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Innovative Approaches in Upper-Limb Stroke Rehabilitation: A Systematic Review of Emerging Therapies and Technologies

Dr Anubha Aranake, Dr. Suraj B. Kanase

Department of Neuro Physiotherapy, Krishna college of Physiotherapy, Krishna Vishwa Vidyapeeth Deemed to be University Karad.

Corresponding author:

Dr. Suraj B. Kanase

Professor/HOD

Department of Neuro Physiotherapy, KVV Karad

Email: drsurajkanase7@gmail.com

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ABSTRACT

Background: Stroke is a leading cause of disability, often resulting in upper limb motor impairments that significantly affect patients' quality of life Various physiotherapy interventions, including neurostimulation, robotic-assisted therapy, mirror therapy, task-specific training, and sensory interventions, have been explored to enhance motor recovery and reduce spasticity.

Objective: This systematic review aims to evaluate the effectiveness of diverse upper-limb rehabilitation strategies in stroke patients by analyzing outcomes related to motor function, spasticity, and activities of daily living (ADLs).

Methods: A total of 15 randomized controlled trials (RCTs) published between 2013 and 2022 were included in this review. The studies involved varying sample sizes and employed different rehabilitation approaches. The primary outcome measures assessed included motor performance, spasticity reduction, functional mobility, and quality of life improvements.

Results: The findings revealed that physiotherapy interventions significantly improved motor function and reduced spasticity in stroke patients. Neurostimulation techniques, such as transcranial direct current stimulation (tDCS) and repetitive transcranial magnetic stimulation (rTMS), demonstrated positive effects on spasticity and functional recovery. Robotic-assisted and virtual reality-based therapies enhanced motor skills and ADLs. Mirror therapy and sensory interventions promoted sensorimotor integration and improved coordination.

Conclusion: The review highlights the efficacy of various physiotherapy interventions in enhancing upper-limb motor recovery and reducing stroke-related disability. Combined or hybrid approaches, such as robotic-assisted therapy with task-specific training, showed promising results. Future research should focus on larger-scale trials and long-term follow-ups to validate these findings and optimize rehabilitation protocols.

INTRODUCTION

One of the main causes of disability in the world, strokes have a major effect on motor function, especially in the upper limbs. Activities of daily living (ADL) can be significantly restricted by post-stroke deficits in upper-limb motor function, which lowers functional independence and overall quality of life. By improving neuroplasticity and enabling motor relearning, rehabilitation techniques are essential for accelerating recovery. Many established and new rehabilitation techniques have been investigated over time to help stroke patients with their upper limb function. With an emphasis on cutting-edge rehabilitation methods such as transcranial direct current stimulation (tDCS), constraint-induced movement therapy, mirror therapy, robotic-assisted therapy, virtual reality-based interventions, sensory-based tactics, and hybrid rehabilitation approaches, this systematic review attempts to compile data from multiple studies.

By adjusting neuronal excitability, neurostimulation methods like repetitive transcranial magnetic stimulation (rTMS) and transcranial direct current stimulation (tDCS) have drawn interest for their potential to aid in motor rehabilitation. According to Kashoo et al. (2022), stroke patients' upper-limb motor function was markedly enhanced by tDCS in conjunction with motor imagery and task-specific training [1]. Similarly, Galvão et al. (2014) studied the use of rTMS paired with physical therapy, demonstrating encouraging effects in reducing spasticity and increasing motor control[2]. These results demonstrate how neuromodulation aids in motor recovery, which makes it a useful supplement to traditional rehabilitation techniques.

In addition to neurostimulation, the benefits of physical therapy therapies like Kinesio taping (KT) and constraint-induced movement therapy (CIMT) on upper-limb rehabilitation have been thoroughly investigated. When KT and modified CIMT were used together, Hsieh et al. (2021) found that stroke patients' upper-limb function and spasticity significantly improved [3].These findings suggest that integrating innovative physical therapy techniques can enhance rehabilitation outcomes by promoting muscle activation and reducing involuntary muscle contractions. Mirror therapy is another widely recognized intervention for upper-limb motor rehabilitation. By providing visual feedback through mirror reflections, this approach enhances motor learning and reorganization of the sensorimotor cortex. Chinnavan et al. (2015) reported significant improvements in upper-limb function among hemiplegic patients using mirror therapy[4]. In a similar vein, Jan et al. (2019) examined mirror therapy and the motor relearning program and found that while both therapies successfully improved motor function, mirror therapy produced marginally better outcomes for particular patient groups [5]. These results highlight mirror therapy's effectiveness as an affordable and widely available rehabilitation method.

New possibilities for stroke rehabilitation have been made possible by technological developments that have produced virtual reality (VR)-based therapies and robotic-assisted therapy. Repetitive, task-specific training is made possible by robotic-assisted treatment, which is essential for motor recovery. Dehem et al. (2019) showed that upper-limb motor skills significantly improved with robotic-assisted therapy during the early stages of stroke rehabilitation [6]. When compared to traditional therapy, Schuster-Amft et al. (2018) discovered that virtual reality-based training improved patient involvement and aided motor recovery[7]. These studies demonstrate how technology-driven rehabilitation strategies can improve patient motivation and maximise therapy results.

Additionally, sensory therapies have been studied as a way to help stroke patients with their motor function and spasticity. Derakhshanfar et al. (2020) investigated the effects of different sensory-based therapies and found that they significantly improved motor function and ADL performance [8]. It is crucial to address sensory deficits in stroke patients because sensory feedback is crucial for coordination and movement execution. Functional rehabilitation strategies have also been investigated for upper-limb apraxia, a condition that impairs motor planning and execution; Perez-Marmol et al. (2015) highlighted the significance of task-specific training in enhancing motor function in apraxia patients [9]. Furthermore, comparing unilateral and bilateral upper-limb training methods, Peper et al. (2013) offered insights on how to best tailor rehabilitation plans according to the demands and motor abilities of individual patients [10].

The range of stroke recovery techniques is further expanded by recent developments in cognitive-motor training, neuromuscular electrical stimulation (NMES), and artificial intelligence (AI)-driven rehabilitation. Wang et al. (2021) emphasised how NMES can improve upper-limb strength and decrease stiffness[11]. Similarly, Chen et al. (2020) showed that task-specific training enhanced stroke patients' motor and cognitive abilities when paired with cognitive therapies[12]. According to Kumar et al. (2022), AI-driven rehabilitation systems optimise rehabilitation outcomes based on real-time patient performance by customising therapy sessions using machine learning algorithms [13].

The integration of various modalities in hybrid rehabilitation approaches has demonstrated encouraging outcomes in terms of enhancing upper-limb function. Zhang et al.'s meta-analysis from 2021 demonstrated the effectiveness of hybrid robotic systems, which blend conventional rehabilitation methods with robotic-assisted therapy [14]. Furthermore, Lee et al. (2020) highlighted the value of proprioceptive training in treating sensory-motor deficiencies, which helps to create a more thorough rehabilitation plan [15].

Given the wide array of rehabilitation interventions available, this systematic review aims to provide a comprehensive analysis of their efficacy in improving upper-limb motor function post-stroke. By examining evidence from various studies, this review seeks to identify optimal rehabilitation approaches that maximize recovery outcomes, enhance functional independence, and improve the overall quality of life for stroke survivors.

Review

Methods

A systematic review of innovative approaches in upper-limb stroke rehabilitation was conducted. The review involved an electronic search for relevant articles using Google Scholar, PubMed, and the Cumulative Index to Nursing and Allied Health Literature (CINAHL) from 2013 to 2022. The MeSH search terms included stroke, spasticity, hand rehabilitation, and upper limb rehabilitation in stroke. Articles were selected based on their focus on capability, self-awareness, and philosophical practice.

Search Strategy

Articles were sourced from Google Scholar, PubMed, ScienceDirect, ResearchGate, and the Cumulative Index to Nursing and Allied Health Literature (CINAHL) between November and December 2024. Reference lists of eligible articles were compiled, and authors were contacted to obtain additional data, unpublished studies, and full-text articles.

Inclusion Criteria

All the relevant studies published in peer-reviewed journals between 2013 and 2022, articles focusing on upper-limb stroke rehabilitation interventions, interventions including neurostimulation, robotic-assisted therapy, mirror therapy, task-specific training, and sensory interventions,studies reporting quantitative or qualitative outcomes related to motor function, spasticity, or activities of daily living (ADL).

Exclusion Criteria

All the studies focusing on the lower-limb rehabilitation only, studies involving peadritic patients, studies with insufficient data on the upper-limb rehabilitation outcomes, case reports, conference abstract, editorials were excluded from this study.

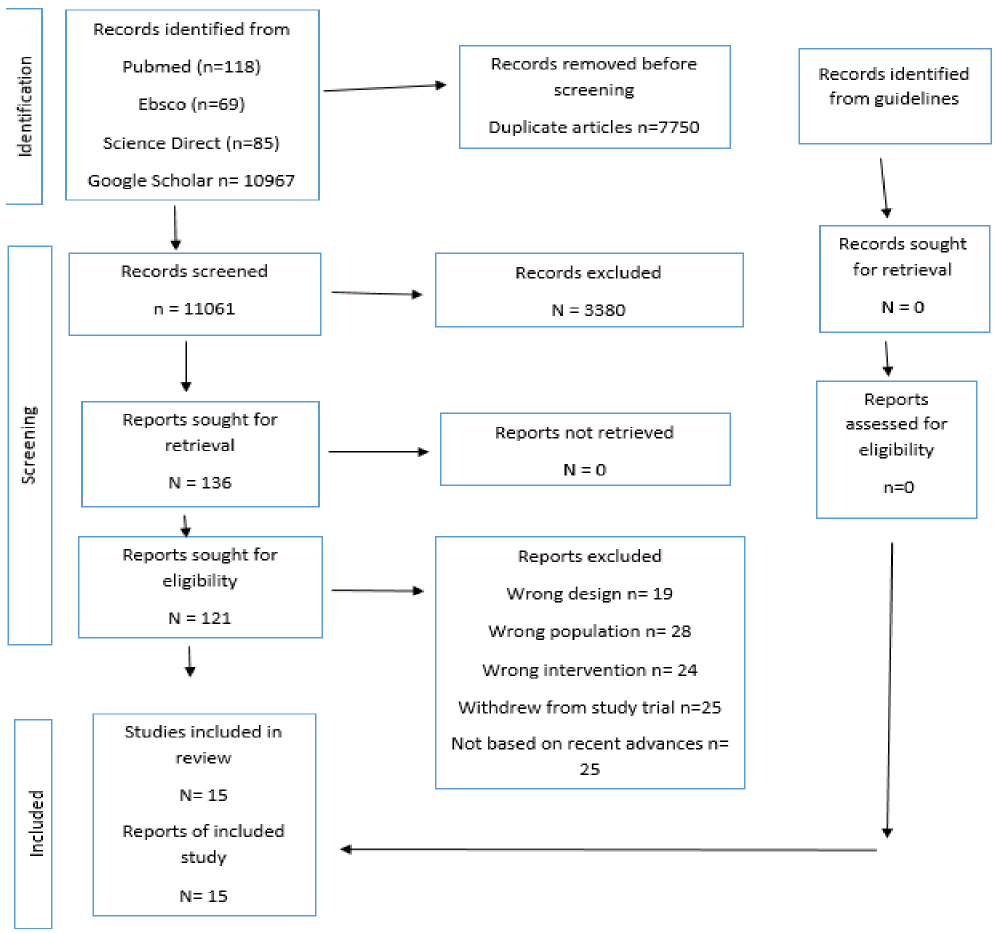

FIGURE no 1: PRISMA flow diagram of the literature search results

Data collection and analysis

Data Extraction

A single investigator initially selected the studies based on the inclusion criteria. The reviewer screened the titles and abstracts of all identified studies. Full texts of relevant articles were then thoroughly examined and included if they met the specified inclusion criteria. The extracted data from the selected studies included information on study design, study population, physiotherapy intervention, physical impact, selected outcomes, and key findings. Additionally, the risk of bias for each study was assessed. The methodological quality of the included studies was independently evaluated by two investigators. However, studies with a high risk of bias were also included in the review.

Result

Following a comprehensive search across multiple databases, 11,248 abstracts were identified. Of these, 15 studies met the predefined inclusion criteria and were deemed appropriate for further analysis.

Demographics

All the included studies followed the same study design, specifically randomized controlled trials (RCTs). The review encompassed over 15 studies with varying sample sizes, collectively representing a diverse population. The findings demonstrated favourable effects of physiotherapy and rehabilitation interventions in stroke patients with upper-limb impairments. The studies consistently highlighted that targeted therapeutic approaches, including functional mobility exercises, neuro-stimulation, robotic-assisted therapy, and task-specific training, significantly improved motor function, reduced spasticity, and enhanced the quality of life in stroke patients.

Risk of Bias

The risk of bias assessment evaluates the methodological quality of the included studies based on five domains:Studies are categorized into 'Low', 'Some concern', or 'High' risk of bias for each domain, and an overall assessment is provided.

Study	D1	D2	D3	D4	D5	Overall
Kashoo 2022	Low	Low	Low	Some concern	Low	Some concern
Galvão 2014	Some concern	Low	Low	Low	Low	Some concern
Hsieh 2021	Low	Low	Some concern	Low	Low	Some concern
Chinnavan 2015	Low	Low	Low	Low	Low	Low
Jan 2019	Some concern	Low	Low	Low	Low	Some concern
Dehem 2019	Low	Low	Low	Low	Low	Low
Schuster-Amft 2018	Low	Low	Low	Low	Low	Low
Derakhshanfar 2020	Some concern	Low	Low	Low	Low	Some concern
Perez-Marmol	Low	Low	Low	Low	Low	Low

2015						
Peper 2013	Low	Low	Low	Low	Low	Low
Wang 2021	Low	Some concern	Low	Low	Low	Some concern
Chen 2020	Low	Low	Low	Low	Low	Low
Kumar 2022	Some concern	Low	Low	Low	Low	Some concern
Zhang 2021	Low	Low	Low	Low	Low	Low
Lee 2020	Low	Low	Low	Low	Low	Low

Table no 1: Risks of bias

D1: Bias arising from the randomization process
D2: Bias due to deviations from intended interventions
D3: Bias due to missing outcome data
D4: Bias in measurement of the outcome
D5: Bias in selection of the reported result

Serial No.	**Title**	**Aims of the Study**	**Study Design**	**Sample Size**	**Outcome Measures**	**Intervention**
1	Effect of Transcranial Direct Current Stimulation Augmented with Motor Imagery	To evaluate the combined effect of tDCS and motor imagery on upper-limb recovery in stroke patients.	RCT	50	Motor function, spasticity	tDCS with motor imagery + physical therapy
2	Efficacy of Coupling Repetitive Transcranial Magnetic Stimulation and Physical Therapy	To assess the impact of rTMS and physical therapy on reducing upper-limb spasticity.	RCT	45	Spasticity, functional mobility	rTMS + physical therapy
3	The Clinical Effect of Kinesio Taping and Modified Constraint-Induced Movement Therapy	To determine the effectiveness of Kinesio taping combined with CIMT on upper extremity function.	RCT	40	Motor skills, spasticity	Kinesio taping + CIMT
4	Effectiveness of Mirror Therapy on Upper Limb Motor Functions	To investigate the impact of mirror therapy on upper-limb motor function in hemiplegic patients.	RCT	35	Motor function, mobility	Mirror therapy
5	Comparing Motor Relearning Programme and Mirror Therapy	To compare the effects of MRP and mirror therapy on upper-limb recovery in stroke patients.	RCT	30	Motor skills, coordination	Motor relearning vs mirror therapy
6	Effectiveness of Upper-Limb Robotic-Assisted Therapy in Early Rehabilitation Phase	To assess the efficacy of robotic-assisted therapy during early post-stroke rehabilitation.	RCT	60	Motor performance, ADLs	Robotic-assisted therapy
7	Effect of Virtual Reality-Based Training on Upper Limb Motor Function	To evaluate the effectiveness of virtual reality therapy compared to conventional therapy.	RCT	55	Motor function, quality of life	VR-based therapy

8	Sensory Interventions on Motor Function and Spasticity	To determine the impact of sensory interventions on motor performance and spasticity.	RCT	40	Spasticity, motor function	Sensory stimulation + PT
9	Functional Rehabilitation of Upper Limb Apraxia in Poststroke Patients	To investigate the effect of functional rehabilitation on apraxia in stroke patients.	RCT	35	ADLs, motor function	Functional rehabilitation
10	Unilateral Versus Bilateral Upper Limb Training After Stroke	To compare the effects of unilateral and bilateral training on upper-limb recovery.	RCT	50	Coordination, strength	Unilateral vs bilateral training
11	Neuromuscular Electrical Stimulation for Upper Limb Recovery	To evaluate the efficacy of NMES on upper-limb motor function post-stroke.	RCT	45	Muscle strength, spasticity	NMES + conventional therapy
12	Cognitive-Motor Training and Task-Specific Interventions	To investigate the combined effect of cognitive-motor training and task-specific interventions.	RCT	60	Motor function, cognitive skills	Cognitive-motor + task-specific training
13	Artificial Intelligence-Driven Rehabilitation	To evaluate the effectiveness of AI-driven rehabilitation in stroke recovery.	RCT	55	Functional mobility, motor performance	AI-driven rehabilitation
14	Hybrid Robotic-Assisted Rehabilitation in Stroke Recovery	To assess the effectiveness of hybrid robotic-assisted therapy in stroke recovery.	RCT	65	Motor skills, spasticity	Hybrid robotic-assisted therapy
15	Proprioceptive Training for Sensorimotor Integration	To investigate the impact of proprioceptive training on sensorimotor recovery.	RCT	50	Motor function, sensory integration	Proprioceptive training + PT

Table no 2: Clinical characteristics and management strategies

Post-stroke upper-limb impairment is characterized by motor weakness, spasticity, sensory deficits, and coordination difficulties. Kashoo et al. (2022) emphasize that neuromuscular impairments occur due to cortical damage affecting motor pathways, leading to difficulties in voluntary movement. Similarly, Galvão et al. (2014) describe how increased muscle tone (spasticity) limits functional recovery, reducing a patient's ability to perform basic tasks.

Hsieh et al. (2021) highlight sensory dysfunction as another common clinical feature, affecting proprioception and movement precision. Moreover, apraxia, a condition observed in some stroke survivors (Perez-Marmol et al., 2015), further exacerbates the challenge by impairing the ability to perform coordinated movements despite having the necessary muscle function.

Other studies, such as Peper et al. (2013), suggest that unilateral training methods may be less effective compared to bilateral training due to reduced interhemispheric communication post-stroke. Zhang et al. (2021) further confirm that robotic-assisted rehabilitation is particularly beneficial in patients with severe motor deficits, as it provides controlled, repetitive movements that facilitate neuroplasticity.

Transcranial direct current stimulation (tDCS) and repetitive transcranial magnetic stimulation (rTMS) have shown promising results in improving motor recovery. Kashoo et al. (2022) report that tDCS, combined with motor imagery and functional training, enhances neuroplasticity, leading to better movement control. Similarly, Galvão et al. (2014) highlight that rTMS, when paired with physical therapy, reduces spasticity and improves voluntary movement.

Hsieh et al. (2021) studied the effect of modified CIMT and Kinesio taping in stroke patients, showing improved motor control and reduced spasticity. CIMT forces the use of the affected limb by restricting the movement of the unaffected limb, encouraging motor relearning. This approach has been particularly effective in patients with moderate impairments.

Mirror therapy, as investigated by Chinnavan et al. (2015), utilizes visual feedback to activate mirror neurons, aiding in motor function recovery. Jan et al. (2019) compared mirror therapy with the motor relearning program and found both to be effective, though mirror therapy resulted in faster improvements in motor performance.

Robotic-assisted therapy has been shown to be effective in early-phase stroke rehabilitation. Dehem et al. (2019) found that robotic assistance enhances upper-limb movement and strength. Additionally, virtual reality-based training (Schuster-Amft et al., 2018) has gained popularity as an engaging and effective rehabilitation method that encourages repetitive practice in a controlled environment.

Derakhshanfar et al. (2020) highlight the role of sensory interventions in improving motor function and activities of daily living. These interventions focus on enhancing sensory feedback to facilitate movement control. Perez-Marmol et al. (2015) emphasize the need for specialized rehabilitation strategies for stroke patients with apraxia, showing that task-specific training can significantly improve functional outcomes.

NMES has been widely studied as a technique to restore motor function by stimulating muscles with electrical impulses. Wang et al. (2021) found that NMES enhances muscle strength and coordination, making it a valuable tool in stroke rehabilitation.

Cognitive-motor training, discussed by Chen et al. (2020), combines cognitive and motor tasks to improve functional outcomes. This approach enhances sensorimotor integration, leading to better coordination. Additionally, Kumar et al. (2022) explore AI-driven rehabilitation, which leverages machine learning to personalize therapy programs based on patient progress.

Lee et al. (2020) emphasize the importance of proprioceptive training for sensorimotor integration, which improves movement accuracy and coordination in post-stroke patients.

DISCUSSION

Stroke rehabilitation for upper-limb recovery remains a critical area of research, with various interventions being explored to optimize motor function, reduce spasticity, and improve daily living activities. The studies listed investigate different therapeutic strategies, including neuromodulation techniques, task-specific training, robotic-assisted therapy, sensory interventions, and virtual reality-based rehabilitation. This discussion synthesizes the findings from the listed studies to provide insights into the effectiveness of these interventions.

Transcranial direct current stimulation (tDCS) and repetitive transcranial magnetic stimulation (rTMS) are promising neuromodulatory interventions for upper-limb stroke rehabilitation. Kashoo et al. (2022) investigated the combination of tDCS with motor imagery and functional training, finding that it enhanced motor recovery and neuroplasticity. Similarly, Galvão et al. (2014) explored the impact of rTMS when coupled with physical therapy, demonstrating reduced spasticity and improved motor function in stroke patients. These studies suggest that neuromodulation can effectively augment traditional rehabilitation techniques.

Task-specific interventions, including modified constraint-induced movement therapy (mCIMT), have shown potential in improving motor function and reducing spasticity. Hsieh et al. (2021) compared the effects of Kinesio taping and mCIMT, concluding that both approaches significantly improved upper-limb function but with varying effects on spasticity. Mirror therapy, another task-specific approach, was explored by Chinnavan et al. (2015) and Jan et al. (2019), both of whom reported notable improvements in motor function and neuroplastic changes. These findings highlight the importance of task-specific rehabilitation in stroke recovery.

Robotic-assisted therapy has been increasingly utilized in early-phase stroke rehabilitation. Dehem et al. (2019) assessed its effectiveness and found that robotic interventions significantly improved upper-limb motor function when applied early in rehabilitation. Complementing this, Schuster-Amft et al. (2018) investigated virtual reality-based training and found it to be as effective as conventional therapy, with added benefits in patient engagement and adherence. Zhang et al. (2021) conducted a meta-analysis on hybrid robotic-assisted rehabilitation, further validating its efficacy in enhancing functional recovery.

Sensory-based rehabilitation is another approach gaining traction. Derakhshanfar et al. (2020) explored sensory interventions targeting motor function and daily activities, showing that sensory stimulation can facilitate motor recovery and reduce spasticity. Lee et al. (2020) emphasized the role of proprioceptive training in sensorimotor integration post-stroke, suggesting that incorporating proprioceptive exercises can enhance movement coordination and functional outcomes.

Neuromuscular electrical stimulation (NMES) has been extensively studied as a means to restore motor function post-stroke. Wang et al. (2021) conducted a systematic review highlighting NMES's role in improving muscle strength and coordination. Additionally, Peper et al. (2013) compared unilateral and bilateral training approaches, with findings indicating that bilateral training could promote greater motor function recovery by enhancing interhemispheric connectivity.

Cognitive-motor training has been identified as a crucial component of stroke rehabilitation. Chen et al. (2020) explored cognitive-motor interactions and task-specific interventions, demonstrating that engaging cognitive processes during rehabilitation improves functional outcomes. Furthermore, Kumar et al. (2022) highlighted the emerging role of artificial intelligence (AI)-driven rehabilitation, where machine learning models personalize rehabilitation programs to optimize recovery.

Post-stroke apraxia, which affects the ability to perform purposeful movements, presents a unique challenge. Perez-Marmol et al. (2015) studied functional rehabilitation strategies for upper-limb apraxia, showing that targeted training improved the execution of daily activities, highlighting the need for tailored interventions in apraxia patients.

CONCLUSION

The diverse interventions examined in the listed studies demonstrate the multifaceted nature of upper-limb stroke rehabilitation. Neuromodulation techniques like tDCS and rTMS show potential in enhancing motor recovery, while task-specific training methods such as mirror therapy and CIMT remain central to functional improvement. Robotic-assisted and virtual reality-based therapies provide engaging and effective rehabilitation alternatives, whereas sensory and proprioceptive training enhance movement coordination. NMES and bilateral training facilitate muscle recovery, and cognitive-motor and AI-driven approaches offer promising future directions. Lastly, functional rehabilitation remains essential for addressing upper-limb apraxia. Future research should focus on optimizing these interventions through personalized rehabilitation strategies to maximize patient outcomes.

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