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Role of Therapeutic Currents on Hand Function in People with Stroke: A Systematic Review and Meta-Analysis

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Abstract

Proper upper limb (UL) function is very crucial for manual exploration and manipulation of the environment. Dexterity is affected after stroke and takes times to recover. Effective and economical treatment approaches are desired to overcome the numerous challenges associated with UL rehabilitation. This review aims at establishing the effectiveness of various therapeutic currents on hand function in individuals with stroke. A search was conducted in three databases for randomized controlled trials published from inception to November 2024. The methodological quality of the included studies was measured by the PEDro scale. Cochrane risk-of-bias tool for randomized trials (RoB 2) was used to assess the risk of bias. Meta-analysis was performed on the studies providing sufficient and complete data. The search identified 334 records from which 12 records met the eligibility criteria. The average PEDro score was 6.92. Majority of the trials presented with low risk of bias. Meta-analysis of functional electrical stimulation (FES) showed no significant effects of FES on dexterity (SMD = 2.03, $Z = 1.81$, $p = .07$). Meta-analysis of FES trials identified a small effect size which, while not significant, warrants further investigation. Large and more robust trials are needed with larger sample size to draw more definite conclusions.

Keywords: electric stimulation; stroke; upper extremity; hand function

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Introduction

Stroke has been identified as the major cause of disability and the second leading cause of death in the world (Katan & Luft, 2018). Spasticity and weakness are primary motor impairments, and they offer serious problems to patient management (Li, 2017). In addition, people with stroke also present seizures (Kammersgaard & Olsen, 2005), emotional lability (Chohan et al., 2019), urinary incontinence (Patel et al., 2001), pain (Chohan et al., 2019), depression (Hackett et al., 2005), and cognitive impairment (Chohan et al., 2019). Stroke also has a major impact on mobility (Hankey, 2003). Motor deficits affecting the upper limb are persistent and disabling (Lai et al., 2002). After 6 months, only 50% of stroke survivors regain upper limb function (Kwakkel et al., 2003). The impairment is very bothersome as proper hand function is requisite for manual exploration and manipulation of the surrounding environment (Fischer et al., 2007).

The hand is a versatile element of the body. It can apply force and manipulate delicate items. It also plays a vital role in verbal communication and serves as a tactile interface that links the body to its environment. About 45% of all activities of daily living (ADL) performed during the day involve hand function (Lucareli et al., 2010). Independent figure movement—which is considered as the primary indicator of manual dexterity—takes time to recover following a stroke. Damage to cerebellum, subcortical structures, and sensory and motor areas of the brain leads to motor impairment, which in turn affects dexterity and coordination between arms, hands, and fingers (Pollock et al., 2014).

Effective and inexpensive approaches are desired which can focus on ecologically valid goal setting with increasing challenges. For the recovery of the upper limbs in chronic stroke patients, a range of different therapies has led to satisfactory results (Lang & Schieber, 2009). The available research emphasizes the need for interdisciplinary and multimodal approaches in the rehabilitation of the paretic hand (Hlustík & Mayer, 2006). Current rehabilitation emphasizes the centrally initiated mechanism of motor learning training defined as the acquisition or modification of movement through practice in addition to the peripherally initiated electrical stimulation to enhance excitability (Holden, 2005; Krakauer, 2006).

To date, research done to investigate the role of therapeutic current in stroke rehabilitation includes the effectiveness of functional electrical stimulation (FES) mobility, hand function, and foot drop (Akter et al., 2023; Dantas et al., 2023; Mijic et al., 2023); neuromuscular electrical stimulation (NMES) for functional connectivity (Crema et al., 2022; Guo et al., 2022; Yang et al., 2018); unilateral/bilateral transcutaneous electrical nerve stimulation (TENS) for upper limb motor recovery and mobility (Chen et al., 2022; Namsawang & Muanjai, 2022; Senarath et al., 2023); efficacy of transcranial direct current stimulation (tDCS) for dysphagia and upper limb motor function (Bengisu et al., 2024; Garrido et al., 2023); and repetitive transcranial magnetic stimulation (rTMS) for pain (Aydın et al., 2024; Du et al., 2019). In addition, NMES (Crema et al., 2022; Huang et al., 2021; Park, 2020), tDCS (Bolognini et al., 2020; Garrido et al., 2023; Morone et al., 2022), FES (Huang et al., 2021; Y.-S. Kim et al., 2023), and rTMS are several promising treatment options available for the rehabilitation of upper limbs in people with stroke. Systematic reviews and meta-analysis have been done investigating the effect of FES (Eraifej et al., 2017), noninvasive brain stimulation (Ahmed et al., 2023; Bai et al., 2019; Xie et al., 2023), and TENS (Mahmood et al., 2019). Yet, there is still lack of clarity on the effectiveness of different therapeutic currents on dexterity in people with stroke. Considering this knowledge gap, the present review aims to summarize the effect of various therapeutic currents on dexterity of people with stroke. This review also aimed to determine the short-term and long-term effectiveness of therapeutic currents on dexterity. It represents an important addition to the literature that focuses on the application of therapeutic currents on dexterity and will help in summarizing and understanding the different currents helpful in improving dexterity in people with stroke. The relative effectiveness of different currents must be known in order to choose an appropriate one. However, there is currently a dearth of thorough overview of studies in this field.

Methods

The protocol of this systematic review was registered in the International prospective register of systematic reviews (PROSPERO) via registration number CRD42021239673.

Eligibility Criteria

Studies were selected according to the eligibility criteria, which were based on the PICO (participant, intervention, comparator, and outcome) format. Studies other than randomized controlled trials (RCT) or in any other language than English were not included. Studies done on animals were excluded. Studies administering therapeutic currents (excluding brain stimulation, both invasive and noninvasive) to stroke patients aged more than or equal to 18 years in order to examine its effect on hand function were included. No restrictions were placed on the controls.

Information Sources

Electronic systematic searches of MEDLINE (accessed by PubMed), Web of Science (Web of Science Core Collection), and Scopus databases were conducted from inception to November 2024. This systematic review and meta-analysis was done following the standard Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) statement (Moher et al., 2009).

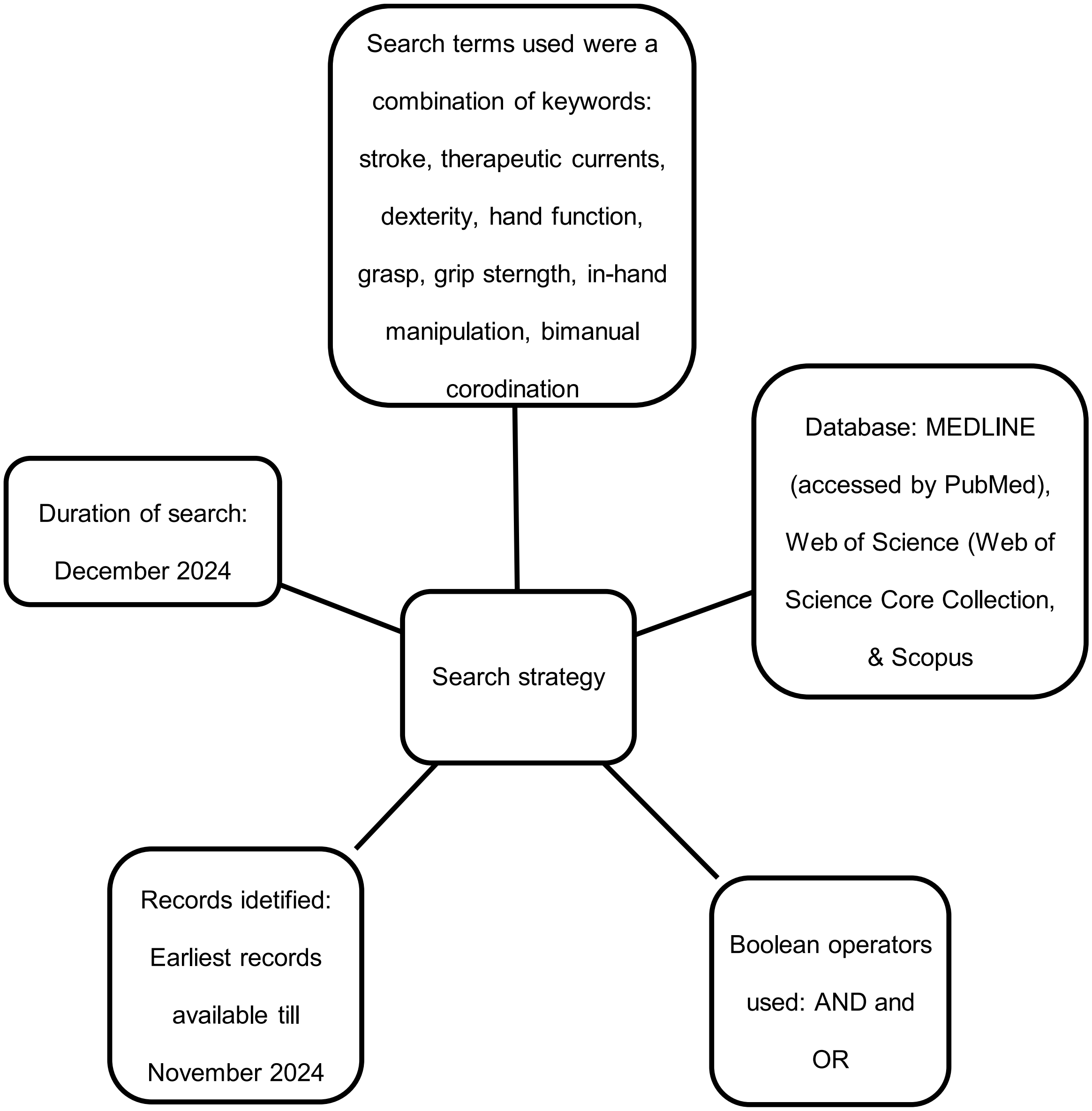
Search Strategy

One author (SP) performed the search in December 2024. A search strategy was developed that focused on the following key search terms: *stroke*, *therapeutic currents*, *dexterity*, *hand function*, *grasp*, *grip strength*, *in-hand manipulation*, and *bimanual coordination*. The keywords were combined with the Boolean operator AND and OR (Figure 1). Detailed search strategy can be seen in supplementary file attached.

Selection Process and Data Extraction

Data on the characteristics of trial author, year of publication, participants (age, gender, Brunnstrom stage), interventions (type, duration, etc.), outcome measures, and significant findings were extracted by two authors independently (SP and MA). Any disagreement was cleared by mutual consensus and unresolved disagreements were taken to the third author (MMN). In case of unclear of incomplete data in included studies, the author(s) of the study was contacted.

Figure 1. *A Schematic Presentation of Search Strategy.*



Quality Assessment of Trials

For assessing the methodological quality of all the retrieved evidence, the authors used an 11-point PEDro scale designed to rate the quality of randomized controlled trials (Verhagen et al., 1998). Each criterion was rated either *yes* (score = 1) or *no* (score = 0) to minimize the ambiguity in responses. The total score for the methodological quality of each included study was calculated by summing all the responses (maximum score = 10). Studies were then classified as poor (score of < 4), fair (score of 4 or 5), good (score of 6 to 8), and excellent (score of > 8) quality based on the total score obtained (de Morton, 2009). Trials were independently assessed for quality by two authors (CAS and SF). If there was any disagreement on any criterion, it was reassessed by each reviewer independently. Unresolved disagreements were identified and discussed in a consensus meeting. Any conflict that remained unresolved was then taken to a third reviewer (MMN), who was independent of the initial deliberations, and a final consensus was reached.

Risk of Bias Assessment

CAS and MA independently assessed risk of bias for included trials using the version 2 of the Cochrane risk-of-bias (RoB 2) assessment tool with the following domains: randomization process, deviations from the intended intervention, missing outcome data, measurement of the outcome, and selection of the reported result. Each domain was categorized as either low, some concerns, or high (Sterne et al., 2019).

Data Synthesis and Analysis

Meta-analysis was performed for only those studies providing sufficient information on the outcome measure. The meta-analysis was performed using Cochrane Collaboration's Review Manager 5.4.1 software. Effect sizes were calculated as standardized mean differences (SMDs) using Hedge's *g*, the bias-adjusted version of Cohen's *d*, as implemented in RevMan 5.4.1. Heterogeneity between the studies was quantified using I2 test, which measures the percentage of the observed variability between effect estimates beyond chance. A value of I2 < 25% indicates low heterogeneity, 25–75% indicates moderate heterogeneity, and > 75% indicates high heterogeneity (Higgins et al., 2003).

Results

Out of the total of 334 records identified, 40 duplicates were removed. A total of 294 records went through the screening process by reading titles and abstracts by two authors (SF and SP). Twelve articles were found to be relevant based on the eligibility criteria (Figure 2).

Study Characteristics

All the studies included in this systematic review were RCT (*n* = 12). Trials included in the review were published from 2007 (Bhatt et al., 2007) to 2021 (Alwhaibi et al., 2021; Ambrosini et al., 2021; Sentandreu-Mañó et al., 2021). Included trials were conducted in various geographical areas including Taiwan (Lee et al., 2015), Korea (S.-H. Kim et al., 2016), Ohio (Knutson et al., 2016; Knutson et al., 2020), Spain (Sentandreu-Mañó et al., 2021), Brazil (Lourenção et al., 2008; Salazar et al., 2020), United States (Bhatt et al., 2007), Denmark (Ghaziani et al., 2018), France (Sattler et al., 2015), Saudi Arabia (Alwhaibi et al., 2021), and Italy (Ambrosini et al., 2021).

The included studies recruited 627 participants. The sample size ranged from 20 (Bhatt et al., 2007; S.-H. Kim et al., 2016; Sattler et al., 2015) to 102 (Ghaziani et al., 2018). A mixed ratio of both genders was observed. Studies included in this review used a variety of outcome measures to assess hand function which includes BBT (Box and Block test; Alwhaibi et al., 2021; Ambrosini et al., 2021; Bhatt et al., 2007; S.-H. Kim et al., 2016; Knutson et al., 2016; Knutson et al., 2020; Lee et al., 2015; Sentandreu-Mañó et al., 2021), functional magnetic resonance imaging (fMRI; Bhatt et al., 2007; S.-H. Kim et al., 2016), maximal voluntary grip force (Salazar et al., 2020), finger tracking test (Bhatt et al., 2007; S.-H. Kim et al., 2016), motor activity log (MAL; Ambrosini et al., 2021; Knutson et al., 2020), and Jebsen and Taylor Hand function test (JHFT; Bhatt et al., 2007; S.-H. Kim et al., 2016; Sattler et al., 2015; Table 1).

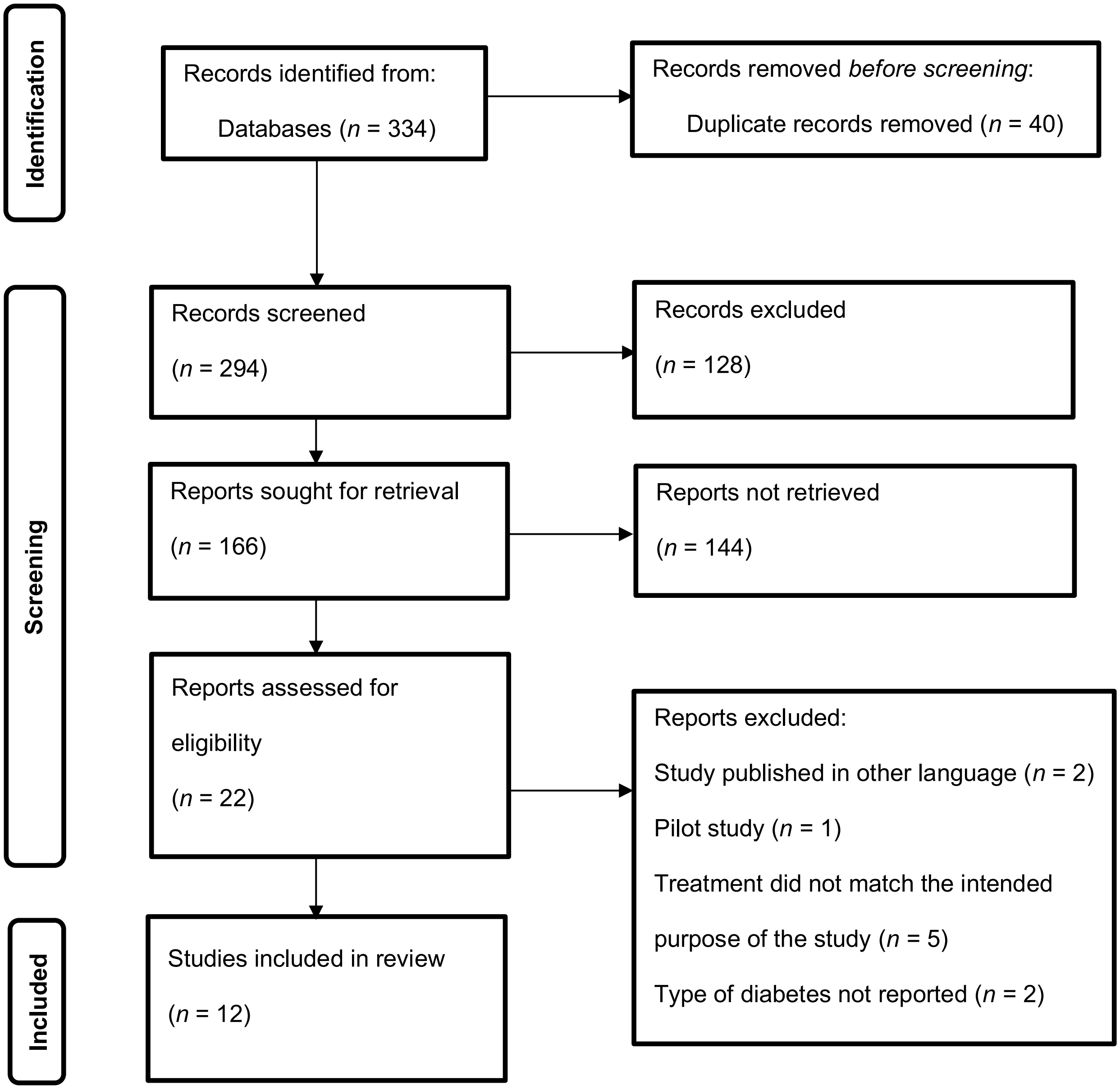
Different types of therapeutic currents either alone or in combination were used. Four trials administered FES (Ambrosini et al., 2021; Knutson et al., 2016; Knutson et al., 2020; Lourenção et al., 2008). One study used NMES (Sentandreu-Mañó et al., 2021), mirror therapy (MT) in addition to mesh glove (MG) afferent stimulation was given in trial (Lee et al., 2015) and one trial delivered electrical somatosensory stimulation (ESS; Ghaziani et al., 2018). One study administered electromyogram (EMG)-triggered NMES (S.-H. Kim et al., 2016), while another used EMG-triggered ES (Bhatt et al., 2007). One trial used TENS (Alwhaibi et al., 2021). Combination of tDCS and repetitive peripheral nerve stimulation (rPNS) was used in one trial (Sattler et al., 2015). One trial delivered concurrent bicephalic tDCS and FES (Salazar et al., 2020). The total number of sessions per week ranged from five consecutive daily sessions (Sattler et al., 2015) to 5 days per week 9 (S.-H. Kim et al., 2016; Lee et al., 2015; Table 1).

The therapeutic currents used in the included trials have varied parameters. The pulse width of the current used varied from 50 s (S.-H. Kim et al., 2016) to 300 ms (Salazar et al., 2020). Frequency of the current ranged from 5 Hz (Sattler et al., 2015) to 100 Hz (Alwhaibi et al., 2021). Duration of intervention varied from 13 min (Sattler et al., 2015) to 1.5 hr (Lee et al., 2015). The intensity of the current was at sensory threshold of paretic hand (Lee et al., 2015) or above the motor threshold (Ambrosini et al., 2021; Table 2).

Quality Assessment of the Trials

The average PEDro score was 6.92 (Table 3). Based on quality scoring, two studies were of fair quality (Knutson et al., 2020; Lourenção et al., 2008), seven studies were of good quality (Alwhaibi et al., 2021; Ambrosini et al., 2021; Bhatt et al., 2007; S.-H. Kim et al., 2016; Knutson et al., 2016; Lee et al., 2015; Sentandreu-Mañó et al., 2021) and three trials were of excellent quality (Ghaziani et al., 2018; Salazar et al., 2020; Sattler et al., 2015). All the included studies lack subject blinding except for one trial (S.-H. Kim et al., 2016). Therapist blinding was reported in only

Figure 2. *Flow Chart of Search Strategy, Retrieval of Articles, Exclusion, Inclusion, and Evidence Synthesis.*



three studies (Bhatt et al., 2007; Ghaziani et al., 2018; S.-H. Kim et al., 2016). Two trials did not report assessor blinding (Ambrosini et al., 2021; Lourenção et al., 2008). All the included trials had reported between-group differences and point measure and variability. Reporting of dropouts was not done in four studies (Alwhaibi et al., 2021; Knutson et al., 2020; Salazar et al., 2020; Sattler et al., 2015). Intention-to-treat analysis was observed in five studies (Bhatt et al., 2007; Ghaziani et al., 2018; S.-H. Kim et al., 2016; Salazar et al., 2020; Sattler et al., 2015).

Risk of Bias Assessment of the Trials

The assessment of risk of bias was depicted in Figure 3 and 4. The overall risk of bias varied across the included trials. Seven trials were judged to have had low overall risk of bias (Alwhaibi et al., 2021; Ambrosini et al., 2021; Ghaziani et al., 2018; Knutson et al., 2016; Lee et al., 2015; Salazar et al., 2020; Sentandreu- Mañó et al., 2021) and one trial reported high risk of bias (Lourenção et al., 2008). The remaining three trials were deemed to have had some concerns (Bhatt et al., 2007; S.-H. Kim et al., 2016; Knutson et al., 2020). Majority of trials

Table 1
Characteristics of the Included Trials

Trial	Sample size (*n*)	Gender (M/F)	Mean age (in years)	Onset of stroke	Outcome measures	Outcome measure tool	Findings
Alwhaibi et al. (2021)	40	19/21	52.5	≥ 6 months poststroke	Motor recovery; dexterity; brain activity	Fugl Meyer Assessment for upper extremity; BBT; quantitative EEG (qEEG)	TST combined with TENS acupoints proved better in improving brain plasticity
Ambrosini et al. (2021)	72	50/22	63.9	Participants were having first stroke; 2 weeks up to 9 months with major unilateral functional impairment	Arm and hand functions; arm motor impairment; manual dexterity; health-related quality of life	ARAT; Motricity Index; motor activity log; BBT; SS-QoL	Significant effects were observed in RETRAINER group in comparison to ACT on both ARAT and BBT; but not in SS-QoL
Bhatt et al. (2007)	20	11/9	66.31	Participants with poststroke duration of at least 6 months	Motor recovery; dexterity; hand functions; brain reorganization	Jebsen Taylor test; finger tracking test; BBT; fMRI	CM intervention more effective on brain reorganization than either intervention alone
Ghaziani et al. (2018)	102	53/49	71.5	Participants diagnosed with acute stroke confirmed by magnetic resonance imaging or CT scan	Manual dexterity; upper limb functions; hand grip strength; palmar, key, and tip pinch strength	BBT; UEFM; hand grip strength; perceptual threshold of touch; modified Rankin scale; palmer, key, and tip pinch strength	ESS protocol (both high-dose and low-dose) prior to arm training equally effective as arm training alone – all outcome measures
S.-H. Kim et al. (2016)	20	11/9	48.2	Participants having more than 6 months of stroke	Dexterity; pinch strength; muscle activity	Jebsen-Taylor test; finger tracking test; BBT; fMRI	EMG-stimulation + TOT more effective than EMG-stimulation alone for motor recovery (FMA) and dexterity (BBT) following arm-paresis poststroke
Knutson et al. (2016)	80	51/29	55.85	Participants enrolled in the study had onset of more than 6 months from hemorrhagic /ischemic stroke	Manual dexterity; upper limb impairment; activity measure (functional ability – upper extremity)	BBT; UEFM; AMAT	Significant group differences were observed in CCFES group than cNMES group on BBT (*p* = .045)

Table 1

Characteristics of the Included Trials

Trial	Sample size (*n*)	Gender (M/F)	Mean age (in years)	Onset of stroke	Outcome measures	Outcome measure tool	Findings
Knutson et al. (2020)	67	43/24	55	Participants had upper limb hemiparesis with moderate to severe hand impairment (within 2 years of first ischemic /hemorrhagic stroke).	Manual dexterity; upper extremity motor impairment; activity limitation	BBT; reachable workspace; SULCS; UEFM; AMAT; MAL	No significant group differences on BBT, SULCS, AMAT; arm and hand CCFES improved RW, UEFM more than hand CCFES
Lee et al. (2015)	48	34/14	52.74	Unilateral stroke with onset greater than 6 months and mild to moderate impairment (Fugl-Meyer Assessment for upper extremity)	Muscular properties (muscle tone and stiffness); sensorimotor functions (limb functions: motor, sensory changes, dexterity, ambulation); daily function	Myoton-3 myometer; Fugl Meyer Assessment for upper extremity, lower extremity; revised Nottingham sensory assessment; BBT; 10-meter walk test; FIM	MT + MG induced significant and distinctive effects on muscular properties, manual dexterity and daily function; no significant group differences seen in upper extremity function
Lourenção et al. (2008)	59	37/22	55.4	Participants were chronic ischemic hemiplegic patients (more than 6 months)	Hand function; manual dexterity index; joint ROM, elbow and wrist; spasticity, elbow and wrist		No significant difference between the groups in terms of manual dexterity index
Salazar et al. (2020)	30	15/15	60	Individuals with ischemic or hemorrhagic chronic stroke confirmed by head CT or MRI at least 6 months before recruitment	Motor performance measures; movement quality measures; handgrip strength; motor impairment	Reach-to-target kinematic analysis; Jamar hydraulic hand dynamometer, Fugl Meyer Assessment for upper extremity	Concurrent bicephalic tDCS and FES slightly improved reaching motor performance and handgrip force

Table 1

Characteristics of the Included Trials

Trial	Sample size (*n*)	Gender (M/F)	Mean age (in years)	Onset of stroke	Outcome measures	Outcome measure tool	Findings
Sattler et al. (2015)	20	14/6	67.6 ± 10	Single, unilateral hemispheric ischemic stroke within 4 weeks	Motor performance; transcranial magnetic stimulation cortical excitability	Jebsen and Taylor Hand Function Test (JHFT); Jamar hydraulic hand dynamometer; Fugl Meyer Assessment for upper extremity; Nine-hole Peg Test; Hand tapping test (9HPT); Motor Evoked Potential (MEP); resting and active motor thresholds (RMT, AMT), TMS	**Anodal tDCS + rPNS significantly improved hand motor function** (JHFT, *p* = .01); no significant differences in grip strength or Fugl-Meyer scores
Sentandreu-Mañó et al. (2021)	69	50Hz NMES: 13/7 30Hz NMES: 11/9 Control: 13/7	70.96	Poststroke spastic hemiparetic patients (poststroke period < 18 months) with clinical stability	Shoulder motor control; range of motion, resting angle; grip strength; pinch strength; muscle tone; manual dexterity; muscle electrical activity; activities of daily living	MESUPES-arm test; JAMAR finger goniometer; dynamometer; hydraulic pinch gauge; MAS; BBT; EMG - radial extensor and radial flexor - carpals; Barthel index	Both NMES protocols produced significant improvements in range of motion, grip and pinch strength, MAS, muscle electrical activity in extensors of wrist; no significant difference in BBT noted

Note. BBT= Box and Block test; MT= Mirror therapy; MG = Mesh gloves; FIM = Functional Independence Measure; NMES = Neuromuscular electrical stimulation; MESUPES=; MAS = Modified Ashworth Scale; EMG = Electromyography; SULCS = Stroke upper limb capacity scale; UEFM = Upper extremity Fugl-Meyer; AMAT = Arm motor abilities test; MAL = Motor activity log; CCFES = Contralaterally controlled functional electrical stimulation; RW = Reachable workspace; cNMES = cyclic Neuromuscular electrical stimulation; SS-QoL= Stroke Specific Quality of Life; ACT = Advanced conventional therapy; ARAT = Action research arm test; ESS = Electrical somatosensory stimulation; TOT= Task-oriented training; FMA = Fugl-Meyer Assessment; CT = computerized topography; CM = combination.

Table 2

Characteristics of the Intervention Used

Trial	Experimental	Device	Parameters used	Control
Alwhaibi et al. (2021)	TENS Acupoint + task-specific training (TST) - 18 sessions for 6 successive weeks, 3 sessions per week	Phyaction 785 (Uniphy B.V., Netherlands)	TENS Acupoint - 100 Hz, 0.2 ms, square pulses, 2–3x sensory threshold, 20 min	TST + sham electrical stimulation (80 min/session, 3 sessions/week, 6 weeks)
Ambrosini et al. (2021)	EMG triggered FES	RehamovePro, Hasomed GmbH	Pulse frequency: 25 Hz; width: 300 µs; intensity: subject specific above motor threshold	ACT: 90 min, three times a week for 9 weeks
Bhatt et al. (2007)	ES group - wrist and finger extensors	Neuromove NM900 (Stroke Recovery systems; Denver, CO, USA)	Asymmetrical, rectangular, biphasic, constant current; pulse width: 200 µs; frequency: 50 Hz; on-off time was 7.15 s	TR group: electro goniometer placed at metacarpophalangeal joint-index finger bilaterally (ten 1-hr sessions over 2–3 weeks)
Ghaziani et al. (2018)	ESS - high/low dose		High dose ESS: suprasensory ESS; mode: continuous; pulse width: 250 µs; frequency: 10 Hz; application time: 1 hr Low dose/placebo ESS: suprasensory ESS; mode: intermittent (active stimulation intervals of 3 s delivered in loops of 2.5 min); pulse width: 250 µs; frequency: 10 Hz; application time: 1 hr	Low dose ESS (1 hr) followed by usual arm training (15 min) Duration: 4 weeks poststroke
S.-H. Kim et al. (2016)	EMG-stimulation: wrist and finger extensors + TOT	81 (W)	Biphasic rectangular electrical impulses with pulse width of 50µs	EMG-stimulation: wrist and finger extensors for 20 min/day, 5 days/week for 4 weeks
Knutson et al. (2016)	Hand CCFES- finger and thumb extensor	-	Pulse frequency: 35 Hz; amplitude: 40 mA; modulated pulse duration: 0 to 250 µs	Arm+Hand cNMES: 60 min/session **×** 10 session/week = 10 hr/week
Knutson et al. (2020)	Arm+Hand CCFES: triceps and finger extensors Hand CCFES: finger extensors	-	Pulse frequency: 35 Hz; amplitude: 40/60 mA; width: 255 µs	cNMES: 60 min/session **×** 10 session/week = 10 hr/week

Table 2
Characteristics of the Intervention Used

Trial	Experimental	Device	Parameters used	Control
Lee et al. (2015)	MT+MG afferent stimulation	Mesh glove (anode) + sleeve electrode around elbow joint (cathode)	Stimulation frequency: 50 Hz; pulse duration: 300 μs; intensity: set at sensory threshold of paretic hand Application time: 30 min	MT followed by functional task training Duration: 1.5 hr/day, daily regimen, 5 days/week MT + sham stimulation Duration: 1.5 hr/day, 5 days/week for 4 weeks
Lourenção et al. (2008)	OT+FES + EMG-BFB	Quadrikron KC 170	-	OT+FES group (twice weekly session of OT+ FES)
Salazar et al. (2020)	tDCS plus FES along with conventional therapy (10 sessions of concurrent tDCS and FES - 30 min, five times a week for 2 weeks) FES - anterior deltoid, serratus anterior, triceps brachii and wrist extensor muscles of the paretic arm	tDCS - TCT neurostimulator (Research Version) FES (Dualpex-071 Quark Medical, Brazil)	tDCS - 2mA bi-cephalic tDCS with a relative current density of 0.08 mA/m^2, for 30 min FES - frequency = 40 Hz, pulse width = 300 ms; ON time (contraction) = 6 or 8 s; OFF time = 2× ON time.	Sham tDCS plus FES along with conventional therapy (30 min, five times a week for 2 weeks)
Sattler et al. (2015)	Anodal tDCS + rPNS (Radial Nerve Stimulation)	Magstim Eldith DC Stimulator Plus (tDCS), DIGITIMER DS7A (rPNS)	**tDCS:** Anodal over ipsilesional M1, 1.2 mA, 13 min/session, 5 days **rPNS:** 5 Hz, intensity below M-response threshold, 13 min/session. **Both stimulations applied simultaneously.**	**Sham tDCS + rPNS**, same protocol
Sentandreu-Mañó et al. (2021)	NMES -35Hz NMES -50Hz	Beac Medical IntelliSTIM BE 28-E	Stimulation frequency: 35 Hz/50 Hz (low frequency), symmetrical rectangular biphasic wave; pulse duration: 300 μs. C-R time: 5–25 s (first 2 weeks), 5–20 s (3rd week), 5–15 s (4th week), 5–10 s (5th–6th week), 5–5 s (7th–8th week) Application time: 20 min (first two sessions) followed by 30 min (for subsequent sessions)	Conventional treatment Duration: 60 min each session, 3 days/week for 8 weeks

Note. MT = Mirror therapy; MG = Mesh glove; NMES = Neuromuscular electrical stimulation; C-R = Contraction: Relaxation; CCFES = Contralaterally-controlled functional electrical stimulation; cNMES = cyclic neuromuscular electrical stimulation; ACT = Advanced conventional therapy; EMG = Electromyography; FES = Functional electrical stimulation; OT = Occupational therapy; EMG-BFB: Electromyography biofeedback; TR = Track training.

Table 3
Methodological Quality Assessment

Trial	Random allocation	Concealed allocation	Group similarity at baseline	Subject Blinding	Therapist Blinding	Assessor Blinding	Drop-outs < 15%	Intention to treat analysis	Between-group difference reported	Point measured and variability data	Total Score	Quality
Alwhaibi et al. (2021)	Yes	No	Yes	Yes	No	Yes	Yes	No	Yes	Yes	7/10	Good
Ambrosini et al. (2021)	Yes	Yes	No	No	No	No	Yes	Yes	Yes	Yes	6/10	Good
Bhatt et al. (2007)	Yes	No	Yes	No	Yes	Yes	Yes	No	Yes	Yes	7/10	Good
Bruchez et al. (2016)	Yes	Yes	Yes	No	No	Yes	Yes	No	Yes	Yes	7/10	Good
Ghaziani et al. (2018)	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	9/10	Excellent
S.-H. Kim et al. (2016)	Yes	No	Yes	No	No	Yes	Yes	No	Yes	Yes	6/10	Good
Knutson et al. (2020)	Yes	No	Yes	No	No	Yes	No	No	Yes	Yes	5/10	Fair
Knutson et al. (2016)	Yes	Yes	No	No	No	Yes	Yes	No	Yes	Yes	6/10	Good
Lourenção et al. (2008)	Yes	No	Yes	No	No	No	Yes	No	Yes	Yes	5/10	Fair
Salazar et al. (2020)	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	9/10	Excellent
Sattler et al. (2015)	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	9/10	Excellent
Sentandreu-Mañó et al. (2021)	Yes	No	Yes	No	No	Yes	Yes	No	Yes	Yes	7/10	Good

presented with low risk of bias arising from randomization process (Bhatt et al., 2007; Ghaziani et al., 2018; S.-H. Kim et al., 2016; Knutson et al., 2016; Lee et al., 2015; Salazar et al., 2020; Sattler et al., 2015; Sentandreu-Mañó et al., 2021). Four trials (Alwhaibi et al., 2021; Bhatt et al., 2007; S.-H. Kim et al., 2016; Sentandreu-Mañó et al., 2021) showed some concerns in the risk of bias due to the deviation from the intended intervention while one study (Lourenção et al., 2008) showed high risk. Two studies (Ambrosini et al., 2021; Knutson et al., 2016) reported some concerns in risk of bias due to missing outcome data and two trials (Bhatt et al., 2007; Lourenção et al., 2008) showed high risk. There was some concern in two studies (Bhatt et al., 2007; Sentandreu-Mañó et al., 2021) for measuring the outcome and high risk for one trial (Lourenção et al., 2008). In the selection of the reported result domain, two trials showed some concern (Alwhaibi et al., 2021; S.-H. Kim et al., 2016).

Figure 3

Risk of Bias Assessment of the Included Trials Using the RoB-2 (Intention-to-Treat Analysis)

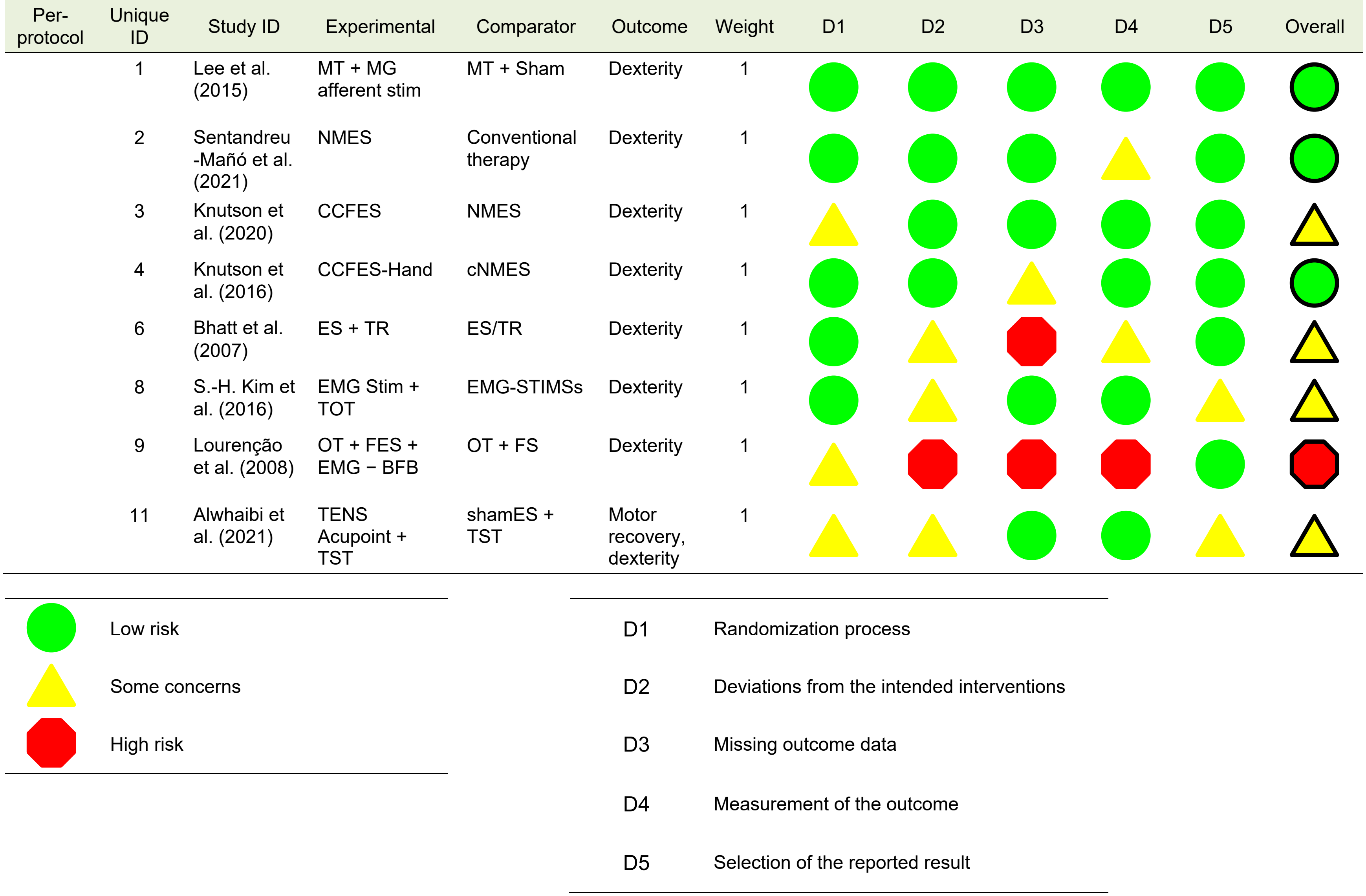
Intention-to-Treat	Unique ID	Study ID	Experimental	Comparator	Outcome	Weight	D1	D2	D3	D4	D5	Overall
	5	Ambrosini et al. (2021)	RETRAINER + EMG − trigger	ACT	Dexterity	1	▲	●	▲	●	●	●
	7	Ghaziani et al. (2018)	High does ESS	Placebo	Dexterity	1	●	●	●	●	●	●
	10	Salazar et al. (2020)	tDCS + FES	Sham tDCS + FES	Motor Performance	1	●	●	●	●	●	●
	12	Sattler et al. (2015)	Anodal tDCS + rPNS	Sham tDCS +rPNS	Motor Performance	1	●	●	●	●	●	●

●	Low risk
▲	Some concerns
🛑	High risk

D1	Randomization process
D2	Deviations from the intended interventions
D3	Missing outcome data
D4	Measurement of the outcome
D5	Selection of the reported result

Figure 4

Risk of Bias Assessment of the Included Trials Using the RoB-2 (Per-Protocol Effect)



Per-protocol	Unique ID	Study ID	Experimental	Comparator	Outcome	Weight	D1	D2	D3	D4	D5	Overall
	1	Lee et al. (2015)	MT + MG afferent stim	MT + Sham	Dexterity	1	●	●	●	●	●	●
	2	Sentandreu -Mañó et al. (2021)	NMES	Conventional therapy	Dexterity	1	●	●	●	▲	●	●
	3	Knutson et al. (2020)	CCFES	NMES	Dexterity	1	▲	●	●	●	●	▲
	4	Knutson et al. (2016)	CCFES-Hand	cNMES	Dexterity	1	●	●	▲	●	●	●
	6	Bhatt et al. (2007)	ES + TR	ES/TR	Dexterity	1	●	▲	⯃	▲	●	▲
	8	S.-H. Kim et al. (2016)	EMG Stim + TOT	EMG-STIMSs	Dexterity	1	●	▲	●	●	▲	▲
	9	Lourenção et al. (2008)	OT + FES + EMG − BFB	OT + FS	Dexterity	1	▲	⯃	⯃	⯃	●	⯃
	11	Alwhaibi et al. (2021)	TENS Acupoint + TST	shamES + TST	Motor recovery, dexterity	1	▲	▲	●	●	▲	▲

●	Low risk
▲	Some concerns
⯃	High risk

D1	Randomization process
D2	Deviations from the intended interventions
D3	Missing outcome data
D4	Measurement of the outcome
D5	Selection of the reported result

The Magnitude of Effect: The Result of Meta-Analysis

Seven studies (Ambrosini et al., 2021; Ghaziani et al., 2018; S.-H. Kim et al., 2016; Knutson et al., 2016; Knutson et al., 2020; Lee et al., 2015; Sentandreu-Mañó et al., 2021) were grouped to determine the effect on dexterity. There is moderate quality evidence suggesting a moderate effect (SMD = 0.85, 95% CI: −0.11, 1.81) favoring control/sham over therapeutic current. Heterogeneity was high (I2 = 94%). The one study with the largest treatment effect was Kim and colleagues (S.-H. Kim et al., 2016) at 0–4 weeks. Two trials (Alwhaibi et al., 2021; Sentandreu-Mañó et al., 2021) assessed the 5- to 8-week effects of therapeutic current versus control treatment. There is low-quality evidence suggesting a small effect (SMD = −0.09, 95% CI: −0.52, 0.35). Three studies (Ambrosini et al., 2021; Knutson et al., 2016; Knutson et al., 2020) examined the 9- to 12-week effects of therapeutic current on dexterity and were meta-analyzed. The meta-analysis favored control treatment (SMD = 2.71, 95% CI: −0.57, 5.99). The heterogeneity was high (I2 = 98%; Figure 5).

Four studies (Ambrosini et al., 2021; Knutson et al., 2016; Knutson et al., 2020; Lee et al., 2015) involving 196 patients with stroke reported the effects of FES on dexterity. High heterogeneity was observed (I2 = 97%, *p* < .00001). The pooled analysis showed no significant difference between the FES and the control group (SMD = 2.03, *Z* = 1.81, *p* = .07; Figure 6).

Figure 5

Forest Plot Illustrating the Overall Effect of Therapeutic Current on Dexterity to Control Treatment in the Immediate to 12 Weeks Showing Low Effect Favoring Control Treatment

	Favors TC			**Favors CT**				**Mean Difference**	
Study or Subgroup	**Mean**	***SD***	**Total**	**Mean**	***SD***	**Total**	**Weight**	**IV, Random, 95% CI**	**Year**
1.1.1 0–4 Weeks									
Bhatt et al. (2007)	0	0	0	0	0	0		Not estimable	2007
Lee et al. (2015)	14.4	13.5	15	13.31	9.25	16	5.3%	1.09 [−7.11, 9.29]	2015
S.-H. Kim et al. (2016)	27.9	1.85	10	29.5	2.41	10	20.0%	−1.60 [−3.48, 0.28]	2016
Ghaziani et al. (2018)	19.2	15.2	53	19.9	16.2	49	8.1%	−0.70 [−6.81, 5.41]	2018
Subtotal (95% CI)			**78**			**75**	**33.3%**	**−1.40 [−3.16, 0.36]**	
Heterogeneity: Tau^2 = 0.00; Chi^2 = 0.45, df = 2 (*P* = .80); I^2 = 0%									
Test for overall effect: *Z* = 1.56 (*P* = .12)									
1.1.2 5–8 Weeks									
Sentandreu-Mañó et al. (2021)	11.62	9.89	21	12.2	12.95	20	6.6%	−0.58 [−7.66, 6.50]	2021
Sentandreu-Mañó et al. (2021)	10.75	9.51	21	12.2	12.95	20	6.7%	−1.45 [−8.43, 5.53]	2021
Alwhaibi et al. (2021)	20	12.3	20	38	22.1	20	3.2%	−18.00 [−29.08, −6.92]	2021
Subtotal (95% CI)			**62**			**60**	**16.5%**	**−5.69 [−14.85, 3.47]**	
Heterogeneity: Tau^2 = 47.39; Chi^2 = 7.53, df = 2 (*P* = .02); I^2 = 73%									
Test for overall effect: *Z* = 1.22 (*P* = .22)									

Figure 5

Forest Plot Illustrating the Overall Effect of Therapeutic Current on Dexterity to Control Treatment in the Immediate to 12 Weeks Showing Low Effect Favoring Control Treatment

	Favors TC			**Favors CT**				**Mean Difference**	
Study or Subgroup	**Mean**	***SD***	**Total**	**Mean**	***SD***	**Total**	**Weight**	**IV, Random, 95% CI**	**Year**
1.1.3 9–12 Weeks									
Knutson et al. (2016)	4.6	0.61	32	1.8	0.31	40	23.5%	2.80 [2.57, 3.03]	2016
Knutson et al. (2020)	13.5	1.8	21	9.6	1.8	8	21.2%	3.90 [2.43, 5.37]	2020
Ambrosini et al. (2021)	61	15	32	58	18	32	5.4%	3.00 [−5.12, 11.12]	2021
Subtotal (95% CI)			**85**			**80**	**50.1%**	**2.88 [2.48, 3.28]**	
Heterogeneity: Tau^2 = 0.03; Chi^2 = 2.11, df = 2 (*P* = .35); I^2 = 5%									
Test for overall effect: *Z* = 14.07 (*P* < .00001)									
Total (95% CI)			**225**			**215**	**100%**	**0.61 [−1.53, 2.76]**	
Heterogeneity: Tau^2 = 5.06; Chi^2 = 40.12, df = 8 (*P* < .00001); I^2 = 80%									
Test for overall effect: *Z* = 0.56 (*P* < .57)									
Test for subgroup differences: Chi^2 = 24.85; df = 2 (*P* < .00001); I^2 = 92%									

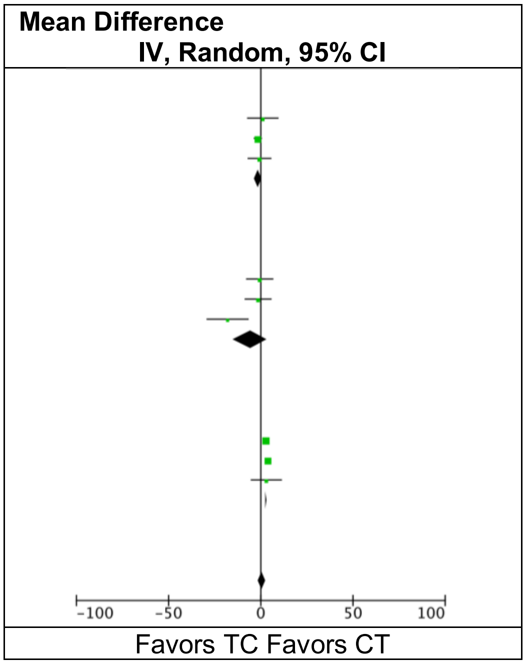


Figure 6

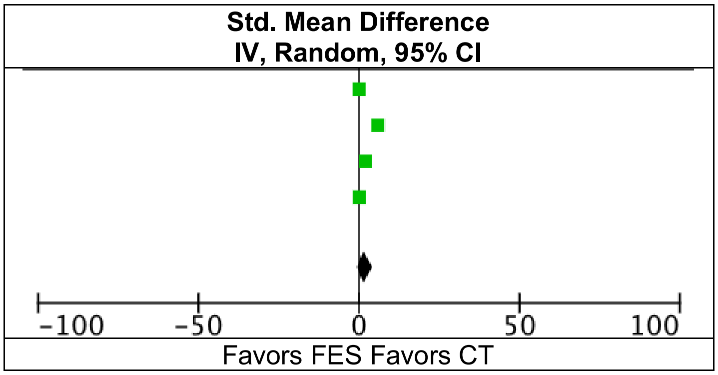
Result of the Meta-Analysis and Forest Plot for the Effect of FES on BBT

	Favors FES			Favors CT				Std. Mean Difference	
Study or Subgroup	**Mean**	***SD***	**Total**	**Mean**	***SD***	**Total**	**Weight**	**IV, Random, 95% CI**	**Year**
1.1.1 0–4 Weeks									
	14.4	13.5	15	13.31	9.25	16	25.3%	0.09 [−0.61, 0.80]	2015
	4.6	0.61	31	1.8	0.31	40	24.4%	5.93 [4.83, 7.03]	2016
	13.5	1.8	21	9.6	1.8	8	24.7%	2.11 [1.10, 3.11]	2020
	61	15	32	58	18	32	25.6%	0.18 [−0.31, 0.67]	2021
Subtotal (95% CI)			**100**			**96**	**100.0%**	**−2.03 [−0.17, 4.24]**	

Heterogeneity: $\text{Tau}^2 = 4.89$; $\text{Chi}^2 = 99.04$, df = 3 ($P < .00001$); $I^2 = 97\%$

Test for overall effect: $Z = 1.81$ ($P = .07$)

Note. FES functional electrical stimulation; BBT Box and Block test.



Discussion

This systematic review sought to summarize and evaluate the existing literature on various therapeutic currents to guide better clinical decision-making for clinicians and physical therapists working in stroke rehabilitation settings with people having dexterity impairment. According to the findings of the present review, therapeutic currents can be used alone or as an adjunct in order to improve the hand functions of the people with stroke; however, they failed to produce any long-term effects.

Two studies investigated the effect of contralaterally-controlled FES (CCFES) on stroke patients. Knutson and colleagues compared the effects of contralaterally controlled FES to cyclic NMES. CCFES is more effective in improving and facilitating motor recovery than NMES. This is because CCFES provides control of stimulation intensity in real-time, synchronized opening of hands, and practice of the task using stimulation (Knutson et al., 2016). Another trial evaluated the effect of adding contralaterally controlled triceps stimulation to hand CCFES by comparing the outcomes of participants receiving hand CCFES to those receiving Arm+Hand CCFES. They also compared the Arm+Hand to Arm+Hand cyclic NMES (cNMES), which stimulated simultaneous elbow extensors with preset timing and timing (i.e., stimulation was not controlled by the participant). After 12 weeks of intervention, it was observed that adding contralaterally controlled elbow extension to hand CCFES does not improve gains in hand dexterity (Knutson et al., 2020). CCFES has a mechanical advantage over cNMES like CCFES provides real-time patient-controlled intensity of stimulation to the paretic hand (i.e., intention-driven movement), synchronized opening of both hands, and stimulation-assisted task practice with the paretic hand (Knutson et al., 2016).

One trial investigated the effect of electromyographic biofeedback (EMG-BFB) in addition to occupational therapy (OT) and functional electrical stimulation on spasticity, range of motion, and upper extremity function. Ischemic stroke patients receiving

OT+FES+EMG-BFD showed greater improvement in upper extremity hand function than those who received only OT+FES indicating that EMG-BFD can be used as an adjunct to other treatment regimen (Lourenção et al., 2008). These findings might result from the fact that biofeedback training involves skilled repetitive movements and inhibition of unwanted activity of antagonistic muscles (Basmajian et al., 1975).

One study investigated the effect of early administration of ESS on arm functioning in people with stroke. The ESS was delivered for 1 hr along with 15 min of task-oriented arm training but was equally beneficial when arm training was given alone (Ghaziani et al., 2018). Bhatt and colleagues evaluated the combined effect of electrical stimulation plus motor learning-based tracking training on cortical reorganization and its relationship to functional recovery. After 2–3 weeks of intervention, ES along with motor learning was effective in cortical reorganization (Bhatt et al., 2007). Electrical stimulation is proposed to work through a sensorimotor coupling mechanism (Cauraugh et al., 2000). Increased proprioceptive signals from evoked movements are thought to bombard the somatosensory cortex, thereby increasing motor corticoneural excitability (Cauraugh et al., 2000). The increased motor cortical excitability facilitates greater voluntary activation of its neuronal networks leading to improved function (Wu et al., 2006).

One study compared the effect of two NMES protocols with different stimulation frequencies on upper limb impairment and upper limb function in older individuals with spastic hemiparesis after stroke. Both the NMES protocols were found to be effective in manual dexterity (Sentandreu-Mañó et al., 2021). The specific mechanisms underlying NMES intervention are complex and unclear, but findings suggest that improvement could be mediated by local and central effects. At the local level, reference has been made to changes in muscular strength, modification of viscoelastic characteristics, and increase of blood flow (de Kroon et al., 2004; Ring & Rosenthal, 2005) and at the central level, NMES was supposed to influence cortical plasticity (Chipchase et al., 2011; Quandt & Hummel, 2014). Low to moderate NMES frequencies were preferred when the function of the muscle is linked to sustained repetition of the fine motor movements (Vromans & Faghri, 2018).

One trial done by Lee and colleagues examined the combined effect of MT+MG on muscular properties, sensorimotor functions, and daily function in people with chronic stroke. The intervention was given for 1.5 hr per day for five days per week for a total of 4 weeks. It was observed that MT+MG was effective in improving muscular properties, manual dexterity, and daily function (Lee et al., 2015). MT in addition to MG stimulation decrease the stiffness of flexors of forearm and simultaneously increasing the tone of extensors, which leads to improvement in ability to grasp and release cubes (Keenan & Matzon, 2011). The sensory inputs from the MG stimulation and the visual inputs from the mirror facilitate neuroplastic changes in the sensorimotor cortex of the brain and enhance improvement in manual dexterity (Michielsen et al., 2011).

Two studies examined the combined effect of tDCS with and rPNS (Sattler et al., 2015) and FES (Salazar et al., 2020). Sattler and colleagues compared the effect of tDCS plus rPNS and rPNS with sham tDCS on the motor recovery using the JHFT. tDCS when added to rPNS may be helpful in improving motor hand recovery in the acute phase after stroke (Sattler et al., 2015). Another study compared the concurrent bicephalic tDCS and FES and sham tDCS and FES on handgrip force in chronic poststroke patients (Salazar et al., 2020).

One trial compared the effects of TENS acupoints and task-specific training (TST) and TST alone on cortical activity and the motor function of the affected UE in people with stroke. Both being equally effective, TST only or combined with TENS can be considered as an effective treatment strategy for improving motor function of hand in chronic stroke patients (Alwhaibi et al., 2021). TENS activates the fibers of small diameters arriving from the muscles (ergo receptors) which results in phasic muscle twitches. These receptors were responsible for the facilitation of proprioception and kinesthetic senses.

Two studies evaluated the effects of EMG-triggered stimulations on the upper extremity function (Ambrosini et al., 2021; S.-H. Kim et al., 2016). One trial investigated the effect of electromyogram-triggered neuromuscular stimulation (EMG-stim) in addition to task-oriented training (TOT) on muscle activation, motor recovery, and dexterity in people with chronic stroke. Following 4 weeks of intervention, EMG-stim in combination with TOT was found to be better than EMG-stim alone for the improvement in dexterity (S.-H. Kim et al., 2016). One study compared the effect of arm training supported by a RETRAINER with electromyograph-triggered functional electrical stimulation and advanced conventional therapy (ACT) on dexterity, arm function, strength, ADL, QoL in people with stroke. Following 9 weeks of training, it was observed that hybrid robotic system, allowing to perform personalized, intensive, and task-oriented training, with enriched sensory feedback, was superior to ACT in improving arm functions and dexterity after stroke (Ambrosini et al., 2021). EMG-stimulation was confirmed to be an effective intervention that accelerates neurological recovery by increasing motor unit. Improved muscle performance may also provide positive effects on motor recovery and hand function after stroke (S.-H. Kim et al., 2016). These therapeutic effects of EMG-stimulation were further significantly improved when an adjunct intervention was added.

The stimulation parameters reported across the included studies—particularly frequencies between 20–50 Hz and pulse durations of 200–300 µs—are consistent with those commonly used in neurorehabilitation for motor recovery after stroke (de Kroon et al., 2004; Sheffler & Chae, 2007). Moderate-frequency stimulation is known to promote muscle contraction, enhance cortical excitability, and facilitate motor learning, especially when combined with voluntary movement or task-specific training (Bergquist et al., 2011; Rushton, 2003). The observed consistency of parameters across trials supports their clinical relevance. However, heterogeneity in session durations, total treatment periods, and stimulation modes (e.g., FES vs. NMES) may explain the variability in clinical outcomes, particularly in studies that did not observe long-term effects.

Seven studies were grouped for meta-analysis to determine the long-term effectiveness of therapeutic currents on dexterity versus control (Ambrosini et al., 2021; Ghaziani et al., 2018; S.-H. Kim et al., 2016; Knutson et al., 2016; Knutson et al., 2020; Lee et al., 2015; Sentandreu-Mañó et al., 2021). During the 9- to 12-week period, the meta-analysis suggests that there is moderate quality evidence that electrical stimulation was not effective in producing any positive effects in the long term. Due to the limited available literature, it was difficult to identify the mechanism behind the inability of therapeutic currents to produce long-lasting positive effects. This may, however, be attributed to factors such as short intervention duration, lack of structured follow-up, or absence of ongoing home-based practice. Some studies suggested that participants may not have adopted long-term behavioral or lifestyle changes supportive of motor function maintenance after the intervention phase, which could limit lasting gains.

This review identified several limitations within the included studies. First, the included trials used different outcome measures to assess dexterity, which might have led to the significant heterogeneity of the results. Second, the present review included a large number of studies in which current was as adjunct component of other intervention. The lack of common outcome measure was also identified as a limitation of the present review that restricted the number of outcomes included in the meta-analysis.
The main strength of the present review is that it provides an RCT update summary of the effects of various therapeutic currents on dexterity of people with stroke, while it implies prospective observations and a causal rationale. The findings imply that the improvement of the dexterity by therapeutic currents in people with stroke is practical and generalizable.

Conclusion

There is growing evidence base regarding trials investigating the effect of different therapeutic currents on upper extremity function in people with stroke. Synthesized data from trials examining the effect of FES showed small to moderate effect size for improving dexterity which, while not significant, warrants further investigation into the practical implications of these findings. In addition to this, therapeutic currents failed to bring any positive change in the long run. However, the application therapeutic currents have demonstrated its feasibility as a tool for the rehabilitation of upper limb function in people with stroke.

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Author Disclosures

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