Post-print of a Meta-Analysis on the Effects of Robot-Assisted Rehabilitation Training on Hand Motor Function Recovery in Stroke Patients at Different Stages

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Abstract

Background Hand dysfunction following stroke severely affects patients' quality of life. In recent years, research on robot-assisted training for functional recovery in stroke patients has been increasing; however, there is a lack of effective systematic evaluation and analysis of improvement effects, and specific protocols for assisted training require further exploration.

Objective To systematically evaluate the effectiveness of rehabilitation robot-assisted training on hand motor function recovery in stroke patients.

Methods A computerized search of PubMed, Embase, Scopus, Cochrane Library, Web of Science, China National Knowledge Infrastructure (CNKI), Wanfang Data Knowledge Service Platform, VIP Database, and Chinese Biomedical Literature Service System (Sinomed) was conducted for randomized controlled studies employing robot-assisted training to intervene in hand function recovery of stroke patients, from inception to December 2023. Literature selection was performed strictly according to inclusion and exclusion criteria, raw data were extracted, and methodological quality assessment of included studies was conducted. Meta-analysis was performed using RevMan 5.4 and Stata 17.0 software.

Results A total of 23 studies involving 693 stroke patients were included. Meta-analysis results showed that the experimental group had higher scores than the control group in Fugl-Meyer Assessment-Upper Limb (FMA-UL) (SMD=0.37, 95%CI=0.17~0.58, P<0.001), wrist FMA-UL (MD=1.66, 95%CI=0.14~3.17, P=0.03), hand FMA-UL (MD=2.00, 95%CI=1.17~2.83, P<0.001), Action Research Arm Test (SMD=0.27, 95%CI=0.01~0.53, P=0.04), hand grip strength (SMD=0.54, 95%CI=0.09~1.00, P=0.02), and hand pinch strength (SMD=0.62, 95%CI=0.16~1.09, P=0.008), with statistically significant differences. No statistically significant differences were found between the two groups in Box and Block Test (MD=1.23, 95%CI=-0.90~3.35, P=0.26), Modified Ashworth Scale (SMD=-0.47, 95%CI=-1.28~0.35, P=0.26), or Barthel Index (SMD=0.38, 95%CI=-0.07~0.83, P=0.10).

Conclusion Rehabilitation robot-assisted training is beneficial for hand motor function recovery in stroke patients and can effectively improve hand motor ability and grip/pinch strength, but shows minimal improvement in hand muscle tone, dexterity, and activities of daily living scores. Future large-sample, multicenter studies with longer follow-up periods are needed to further evaluate its efficacy and safety.

Full Text

Effect of Robot-assisted Training on the Recovery of Hand Motor Function in Patients with Different Stages of Stroke: A Meta-analysis

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Abstract

Background Hand dysfunction following stroke severely impacts patients' quality of life. While robot-assisted training for stroke rehabilitation has gained increasing research attention, its effectiveness lacks systematic evaluation, and optimal training protocols remain to be established.

Objective To systematically evaluate the effect of rehabilitation robot-assisted training on hand motor function recovery in stroke patients.

Methods Randomized controlled trials of robot-assisted training for hand function recovery in stroke patients were searched in PubMed, Embase, Scopus, Cochrane Library, Web of Science, CNKI, Wanfang Data, VIP, and Sinomed from database inception to December 2023. Literature screening, data extraction, and methodological quality assessment were conducted according to predefined inclusion and exclusion criteria. Meta-analysis was performed using RevMan 5.4 and Stata 17.0.

Results Twenty-three studies involving 693 stroke patients were included. Meta-analysis showed that the experimental group achieved significantly higher scores than the control group in Fugl-Meyer Assessment-Upper Limb (FMA-UL) (SMD=0.37, 95%CI=0.17~0.58, P<0.001), wrist FMA-UL (MD=1.66, 95%CI=0.14~3.17, P=0.03), hand FMA-UL (MD=2.00, 95%CI=1.17~2.83, P<0.001), Upper Extremity Movement Study Scale (SMD=0.27, 95%CI=0.01~0.53, P=0.04), hand grip strength (SMD=0.54, 95%CI=0.09~1.00, P=0.02), and hand pinch strength (SMD=0.62, 95%CI=0.16~1.09, P=0.008). No significant differences were found between groups in Box and Block Test (MD=1.23, 95%CI=-0.90~3.35, P=0.26), Modified Ashworth Scale (SMD=-0.47, 95%CI=-1.28~0.35, P=0.26), or Barthel Index (SMD=0.38, 95%CI=-0.07~0.83, P=0.10).

Conclusion Robot-assisted training benefits hand motor function recovery in stroke patients by effectively improving hand mobility, grip, and pinch strength, though improvements in hand muscle tone, dexterity, and daily living ability are relatively modest. Future research requires large-scale, multicenter studies with longer follow-up periods to further evaluate efficacy and safety.

Keywords Stroke; Robot-assisted training; Hand; Motor function; Meta-analysis

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1. Materials and Methods

1.1 Literature Search

A comprehensive search was conducted in PubMed, Embase, Scopus, Cochrane Library, Web of Science, CNKI, Wanfang Data, VIP, and Sinomed from database inception to December 2023. The search combined subject headings and free-text terms, adjusted according to each database’ s characteristics, with language limited to Chinese and English. Chinese search terms included: “stroke” , “cerebral ischemia” , “cerebrovascular accident” , “cerebral embolism” , “cerebral infarction” , “cerebral hemorrhage” , “hand” , “fingers” , “robot” , “robotic hand” , “exoskeleton” , “soft glove” , “end-effector” . English search terms included: “stroke” , “apoplexy” , “cerebrovascular apoplexy” , “brain vascular accidents” , “cerebrovascular accident” , “cerebrovascular stroke” , “cerebral stroke” , “hand” , “hands” , “fingers” , “robot” , “robotic” , “exoskeleton” , “soft glove” , “end-effector robotic” . This study was registered with PROSPERO (CRD42023416320).

1.2 Inclusion Criteria

Based on the PICOS (patients/population, interventions, comparisons, outcomes, study design) framework, inclusion criteria were: (1) Participants:

stroke patients diagnosed by CT or MRI with hand function limitations; (2) Interventions: experimental group received robot-assisted training; control group received conventional rehabilitation training; (3) Outcomes: Fugl-Meyer Assessment-Upper Limb (FMA-UL), Action Research Arm Test (ARAT), Box and Block Test (BBT), hand grip strength, hand pinch strength, Modified Ashworth Scale (MAS), and Barthel Index (BI); (4) Study design: randomized controlled trials; (5) Languages: Chinese and English.

1.3 Exclusion Criteria

Studies were excluded if: (1) data were incomplete or effective outcome data could not be extracted; (2) they were conference papers or animal experiments.

1.4 Literature Screening and Data Extraction

Two researchers independently conducted the literature search using NoteExpress to remove duplicates. Titles and abstracts were screened first, followed by full-text review according to inclusion/exclusion criteria. Disagreements were resolved by consulting a third researcher. Data were independently extracted using a customized Microsoft Excel form and cross-checked. Extracted data included: (1) general information (author, publication year); (2) participant characteristics (age, gender, sample size, disease course, stroke type); (3) intervention details (method, duration, frequency); and (4) outcome measures. Authors were contacted for missing data; studies were excluded if data remained unavailable.

1.5 Risk of Bias Assessment

The Cochrane Collaboration' s risk of bias tool for RCTs (Cochrane Handbook 5.1.0) was used to evaluate selection bias, performance bias, attrition bias, reporting bias, and other biases, with judgments of low risk, high risk, or unclear risk. Two researchers independently performed the assessment, with disagreements resolved through discussion or by a third researcher.

1.6 Evidence Quality Evaluation

The GRADE (Grading of Recommendations Assessment, Development and Evaluation) system was used to assess evidence quality through GRADEpro software. Each outcome was evaluated for risk of bias, inconsistency, imprecision, indirectness, and publication bias. Evidence quality was rated as high, moderate, low, or very low, with RCT evidence starting at high quality and downgraded accordingly.

1.7 Statistical Analysis

Data were analyzed using RevMan 5.4 and Stata 17.0. Effect sizes were expressed as mean difference (MD) or standardized mean difference (SMD) with

95% confidence intervals (CI). Heterogeneity was assessed using I^2 statistics: fixed-effects models were used when $I^2 \leq 50\%$ and $P \geq 0.1$, while random-effects models were applied when $I^2 > 50\%$ and $P < 0.1$. Subgroup analysis explored heterogeneity sources; descriptive analysis was used when sources could not be identified. Sensitivity analysis was performed using the leave-one-out method. Publication bias was assessed via funnel plots for outcomes with \$ \$10 studies, with Egger's and Begg's tests for quantitative evaluation. Statistical significance was set at $P < 0.05$.

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2. Results

2.1 Literature Search Results

The initial search yielded 1,855 records. After removing 823 duplicates and screening titles/abstracts (excluding 953 irrelevant studies and reviews), 79 articles remained. Full-text review excluded 56 studies (26 with inappropriate design, 3 with unsuitable participants, 12 with mismatched outcomes, 10 with low quality, 5 with incomplete data), leaving 23 studies for inclusion [Figure 1: see original paper].

2.2 Basic Characteristics of Included Studies

Twenty-three studies [18-40] involving 693 participants (mean age 60 years) were included. Intervention frequency ranged from 20-100 minutes per session, 3-5 times per week for 2-8 weeks. The experimental group received robot-assisted training, while controls received alternative treatments. Outcome measures included: FMA-UL (11 studies [18-19,23,25-29,36-37,39]), wrist FMA-UL (10 studies [20,23,26-30,35-36,40]), hand FMA-UL (4 studies [21-22,32,34]), ARAT (8 studies [18,21,23-24,28-29,35-36]), BBT (3 studies [26,38-39]), grip strength (7 studies [21-22,25-26,33,39-40]), pinch strength (3 studies [25,33,40]), MAS (8 studies [27,29-31,35,37-38,40]), and BI (5 studies [19,21-22,27,31]) .

2.3 Risk of Bias Assessment

Twenty-three studies described random sequence generation (low risk). Ten studies [21-23,25,27-28,31-32,37,39] implemented allocation concealment. Seven studies [19-22,30,32,40] had unclear blinding. Attrition bias, reporting bias, and other biases were generally low risk [FIGURE:2, FIGURE:3].

2.4 Quality Evaluation

GRADE assessment showed high-quality evidence for FMA-UL (11 studies [18-19,23,25-29,36-37,39]), wrist FMA-UL (10 studies [20,23,26-30,35-36,40]), hand FMA-UL (4 studies [21-22,32,34]), and grip strength (7 studies [21-22,25-26,33,39-40]). MAS (8 studies [27,29-31,35,37-38,40]) was moderate quality.

BBT (3 studies [26,38-39]), pinch strength (3 studies [25,33,40]), and BI (5 studies [19,21-22,27,31]) were low-quality evidence .

2.5 Meta-Analysis Results

2.5.1 Upper Limb Motor Function Eleven studies [18-19,23,25-29,36-37,39] using FMA-UL for 366 patients showed low heterogeneity (I^2=10%, P=0.35). The fixed-effects model revealed significantly higher scores in the experimental group (SMD=0.37, 95%CI=0.17~0.58, P<0.001). Subgroup analysis by stroke stage showed significant improvements in acute (SMD=0.82, 95%CI=0.3~1.34, P=0.002) and subacute phases (SMD=0.43, 95%CI=0.03~0.82, P=0.03), but not in chronic phase (SMD=0.22, 95%CI=-0.06~0.50, P=0.13) [Figure 4: see original paper].

2.5.2 Wrist Motor Function Ten studies [20,23,26-30,35-36,40] assessed wrist function in 250 patients using wrist FMA-UL. High heterogeneity (I^2=71%, P=0.0003) required a random-effects model. Subgroup analysis showed significant improvements in acute (MD=4.54, 95%CI=3.68~5.40, P<0.001) and subacute phases (MD=2.78, 95%CI=1.74~3.82, P<0.001), but not chronic phase (MD=0.52, 95%CI=-0.85~1.90, P=0.46) [Figure 5: see original paper].

2.5.3 Hand Motor Function Four studies [21-22,32,34] evaluated hand function in 130 patients using hand FMA-UL. High heterogeneity (I^2=77%, P=0.004) was addressed with a random-effects model. The experimental group showed significantly higher scores (MD=2.00, 95%CI=1.17~2.83, P<0.001) [Figure 6: see original paper].

2.5.4 Upper Extremity Motor Ability Eight studies [18,21,23-24,28,29,35-36] using ARAT for 234 patients showed low heterogeneity (I^2=0%, P=0.65). The fixed-effects model revealed significantly higher ARAT scores in the experimental group (SMD=0.27, 95%CI=0.01~0.53, P=0.04) [Figure 7: see original paper].

2.5.5 Hand Dexterity Three studies [26,38-39] using BBT for 70 patients showed low heterogeneity (I^2=0%, P=0.93). No significant difference was found between groups (MD=1.23, 95%CI=-0.90~3.35, P=0.26) [Figure 8: see original paper].

2.5.6 Hand Grip Strength Seven studies [21-22,25-26,33,39-40] assessed grip strength in 208 patients. Moderate heterogeneity (I^2=59%, P=0.02) required a random-effects model. The experimental group showed significantly higher grip strength (SMD=0.54, 95%CI=0.09~1.00, P=0.02) [Figure 9: see original paper].

2.5.7 Hand Pinch Strength Three studies [25,33,40] evaluated pinch strength in 78 patients with low heterogeneity (I^2=11%, P=0.32). The fixed-effects model showed significantly higher pinch strength in the experimental group (SMD=0.62, 95%CI=0.16~1.09, P=0.008) [Figure 10: see original paper].

2.5.8 Muscle Tone Eight studies [27,29-31,35,37-38,40] using MAS for 215 patients showed high heterogeneity (I^2=86%, P<0.001). No significant difference was found between groups (SMD=-0.47, 95%CI=-1.28~0.35, P=0.26) [Figure 11: see original paper].

2.5.9 Activities of Daily Living Five studies [19,21-22,27,31] using BI for 198 patients showed moderate heterogeneity (I^2=58%, P=0.05). No significant difference was found between groups (SMD=0.38, 95%CI=-0.07~0.83, P=0.10) [Figure 12: see original paper].

2.5.10 Adverse Events None of the 23 included studies reported adverse events related to robot-assisted training.

2.6 Sensitivity Analysis

Sensitivity analysis using the leave-one-out method for FMA-UL, wrist FMA-UL, ARAT, grip strength, MAS, and BI showed no significant impact from removing any single study, indicating robust results [Figure 13: see original paper].

2.7 Publication Bias

Funnel plots for FMA-UL and wrist FMA-UL showed no publication bias for FMA-UL (P>0.05) but potential bias for wrist FMA-UL (P<0.05). Trim-and-fill analysis confirmed result robustness: pre-trim fixed-effects model (MD=0.394, 95%CI=0.127~0.661, P<0.05) and post-trim (MD=1.483, 95%CI=1.135~1.937, P<0.05) both showed significant effects without adding virtual studies [Figure 14: see original paper].

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3. Discussion

The number of stroke patients is increasing annually, with most survivors experiencing limb dysfunction. Hand function constitutes a crucial component of upper extremity function and forms the foundation for daily activities. However, hand motor recovery after stroke remains a rehabilitation challenge due to the dense and intricate nerve distribution, close brain-hand neural connections, and large cortical representation areas controlling hand movement.

Currently, conventional therapist-led motor rehabilitation, including occupational therapy and constraint-induced movement therapy, faces limitations such as insufficient therapist numbers, inconsistent skill levels, lengthy training periods, monotonous procedures, poor patient compliance, and lack of objective evaluation and real-time feedback. Rehabilitation robots can provide high-intensity, high-repetition, precise active training to facilitate neural reorganization and motor recovery, gaining widespread application in stroke rehabilitation. While numerous studies have examined mechanisms, clinical protocols, and efficacy of robot-assisted hand training, outcomes vary and optimal timing and protocols remain unstandardized. Evidence synthesis specifically targeting hand function recovery across different stroke stages is lacking.

This meta-analysis demonstrates that robot-assisted training significantly improves FMA-UL scores, benefiting upper limb motor recovery with enhanced wrist and hand function, consistent with previous research. Stroke recovery depends heavily on neuroplasticity, where repetitive training establishes new neural connections to prevent disuse atrophy. Robot training may promote latent neural pathway activation and axonal sprouting, expanding cortical representation and improving signal transmission efficiency while stimulating peripheral nerves to facilitate motor planning.

Subgroup analysis revealed superior effects in acute and subacute phases, likely because early intervention addresses limited initial impairment and prevents muscle atrophy and functional disuse. In chronic phases, benefits were limited, possibly due to severe residual hand dysfunction and established learned non-use patterns. The intervention durations may have been insufficient to overcome chronic-phase challenges.

Robot-assisted training also improved hand fine motor function, as evidenced by enhanced grip and pinch strength—critical indicators of hand function. These improvements may relate to peripheral mechanisms strengthening muscles and coordinating joints while integrating training with daily activities, reducing injury risk from human factors.

However, robot-assisted training showed limited effects on muscle tone, overall dexterity, and daily living abilities. Muscle spasticity typically evolves from flaccidity to hypertonicity after stroke, and prolonged spasticity reduces range of motion, causes atrophy, and leads to contractures. Short intervention durations may explain the modest effects on tone and dexterity. The small number of studies and sample sizes for these outcomes necessitate cautious interpretation.

Limitations: (1) Outcome measures varied across studies with different assessment tools, potentially introducing bias. (2) While all used robot-assisted training, robot types differed and were not compared. (3) Sample sizes were generally small; sensitivity analysis confirmed stability for outcomes with $ $5 studies, but hand function, dexterity, and pinch strength analyses lacked sufficient studies. (4) No follow-up studies were included, and maximum intervention duration was 8 weeks, limiting assessment of long-term efficacy and time-dependent effects. (5) Intervention protocols lacked systematic standardization, and combined approaches were not compared.

Conclusion: Hand rehabilitation robots positively impact motor function recovery in stroke patients, particularly for hand mobility, grip, and pinch strength, with differential effects across stroke stages. Large-scale, multicenter RCTs with longer follow-up are needed to optimize clinical protocols and improve hand function to facilitate community reintegration.

Author Contributions: TIAN Anni designed the study, analyzed data, and drafted the manuscript; YANG Jing supervised quality and took overall responsibility; SUN Jing and WANG Shichun conducted literature searches, screening, data extraction, and organization.

Conflict of Interest: The authors declare no conflict of interest.

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