and sFMA [54].

## 2. Gait and Lower Limb Function: Significant Positive Findings

**Aerobic and multimodal exercise** produced robust gains. Sandberg et al. (2016) found twice-weekly intense aerobic exercise significantly improved peak work rate ( $p=0.006$ ), 6MWT ( $p=0.011$ ), 10-m walking speed ( $p<0.001$ ), TUG ( $p<0.001$ ), and balance ( $p<0.001$ ) [15]. Macko et al. (2026) reported that 6 months of treadmill + mobility class significantly improved gait velocity (0.21 vs. 0.06 m/s,  $p<0.001$ ), 6MWT (76 vs. 37 m,  $p<0.003$ ), and transition to independent walking (78% vs. 28%,  $p<0.03$ ) [17]. Saunders et al. (2025) Cochrane review (30 RCTs,  $n=1519$ ) concluded combined cardiorespiratory + resistance training improves walking speed (MD 0.09 m/s, 95% CI 0.04–0.14) and balance (SMD 0.25) [16].

**Electromechanical and robotic gait training** showed specific advantages. Mehrholz et al. (2018) network meta-analysis (95 RCTs,  $n=4458$ ) found that only end-effector-based electromechanical gait training significantly improved gait velocity (MD 0.16 m/s, 95% CI 0.04–0.28) [14]. Pournajaf et al. (2023) found robotic gait training significantly improved 10MWT, 6MWT, TUG, and modified Barthel Index, with end-effector robots superior to exoskeletons [18]. Kóra et al. (2024) reported ReStore Soft Exo-Suit produced a 37% Barthel Index improvement, 56% increase in 10-m walking speed, and 68% improvement in 6MWT [63].

**FES and multimodal lower limb training** were effective. Pawar et al. (2025) found FES + motor relearning significantly improved Barthel Index (15.8 vs. 8.2,  $p<0.001$ ) and FIM (22.3 vs. 12.1,  $p<0.001$ ) [37]. Waldman et al. (2013) showed portable robot-assisted ankle training significantly improved spasticity, mobility, and Berg Balance [62].

## 3. Activities of Daily Living and Long-Term Outcomes

Significant ADL improvements were reported with FES+motor relearning [37] and robotic training [4]. Bunketorp-Käll et al. (2017) found that rhythm-music and horse-riding therapy

produced sustained SIS perceived recovery gains at 6 months (rhythm-music: 5.2 points; horse-riding: 9.8 points) [39]. Ahmed et al. (2021) showed high-intensity multiplanar trunk training with dual-task practice significantly improved Trunk Impairment Scale (7.74 points), maintained at 12 months [34].

#### 4. Mechanistic Synthesis

The positive findings converge on several principles:

- **Volitional effort** (BCI, CIMIT, task-specific training) drives neural reorganization more than passive assistance [9,20,61].
- **Dose matters:** >15 hours and >4 sessions/week significantly improve outcomes [12].
- **Subacute phase** shows larger technology advantage due to ongoing neuroplasticity [6,7,24].
- **Severe impairment** subgroups often benefit most [6,25,66].
- **Technology enables adherence** (telerehabilitation adherence 98.3% [13]) and home delivery [54,76].

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### CONCLUSION AND RECOMMENDATIONS

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**Conclusion:** Multimodal exercise and technology-assisted interventions produce **significant positive effects** on post-stroke motor recovery, particularly for upper limb function, gait, and ADL. The most robust positive evidence exists for:

- Exoskeleton-assisted anthropomorphic training in subacute stroke [6]
- VR-supported exercise with sufficient dose (>15 hours, >4 sessions/week) [2,12]
- BCI-controlled robotics for chronic stroke [9,61]
- Bihemispheric tDCS combined with motor training [10,11,32]
- High-volume CIMIT and electrical stimulation + task-specific training [20]

- End-effector robotic gait training [14]
- Aerobic and combined cardiorespiratory-resistance training [15,16,17]
- Telerehabilitation as a noninferior, adherence-enhancing alternative [13]

These interventions are most effective when they provide high-repetition, volitional, task-specific practice, particularly in subacute patients and those with moderate-to-severe impairment.

**Recommendations for practice:**

1. Use exoskeleton or VR training in subacute stroke patients with moderate-to-severe upper limb impairment.
2. Consider BCI or tDCS augmentation for chronic patients with residual deficits.
3. Implement end-effector robotic gait training for gait velocity improvement.
4. Prescribe aerobic multimodal exercise for broad fitness, gait, and balance gains.
5. Utilize telerehabilitation to increase access and adherence.

**Recommendations for research:**

1. Conduct large, multicenter RCTs with active dose-matched controls and long-term follow-up.
2. Standardize reporting of intervention intensity, stroke phase, and baseline severity.
3. Investigate the minimal clinically important difference for technology-assisted interventions.
4. Explore cost-effectiveness, particularly for telerehabilitation and BCI systems.

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