Cureus
Part of SPRINGER NATURE

Open Access Review Article

Robotic Exoskeleton-Assisted Training for Upper Limb Recovery After Stroke: A Systematic Review and Meta-Analysis of Randomized Controlled Trials

Review began 10/24/2026
Review ended 11/11/2026
Published 11/13/2026

© Copyright 2026
Sager et al. This is an open access article distributed under the terms of the Creative Commons Attribution License CC-BY 4.0., which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

DOI: 10.7759/cureus.119596

Malek Sager [1], Ali Abusbaeh [2], Marwan Tantoush [3], Abdelrahman Najaim [4], Hasan Almgherbi [5], Bahaeddin Ben Hamida [6], Allaeddin Abusbaeh [1], Mohammed Alhamadi [7], Ayoub Tantush [8], Mohamad Alemam [9], Moaaz Shaded [10, 11], Nada G. Madkour [12]

1. General Medicine, Heartlands Hospital, University Hospitals Birmingham NHS Foundation Trust, Birmingham, GBR 2. General Practice, Calderdale and Huddersfield NHS Foundation Trust, Huddersfield, GBR 3. Internal Medicine, University Hospitals Birmingham NHS Foundation Trust, Birmingham, GBR 4. Internal Medicine, Russells Hall Hospital, The Dudley Group NHS Foundation Trust, Dudley, GBR 5. General Internal Medicine, University Hospitals Birmingham NHS Foundation Trust, Birmingham, GBR 6. General Practice, Heartlands Hospital, University Hospitals Birmingham NHS Foundation Trust, Birmingham, GBR 7. General Practice, Queen Elizabeth Hospital, University Hospitals Birmingham NHS Foundation Trust, Birmingham, GBR 8. General Medicine, University Hospitals Birmingham NHS Foundation Trust, Birmingham, GBR 9. General Practice, Faculty of Medicine, Alexandria University, Alexandria, EGY 10. General Practice, Humboldt Park Health, Chicago, USA 11. General Practice, Faculty of Medicine, Menoufia University, Menoufia, EGY 12. Community Medicine, Industrial Medicine and Occupational Health, Faculty of Medicine, Alexandria University, Alexandria, EGY

Corresponding author: Ayoub Tantush, ayoub.tantush@uhb.nhs.uk

Abstract

Upper limb motor impairment is among the most common and most persistent consequences of stroke. Robotic exoskeletons may deliver the high-intensity, repetitive, task-specific practice that drives motor recovery, but their efficacy as a distinct device class remains undetermined, since previous syntheses pooled them with end-effector devices. We searched PubMed, Scopus, Web of Science, the Cochrane Library, and Embase from inception until July 3, 2026, for randomized controlled trials comparing upper limb exoskeleton training with conventional therapist-mediated therapy in adults with stroke. We included 11 trials randomizing 371 patients and analyzing 338. Exoskeleton training produced greater improvement in total Fugl-Meyer Assessment for Upper Extremity (FMA-UE) score (mean difference 2.45, 95% CI 0.88 to 4.01, p = 0.002). Subgroup analysis by stroke phase showed a significant difference between strata (p = 0.011), with a large effect in subacute stroke (mean difference 5.31, 95% CI 2.73 to 7.89, p < 0.0001) and no significant effect in chronic stroke (mean difference 1.46, 95% CI 0.00 to 2.93, p = 0.05). Exoskeleton training also improved the proximal FMA-UE subscore (p < 0.0001), the Action Research Arm Test (p = 0.0003), and the distal FMA-UE subscore (p = 0.02), but did not affect spasticity measured by the Modified Ashworth Scale. Robotic exoskeleton training confers a statistically significant but modest advantage for upper limb motor impairment after stroke. The benefit is concentrated in the subacute phase and is greater proximally than distally, supporting its use.

Categories: Neurology, Physical Medicine & Rehabilitation, Healthcare Technology
Keywords: exoskeleton, fugl-meyer assessment, meta-analysis, robot-assisted therapy, stroke rehabilitation, upper extremity

Introduction And Background

Stroke remains one of the largest contributors to death and long-term disability worldwide. According to the most recent Global Burden of Disease analysis, there were 11.9 million incident strokes and 93.8 million prevalent cases globally in 2021, accounting for 7.3 million deaths and 160.5 million disability-adjusted life years. Stroke was the third leading cause of death and the fourth leading cause of disability-adjusted life years among all level 3 causes, and the absolute burden has continued to rise [1]. Despite progress in acute stroke management, several interventions have failed to translate radiological or physiological gains into improved functional outcomes; tranexamic acid, for example, limits hematoma expansion after intracerebral hemorrhage without improving functional recovery [2]. Rehabilitation therefore remains the principal route to functional recovery.

Motor impairment of the upper limb is among the most common and most persistent consequences of stroke. Approximately 80% of survivors have upper extremity dysfunction at onset, and between 30% and 66% still have measurable motor impairment even after six months [3,4]. Recovery of the arm and hand is slower and less complete than recovery of the lower limb, with full functional recovery reported in only a small minority [5]. Because reaching, grasping, and manipulation support most activities of daily living, residual upper limb impairment translates directly into dependence in self-care, restricted social

participation, and reduced quality of life [6].

Current rehabilitation practice is built on the principle that motor recovery is driven by high-intensity, repetitive, task-specific practice that exploits use-dependent neuroplasticity [7]. Delivering that intensity by conventional one-to-one therapy is labor-intensive and constrained by therapist availability, and the number of repetitions achieved in a typical therapy session falls well short of the doses associated with neuroplastic change in experimental work [8].

Robot-assisted therapy addresses this constraint, since a device can deliver hundreds of consistent repetitions per session with less therapist input. Such devices are divided into end-effectors, which guide the limb from a single distal contact point in a restricted workspace, and exoskeletons, which align with the limb and actuate individual joints [9]. Upper-limb recovery is not uniform along its length because proximal and distal control depend on different descending systems. Shoulder and elbow musculature receives substantial input from bilaterally projecting reticulospinal and other brainstem pathways, which unilateral cortical injury largely spares, whereas dexterous control of the wrist and hand depends on the crossed corticospinal tract, which has far less redundancy [10]. Stroke subtype and lesion location therefore determine which pathways remain available, and recovery trajectories differ accordingly.

The evidence for robot-assisted upper limb training is substantial but not uniform. A Cochrane review of electromechanical and robot-assisted arm training concluded that such training may improve activities of daily living, arm function, and arm muscle strength after stroke [11]. Another meta-analysis has reported favorable effects on motor impairment relative to dose-matched conventional therapy [12]. Against this, the pooled effects reported in several syntheses have been small and of uncertain clinical importance, and benefits have often failed to generalize from impairment measures to functional capacity or activities of daily living [13].

Two large multicenter trials of end-effector devices found no advantage over usual care or over dose-matched conventional therapy [14,15]. Even the largest exoskeleton trial, which favored robotic training, reported a difference below the minimal clinically important difference, and its authors questioned the clinical relevance of their own result [16]. We therefore conducted this systematic review and meta-analysis to determine whether exoskeleton training improves upper limb recovery after stroke compared with conventional therapy, and whether any benefit depends on the stage of recovery and the limb segment trained.

Review

Methodology

Study Design

We followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines in this study [17]. We also adhered to the steps described by the Cochrane Handbook for Systematic Reviews of Interventions [18]. The review protocol was registered with the International Prospective Register of Systematic Reviews (PROSPERO; registration number CRD420261484111).

Literature Search Strategy

We conducted a systematic search in PubMed, Scopus, Web of Science, the Cochrane Library, and Embase from inception to July 3, 2026. The search combined four concept blocks using the Boolean operator AND: exoskeleton; robotic, powered, active, or wearable; upper limb and its individual segments; and stroke and its synonyms. We restricted searches in Scopus, Web of Science, and Embase to title and abstract fields; restricted the Cochrane Library search to title, abstract, and keyword fields; and ran the PubMed search across all fields. The full database-specific search strings are presented in the Appendix. All included articles were in English, and we manually screened the references of included articles and relevant previous reviews to ensure we included all matching articles.

Inclusion and Exclusion Criteria

Studies were eligible for inclusion if they were randomized controlled trials enrolling adult patients, aged 18 years or older, with a clinical diagnosis of stroke of any type and in any phase of recovery. The intervention had to be upper limb training delivered with a robotic exoskeleton, whether whole-arm or hand, actuated or passive, used alone. The device itself provided visual, game-based, or virtual reality feedback, which was considered part of the device rather than a co-intervention. Eligible comparators were conventional or usual physiotherapy or occupational therapy. Trials had to be dose-matched, with the exoskeleton replacing an equal block of conventional therapy or compared head to head, so that the exoskeleton arm received no additional therapy time. Trials with more than two arms were eligible, and trials of any crossover or parallel randomized design were accepted. Studies had to report at least one of the outcomes of interest, and sufficient postintervention data had to be available, either directly or through accepted statistical

conversion, to allow pooling. We considered only articles published in English with an accessible full text.

We excluded studies that used a nonrandomized design, including observational studies, single-arm or pre-post studies, case reports, and case series, or that were narrative or systematic reviews, study protocols, or conference abstracts without an accompanying full report. Trials evaluating end-effector robots alone, in which the device contacted the limb at a single distal point rather than aligning with and actuating individual joints, were excluded, as were trials of robotic devices targeting only the lower limb or trunk. Studies enrolling populations other than stroke, such as spinal cord injury, traumatic brain injury, multiple sclerosis, or cerebral palsy, were excluded, as were mixed-population studies in which outcomes for patients with stroke could not be separated. Reports that provided no extractable postintervention data for either arm and publications in languages other than English were also excluded.

Data Extraction

Two authors independently used the search strategy to review the literature and select articles that met the inclusion and exclusion criteria. Both authors also independently extracted data from the selected articles and resolved disagreements through discussion. Data were extracted into a standardized spreadsheet comprising a study-level summary sheet and an arm-level baseline sheet, and included study identification, country, total and arm-level sample size, stroke phase and time since onset, baseline impairment severity, device name and trained segment, training mode, treatment dose, comparator, outcome measures, assessment time points, and baseline demographic and clinical characteristics. Where a trial included more than one robotic arm, the arm most consistent with the intervention definition of this review was extracted. In one study, the unilateral arm was used, and for the single crossover trial, only first-period data were extracted.

We reported continuous variables as mean (SD), and for every outcome, the effect measure was the change from baseline, calculated as the endpoint mean minus the baseline mean. We applied four conversions when a trial did not report the required statistics directly. We converted a mean with a 95% confidence interval by deriving the standard error from the interval width and the t critical value for n − 1 degrees of freedom, since no study arm exceeded 60 participants. We converted a median with first and third quartiles by taking the mean of the three values and the SD as the interquartile range divided by 1.35. We converted a reported standard error to an SD by multiplying by the square root of the sample size. Where only baseline and endpoint SDs were available, the SD of the change score was derived from both, assuming a within-person correlation of 0.5; where a trial reported the change with its own confidence interval, that interval was used instead. We marked all derived values as estimates at the point of extraction. Where a study reported a mean with a 95% confidence interval, we derived the SD from the interval half-width, the sample size, and the corresponding t value. We marked values derived by either method as estimates at the point of extraction.

Quality Assessment

We assessed the methodological quality of the included trials using the Cochrane risk-of-bias tool for randomized trials, version 2 (RoB 2) [19]. We appraised each trial across the five RoB 2 domains: bias arising from the randomization process, bias due to deviations from the intended interventions, bias due to missing outcome data, bias in measurement of the outcome, and bias in selection of the reported result. Each domain was rated as low risk of bias, some concerns, or high risk of bias, and we assigned an overall judgment to each trial according to the tool's algorithm, with an overall rating of high risk applied if any single domain was judged to be at high risk. Domain-level and overall judgments are presented as a traffic-light plot.

Outcomes of Interest

The following outcomes were used: change in total Fugl-Meyer Assessment for Upper Extremity (FMA-UE) score [20], which was the primary outcome; change in the proximal (shoulder and elbow) FMA-UE subscore; change in Action Research Arm Test (ARAT) score [21]; change in the distal (wrist and hand) FMA-UE subscore; and change in Modified Ashworth Scale (MAS) score [22] in the affected upper limb.

Statistical Analysis

All analyses were conducted using OnlineMeta version 1.1 [23]. We set the p-value <0.05 as the level of significance. We calculated the mean difference (MD) and 95% confidence interval (95% CI) for the continuous outcome data. We also tested the heterogeneity of the data using the I^2 test and the chi-square test. We considered the data to be heterogeneous if the p-value of the chi-square was less than 0.1 and the I^2 value was more than 50%. We used the fixed-effect model to analyze the data that were homogeneous, and the random-effect model to analyze the data that were heterogeneous. Subgroup analysis was performed according to stroke phase, classified as subacute or chronic, and according to the joint assessed for spasticity. We assessed the robustness of the primary outcome using leave-one-out sensitivity analysis. Publication bias was assessed for the primary outcome by visual inspection of the funnel plot and by Egger's regression test and Begg's rank correlation test. These tests were not applied to the remaining outcomes, because fewer

than 10 trials contributed to each and the tests have insufficient power below this number.

Results

Literature Search

Our literature search yielded 2,381 records, comprising 522 from PubMed, 383 from Scopus, 174 from the Cochrane Library, 742 from Web of Science, and 560 from Embase. After removing 746 duplicates, 1,635 records remained and were screened by title and abstract. We excluded 1,554 records: 1,068 that were not randomized controlled trials, 278 that evaluated an irrelevant intervention, 138 reviews or conference abstracts, 51 that did not evaluate an upper limb intervention, and 19 that did not enroll a stroke population. We retrieved all 81 remaining articles for full-text screening, of which 70 were excluded: 15 available as abstracts only, 13 reviews, 11 protocols, 10 single-arm studies, nine enrolling a different population, six case reports, three not published in English, two evaluating a different intervention, and one with insufficient data for pooling. Finally, 11 studies [3,5,16,24-31] met our inclusion criteria for qualitative and quantitative synthesis (Figure *1*).

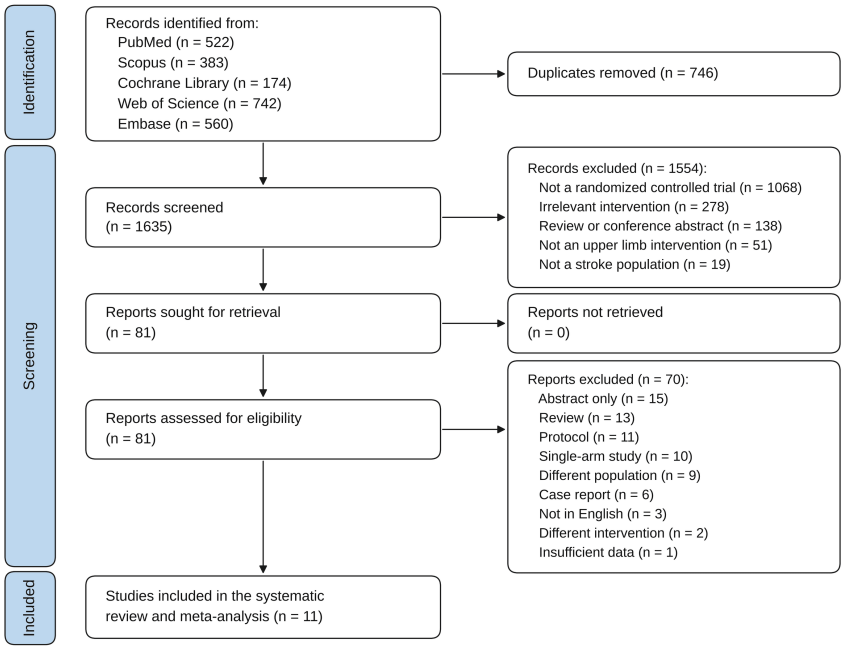


FIGURE 1: PRISMA flow diagram

PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses [17]

Characteristics of Included Studies

Eleven randomized controlled trials published between 2009 and 2024 met the inclusion criteria. Together, they randomized 371 patients and analyzed 338, comprising 174 in the exoskeleton arms and 164 in the control arms, an overall attrition of 8.9%. The trials were small, with analyzed samples ranging from 10 to 80 patients, and seven of the 11 analyzed fewer than 30. They were conducted in the United States (n = 3), China (n = 3), Turkey, Italy, Switzerland, Hong Kong, and India (n = 1 each).

Seven trials enrolled patients with chronic stroke and four with subacute stroke; none recruited in the acute phase. Phase tracked closely with setting, all four subacute trials being inpatient and the chronic trials outpatient or community-based. Mean age ranged from 41.1 to 70.0 years, mean time since stroke from 1.6 to 122.4 months, and mean baseline FMA-UE from 18.1 to 37.5, indicating moderate to severe impairment throughout. Five trials restricted enrollment to first-ever stroke, and most applied an FMA-UE entry band to exclude floor and ceiling cases. Seven trials reported stroke subtype, with ischemic stroke ranging from 38% to 89%; four did not report it, and none reported outcomes by subtype or lesion location.

Nine devices were used, with the ARMin III (ETH Zurich and Balgrist University Hospital, Zurich, Switzerland) and the Armule (Intelbot Intelligent Machine Co., Ltd., Wuhan, China) each appearing twice. Three trained the whole upper limb, including the hand; two trained the shoulder and elbow only; and six trained intermediate or distal segments. One was passive, relying on elastic gravity support rather than

motorized assistance, and one combined the exoskeleton with neuromuscular electrical stimulation. Nine of the 11 delivered training through virtual reality or game-based tasks. Training ran 12 to 24 sessions of 40 to 90 minutes, two to five times weekly, over four to nine weeks, against comparators of conventional physiotherapy or occupational therapy, Bobath-based therapy, standard inpatient care, or matched tabletop exercise.

All 11 reported total FMA-UE, six also reported proximal and distal subscores, four reported the ARAT, and six reported the Modified Ashworth Scale, of which four used a poolable per-joint rating. Three trials assessed patients beyond the end of treatment, at three months, six months, and 34 weeks. Summary and baseline characteristics are presented in Tables *1*, *2*.

Study	Country	Total sample size	Population	Intervention	Dose	Outcome measures	Assessment timepoints
Akgun 2024 [28]	Turkey	N = 30 randomized (24 analyzed)	Chronic stroke (>=6 months); mean 3.9-4.8 years since onset; moderate impairment (baseline FMA-UE 27.8-31.7); outpatient	ExoRehab X; elbow, forearm, wrist; active and active-resistive, VR games	40-60 min x 2/week x 6 weeks (12 sessions)	FMA-UE (primary); MAS [22] elbow and wrist; adverse events	Baseline and post-intervention (6 weeks); no follow-up
Brokaw 2014 [27]	USA	N = 12 enrolled (10 completed both blocks)	Chronic stroke (>=6 months); mean 3.0 years since onset; moderate to severe (baseline FM 13-34)	ARMin III + HandSOME; whole arm and hand; assist-as-needed, VR and real objects	12 h per block (~1 month/block), crossover with 1-month washout; 3-month total protocol	FMA-UE; ARAT [21]	4 timepoints: baseline, after block 1, after washout, after block 2
Byl 2013 [26]	USA	N = 15 (5 per arm)	Chronic stroke (>6 months, 2-16 years since onset); community-independent; baseline ULFM 16-39 (mild to severe)	UL-EXO7; shoulder, elbow, wrist; unilateral or bilateral, gravity-supported VR games	90 min x 2/week x 6 weeks (12 sessions, 18 h)	ULFM (FMA-UE); total active ROM; strength; MAS	Baseline and post-intervention (6 weeks); no follow-up
Chen 2021 [25]	China	N = 20	Subacute stroke (first-ever, unilateral, <=6 months; mean 50-75 days); moderate to severe (FMA-UE 8-47); inpatient rehabilitation unit	Armule; shoulder to wrist; passive then active-assistive, VR games	45 min/day x 5 days/week x 4 weeks (20 sessions)	Feasibility (primary: recruitment, retention, safety); FMA-UE (with FMA-UA and FMA-WH); ARAT; exoskeleton kinematics (movement time, smoothness, postural error)	Baseline and post-intervention (4 weeks); no follow-up
Chen 2023 [3]	China	N = 80	Subacute stroke (first-ever, unilateral, <=6 months; mean 54.6 days); moderate to severe (FMA-UE 8-38); inpatient	Armule; shoulder and elbow; passive then active-assistive, VR games	45 min/day x 5 days/week x 4 weeks (20 sessions)	FMA-UE change (primary); FMA-UA; FMA-WH; kinematics; adverse events	Baseline, 2 weeks, 4 weeks; no post-treatment follow-up
Frisoli 2022 [24]	Italy	N = 26 enrolled (22 analyzed)	Chronic stroke (>=6 months, minimum 7; mean 30-37 months); first-ever left-hemisphere stroke; FMA-UE >=15; outpatient	L-EXOS; shoulder and elbow; assist-as-needed, 3D VR reaching tasks	>=45 min x 3/week x 6 weeks (18 sessions)	FMA-UE (primary), with proximal and distal subscores; MAS; robotic biomarkers (execution time, smoothness)	Baseline (enrolment) and post-intervention (discharge, 6 weeks); no follow-up
Housman 2009 [31]	USA	N = 34 enrolled (28 analyzed)	Chronic stroke (>=6 months; mean 85-112 months); moderate to severe hemiparesis (arm motor FM 10-30)	T-WREX (passive); shoulder, elbow, hand grip; gravity-supported VR games	60 min x ~3/week x 8-9 weeks (24 sessions)	Arm motor FMA-UE (primary); grip strength; reaching ROM deficit; treatment-preference survey	Baseline, post-24 sessions, and 6-month follow-up

Klamroth-Marganska 2014 [16]	Switzerland	N = 77 randomized (73 analyzed)	Chronic stroke (>=6 months; mean 40-52 months); first-ever CVA; moderate to severe arm paresis (FMA-UE 8-38); in- and outpatient	ARMin III; whole arm and hand; assist-as-needed, VR games and ADL training	>=45 min x 3/week x 8 weeks (24 sessions)	FMA-UE change (primary); MAS; mean strength (ARMin); grip strength	Screening (-3 to -4 weeks), baseline, 4 weeks, 8 weeks (end of therapy), 16 weeks, 34 weeks
Ma 2022 [30]	China	N = 26 randomized (19 analyzed)	Subacute stroke (first-ever, unilateral, 1-6 months; mean ~10 weeks); Brunnstrom 2-4; MAS <3; moderate to severe (FMA-UE 22.6-27.2); inpatient	Exoskeleton (hand); Mirror Hand (HS 001, Rehabotics) with sensor glove; robot-assisted bimanual task-oriented training of the fingers; CPM plus mirror-guided object manipulation	60 min robot + 30 min conventional therapy/day x 5 days/week x 4 weeks (20 sessions)	FMA-UE with FMA-SE and FMA-WH; ARAT; proportion reaching MCID	Baseline, after 10th session (T1), after 20th session (T2); no follow-up
Qian 2017 [5]	Hong Kong	N = 24	Subacute stroke (single unilateral lesion within 4 months; 14-148 days); severe to moderate (FMA-UE 15-45); MAS <3; inpatient	EMG-driven NMES-robot; elbow, wrist, fingers; EMG-triggered, with NMES	40 min x 5 days/week x 4 weeks (20 sessions)	FMA-UE with shoulder/elbow and wrist/hand subscores and MAS at elbow, wrist and fingers (co-primary); ARAT; session-by-session EMG activation and co-contraction indices	Baseline, post-intervention (20 sessions), and 3-month follow-up
Singh 2021 [29]	India	N = 27 randomized (23 analyzed)	Chronic stroke (3-24 months; mean 10-14 months); Brunnstrom 3-5; MAS 1 to 2; MMSE 24-30; outpatient	Exoskeleton hand (wrist-MCP); wrist and metacarpophalangeal joints	45 min/day x 5 days/week x 4 weeks (20 sessions)	MAS (wrist); active ROM (wrist); FMA-UE with FMA-WH and FMA-SE (primary); TMS cortical excitability (resting motor threshold, MEP amplitude, interhemispheric asymmetry) (secondary)	Baseline (pre-therapy) and post-intervention (4 weeks); no follow-up

TABLE 1: Summary of the characteristics of the included studies

Abbreviations: 3D: three-dimensional; ADL: activities of daily living; ARAT: Action Research Arm Test; CPM: continuous passive motion; CVA: cerebrovascular accident; EMG: electromyography; FM: Fugl-Meyer; FMA-SE: Fugl-Meyer Assessment, shoulder and elbow subscore; FMA-UA: Fugl-Meyer Assessment, upper arm subscore; FMA-UE: Fugl-Meyer Assessment for Upper Extremity; FMA-WH: Fugl-Meyer Assessment, wrist and hand subscore; HandSOME: Hand Spring Operated Movement Enhancer; L-EXOS: Light Exoskeleton; MAS: Modified Ashworth Scale; MCID: minimal clinically important difference; MMSE: Mini-Mental State Examination; MEP: motor evoked potential; N: number of patients; NMES: neuromuscular electrical stimulation; ROM: range of motion; TMS: transcranial magnetic stimulation; T-WREX: Therapy Wilmington Robotic Exoskeleton; UL-EXO7: seven degree-of-freedom upper limb exoskeleton; ULFM: upper limb Fugl-Meyer; VR: virtual reality

Devices: ARMin III: ETH Zurich and Balgrist University Hospital, Zurich, Switzerland; Armule: Intelbot Intelligent Machine Co., Ltd., Wuhan, China; EMG-driven NMES-robot: The Hong Kong Polytechnic University, Hong Kong, China; ExoRehab X: HoustonBionics, Houston, TX, USA; Exoskeleton hand (wrist-MCP): Indian Institute of Technology Delhi and All India Institute of Medical Sciences, New Delhi, India; HandSOME: The Catholic University of America, Washington, DC, USA; L-EXOS: Scuola Superiore Sant'Anna, Pisa, Italy; Mirror Hand (HS 001): Rehabotics Medical Technology, Zhubei, Taiwan; T-WREX: University of California, Irvine, CA, USA, and Rehabilitation Institute of Chicago, Chicago, IL, USA; UL-EXO7: University of Washington, Seattle, WA, USA, and University of California, Santa Cruz, CA, USA

Study	Arm (N analyzed/randomized)	Age, mean ± SD (years)	Male, n (%)	Time since stroke, mean ± SD (months)	Ischemic / left-affected, n (%)	Baseline FMA-UE, mean ± SD	Baseline MAS, mean ± SD
Akgun 2024 [28]	Exoskeleton (ExoRehab X) 12/15	57.3 ± 12.1	9 (75)	46.8 ± 36.0	11 (91) / 9 (75)	27.8 ± 9.1	Elbow 1.67 ± 0.84; wrist 1.67 ± 0.84
	Control (Bobath) 12/15	66.7 ± 10.5	5 (42)	57.6 ± 48.0	10 (83) / 6 (50)	31.7 ± 14.9	Elbow 1.67 ± 0.84; wrist 1.33 ± 0.84
Brokaw 2014 [27]	Whole crossover sample 10/12	57.0 ± 11.7	9 (75)	36.0 ± 22.8	NR / 7 (58)	22.4 ± 7.4	NR
Byl 2013	Robotic orthosis, unilateral 5/5	54.2 ± 20.5	4 (80)	122.4 ± 60.0	NR / 2 (40)	23.8 ± 7.7	9.8 (summed multi-joint total)
	Robotic orthosis,	65.2 ±					9.6 (summed multi-

[26]	bilateral 5/5	5.4	5 (100)	100.8 ± 50.4	NR / 1 (20)	24.4 ± 5.2	joint total)
	Control (physical therapy) 5/5	59.3 ± 6.8	4 (80)	76.8 ± 52.8	NR / 2 (40)	24.6 ± 6.8	9.2 ± 3.10 (summed multi-joint total)
Chen 2021 [25]	Exoskeleton (Armule, EAMT) 10/10	47.10 ± 11.11	10 (100)	2.5 ± 1.8	4 (40) / 7 (70)	22.30 ± 11.42	Not assessed
	Control (conventional therapy) 10/10	54.90 ± 14.49	7 (70)	1.6 ± 1.3	5 (50) / 5 (50)	20.20 ± 9.48	Not assessed
Chen 2023 [3]	Exoskeleton (Armule, EAMT) 40/40	50.1 ± 10.0	34 (85.0)	1.7 ± 1.3	21 (52.5) / 22 (55.0)	18.5 ± 10.5	NR
	Control (conventional therapy) 40/40	53.7 ± 9.4	33 (82.5)	1.9 ± 1.2	20 (50.0) / 17 (42.5)	19.4 ± 10.4	NR
Frisoli 2022 [24]	Exoskeleton (L-EXOS) 11/13	62 ± 12	7 (64)	30 ± 20	9 (82) / 0 (0)	25.6 ± 12.3	17.1 ± 11.5 (summed multi-joint total)
	Control (manual physical therapy) 11/13	70 ± 11	8 (73)	37 ± 24	8 (73) / 0 (0)	26.7 ± 16.3	20.6 ± 9.8 (summed multi-joint total)
Housman 2009 [31]	Exoskeleton (T-WREX) 14/17	54.2 ± 11.9	11 (79)	84.5 ± 96.3	9 (64) / 10 (71)	21.7 ± 5.9	Not assessed
	Control (tabletop exercise) 14/17	56.4 ± 12.8	7 (50)	112.4 ± 128.5	8 (57) / 10 (71)	18.1 ± 5.0	Not assessed
Klamroth-Marganska 2014 [16]	Exoskeleton (ARMin III) 38/39	55 ± 13	21 (55)	52 ± 44	NR / 19 (50)	20.2 ± 7.1	0.8 ± 0.4
	Control (conventional OT/PT) 35/38	58 ± 14	25 (71)	40 ± 45	NR / 19 (54)	20.7 ± 8.2	0.6 ± 0.4
Ma 2022 [30]	Exoskeleton hand (Mirror Hand, RBMT) 10/13	59.00 ± 10.60	9 (90)	2.3 ± 1.3	10 (100) / 4 (40)	27.20 ± 17.03	NR
	Control (conventional therapy) 9/13	56.44 ± 8.79	5 (56)	2.4 ± 1.4	7 (78) / 5 (56)	22.56 ± 17.17	NR
Qian 2017 [5]	Exoskeleton + NMES (EMG-driven NMES-robot) 14/14	54.6 ± 11.3	9 (64)	2.84 ± 1.18	5 (36) / 3 (21)	22.3 ± 10.05	Elbow 0.8 ± 0.87; wrist 0.7 ± 0.61; finger 0.5 ± 0.61
	Control (traditional therapy) 10/10	64.6 ± 3.43	6 (60)	2.56 ± 1.36	4 (40) / 1 (10)	20.3 ± 8.53	Elbow 0.3 ± 0.56; wrist 0.3 ± 0.49; finger 0.4 ± 0.42
Singh 2021 [29]	Exoskeleton hand (wrist-MCP) 12/13	41.1 ± 12.8	NR (whole sample 19/23, 83%)	13.8 ± 9.1	NR	36.0 ± 7.7	1.75 ± 0.2
	Control (conventional therapy) 11/14	42.7 ± 9.3	NR (whole sample 19/23, 83%)	10.3 ± 5.0	NR	37.45 ± 9.1	1.86 ± 0.5

TABLE 2: Baseline characteristics of the included studies

Abbreviations: EAMT: exoskeleton-assisted anthropomorphic movement training; EMG: electromyography; FMA-UE: Fugl-Meyer Assessment for Upper Extremity; L-EXOS: Light Exoskeleton; MAS: Modified Ashworth Scale; MCP: metacarpophalangeal; N: number randomized; n: number of patients; NMES: neuromuscular electrical stimulation; NR: not reported; OT: occupational therapy; PT: physical therapy; RBMT: robot-assisted bimanual training; SD: standard deviation; T-WREX: Therapy Wilmington Robotic Exoskeleton

Devices: ARMin III: ETH Zurich and Balgrist University Hospital, Zurich, Switzerland; Armule: Intelbot Intelligent Machine Co., Ltd., Wuhan, China; EMG-driven NMES-robot: The Hong Kong Polytechnic University, Hong Kong, China; ExoRehab X: HoustonBionics, Houston, TX, USA; Exoskeleton hand (wrist-MCP): Indian Institute of Technology Delhi and All India Institute of Medical Sciences, New Delhi, India; L-EXOS: Scuola Superiore Sant'Anna, Pisa, Italy; Mirror Hand: Rehabotics Medical Technology, Zhubei, Taiwan; T-WREX: University of California, Irvine, CA, USA, and Rehabilitation Institute of Chicago, Chicago, IL, USA

Quality Assessment Results

Eleven trials were assessed with RoB 2. Four were rated at low risk of bias overall, six raised some concerns, and one was rated at high risk. Concerns most often arose in the domain of deviations from the intended interventions, affecting six trials and reflecting the impracticality of blinding participants and therapists to a visible robotic device. The randomization domain accounted for the remaining concerns in three trials and for the single high-risk judgment, which was assigned to Frisoli et al. [24] because neither the randomization procedure nor the method of allocation concealment was described. Most trials were judged low risk for missing outcome data, outcome measurement, and selective reporting. Domain-level and overall judgments are presented in Figure 2.

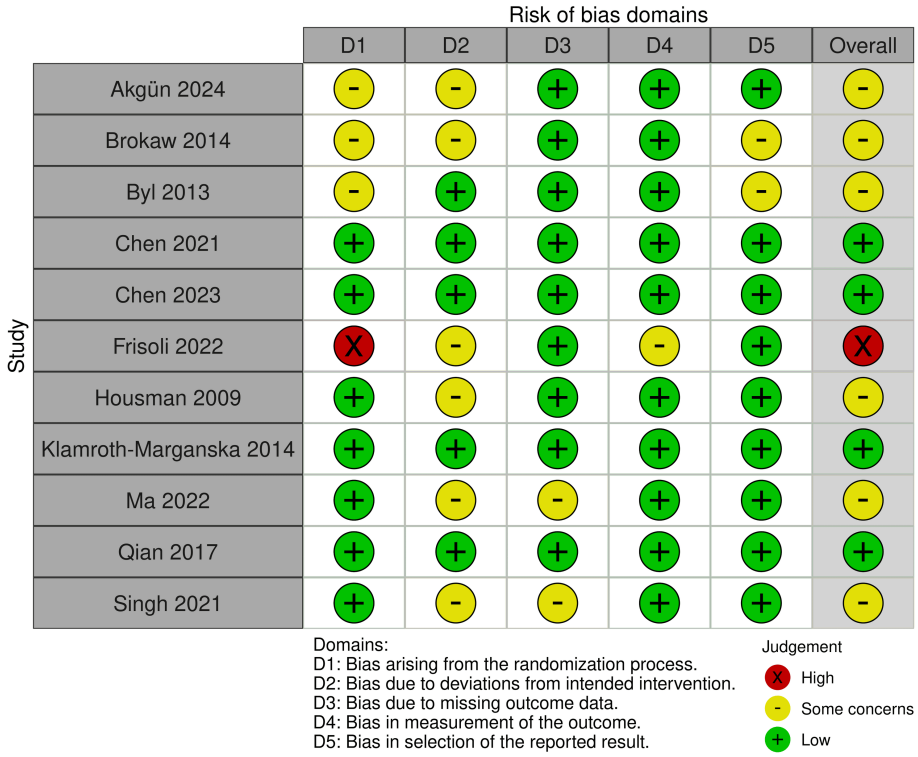


FIGURE 2: Quality assessment of randomized controlled trials (RCTs) (RoB 2)

References: Chen et al. (2023) [3], Qian et al. [5], Klamroth-Marganska et al. [16], Frisoli et al. [24], Chen et al. (2021) [25], Byl et al. [26], Brokaw et al. [27], Akgün et al. [28], Singh et al. [29], Ma et al. [30], Housman et al. [31], RoB 2 [19]

Change in Total Fugl-Meyer Assessment for Upper Extremity

This outcome included 11 articles with 338 patients. Results showed an overall significant difference favoring exoskeleton training over conventional therapy (MD = 2.45, 95% CI = 0.88 to 4.01, p = 0.002). Pooled results were heterogeneous (p = 0.002, I^2 = 63%), so we used a random-effects model (Figure 3). Between-study variance was tau^2 = 3.05, and the 95% prediction interval ranged from -1.90 to 6.79 points.

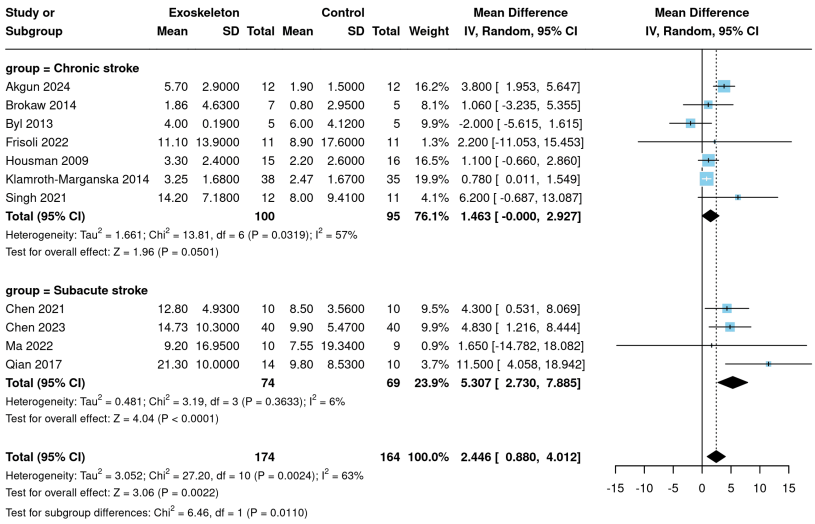


FIGURE 3: Change in Total Fugl-Meyer Assessment for Upper Extremity

References: Chen et al. (2023) [3], Qian et al. [5], Klamroth-Marganska et al. [16], Frisoli et al. [24], Chen et al. (2021) [25], Byl et al. [26], Brokaw et al. [27], Akgün et al. [28], Singh et al. [29], Ma et al. [30], Housman et al. [31], Fugl-Meyer Assessment for Upper Extremity [20]

Subgroup analysis by stroke phase showed a significant difference between the two arms (p = 0.011). In patients with subacute stroke, four studies showed a significant difference favoring exoskeleton training (MD = 5.31, 95% CI = 2.73 to 7.89, p < 0.0001), with homogeneous results (p = 0.36, I^2 = 6%). In patients with chronic stroke, seven studies showed no significant difference (MD = 1.46, 95% CI = 0.00 to 2.93, p = 0.05), with heterogeneous results (p = 0.03, I^2 = 57%). Stratification by stroke phase therefore accounted for a substantial part of the heterogeneity observed in the overall analysis.

Leave-one-out analysis confirmed the stability of this estimate. Omitting each trial in turn produced pooled mean differences ranging from 2.04 to 2.92 points, and the effect remained statistically significant in every iteration, with p-values between 0.0004 and 0.011 (Figure *4*). Residual heterogeneity remained moderate throughout, with I^2 between 55% and 67%, indicating that no single trial accounted for the observed variance. The lowest estimate followed omission of Qian 2017 [5] and the highest followed omission of Klamroth-Marganska 2014 [16].

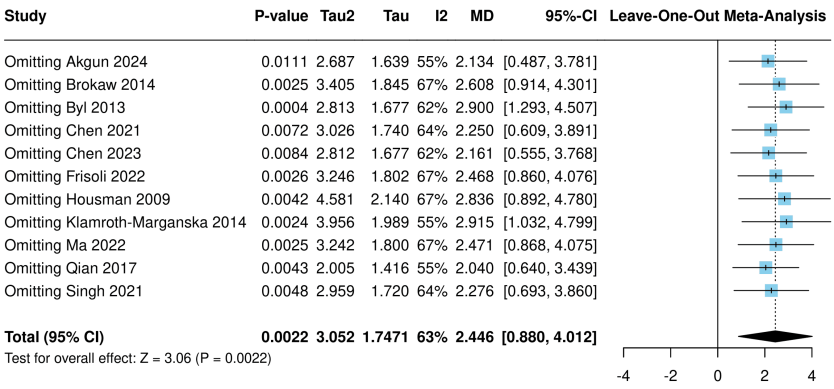


FIGURE 4: Leave-one-out sensitivity analysis of change in total Fugl-Meyer Assessment for Upper Extremity score

References: Chen et al. (2023) [3], Qian et al. [5], Klamroth-Marganska et al. [16], Frisoli et al. [24], Chen et al. (2021) [25], Byl et al. [26], Brokaw et al. [27], Akgün et al. [28], Singh et al. [29], Ma et al. [30], Housman et al. [31], Fugl-Meyer Assessment for Upper Extremity [20]

Visual inspection of the funnel plot showed a broadly symmetrical distribution of trials about the pooled estimate (Figure *5*). Neither Egger's regression test (p = 0.112) nor Begg's rank correlation test (p = 0.586) indicated small-study effects.

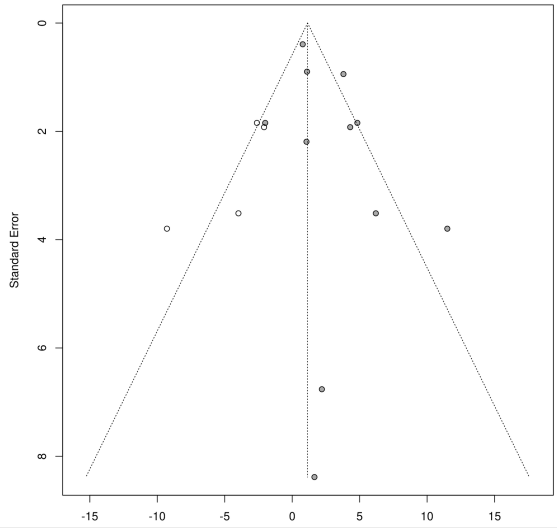


FIGURE 5: Funnel plot for change in total Fugl-Meyer Assessment for Upper Extremity score

References: Chen et al. (2023) [3], Qian et al. [5], Klamroth-Marganska et al. [16], Frisoli et al. [24], Chen et al. (2021) [25], Byl et al. [26], Brokaw et al. [27], Akgün et al. [28], Singh et al. [29], Ma et al. [30], Housman et al. [31], Fugl-Meyer Assessment for Upper Extremity [20]

Change in Proximal Fugl-Meyer Assessment Subscore

Six articles with 188 patients reported the proximal FMA-UE subscore. Results showed a significant difference favoring exoskeleton training (MD = 3.37, 95% CI = 1.93 to 4.81, p < 0.0001). Pooled results were homogeneous (p = 0.89, I^2 = 0%), so we used the fixed-effect model. In subgroup analysis, the difference was significant in subacute stroke (MD = 3.32, 95% CI = 1.79 to 4.86, p < 0.0001) and did not reach significance in chronic stroke (MD = 3.73, 95% CI = -0.52 to 7.98, p = 0.09), with no significant difference between subgroups (p = 0.86) (Figure *6*).

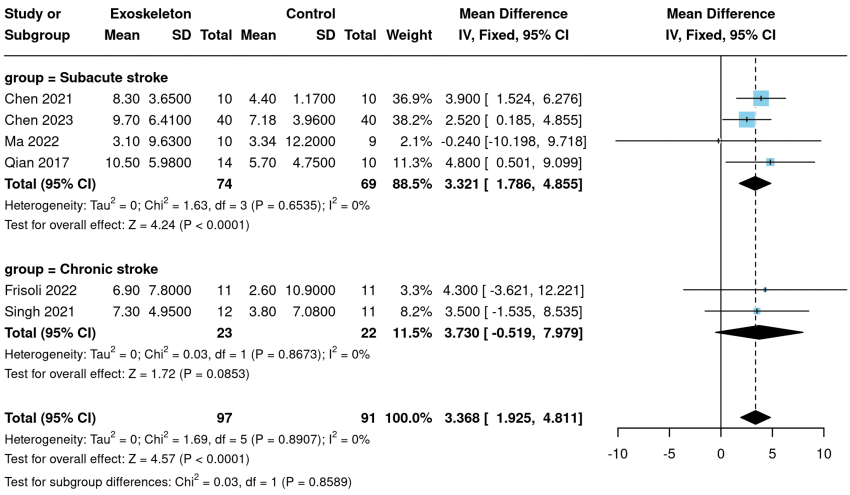


FIGURE 6: Proximal Fugl-Meyer Assessment for Upper Extremity subscore

References: Chen et al. (2023) [3], Qian et al. [5], Frisoli et al. [24], Chen et al. (2021) [25], Singh et al. [29], Ma et al. [30], Fugl-Meyer Assessment for Upper Extremity [20]

Change in Action Research Arm Test

Four articles with 75 patients reported the ARAT. Results showed a significant difference favoring exoskeleton training (MD = 4.37, 95% CI = 2.02 to 6.72, p = 0.0003). Pooled results were homogeneous (p = 0.91, I^2 = 0%), and the fixed-effect model was therefore used. The single study in chronic stroke showed a significant difference (MD = 4.80, 95% CI = 2.03 to 7.57), whereas the pooled estimate of three studies in subacute stroke did not reach significance (MD = 3.25, 95% CI = -1.22 to 7.72, p = 0.15) (Figure 7).

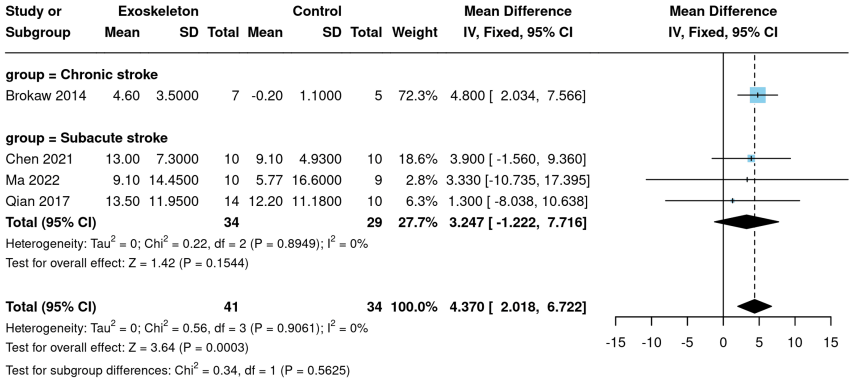


FIGURE 7: Change in Action Research Arm Test score

References: Qian et al. [5], Chen et al. (2021) [25], Brokaw et al. [27], Ma et al. [30], Action Research Arm Test [21]

Change in Distal Fugl-Meyer Assessment Subscore

The same six articles with 188 patients reported distal FMA-UE subscore changes. Results showed a significant difference favoring exoskeleton training (MD = 2.19, 95% CI = 0.42 to 3.96, p = 0.02), with moderate heterogeneity (p = 0.14, I^2 = 40%). On subgroup analysis, the difference was significant in subacute stroke (MD = 2.40, 95% CI = 0.11 to 4.68, p = 0.04) but not in chronic stroke (MD = 1.27, 95% CI = -3.69 to 6.23, p = 0.62), with no significant difference between subgroups (p = 0.69) (Figure 8).

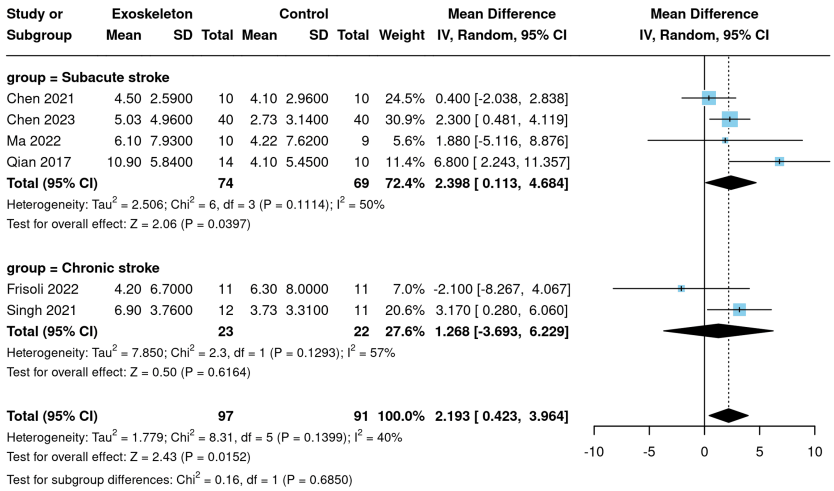


FIGURE 8: Change in Distal Fugl-Meyer Assessment for Upper Extremity Subscore

References: Chen et al. (2023) [3], Qian et al. [5], Frisoli et al. [24], Chen et al. (2021) [25], Singh et al. [29], Ma et al. [30], Fugl-Meyer Assessment for Upper Extremity [20]

Change in Modified Ashworth Scale

Three articles reported the MAS at the wrist and two at the elbow, with 119 patients in total. Results showed no significant difference between exoskeleton training and conventional therapy at the wrist (MD = -0.42, 95% CI = -1.10 to 0.27, p = 0.23), at the elbow (MD = -0.35, 95% CI = -1.66 to 0.97, p = 0.61), or overall (MD = -0.40, 95% CI = -0.93 to 0.14, p = 0.15), with no significant difference between subgroups (p = 0.92). Pooled results were highly heterogeneous (I^2 = 82% overall, 85% at the wrist, and 89% at the elbow), and the effect direction was inconsistent across studies (Figure 9).

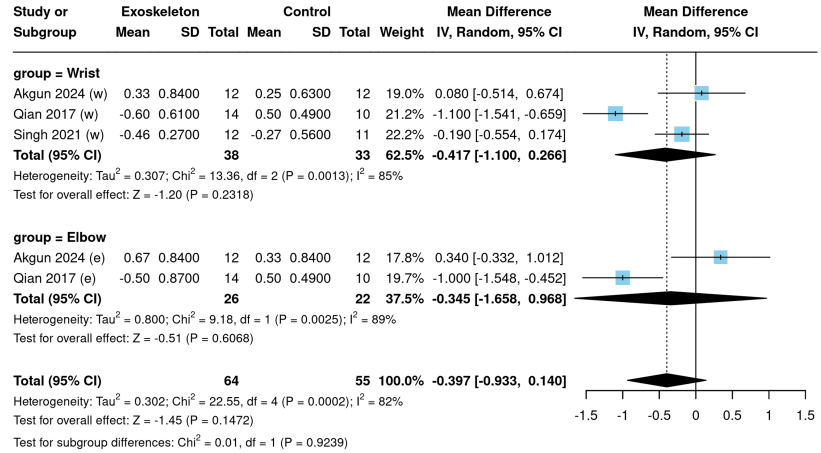


FIGURE 9: Change in Modified Ashworth Scale

References: Qian et al. [5], Akgün et al. [28], Singh et al. [29], Modified Ashworth Scale [22]

Discussion

This systematic review and meta-analysis pooled randomized controlled trials comparing robotic exoskeleton-assisted training with conventional therapist-mediated therapy for upper limb recovery after stroke. Across every motor outcome examined, the direction of effect favored the exoskeleton. Overall upper limb impairment on the Fugl-Meyer scale improved more with exoskeleton training, and the same direction

held for the proximal and distal components of that scale and for arm function measured with the Action Research Arm Test. The single exception was spasticity, where the two approaches did not differ. The primary finding was robust to leave-one-out analysis, remaining significant with each trial removed in turn, and neither Egger's regression test nor Begg's rank correlation test suggested small-study effects. The prediction interval, however, includes no benefit, so the pooled estimate should not be read as predicting improvement in a future setting.

The clearest signal in this synthesis was the difference between recovery phases, with a pooled gain of 5.31 points in subacute patients against 1.46 points in chronic patients. Neither estimate reaches the minimal clinically important difference proposed for the FMA-UE in subacute stroke [32], and the chronic estimate falls well below the 6.6-point threshold established in chronic stroke [33], so the phase contrast reflects a difference in the magnitude of a modest effect rather than a threshold crossed in one group and missed in the other. These thresholds describe within-person change over a course of rehabilitation rather than an increment over an active comparator, so they understate what the device adds to a program already producing meaningful change.

The most widely advanced explanation for such a contrast is a time-limited period of heightened plasticity after infarction, during which peri-infarct and contralesional cortex show increased spine turnover and axonal sprouting and the motor system is unusually responsive to task practice. The CPASS trial supports this account, showing that an identical dose of upper limb therapy produced greater gains when delivered 60 to 90 days after stroke than earlier or later [34]. A device whose principal contribution is a high volume of consistent assisted repetitions would be expected to act most effectively while that substrate remains responsive, and to yield less once recovery has plateaued and compensatory patterns have consolidated [35]. Some caution is warranted, since the subacute trials were uniformly inpatient, delivered a higher weekly dose than most chronic trials, and enrolled patients with lower baseline FMA-UE scores. Phase cannot be fully separated from these characteristics in the present dataset, so the subgroup difference is best regarded as hypothesis-generating.

Benefit was also unevenly distributed along the limb. The pooled effect on the shoulder and elbow was larger, more precise, and entirely homogeneous, whereas the effect on the wrist and hand was smaller, less precise, and more variable across trials. This matters clinically, because distal dexterity rather than proximal strength is what determines whether a patient can use the arm in daily life, and it offers a plausible account of a recurring pattern in this field, in which robotic training reduces impairment without producing matching gains in function. The gradient may also reflect the neural substrate of recovery rather than the intervention, since proximal control draws on bilaterally projecting brainstem pathways that are relatively preserved after unilateral stroke, whereas distal dexterity depends on the crossed corticospinal tract [10]. Two features of the evidence base point the same way. Most of the included exoskeletons actuated the shoulder and elbow and only three incorporated a hand component, so the segment that improved most is also the segment that was trained most. The outcome scale compounds this, since the FMA-UE allots more points to proximal than to distal function, which means a device targeting the hand is judged partly on a subscale it never addressed.

The evidence on function and on tone is thinner than the evidence on impairment. Arm function measured by the ARAT improved significantly, but the estimate rests on four trials and 75 patients, draws almost three-quarters of its weight from a single small crossover trial [27], and falls below the 5.7 to 12-point thresholds reported for a clinically important change on this scale [32,33]. Spasticity showed no difference between groups, and here the data are weaker still: four trials, scales that were not comparable between studies, heterogeneity above 80%, and effects pointing in opposite directions.

Dose and effect were unrelated. The two highest-dose protocols produced the two smallest individual effects, 1.10 and 0.78 FMA-UE points [16,31], while subacute trials delivering less training produced gains of 4.30 to 11.50 points. Phase, not exposure, tracked with benefit, favoring earlier deployment of fewer devices over longer programs offered later.

Restricting the synthesis to exoskeletons did not produce a larger effect. Our estimate matches the two- to three-point differences reported by syntheses that pooled exoskeletons with end-effector devices [11,12], suggesting device class is not the determining factor. A 2025 umbrella review of 16 meta-analyses covering 396 trials reached the same conclusion for robot-assisted therapy as a whole, reporting statistically significant Fugl-Meyer gains that fell below thresholds for clinical importance [36]. Phase of recovery and trained segment are. That reconciles the positive conclusions of earlier reviews with the null results of the large pragmatic trials [14,15], which enrolled mainly chronic patients and used devices with a restricted workspace.

This review has several strengths. Only randomized controlled trials were eligible, so the synthesis rests on the highest level of primary evidence available in this field. The device class was defined a priori and applied strictly, excluding end-effector robots, which distinguishes it from previous syntheses that pooled device classes. To our knowledge, this is the first synthesis to restrict inclusion to exoskeletons while stratifying simultaneously by stroke phase and by limb segment. Stratification by phase explained a substantial part of

the observed heterogeneity, and analyzing the proximal and distal components of the Fugl-Meyer scale separately revealed a gradient that an aggregate analysis would have concealed. The robustness of the primary estimate was confirmed by leave-one-out analysis and by two formal tests of publication bias.

Some limitations should be noted. The evidence base is modest, comprising 11 trials and 338 patients, which limits the precision of the subgroup comparisons. Eligibility was deliberately broad by recovery phase and limb segment, since stratification by these was a primary objective. Stroke subtype was reported in only seven trials, and none stratified outcomes by subtype or lesion location; subtype was balanced between arms within each reporting trial, so it does not bias the pooled contrasts, but it limits generalizability. The included trials spanned nine devices and a range of trained segments and doses, and few assessed outcomes beyond the end of treatment, so the durability of benefit remains open. Spasticity was reported on scales that were not directly comparable, and a small number of standard deviations were estimated rather than reported. One trial combined the exoskeleton with neuromuscular electrical stimulation [5], and one used a crossover design from which only the first period was used [27].

Conclusions

Robotic exoskeleton-assisted training may improve upper limb motor impairment after stroke compared with conventional therapy, but the gain is modest, and its size depends on when training is given. Benefit was concentrated in the subacute phase and was not demonstrated in chronic stroke, and it was greater at the shoulder and elbow than at the wrist and hand, mirroring what the available devices actually train. No effect on spasticity was found. Exoskeleton training is therefore best positioned as an adjunct to conventional therapy in the subacute period rather than as a general-purpose rehabilitation tool, and adequately powered trials in subacute cohorts, with devices that actively train the hand, stratification by stroke subtype, and follow-up beyond the end of treatment, are needed before firmer recommendations can be made.

Appendices

Database	Fields searched	Records	Search string
PubMed	All fields	522	(exoskeleton*) AND (robot* OR power* OR active OR wearable) AND (upper-limb* OR "upper limb*" OR upper-extremit* "upper extremit*" OR arm OR shoulder OR elbow OR forearm OR wrist OR hand OR finger* OR thumb) AND (stroke OR cerebrovascular OR apoplexy OR "brain vascular accident" OR CVA OR infarction OR "intracerebral haemorrhage" OR "intracerebral hemorrhage" OR "cerebral haemorrhage" OR "cerebral hemorrhage" OR ICH OR "brain haemorrhage" OR "brain hemorrhage" OR Ischemi*)
Scopus	Title, abstract	383	(TITLE ((exoskeleton*) AND (robot* OR power* OR ACTIVE OR wearable) AND (upper-limb* OR "upper limb*" OR upper-extremit* "upper extremit*" OR arm OR shoulder OR elbow OR forearm OR wrist OR hand OR finger* OR thumb) AND (stroke OR cerebrovascular OR apoplexy OR "brain vascular accident" OR CVA OR infarction OR "intracerebral haemorrhage" OR "intracerebral hemorrhage" OR "cerebral haemorrhage" OR "cerebral hemorrhage" OR ICH OR "brain haemorrhage" OR "brain hemorrhage" OR Ischemi*)) OR ABS ((exoskeleton*) AND (robot* OR power* OR ACTIVE OR wearable) AND (upper-limb* OR "upper limb*" OR upper-extremit* "upper extremit*" OR arm OR shoulder OR elbow OR forearm OR wrist OR hand OR finger* OR thumb) AND (stroke OR cerebrovascular OR apoplexy OR "brain vascular accident" OR CVA OR infarction OR "intracerebral haemorrhage" OR "intracerebral hemorrhage" OR "cerebral haemorrhage" OR "cerebral hemorrhage" OR ICH OR "brain haemorrhage" OR "brain hemorrhage" OR Ischemi*)))
Web of Science	Title, abstract	742	TI=((exoskeleton*) AND (robot* OR power* OR active OR wearable) AND (upper-limb* OR "upper limb*" OR upper-extremit* "upper extremit*" OR arm OR shoulder OR elbow OR forearm OR wrist OR hand OR finger* OR thumb) AND (stroke OR cerebrovascular OR apoplexy OR "brain vascular accident" OR CVA OR infarction OR "intracerebral haemorrhage" OR "intracerebral hemorrhage" OR "cerebral haemorrhage" OR "cerebral hemorrhage" OR ICH OR "brain haemorrhage" OR "brain hemorrhage" OR Ischemi*)) OR AB=((exoskeleton*) AND (robot* OR power* OR active OR wearable) AND (upper-limb* OR "upper limb*" OR upper-extremit* "upper extremit*" OR arm OR shoulder OR elbow OR forearm OR wrist OR hand OR finger* OR thumb) AND (stroke OR cerebrovascular OR apoplexy OR "brain vascular accident" OR CVA OR infarction OR "intracerebral haemorrhage" OR "intracerebral hemorrhage" OR "cerebral haemorrhage" OR "cerebral hemorrhage" OR ICH OR "brain haemorrhage" OR "brain hemorrhage" OR Ischemi*))
Cochrane Library	Title, abstract, keyword	174	((exoskeleton*) AND (robot* OR power* OR active OR wearable) AND (upper-limb* OR "upper limb*" OR upper-extremit* "upper extremit*" OR arm OR shoulder OR elbow OR forearm OR wrist OR hand OR finger* OR thumb) AND (stroke OR cerebrovascular OR apoplexy OR "brain vascular accident" OR CVA OR infarction OR "intracerebral haemorrhage" OR "intracerebral hemorrhage" OR "cerebral haemorrhage" OR "cerebral hemorrhage" OR ICH OR "brain haemorrhage" OR "brain hemorrhage" OR Ischemi*)):ti,ab,kw
Embase	Title, abstract	560	exoskeleton*:ab,ti AND (robot*:ab,ti OR power*:ab,ti OR active:ab,ti OR wearable:ab,ti) AND ('upper limb*':ab,ti OR 'upper-extremit* upper extremit*':ab,ti OR arm:ab,ti OR shoulder:ab,ti OR elbow:ab,ti OR forearm:ab,ti OR wrist:ab,ti OR hand:ab,ti OR finger*:ab,ti OR thumb:ab,ti) AND (stroke:ab,ti OR cerebrovascular:ab,ti OR apoplexy:ab,ti OR 'brain vascular accident':ab,ti OR cva:ab,ti OR infarction:ab,ti OR 'intracerebral haemorrhage':ab,ti OR 'intracerebral hemorrhage':ab,ti OR 'cerebral haemorrhage':ab,ti OR 'cerebral hemorrhage':ab,ti OR ich:ab,ti OR 'brain haemorrhage':ab,ti OR 'brain hemorrhage':ab,ti OR ischemi*:ab,ti)
Total		2381	

TABLE 3: Advanced detailed search strategy

Abbreviations: AB/ABS: abstract field; CVA: cerebrovascular accident; ICH: intracerebral hemorrhage; kw: keyword field; TI/TITLE: title field; ti,ab: title and abstract fields.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Concept and design: Ayoub Tantush, Marwan Tantoush, Bahaeddin Ben Hamida, Malek Sager, Ali Abusbaeh, Hasan Almgherbi, Mohammed Alhamadi, Allaeddin Abusbaeh, Nada G. Madkour, Mohamad

Alemam

Drafting of the manuscript: Ayoub Tantush, Marwan Tantoush, Bahaeddin Ben Hamida, Malek Sager, Ali Abusbaeh, Hasan Almgherbi, Abdelrahman Najaim, Nada G. Madkour, Mohamad Alemam, Moaaz Shaded

Critical review of the manuscript for important intellectual content: Ayoub Tantush, Marwan Tantoush, Malek Sager, Ali Abusbaeh, Hasan Almgherbi, Abdelrahman Najaim, Mohammed Alhamadi, Allaeddin Abusbaeh, Mohamad Alemam, Moaaz Shaded

Acquisition, analysis, or interpretation of data: Bahaeddin Ben Hamida, Malek Sager, Ali Abusbaeh, Abdelrahman Najaim, Mohammed Alhamadi, Allaeddin Abusbaeh, Nada G. Madkour, Moaaz Shaded

Supervision: Malek Sager, Ali Abusbaeh, Nada G. Madkour

Disclosures

Conflicts of interest: In compliance with the ICMJE uniform disclosure form, all authors declare the following: **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work. **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work. **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

References

1. Global, regional, and national burden of stroke and its risk factors, 1990-2021: a systematic analysis for the Global Burden of Disease Study 2021. Lancet Neurol. 2024, 23:973-1003. 10.1016/S1474-4422(24)00369-7
2. Elhady MM, Rabea EM, Ebaed SB, et al.: Tranexamic acid for spontaneous intracerebral hemorrhage: hematoma control without clinical benefits? A meta-analysis of RCTs. Naunyn Schmiedebergs Arch Pharmacol. 2026, 399:1109-20. 10.1007/s00210-025-04473-5
3. Chen ZJ, He C, Xu J, et al.: Exoskeleton-assisted anthropomorphic movement training for the upper limb after stroke: the EAMT randomized trial. Stroke. 2023, 54:1464-73. 10.1161/STROKEAHA.122.041480
4. Winters C, van Wegen EE, Daffertshofer A, Kwakkel G: Generalizability of the proportional recovery model for the upper extremity after an ischemic stroke. Neurorehabil Neural Repair. 2015, 29:614-22. 10.1177/1545968314562115
5. Qian Q, Hu X, Lai Q, Ng SC, Zheng Y, Poon W: Early stroke rehabilitation of the upper limb assisted with an electromyography-driven neuromuscular electrical stimulation-robotic arm. Front Neurol. 2017, 8:447. 10.3389/fneur.2017.00447
6. Veerbeek JM, Kwakkel G, van Wegen EE, Ket JC, Heymans MW: Early prediction of outcome of activities of daily living after stroke: a systematic review. Stroke. 2011, 42:1482-8. 10.1161/STROKEAHA.110.604090
7. Stinear CM, Lang CE, Zeiler S, et al.: Advances and challenges in stroke rehabilitation. Lancet Neurol. 2020, 19:348-60. 10.1016/S1474-4422(19)30415-6
8. Lang CE, Lohse KR, Birkenmeier RL: Dose and timing in neurorehabilitation: prescribing motor therapy after stroke. Curr Opin Neurol. 2015, 28:549-55. 10.1097/WCO.0000000000000256
9. Mehrholz J, Pollock A, Pohl M, Kugler J, Elsner B: Systematic review with network meta-analysis of randomized controlled trials of robotic-assisted arm training for improving activities of daily living and upper limb function after stroke. J Neuroeng Rehabil. 2020, 17:83. 10.1186/s12984-020-00715-0
10. Baker SN: The primate reticulospinal tract, hand function and functional recovery . J Physiol. 2011, 589:5603-12. 10.1113/jphysiol.2011.215160
11. Mehrholz J, Pohl M, Platz T, Kugler J, Elsner B: Electromechanical and robot-assisted arm training for improving activities of daily living, arm function, and arm muscle strength after stroke. Cochrane Database Syst Rev. 2018, 9:CD006876. 10.1002/14651858.CD006876.pub5
12. Wu J, Cheng H, Zhang J, Yang S, Cai S: Robot-assisted therapy for upper extremity motor impairment after stroke: a systematic review and meta-analysis. Phys Ther. 2021, 101:10.1093/ptj/pzab010
13. Veerbeek JM, Langbroek-Amersfoort AC, van Wegen EE, Meskers CG, Kwakkel G: Effects of robot-assisted therapy for the upper limb after stroke. Neurorehabil Neural Repair. 2017, 31:107-21. 10.1177/1545968316666957
14. Rodgers H, Bosomworth H, Krebs HI, et al.: Robot assisted training for the upper limb after stroke (RATULS): a multicentre randomised controlled trial. Lancet. 2019, 394:51-62. 10.1016/S0140-6736(19)31055-4
15. Lo AC, Guarino PD, Richards LG, et al.: Robot-assisted therapy for long-term upper-limb impairment after stroke. N Engl J Med. 2010, 362:1772-83. 10.1056/NEJMoa0911341
16. Klamroth-Marganska V, Blanco J, Campen K, et al.: Three-dimensional, task-specific robot therapy of the arm after stroke: a multicentre, parallel-group randomised trial. Lancet Neurol. 2014, 13:159-66. 10.1016/S1474-4422(13)70305-3
17. Page MJ, McKenzie JE, Bossuyt PM, et al.: The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ. 2021, 372:n71. 10.1136/bmj.n71
18. Cumpston M, Li T, Page MJ, Chandler J, Welch VA, Higgins JP, Thomas J: Updated guidance for trusted systematic reviews: a new edition of the Cochrane Handbook for Systematic Reviews of Interventions. Cochrane Database Syst Rev. 2019, 10:ED000142. 10.1002/14651858.ED000142
19. Sterne JA, Savović J, Page MJ, et al.: RoB 2: a revised tool for assessing risk of bias in randomised trials . BMJ. 2019, 366:l4898. 10.1136/bmj.l4898
20. Fugl-Meyer AR, Jääskö L, Leyman I, et al.: The post-stroke hemiplegic patient. 1. A method for evaluation of

physical performance. Scand J Rehabil Med. 1975, 7:13-31. 10.2340/1650197771331
21. Lyle RC: A performance test for assessment of upper limb function in physical rehabilitation treatment and research. Int J Rehabil Res. 1981, 4:483-92. 10.1097/00004356-198112000-00001
22. Bohannon RW, Smith MB: Interrater reliability of a modified Ashworth scale of muscle spasticity . Phys Ther. 1987, 67:206-7. 10.1093/ptj/67.2.206
23. Dai W, Yi Y, Lin A, et al.: Onlinemeta: a web server for meta-analysis based on shiny framework . Curr Radiopharm. 2026, 19:10.1016/j.craph.2025.100023
24. Frisoli A, Barsotti M, Sotgiu E, Lamola G, Procopio C, Chisari C: A randomized clinical control study on the efficacy of three-dimensional upper limb robotic exoskeleton training in chronic stroke. J Neuroeng Rehabil. 2022, 19:14. 10.1186/s12984-022-00991-y
25. Chen ZJ, He C, Guo F, Xiong CH, Huang XL: Exoskeleton-assisted anthropomorphic movement training (EAMT) for poststroke upper limb rehabilitation: a pilot randomized controlled trial. Arch Phys Med Rehabil. 2021, 102:2074-82. 10.1016/j.apmr.2021.06.001
26. Byl NN, Abrams GM, Pitsch E, et al.: Chronic stroke survivors achieve comparable outcomes following virtual task specific repetitive training guided by a wearable robotic orthosis (UL-EXO7) and actual task specific repetitive training guided by a physical therapist. J Hand Ther. 2013, 26:343-52; quiz 352. 10.1016/j.jht.2013.06.001
27. Brokaw EB, Nichols D, Holley RJ, Lum PS: Robotic therapy provides a stimulus for upper limb motor recovery after stroke that is complementary to and distinct from conventional therapy. Neurorehabil Neural Repair. 2014, 28:367-76. 10.1177/1545968313510974
28. Akgün İ, Demirbüken İ, Timurtaş E, et al.: Exoskeleton-assisted upper limb rehabilitation after stroke: a randomized controlled trial. Neurol Res. 2024, 46:1074-82. 10.1080/01616412.2024.2381385
29. Singh N, Saini M, Kumar N, Srivastava MV, Mehndiratta A: Evidence of neuroplasticity with robotic hand exoskeleton for post-stroke rehabilitation: a randomized controlled trial. J Neuroeng Rehabil. 2021, 18:76. 10.1186/s12984-021-00867-7
30. Ma D, Li X, Xu Q, et al.: Robot-assisted bimanual training improves hand function in patients with subacute stroke: a randomized controlled pilot study. Front Neurol. 2022, 13:884261. 10.3389/fneur.2022.884261
31. Housman SJ, Scott KM, Reinkensmeyer DJ: A randomized controlled trial of gravity-supported, computer-enhanced arm exercise for individuals with severe hemiparesis. Neurorehabil Neural Repair. 2009, 23:505-14. 10.1177/1545968308331148
32. Arya KN, Verma R, Garg RK: Estimating the minimal clinically important difference of an upper extremity recovery measure in subacute stroke patients. Top Stroke Rehabil. 2011, 18 Suppl 1:599-610. 10.1310/tsr18s01-599
33. van der Lee JH, Beckerman H, Lankhorst GJ, Bouter LM: The responsiveness of the Action Research Arm test and the Fugl-Meyer Assessment scale in chronic stroke patients. J Rehabil Med. 2001, 33:110-3. 10.1080/165019701750165916
34. Dromerick AW, Geed S, Barth J, et al.: Critical Period After Stroke Study (CPASS): a phase II clinical trial testing an optimal time for motor recovery after stroke in humans. Proc Natl Acad Sci U S A. 2021, 118:10.1073/pnas.2026676118
35. Zeiler SR, Krakauer JW: The interaction between training and plasticity in the poststroke brain . Curr Opin Neurol. 2013, 26:609-16. 10.1097/WCO.0000000000000025
36. Park JM, Park HJ, Yoon SY, Kim YW, Shin JI, Lee SC: Effects of robot-assisted therapy for upper limb rehabilitation after stroke: an umbrella review of systematic reviews. Stroke. 2025, 56:1243-52. 10.1161/STROKEAHA.124.048183