

Systematic Review

EMG-Driven Robotic Therapy for Neurological Rehabilitation: A Systematic Review and Meta-Analysis

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Abstract

Surface electromyography (EMG) can drive assistive training systems in neurorehabilitation. This systematic review and meta-analysis evaluated whether EMG-driven device-assisted rehabilitation improves upper-limb (UL) and lower-limb (LL) outcomes versus conventional therapy (CT). The review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) and was registered in PROSPERO (CRD420251029642). We searched databases for randomized controlled trials in adults with neurological disorders; three reviewers screened records, extracted data, and assessed risk of bias using the Revised Cochrane risk-of-bias tool (RoB 2). Seven trials ($n = 160$) were included, all in post-stroke populations (UL: 3; LL: 4). UL trials showed mixed findings, and pooled effects were imprecise and not statistically significant for activities of daily living (ADL) (standardized mean difference, SMD -0.55 ; $p = 0.09$; $I^2 = 0\%$). LL pooled estimates showed no significant differences in motor function (Fugl-Meyer Assessment, lower extremity, FMA-LE) (mean difference, MD -1.69 ; $p = 0.40$), walking independence (Functional Ambulation Categories, FAC) (MD -0.24 ; $p = 0.61$), balance (SMD 0.12 ; $p = 0.61$), mobility (Timed Up and Go, TUG) (MD -3.24 ; $p = 0.71$), or endurance (SMD -0.19 ; $p = 0.43$). Current evidence does not demonstrate clinical superiority over CT. EMG-driven systems may be used as an adjunct, but larger trials with standardized protocols, implementation outcomes, and neurological pathologies beyond stroke are needed.

Keywords: physiotherapy; neurological rehabilitation; robotics; electromyography; stroke; exoskeleton; gait training; device-assisted rehabilitation



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1. Introduction

Neurological diseases are the leading cause of disability and the second leading cause of death worldwide. Almost a third of the global population will develop a neurological disorder in their lifetime [1]. Conditions such as strokes, multiple sclerosis (MS), Parkinson’s disease (PD), traumatic brain injury (TBI), and spinal cord injury (SCI) have an impact on sensory-motor functions, which directly reduce functionality, independence in activities of daily living (ADLs), and patients’ quality of life (QoL) [2]. Given the growing prevalence,

the demand for effective and sustainable functional neurorehabilitation could intensify in the coming years [3].

Neurological rehabilitation is one of the crucial ways of restoring affected sensory–motor functions, promoting brain plasticity, and preventing complications secondary to the disease [4]. This rehabilitation is traditionally delivered through individualized, function-oriented physiotherapy, targeting sensorimotor impairments via strengthening, motor control training, and task-oriented or task-specific practice. This approach has demonstrated effectiveness and remains fundamental for optimal physical and functional independence for the neurological population [5].

In recent years, advances in technology-based interventions have enabled the development of new therapeutic methods in neurophysiotherapy, particularly through the use of robotics and surface electromyography (EMG) [6,7]. EMG contributes to rehabilitation by analyzing muscle activity during functional tasks and movements, offering insight into motor control and providing individualized rehabilitation strategies [8]. Studies have demonstrated that robotics, especially exoskeletons, has been reported to be effective in rehabilitation, providing improvements in cerebral cortical excitability and enhancing balance and motor function recovery in stroke patients [9,10]. Those two technologies could be beneficial to neurorehabilitation; while exoskeletons offer passive or pre-programmed support, adding EMG provides an interactive approach for better adapted upper and lower limb functional rehabilitation [11]. EMG-driven devices offer active and personalized interaction that encourages patient involvement in their therapy [12,13]. They detect residual muscle electrical activity via surface electrodes, enabling the robotic assistance provided to adjust and adapt in real time to the patient's movement [6]. This approach makes it possible to provide more individualized rehabilitation, compared with conventional therapy (CT).

However, this technological evolution in neurophysiotherapy is controversial because clinical evidence remains inconsistent. Some studies report significant improvements in upper (UL) and lower limb (LL) motor functions, such as strength, coordination, or functionality, compared to CT [14]. On the other hand, others have evaluated that EMG-driven robots do not provide better results than CT in similar areas [6]. Explanations may be provided by the protocol's parameters, populations studied, assessment criteria, and scales chosen, or different interpretations of the results from one study to another. As a result, the real effectiveness of EMG-driven robots in neurological rehabilitation is still open to debate.

Against this background, findings remain inconsistent. This systematic review with meta-analysis aims to evaluate the effectiveness of EMG-driven robots compared to CT in improving UL and LL functionality of patients with neurological disorders. In-depth analysis assesses whether EMG-driven robots lead to greater improvements in muscle strength, balance, and gait, and also the impact of EMG-driven robotic therapy on QoL and ADL.

2. Materials and Methods

2.1. Design and Protocol Registration

This study was designed as a systematic review with meta-analysis. The protocol of this review was registered with the PROSPERO database (CRD420251029642). The Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) Statement was followed for reporting [15,16] (checklist available in Supplementary File S1).

2.2. Search Strategy and Study Selection

The search strategy was developed using a structured three-step approach. First, a preliminary search in PubMed was conducted to identify relevant keywords through titles

and abstracts analysis. Second, the strategy was refined and expanded by incorporating the identified keywords with their synonyms and related terms. Third, the search terms were tailored to match the syntax and requirements of each database. Additional relevant articles were identified by reviewing the reference lists of the included studies. Articles were included without restrictions on publication date, provided they were available in English. The databases consulted were PubMed, EMBASE, Cochrane Library, Scopus, and Web of Science. The final search was completed on 21 May 2025. Full database-specific strings are provided in Supplementary File S2, and the full-text screening flow with exclusion reasons is detailed in Supplementary File S3.

All records were imported into Rayyan software (Qatar Computing Research Institute, Qatar) for management and screening [17]. Three independent reviewers screened titles and abstracts against the inclusion criteria. Disagreements at the title and abstract stage were resolved through discussion with a fourth reviewer. Full texts were then obtained for all potentially eligible studies and assessed independently by the same three reviewers. Any discrepancies at the full-text stage were resolved with the input of a fourth reviewer.

2.3. Eligibility Criteria

This systematic review included randomized controlled trials (RCTs) enrolling adults with neurological disorders (stroke, TBI, SCI, PD, MS). Eligible interventions were EMG-driven, robot-assisted rehabilitation (i.e., the robotic device used EMG signals to control or adapt assistance). Studies in which EMG was used only for diagnosis/assessment, or robotic rehabilitation was delivered without EMG-driven control, were excluded.

Comparators were eligible if they did not include any robotic or electromechanical device. Conventional therapy and/or usual care (including standard physiotherapy and occupational therapy components) was permitted in both study arms. Co-interventions delivered as part of routine care were eligible provided that the only systematic between-group difference was exposure to the EMG-driven robotic intervention (time-matched where feasible). Trials were excluded if the control arm received any robotic intervention, or if the experimental arm combined the EMG-driven robot with an additional active component that was not matched in the comparator, such that the independent effect of the EMG-driven robot could not be isolated. Primary outcome domains were upper-limb and lower-limb function. Secondary outcome domains included gait parameters, balance, muscle strength, quality of life, and activities of daily living. Non-RCT designs (including conference abstracts, short communications, quasi-RCTs, controlled clinical trials, and observational studies) were excluded. Studies enrolling non-neurological populations were excluded.

2.4. Risk of Bias Assessment

Three reviewers independently assessed risk of bias using the Revised Cochrane risk-of-bias tool for randomized trials (RoB 2) [18]. Disagreements were resolved by consensus, with a fourth reviewer adjudicating when required. RoB 2 evaluates five domains: (1) bias arising from the randomization process, (2) bias due to deviations from intended interventions, (3) bias due to missing outcome data, (4) bias in measurement of the outcome, and (5) bias in selection of the reported result. Each domain, and the overall risk of bias, was judged as low risk, some concerns, or high risk, following the RoB 2 signaling questions and algorithms.

2.5. Data Analysis

All statistical analyses were conducted using Review Manager (RevMan), version 5.4. Continuous outcomes were analyzed using mean differences (MD) when all included studies reported results on the same measurement scale. For conceptually similar out-

comes assessed with different instruments, standardized mean differences (SMD) were calculated to enable pooling across studies. For crossover trials, only first-period (pre-crossover) data were extracted and analyzed as a parallel-group comparison based on randomized sequence allocation, to avoid unit-of-analysis errors and potential carryover effects. Effect estimates were based on post-intervention endpoint values (mean and SD). Where multiple post-intervention assessments were reported, the timepoint closest to the end of the planned intervention was selected for meta-analysis; longer-term follow-ups were not pooled. We prespecified the meta-analytic model based on statistical heterogeneity and clinical/methodological comparability. A random-effects model was used when heterogeneity was at least moderate ($I^2 \geq 50\%$) or when the Chi² test for heterogeneity (Cochran's Q) suggested heterogeneity ($p < 0.10$). A fixed-effect model was applied only when heterogeneity was low ($I^2 < 50\%$ and $p \geq 0.10$) and studies were judged clinically and methodologically comparable.

3. Results

3.1. Search Results and Study Characteristics

Figure 1 presents the flow of the study identification and selection process. The systematic search yielded 791 records. After duplicate removal ($n = 435$), 356 records were screened by title and abstract, and 345 records were excluded. In addition, one additional record was identified through citation searching (reference list screening) and assessed at full text. Twelve full-text articles were assessed for eligibility. Following full-text assessment, 7 studies comprising 160 participants were included in the qualitative synthesis and meta-analysis (full-text exclusion reasons are provided in Supplementary File S3). All included trials enrolled post-stroke participants; no eligible RCTs were identified for the other prespecified neurological disorders.

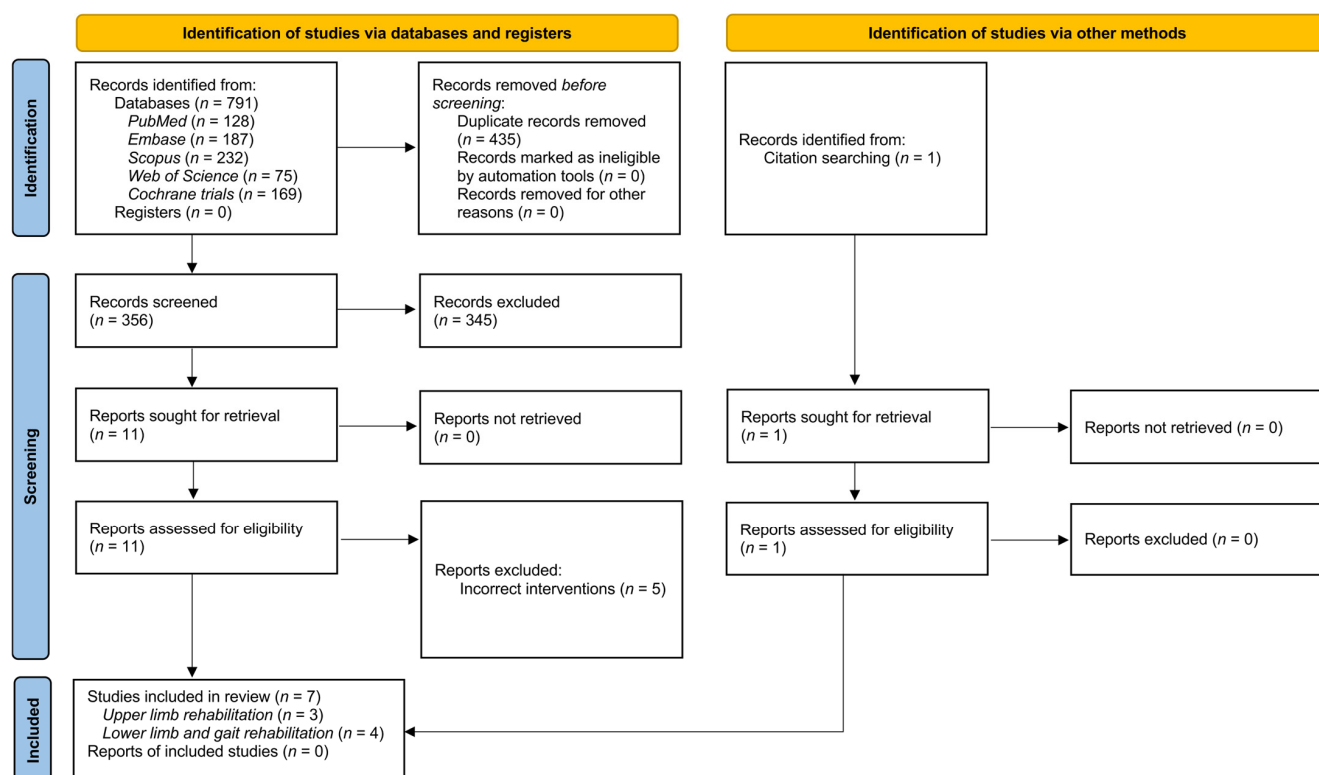


Figure 1. PRISMA Flow Diagram.

The data extracted from the included studies are summarized in Table 1. Four studies addressed LL and gait rehabilitation, all of which utilized the Hybrid Assistive Limb (HAL) system as the robotic intervention [19–22]. In addition, three studies investigated UL rehabilitation: one used the Hand of Hope (HOH) robotic hand system [6], one employed an integrated electromyography-driven neuromuscular electrical stimulation (NMES) robotic training system [23], and one used the Myomo e100 portable EMG-controlled orthosis [24].

Table 1. Data extraction table for included trials. All included RCTs enrolled post-stroke participants (UL: 3; LL: 4); no eligible RCTs were identified for PD, MS, TBI, or SCI.

Author(s), Year	Population Characteristics	Robotic Intervention	EMG Control Muscles	Comparator Intervention	Dose	Outcome Measures	Key Findings
Upper limb (n = 3)							
Chen et al. (2022) [6]	n = 24; age 58.9 (11.1) y; time since stroke 46.6 (39.2) mo	Hand of Hope hand exoskeleton; sEMG-triggered assistance with biofeedback and interactive games	Extensor digitorum; flexor digitorum superficialis	Task-oriented ADL training	12 sessions/4 weeks (3 × /wk) per period; 20 min CPM + 20 min active + 30 min gaming; washout 1 month	Primary: FMA-UE Secondary: WMFT, ARAT, MAL	Both conditions improved; WMFT-Time improved more after HOH (p = 0.004), whereas task-oriented training improved MAL (p = 0.014)
Qian et al. (2017) [23]	n = 24; age 58.8 (10.1) y; time since stroke 14–148 d (range)	EMG-driven NMES-robotic arm; robotic assistance synchronized with NMES	Biceps brachii; triceps brachii; flexor carpi radialis; extensor carpi ulnaris; extensor digitorum	Conventional rehabilitation	20 sessions/4 weeks (5 × /wk); 40 min training (2 × 20 min with 10 min break); routine rehabilitation in both groups	Primary: FMA, MAS Secondary: ARAT, FIM, EMG	Group × time effects favored NMES-robot for FMA total and wrist/hand and for MAS (wrist, fingers); ARAT and FIM showed no between-group differences; effects maintained at 3 months
Page et al. (2013) [24]	n = 16; age 57.0 (11.0) y; time since stroke 75.0 (87.6) mo	Myomo e100 wearable powered orthosis; EMG-triggered assistance during task-specific practice	Biceps brachii; triceps brachii	Therapist-supervised task-specific practice (no device)	24 sessions/8 weeks (3 × /wk); 60 min/session; outpatient	Primary: FMA-UE Secondary: COPM, ADL, mobility, hand	No significant between-group differences; both groups improved similarly (FMA change +2.13 vs. +2.25; p = 0.93)
Lower limb (n = 4)							
Wall et al. (2020) [20]	n = 32; age 56.4 (8.2) y; time since stroke 34.0 (15.4) d	HAL-assisted treadmill gait training with body-weight support (CVC/CAC), embedded in inpatient rehabilitation	Biceps femoris; vastus lateralis; rectus femoris; gluteus maximus	Conventional gait training	16 sessions/4 weeks (4 × /wk); ≤60 min gait training (≤90 min total incl. donning/doffing); standard rehabilitation in both groups	Primary: FAC Secondary: FMA-LE, 2 MWT, BBS, BI	No significant between-group differences post-intervention or at 6 months; no adverse events reported
Sczesny-Kaiser et al. (2019) [19]	n = 18; age 64.8 (7.1) y; time since stroke 82.3 (83.9) mo	HAL-assisted BWSTT (double-leg exoskeleton; EMG-based support)	Hip and knee flexors/extensors (not specified by muscle)	Conventional physiotherapy	Crossover: 2 × 6-week periods (30 sessions/period; 5 × /wk; 30 min/session) with 1-week break; analysis based on first period	Primary: 10 MWT, 6 MWT, TUG Secondary: FAC, BBS	No significant HAL vs. CT differences; improvements over time for multiple gait outcomes; no carryover effects reported
Watanabe et al. (2017) [22]	n = 24; age 71.9 (15.5) y; time since stroke 52.6 (38.6) d	Single-leg HAL gait training (paretic side; CVC/CAC)	Not reported	Conventional gait training	12 sessions/4 weeks (3 × /wk; 20 min/session); follow-up at 8 and 12 weeks	Primary: FAC Secondary: walking speed, stride, cadence, 6MWD, TUG, FMA-LE	Group × time interaction for FAC favored HAL (p = 0.026); secondary outcomes did not differ between groups

Table 1. Cont.

Watanabe et al. (2014) [21]	<i>n</i> = 22; age 71.3 (15.7) y; time since stroke 54.8 (39.9) d	Single-leg HAL gait training (paretic side; mainly CVC, CAC if needed); suspension as required	Not reported	Conventional gait training	12 sessions/4 weeks (3 × /wk; 20 min/session); inpatient rehabilitation continued, similar total therapy hours	Primary: FAC Secondary: 10 m walking speed, stride, cadence, TUG, 6MWD, SPPB, FMA-LE, strength	FAC improved in both groups; between-group difference favored HAL (MD 0.45; 95% CI 0.02–0.88; <i>p</i> = 0.04); no significant differences for secondary outcomes
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Abbreviations: y, years; mo, months; wk, weeks; d, days; 10 MWT, 10 m walk test; 2 MWT, 2 min walk test; 6 MWT, 6 min walk test; 6MWD, 6 min walk distance; ARAT, Action Research Arm Test; BI, Barthel Index; BBS, Berg Balance Scale; BWSTT, body weight supported treadmill training; CAC, cybernetic autonomous control; CPM, continuous passive motion; CVC, cybernetic voluntary control; COPM, Canadian Occupational Performance Measure; FAC, Functional Ambulation Category; FIM, Functional Independence Measure; FMA, Fugl-Meyer Assessment; HAL, Hybrid Assistive Limb; HOH, Hand of Hope; MAL, Motor Activity Log; MAS, Modified Ashworth Scale; MS, Multiple Sclerosis; NMES, neuromuscular electrical stimulation; PD, Parkinson Disease; sEMG, surface electromyography; SCI, Spinal Cord Injury; SPPB, Short Physical Performance Battery; TBI, Traumatic Brain Injury; TUG, Timed Up and Go; WMFT, Wolf Motor Function Test.

3.2. Upper Limb Rehabilitation

3.2.1. Narrative Synthesis of the Included Studies

Chen et al. (2022) conducted a randomized, single-blind, two-period crossover trial to compare an EMG-driven robotic hand exoskeleton (Hand of Hope, HOH) with task-oriented training for upper-limb rehabilitation in chronic stroke survivors [6]. A total of 31 participants were randomized to either robot-assisted intervention first or task-oriented training first. Seven participants discontinued during the first intervention period, resulting in 24 participants completing the first period and being included in the analysis (Group A, *n* = 14; Group B, *n* = 10). Each condition consisted of 12 sessions delivered over 4 weeks (3 sessions/week), separated by a 1-month washout. Outcomes included the Fugl-Meyer Assessment for the upper extremity (FMA-UE), Wolf Motor Function Test (WMFT), Action Research Arm Test (ARAT), and Motor Activity Log (MAL). Both interventions were associated with improvements in UL performance. The authors reported greater improvement in movement time during functional tasks following HOH (WMFT-Time, *p* = 0.004), whereas task-oriented training led to greater improvement in spontaneous affected-arm use during daily activities (*p* = 0.014). Overall, the study did not demonstrate clear superiority of HOH over task-oriented training across UL outcomes, suggesting broadly comparable effects with outcome-specific differences [6].

Qian et al. (2017) conducted a pilot RCT to evaluate the effects of an electromyography-driven NMES-robotic arm on UL rehabilitation in subacute stroke patients [23]. Twenty-four participants were randomized into two groups: the NMES-robot group (*n* = 14) and a time-matched traditional therapy control group (*n* = 10), both receiving 20 sessions over 4 weeks. Both groups demonstrated significant improvements in FMA total, shoulder/elbow subscore, ARAT, and Functional Independence Measure (FIM) (*p* < 0.001 for most outcomes), with moderate to large effect sizes. Notably, only the NMES-robot group exhibited significant improvements in the FMA wrist/hand subscore (*p* < 0.001, η^2 = 0.435) and a significant reduction in wrist spasticity assessed by the Modified Ashworth Scale (MAS) (*p* < 0.05). The NMES-robot group also demonstrated improved muscle coordination patterns, evidenced by decreased co-contraction and reduced wrist flexor overactivity. Improvements were largely maintained at the 3-month follow-up. The authors concluded that NMES-robot-assisted therapy may offer superior benefits at distal joints and spasticity reduction compared to CT [23].

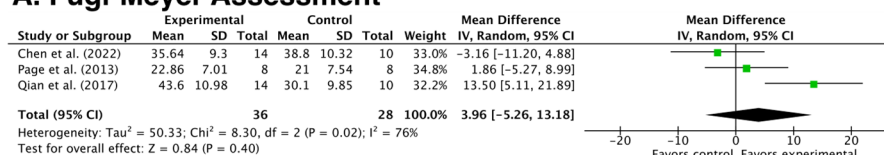
Page et al. (2013) performed a phase 2a randomized controlled pilot study to assess the efficacy of integrating a portable electromyography-controlled robotic orthosis (Myomo e100) into repetitive task-specific practice for patients with chronic moderate upper extrem-

ity impairment after stroke [24]. Sixteen participants (mean time post-stroke 75 months) were randomized to either robotic-assisted therapy or therapist-supervised conventional task-specific practice, both delivered 3 times per week for 8 weeks. Both groups showed comparable improvements on the primary outcome (FMA-UE score: approximately 2-point increase), with no significant between-group differences. On secondary outcomes (Canadian Occupational Performance Measure and Stroke Impact Scale), no statistically significant between-group differences were observed. Although some patient-reported domains (for example, SIS ADL, hand function, perceived recovery) were numerically higher in the robotic group, these differences were not statistically significant and should be considered inconclusive [24].

3.2.2. Quantitative Synthesis

Three RCTs evaluating the effect of EMG-driven robotic training versus CT on upper extremity motor function (measured by the FMA) were included [6,23,24]. The pooled analysis demonstrated no statistically significant difference between robotic and conventional interventions (Mean Difference = 3.96, 95% CI: −5.26 to 13.18; $p = 0.40$). Substantial heterogeneity was observed across studies ($I^2 = 76\%$, $\text{Tau}^2 = 50.33$, $p = 0.02$), indicating variability in treatment effects among the included trials. Anchor-based clinically important change estimates for within-person improvement on the FMA-UE vary by context, for example, 4.25–7.25 points in chronic stroke with minimal to moderate impairment, depending on the movement facet, and higher values have been reported in convalescent, more severely impaired cohorts (for example, 12.4 points) [25,26]. Therefore, while the pooled between-group estimate (MD 3.96) is below these commonly cited within-person thresholds, the confidence interval is wide and clinical importance remains uncertain. The corresponding forest plot is presented in Figure 2.

A. Fugl-Meyer Assessment



B. Activities of Daily Living

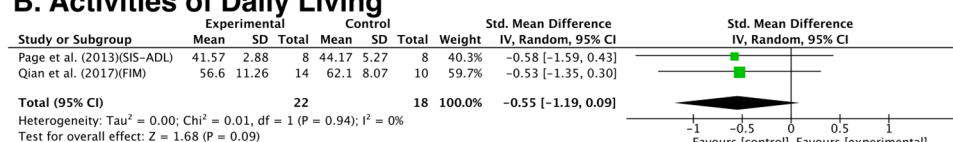


Figure 2. Forest plots of intervention effects on motor function (A) and activities of daily living (B).

Substantial heterogeneity ($I^2 = 76\%$) is plausible given marked between-study differences in clinical context and interventions. Included UL trials enrolled participants in different recovery phases (subacute vs. chronic), which affects spontaneous recovery potential and responsiveness to training. Intervention dose and structure also varied meaningfully across studies (session duration and total training time), which can influence effect size. Finally, the devices differed in control strategy and training content (e.g., robotic hand exoskeleton with task/gaming elements, EMG-driven NMES-robotic arm, and a portable EMG-triggered orthosis), so pooled effects likely reflect non-equivalent interventions rather than a single class effect.

In addition to motor function, two studies assessed the impact of the interventions on activities of daily living (ADL), although using different outcome measures (ADL subsection of stroke impairment scale (SIS), and FIM). The pooled standardized mean difference showed no statistically significant advantage of robotic therapy (SMD = −0.55,

95% CI: -1.19 to 0.09 ; $p = 0.09$). No heterogeneity was observed ($I^2 = 0\%$, $\text{Tau}^2 = 0.00$, $p = 0.94$). Because ADL outcomes were pooled using an SMD across different instruments, Minimal Clinically Important Difference (MCID) thresholds cannot be applied consistently at the meta-analytic level, so interpretation is based on the magnitude and precision of the pooled estimate rather than an MCID benchmark.

3.3. Lower Limb and Gait Rehabilitation

3.3.1. Narrative Synthesis of the Included Studies

Watanabe et al. (2014) conducted a randomized controlled pilot trial to compare the effects of gait training with the single-leg HAL to conventional gait training (CGT) in subacute stroke patients [21]. A total of 22 patients (11 per group) completed the 4-week intervention, which involved twelve 20 min sessions of HAL-assisted training or CGT. The primary outcome was the Functional Ambulation Category (FAC), with secondary outcomes including walking speed, Timed Up and Go (TUG), 6-Minute Walk Test (6 MWT), Fugl-Meyer Lower Extremity (FMA-LE), Short Physical Performance Battery, and isometric muscle strength. The HAL group demonstrated significantly greater improvement in FAC compared to CGT ($p = 0.04$), while no significant between-group differences were observed for secondary outcomes. The authors concluded that HAL-assisted training may enhance independent walking capacity more effectively than conventional therapy in the early post-stroke period [21].

In an extension of their earlier trial, Watanabe et al. (2017) conducted a randomized controlled study evaluating the medium-term efficacy of HAL-assisted gait training compared to CGT in recovery-phase stroke patients [22]. Twenty-four participants (12 per group) completed 12 sessions over 4 weeks. Outcomes were assessed at baseline, after intervention, and at 8 and 12 weeks. The primary outcome, FAC, showed significantly greater improvements in the HAL group at all follow-up points ($p = 0.02$), while no significant between-group differences were found in secondary outcomes (maximum walking speed, stride, cadence, 6 MWT, TUG, FMA-LE). These findings suggest sustained benefits of HAL-assisted gait training on walking independence compared to CGT [22].

Sczesny-Kaiser et al. (2019) conducted a randomized controlled crossover trial (HALE-STRO study) with 18 chronic stroke patients (≥ 6 months post-stroke) [19]. Participants received both HAL-assisted body-weight-supported treadmill training (BWSTT) and CT, each consisting of 30 sessions over 6 weeks. Primary outcomes included 10-Meter Walk Test (10 MWT), TUG, and 6 MWT, while secondary outcomes were FAC and Berg Balance Scale (BBS). No significant differences were found between HAL and CT interventions when directly compared. However, both interventions led to significant within-subject improvements across walking speed, endurance, balance, and walking independence (FAC improved from dependent to independent levels). The authors concluded that HAL is equally effective as conventional physiotherapy but not superior; combining both may optimize rehabilitation outcomes in chronic stroke patients [19].

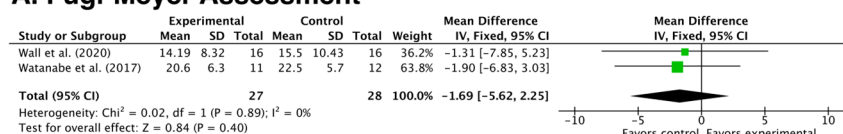
Wall et al. (2020) performed a randomized, open-label, assessor-blinded controlled trial involving 32 subacute stroke patients with severe gait impairments (FAC 0–1) [20]. Participants were randomized to receive either incorporated HAL training (4 sessions/week for 4 weeks) or CGT only, both within comprehensive inpatient rehabilitation. The primary outcome was walking independence (FAC), with secondary outcomes including FMA-LE, 2-Minute Walk Test (2 MWT), BBS, and Barthel Index. No significant between-group differences were observed in primary or secondary outcomes at post-intervention or 6-month follow-up. Independent walking at 6 months was predicted by younger age but not by intervention type. Despite no added benefit from HAL over CT, substantial functional

improvements were observed in both groups, reflecting the effectiveness of intensive early rehabilitation [20].

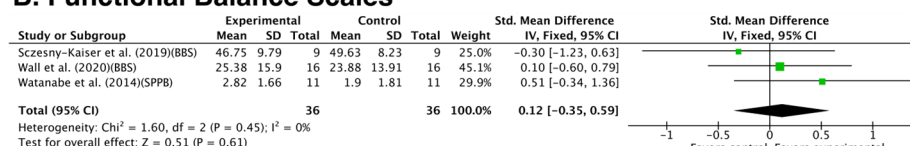
3.3.2. Quantitative Synthesis

Two RCTs [20,22] evaluated the effect of HAL-assisted gait training versus CT on lower extremity motor function, assessed by the FMA-LE. The pooled analysis demonstrated no statistically significant difference between groups (MD = −1.69; 95% CI: −5.62 to 2.25; $p = 0.40$), with no heterogeneity observed ($I^2 = 0\%$) (Figure 3). For FMA-LE, an anchor-based MCID of 6 points has been reported for within-person change in chronic post-stroke hemiparesis, but MCID availability and applicability vary by phase post-stroke and patient characteristics [27,28]. Accordingly, the pooled between-group estimate (MD −1.69) is clearly smaller than this chronic-stroke anchor, and the current evidence does not support a clinically important between-group difference.

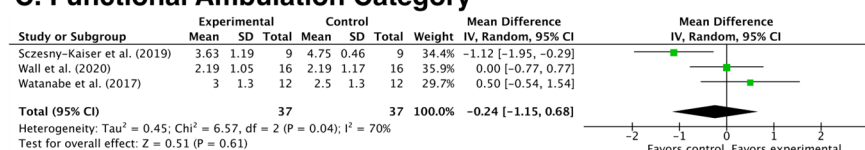
A. Fugl-Meyer Assessment



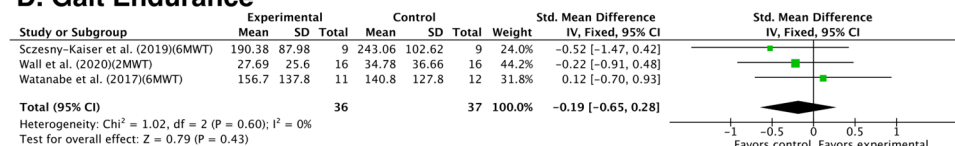
B. Functional Balance Scales



C. Functional Ambulation Category



D. Gait Endurance



E. Timed Up and Go

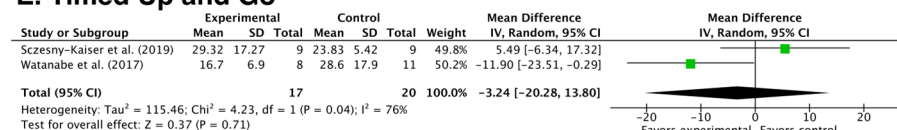


Figure 3. Forest plots of intervention effects on motor function (A), balance (B), ambulation (C), endurance (D), and mobility (E). For outcomes where lower values indicate better performance (e.g., TUG in panel (E)), the ‘Favors’ direction is reversed.

Three studies [19,20,22] assessed various functional outcomes. For the HALESTRO crossover trial [19], only first-period (pre-crossover) data were included in the meta-analysis. The pooled analysis for walking independence, measured by the FAC, showed no significant between-group difference (MD = −0.24; 95% CI: −1.15 to 0.68; $p = 0.61$), with high heterogeneity ($I^2 = 70\%$). Given that FAC is an ordinal scale, a one-category change is often considered a pragmatic marker of meaningful improvement, and the pooled mean difference suggests a smaller average between-group difference than one category, although imprecision and heterogeneity remain. Similarly, balance outcomes assessed by the BBS or comparable measures revealed no significant effect of HAL-assisted training (SMD = 0.12;

95% CI: -0.35 to 0.59 ; $p = 0.61$), with no heterogeneity ($I^2 = 0\%$). This corresponds to a small standardized effect and is unlikely to reflect an MCID-sized difference on commonly used balance scales. For functional mobility assessed by the TUG test, the meta-analysis showed no significant difference between groups (MD = -3.24 ; 95% CI: -20.28 to 13.80 ; $p = 0.71$), with high heterogeneity ($I^2 = 76\%$). Because an established, uniform MCID for TUG in stroke is not available and the confidence interval is wide, the data do not allow a firm conclusion regarding clinical importance. Finally, no significant effect was observed for walking endurance (SMD = -0.19 ; 95% CI: -0.65 to 0.28 ; $p = 0.43$), with low heterogeneity ($I^2 = 0\%$). The standardized effect is small and, in the absence of a single common metric across studies, clinical importance cannot be benchmarked to a single MCID threshold.

3.4. Risk of Bias Assessment

Of the seven randomized controlled trials, one (14%) was rated low risk, four (57%) raised some concerns, and two (29%) were high risk. The randomization process was the most frequent source of bias; five studies (71%) lacked adequate information on allocation concealment, followed by bias in selection of the reported result, which affected four studies (57%) (two high risk, two with some concerns). Missing outcome data raised some concerns in three trials (43%), and one study (14%) exhibited bias in measurement of the outcome. All seven studies were judged low risk for deviations from intended interventions.

In the upper-limb subgroup, Qian et al. [23] was rated low risk across all five domains. Chen et al. [6] raised some concerns for the randomization process and missing outcome data but was low risk in the remaining domains, including selection of the reported result, whereas Page et al. [24] raised some concerns in both the randomization process and bias in selection of the reported result but was low risk elsewhere. Among lower-limb interventions, Watanabe et al. [21] and Watanabe et al. [22] were classified as high overall risk, primarily due to allocation concealment and bias in selection of the reported result, while Wall et al. [20] and Sczesny-Kaiser et al. [19] raised some concerns, notably in randomization and bias in selection of the reported result. Sczesny-Kaiser et al. additionally raised concerns over missing outcome data [19]. All four lower-limb trials were low risk for deviations from intended interventions. Figure 4 depicts, for each trial, the proportion of domains rated low risk, raising some concerns, or high risk.

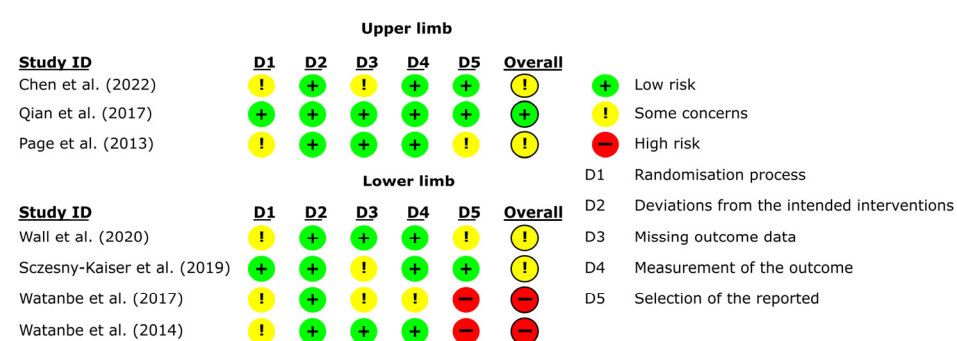


Figure 4. Risk of bias assessment results.

4. Discussion

This systematic review and meta-analysis evaluated the effects of EMG-driven robotic rehabilitation compared to CT in patients suffering from neurological disorders. Although eligibility encompassed stroke, TBI, SCI, PD, and MS, the eligible randomized evidence identified was confined to post-stroke populations; therefore, findings apply to stroke rehabilitation. Examination of the results of seven RCTs, three focusing on UL function and four on LL function, revealed the following conclusions.

Three UL trials yielded mixed findings. Qian et al. reported that EMG-driven NMES-robot training produced greater improvements in distal motor function and reduced spasticity compared with time-matched conventional therapy [23]. In contrast, Page et al. found no significant between-group differences between the Myomo e100-assisted repetitive task practice and therapist-delivered repetitive task practice, with both groups improving similarly on the FMA-UE (approximately 2 points) [24]. Similarly, Chen et al. reported broadly comparable effects of EMG-driven Hand of Hope training and task-oriented therapy, with outcome-specific differences (greater improvement in WMFT-Time after robot-assisted therapy, whereas task-oriented training improved spontaneous affected-arm use in daily activities) [6].

On the other hand, two studies by Watanabe et al. (2014) reported positive results of robotics on LL rehabilitation. The study by Watanabe et al. 2014 demonstrated significant improvements in the gait independence scales of the HAL group [21]. These improvements were confirmed in the study by Watanabe et al. 2017, suggesting that the HAL system can facilitate sustained gains in gait parameters during the sub-acute recovery phase of stroke patients [22]. Conversely, two other studies using the HAL system demonstrated no significant superiority over CGT [19,20]. Although improvements in gait and balance scales were observed, the differences with CT were not significant.

The divergent results of these studies can be explained in several ways. The articles included had small sample sizes, ranging from 16 to 32 participants, thus resulting in limited statistical power [29]. This risk of error could therefore influence the conclusion of a study.

The diversity of participants' characteristics, such as stroke phase, severity of impairment, or cognitive function, probably contributed to inconsistent responses to robotic interventions. A population with different characteristics and levels of impairment can produce distinct results [30]. The included studies proposed non-standardized study protocols with different inclusion and exclusion criteria, limiting comparability across trials.

Motor learning versus passive learning must be addressed. In the context of HAL-based LL rehabilitation, individual variability in the ability to activate the device's cybernetic voluntary control mode is particularly relevant and decisive in clinical outcomes. The system requires patients to generate voluntary EMG signals to create movement. If patients are unable to do this effectively, the device switches to autonomous mode and partially or fully assists movements [31]. Unfortunately, this feature may reduce patient engagement and limit the desired neuroplastic benefits [32]. The four LL studies proposed different uses of this notion of motor versus passive learning. Watanabe et al. [21,22] explicitly reported the use of the passive mode for less autonomous participants, while Sczesny-Kaiser et al. and Wall et al. [19,20] did not systematically stratify results according to control mode. It is necessary to take this aspect into account since favoring a dependence on the passive effect of HAL rather than active motor learning may engender less motor involvement from the patient and influence the final clinical outcome in the neurological population [32].

The frequency, duration, and intensity of the intervention varied between studies. For the UL, Page et al. proposed an 8-week program with 24 sessions [24], and Qian et al. applied a 4-week program with 20 sessions [23]. For the LL, Watanabe et al. used a 4-week protocol with 12 sessions in both studies [21,22], while Sczesny-Kaiser et al. implemented a 12-week crossover plan with 60 sessions [19], and Wall et al. applied 4-week training ranging from 16 sessions for the robotic group to 20 sessions for the CGT [20]. This aspect can be a major determinant of a study's outcome, since group dosages are not identical between studies. Subtle inter- and intra-study variations in dose, frequency, and task design can significantly influence neuroplastic changes and clinical outcomes [33]. However, even

the longest programs may have been insufficient to induce robust improvements in the most complex outcomes, particularly for chronic stroke populations [34].

The selection of scales and outcomes may affect sensitivity to change. The included studies used different scales to present results on the same domain. The non-standardization of study scales could influence interpretation and conclusions [35]. EMG-robotized systems are recent, with no standardization in their use. Lack of technological maturity may explain the heterogeneity of results. Calibration and parameter selection may influence the level of assistance and patient engagement, potentially affecting treatment response [11,36,37]. Finally, it is important to note that the methodological design of a study can significantly influence the results. Therefore, design differences between trials must be carefully considered when comparing results.

Electromechanical gait training increases the chances of independent walking in non-ambulatory patients, with effects highly variable depending on patient selection and the timing of the intervention [38]. Watanabe et al. stand out by showing sustained benefits of HAL on FAC at both 8 and 12 weeks, supporting the idea that HAL may be most effective during the subacute phase of recovery [22]. In contrast, Wall et al. found no difference between groups after intervention or 6-month follow-up, despite intensive therapy in the early phase [20]. Similarly, Sczesny-Kaiser et al. emphasize that HAL-assisted physiotherapy and conventional physiotherapy are not superior to each other [19].

In UL rehabilitation, the divergent results between Qian et al. [23] and Page et al. [24] highlight the role of robotic system design. The first system integrated EMG with NMES and focused on active distal control, resulting in improved motor coordination and reduced spasticity [23]. The other, based on wearable orthosis without NMES, may not have been sufficiently stimulating to effect change in a chronic stroke population [24]. Patient selection and stage of stroke recovery are important factors to consider as much as the total duration of training and the intervention combination with other therapies [38]. These results suggest that while EMG-driven robotic therapy holds promise for improving UL function, outcomes may be optimized through careful patient selection and individualized, goal-oriented intervention planning.

4.1. Clinical Implications

Considering studies with noted clinical improvement, we observed that EMG-driven robotics may offer clinical value alongside CT in neurological patients. These systems may be used alongside conventional therapy to support structured, high-repetition practice and increase task variety during training [6]. In this review, pooled effects were largely comparable to conventional therapy, suggesting that these systems should be considered an adjunct to increase training dose or delivery efficiency rather than a replacement for standard care. This may be particularly relevant in the early post-stroke phase, when intensive, task-specific practice is recommended to support recovery [39]. Even when endpoint outcomes are similar, robotics has been proposed to accelerate attainment of functional milestones by enabling higher volumes of practice within a given time window [40]. If confirmed, this could translate into shorter time-to-target outcomes and more efficient resource use, but this hypothesis requires direct testing in adequately powered trials that report time-based and health service outcomes.

4.2. Limitations

This systematic review with meta-analysis has several limitations. First, the overall certainty of the evidence is constrained by risk of bias and incomplete reporting in the included RCTs. Using RoB 2 terminology, the most frequent concerns related to the randomization process (insufficient detail on sequence generation and allocation concealment in some

trials) and selection of the reported result (limited access to prespecified protocols or analysis plans in some studies). Although blinding of participants and therapists is often not feasible in rehabilitation trials, we generally judged deviations from intended interventions as low risk; nevertheless, expectation effects and imbalances in co-interventions cannot be fully excluded and may have influenced some outcomes. Bias in measurement of the outcome was a concern particularly for outcomes relying on subjective or observer-rated scales, and outcome reporting was sometimes incomplete across time points.

Second, substantial clinical and methodological heterogeneity limited comparability and contributed to imprecision. Participant characteristics (severity, chronicity, and potentially lesion-related factors), intervention protocols (devices, control strategies, supervision, and dose), and outcome sets varied across studies. In addition, all lower-limb trials used HAL, limiting generalizability to other EMG-driven devices and introducing potential device-specific bias. Several measures (for example Barthel Index, BBS, SIS) were not applied uniformly across trials, which limited pooling, reduced interpretability across studies, and increased uncertainty in the synthesis.

Third, although eligibility covered multiple neurological disorders, all included RCTs were conducted in stroke; therefore, the review provides evidence only for post-stroke populations and cannot inform effectiveness in MS, PD, TBI, or SCI. Moreover, the evidence base is small and largely based on single-center studies with limited sample sizes, often without formal power calculations, which restricts generalizability and increases the likelihood of imprecise estimates. The inclusion of a crossover trial reduces inter-individual variability but may introduce carry-over effects if washout periods are insufficient, which can bias treatment contrasts.

Finally, implementation-focused outcomes were inconsistently reported. Feasibility and user experience outcomes were limited, and safety reporting was often brief or non-systematic. While some trials stated that no adverse events occurred, overall adverse event reporting, fatigue, and therapist workload were not consistently assessed or presented, limiting real-world interpretability for service planning and adoption.

4.3. Additional Considerations: Cost, Feasibility, and Accessibility

The high acquisition and implementation costs of EMG-driven robotic systems remain a barrier and are not consistently reimbursed [41,42]. These systems also require infrastructure, maintenance, and staff training, which can limit scalability beyond high-resource settings [43]. However, if robotic approaches improve delivery efficiency (for example, reducing the time needed to reach comparable functional levels), some upfront costs could be partially offset through reduced staff time or shorter episodes of care, although such effects are rarely evaluated alongside clinical outcomes [40].

Additionally, none of the studies reported cost-effectiveness analyses or health economic outcomes. These data are essential to inform reimbursement policies and guide healthcare planning. Device portability, maintenance, and patient fatigue remain under research. Although systems such as the Myomo e100 aim to remove some of these obstacles, their clinical effectiveness in the real world requires further evaluation.

4.4. Future Research Directions

The present study highlights both the potential and current limitations of EMG-driven robotic rehabilitation systems in neurological care. To advance the field, future studies should aim to fill several important gaps.

A larger multicenter randomized controlled trial is needed to increase statistical reliability and make the results more applicable to broader clinical settings. The current database is limited by small sample sizes, single-center or crossover designs, which restrict

conclusions. Associated with this, future RCTs should include longer-term follow-up assessments ranging from 6 to 12 months to assess the durability of motor and functional gains. The standardization of intervention dosages over this period is essential if valid comparisons are to be made between studies. Several studies comparing a robotic group and a conventional therapy group with a program of equivalent duration comprising the same number of sessions per week will facilitate systematic analyses and rigorous meta-analyses. Stratified analyses should be carried out to understand which patient profiles might benefit most from EMG-driven robotics. A precise analysis comparing several subgroups, categorized by lesion location and level of impairment, could help personalize treatments and make better clinical decisions. The selection and assessment of patients' cognitive status and their ability to voluntarily activate muscles are also essential, as these are prerequisites for the effective use of EMG-robot systems.

Future RCTs should prespecify and report efficiency and health service outcomes alongside clinical endpoints, including therapy time per session, total therapist time, time-to-milestone attainment, length of stay, discharge destination, and follow-up service use. Economic evaluations (cost-effectiveness and cost-utility) should be incorporated to determine whether any gains in delivery efficiency translate into meaningful reductions in overall resource use.

Other crucial considerations are feasibility, accessibility, and ease of use of these devices. So far, few studies have looked at patients' or therapists' experience, fatigue levels, training time, or the learning curve required to use the device. These factors influence real-world implementation and long-term adherence. Research should explore ways of reducing logistical barriers, such as portability and set-up time, to facilitate outpatient or community use.

5. Conclusions

This systematic review with meta-analysis evaluated the clinical effects of surface EMG-driven robotic rehabilitation versus conventional therapy on upper- and lower-limb function in post-stroke patients. Secondary outcomes were also examined, including limb-specific strength, quality of life, and independence in activities of daily living, as well as balance and gait parameters (e.g., walking speed and endurance).

Overall, EMG-driven robotic systems appear to be a promising adjunct in neurological rehabilitation, with potential therapeutic value. However, the current evidence base is not sufficient to demonstrate clear superiority over conventional therapy. Accordingly, these technologies may be best positioned as a complementary component within individualized rehabilitation programs rather than a replacement for standard care. Future studies should prioritize clearly defined target populations, standardized intervention protocols and outcome measures, and robust evaluations of cost-effectiveness.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/technologies14020119/s1>. Supplementary File S1: PRISMA 2020 Checklist; Supplementary File S2: Search strategy for databases; Supplementary File S3: List of excluded studies with reason.

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Abbreviations

The following abbreviations are used in this manuscript.

2 MWT	2 min Walk Test
6 MWD	6 min Walk Distance
6 MWT	6 min Walk Test
10 MWT	10 m Walk Test
ADL	Activities of Daily Living
ARAT	Action Research Arm Test
BBS	Berg Balance Scale
BI	Barthel Index
BWS	Body Weight Support
BWSTT	Body-Weight-Supported Treadmill Training
CG	Control Group
CGT	Conventional Gait Training
COPM	Canadian Occupational Performance Measure
CPT	Conventional Physiotherapy
CPM	Continuous Passive Motion
CT	Conventional Therapy
d	Days
EMG	Electromyography
FAC	Functional Ambulation Category
FIM	Functional Independence Measure
FMA	Fugl-Meyer Assessment
FMA-LE	Fugl-Meyer Lower Extremity
HOH	Hand of Hope
HAL	Hybrid Assistive Limb
LL	Lower Limb
MAL	Motor Activity Log
MAS	Modified Ashworth Scale
MCID	Minimal Clinically Important Difference
MD	Mean Differences
mo	Months
MS	Multiple Sclerosis
NMES	Neuromuscular Electrical Stimulation
PD	Parkinson Disease
QoL	Quality of Life

RCT	Randomized Controlled Trial
RoB2	Risk of Bias 2
SCI	Spinal Cord Injury
sEMG	Surface Electromyography
SIS	Stroke Impact Scale
SMD	Standardized Mean Differences
SPPB	Short Physical Performance Battery
TBI	Traumatic Brain Injury
TUG	Timed Up and Go
UL	Upper Limb
wk	Weeks
WMFT	Wolf Motor Function Test
y	Years

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