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Systematic Review

Virtual Reality Associated with Functional Electrical Stimulation for Upper Extremity in Post-Stroke Rehabilitation: A Systematic Review

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Abstract: Background: This systematic literature review aims to explore the impact of rehabilitation in post-stroke patients, particularly highlighting the roles of virtual reality (VR) technology and functional electrical stimulation (FES). Methods: To ensure all relevant studies were included, a thorough search was conducted in PubMed and Web of Science databases using keywords such as 'post-stroke', 'FES', 'functional electrical stimulation', 'virtual reality', and 'VR'. Studies on rehabilitating upper limb function through VR and FES in post-stroke patients were included, regardless of publication year. Studies had to compare this combination therapy with conventional methods and report outcomes related to upper limb coordination, functional mobility, and daily activities. Studies not meeting these criteria were excluded. The selection process involved screening titles, abstracts, and full texts by four independent reviewers. The quality and risk of bias of the included studies were assessed using the PEDro scale and Robvis tool. Results: The review included four studies involving 135 post-stroke patients. Two articles examined the effectiveness of an approach involving virtual reality, robotic therapy, and functional electrical stimulation in rehabilitating upper limbs in post-stroke patients, showing significant improvements in motor function and quality of life. The other two studies explored the effects of rehabilitation therapy using virtual reality combined with functional electrical stimulation on upper limb function in stroke patients, finding that combined therapy (FES with VR) was superior to functional electrical stimulation or robotic therapy. Discussion: The review was limited by the small number of studies and participants, which may affect the generalizability of the results. Variations in intervention protocols and outcome measures across studies posed challenges in synthesis. Integrating these technologies brings benefits and increases the potential for personalizing and optimizing the rehabilitation process, enhancing patient engagement and satisfaction, and promoting a holistic approach to post-stroke management. Future research should focus on larger, more standardized trials to confirm these findings and optimize intervention protocols.

Keywords: stroke rehabilitation; virtual reality; functional electrical stimulation; upper extremity; motor function; physical therapy modalities; systematic review

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1. Introduction

1.1. Stroke-Rehabilitation Treatment

Stroke is a major global health issue, leading to significant disability for millions each year. Approximately 15 million people suffer a stroke annually, with 5 million of these cases resulting in permanent neurological and motor deficits, according to the World Health Organization [1]. This substantial burden underscores the urgent need for effective rehabilitation strategies to improve patient outcomes. Post-stroke rehabilitation often requires an extended period, depending on the severity of the stroke, associated pathologies, the patient's age, and the time elapsed since the stroke when rehabilitation began [2]. Rehabilitation is recommended for most patients to assist individuals with disabilities in regaining independence and improving their quality of life by restoring lost functions or increasing their functional level [3].

Medical rehabilitation plays a critical role in the recovery process following a stroke. It emphasizes physical therapy and personalized physiotherapy programs tailored to the individual rather than directly targeting the affected brain regions [4]. The rehabilitation of patients who have suffered a stroke is based on several principles; the most important is represented by the early intervention of the rehabilitation program [5]. Conventional rehabilitation emphasizes therapeutic exercises, and occupational therapy exercises aim to reintegrate the patient into daily activities (ADLs) and enhance communication skills through speech therapy [6–8].

Neurological rehabilitation should begin as soon as possible when the medical condition is considered stable [9]. The rehabilitation program should be customized for each patient, starting during early hospitalization, continuing long-term, and concluding after discharge.

Stroke symptoms depend on the affected area of the central nervous system. Primary motor deficits such as spasticity and paralysis pose challenges for treatment. Other symptoms include sudden, severe headaches, lack of movement coordination (ataxia), reduced sensitivity, impairments of the optic system, and speech disorders. The most severe symptom is the functional deficit, significantly reducing the patient's quality of life [4,10]. Most rehabilitation occurs within the first three months after the stroke, primarily through spontaneous restoration of blood flow. In the acute stage, motor function rehabilitation is faster as the brain has a greater capacity to respond to external stimuli due to its remodeling characteristics, essentially relearning what it knew before the stroke. However, rehabilitation is slower and more challenging in the subacute and chronic stages [11].

Following a stroke, the upper extremities commonly experience various degrees of impairment, impacting functional abilities and quality of life. These impairments typically include motor deficits, sensory disturbances, and altered muscle tone. Motor deficits often involve weakness or paralysis, affecting the ability to initiate or control movements and reducing dexterity, coordination, and precision in upper limb tasks. Additionally, sensory disturbances such as numbness, tingling, or loss of proprioception can further compromise motor function and contribute to difficulties in manipulation and spatial awareness. Changes in muscle tone, including spasticity or flaccidity, frequently accompany upper extremity impairment post-stroke, further complicating functional rehabilitation efforts [12].

However, despite the conventional methods described, many stroke survivors still experience residual functional disability that affects their ability to perform activities involved in daily living. The lack of significant improvement in motor function may be due to inadequate therapy dosage, poor patient engagement and motivation, and a shortage of objective feedback [13].

Various technology-based rehabilitation interventions have been developed in recent decades, showing promising results in improving functional mobility and independence in patients with such conditions [14]. Technology promotes the repetitive execution of specific movements affected by the pathology, physical and psychological rehabilitation of patients through environmental modifications, integration of constructive feedback, creation of personalized exercises, and daily monitoring of the patient's progress [15].

Rehabilitation after a stroke can be improved through interventions focused on enhancing deficits and functional limitations [16].

1.1.1. Virtual Reality

VR has emerged as a new treatment approach in stroke rehabilitation, involving exercise programs designed to simulate real-life objects and events through a computer interface. VR systems are classified into three immersion levels: fully immersive (which completely obstructs real-world perception), non-immersive (enabling simultaneous real and virtual environment experiences), and semi-immersive (utilizing screens or headsets for partial immersion) [17]. The potential benefits of VR are significant, as rehabilitation programs are often designed to be more engaging and enjoyable than traditional therapy tasks, encouraging more repetitions and concurrently addressing the patient's mental well-being. Physical exercise can improve health by reducing the risk of various health issues. Engaging in movement while enjoying virtual activities can help individuals stay motivated to adopt a healthier lifestyle, build confidence, and prevent hopelessness [18]. However, it is crucial to acknowledge the challenges, such as the necessary technological skills, expense, and cyber-sickness [19].

1.1.2. FES

The rehabilitation of stroke patients is a comprehensive process that involves improving muscle strength and training gait using various methods and devices, including functional electrical stimulation (FES) [20].

FES is a supplementary therapy in rehabilitation guidelines. It benefits patients suffering from central motor neuron pathologies by leveraging brain plasticity to restore the ability to perform voluntary movements [21]. FES is an integral part of stroke rehabilitation guidelines, serving as an adjunct technology with significant benefits for patients with such conditions [22]. It is widely recognized and utilized in medical rehabilitation [23], and FES sessions entail the precise application of electrical stimuli to the muscle at motor points. These stimuli are often synchronized with specific physical activities tailored to the patient's needs, such as walking, cycling, or arm exercises [24]. The current can be delivered to the muscles through various types of electrodes that can operate on the surface, percutaneously, or subcutaneously, thus producing muscle contraction through the depolarization of motor units. Functional electrical stimulation is divided into two distinct categories: assistive FES, which is used for the complete replacement of motor function, and therapeutic FES, which is used for rehabilitation purposes [21].

Therapeutic FES has a wide range of applications, mainly benefiting the rehabilitation of patients with central motor neuron damage. Additionally, it plays a crucial role in preventing muscle atrophy and maintaining the health of the muscular system. Assistive FES, however, is designed to restore motor function in patients with central neuron syndrome by completely replacing motor signals [22].

Nerve stimulation is the preferred method for FES due to its significantly lower electrical charge. This reduces the risk of burns or other tissue damage and instills trust in the procedure's safety [23].

Percutaneous FES, a technique involving intramuscular electrodes, offers unparalleled precision and control, even of deeper muscle structures. While it requires surgical procedures with risks such as postoperative infection and higher costs, it also provides several advantages. Implantable electrodes are more efficient and reliable, and their configuration is more precise compared to systems using surface electrodes. However, it is important to note that surface electrodes, while easier to configure, may be less accurate. This comprehensive view allows the audience to make informed decisions about the best approach for their patients [25].

Implementing the most effective rehabilitation program is a significant challenge for individuals who have had a stroke. However, effective therapeutic strategies, especially those incorporating new rehabilitation approaches, have not been thoroughly explored. The combination of VR and FES in stroke rehabilitation is grounded in their complementary strengths, offering a promising approach to addressing stroke survivors' persistent challenges. The necessity for this study arises from the need to enhance rehabilitation outcomes by leveraging the benefits of both VR and FES, particularly for upper limb rehabilitation, where motor deficits, sensory disturbances, and altered muscle tone significantly impact functional abilities and quality of life. With its immersive and engaging environments, VR encourages greater patient engagement and motivation by making repetitive exercises more enjoyable and mentally stimulating, which is crucial for long-term rehabilitation success. However, VR alone may not be sufficient for restoring motor function, especially in severe cases where muscle activation is compromised. Conversely, FES directly stimulates muscle contractions through electrical impulses, promoting muscle strength and neuroplasticity, which are essential for regaining voluntary movement. Combining VR and FES, the study aims to create a synergistic effect where VR enhances the patient's psychological and cognitive engagement while FES ensures effective muscle activation and motor recovery. The decision to focus on VR and FES, rather than combining them with other treatment methods, is driven by the need to systematically explore and evaluate the efficacy of this specific combination, as it holds significant potential for creating more personalized and effective rehabilitation programs. This focused approach allows for a clearer understanding of how these technologies can be integrated and optimized, potentially leading to more impactful and targeted interventions in stroke rehabilitation.

The current understanding of the effectiveness, potential challenges, and facilitators of using VR and FES for upper limb rehabilitation in stroke patients is limited. Despite the growing interest in physical approaches, there is still a notable gap in the literature regarding identifying effective rehabilitation methods and interventions for the most effective treatment following a stroke. We believe that combining VR and FES could offer a more effective rehabilitation approach for helping post-stroke patients recover upper extremity motor function compared to conventional therapies or using VR or FES alone. Specifically, we expect that integrating these technologies will enhance motor function, increase patient engagement, and improve outcomes in upper limb rehabilitation.

This systematic literature review aims to address this research gap by examining the characteristics and clinical outcomes of studies focusing on rehabilitation through VR and FES and by identifying the current state of research and rehabilitation systems that use customized exercises for each patient, combining virtual reality technology with functional electrical stimulation devices. The potential impact of this research on stroke rehabilitation is significant, as it could lead to the development of more effective and personalized treatment methods.

2. Materials and Methods

This study follows and meets the standards of the essential elements of PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) [26].

2.1. Search Strategy

The search for publications in scientific databases, such as PubMed and Web of Science Core Collection, was meticulously conducted in English. The following databases have been carefully chosen: MEDLINE, PsychINFO, EMBASE, CENTRAL, ISRCTN, and ICTRP from the WOS platform for their extensive coverage of medical specialties, particularly rehabilitation, as previously reviewed by Zieliński et al. [27] and Mat Rifin et al. [28]. The search was conducted from 22nd May to 3rd June 2024, followed by a thorough study refinement process from 4th June to 15th June 2024.

A comprehensive search strategy was employed, incorporating a combination of MeSH terms such as "stroke" AND "FES" AND "VR"—23 results, "stroke" AND "functional electrical stimulation" AND "VR"—63 results, "stroke" AND "FES" AND "virtual reality"—41 results, "stroke" AND "functional electrical stimulation" AND "virtual reality"—140 results. Studies were included regardless of publication year to ensure a comprehensive and up-to-date perspective.

The eligibility criteria identified (1) the population, (2) interventions, (3) comparisons, (4) outcomes, and (5) study designs. The PICOS strategy [29] was followed during the preliminary search. Criterion (1) included patients who have suffered a stroke, both men and women, with a focus on those experiencing upper limb impairments. Criterion (2) interventions were studies examining the use of VR combined with FES as a rehabilitation intervention for upper extremity function. Criterion (3) comparison consisted of the intervention on VR and FES intervention against conventional therapy, other forms of rehabilitation, or no intervention at all. Criterion (4) outcome was related to improving upper limb coordination, functional mobility, and the ability to perform daily activities, including enhanced fine motor skills. Criterion (5) study design consisted of randomized clinical trials (RCTs) (without group limitation) that used VR (immersive and non-immersive), and FES were included. Review and meta-analysis papers, case reports, pilot, and validation studies were excluded.

Irrelevant to the research were studies not conducted on human subjects or adults, investigations employing multiple types of electrostimulation simultaneously without distinct patient groups or lacking virtual reality exercise rehabilitation, studies exclusively focused on patient evaluation without implementing a rehabilitation program or intervention, studies with fewer than ten rehabilitation sessions, studies comparing healthy individuals to those with post-stroke lesions, research unrelated to the subject matter, and studies with fewer than eight participants. Finally, studies that did not have the text published in English were excluded.

2.2. Selection Process

The titles and abstracts of eligible studies were analyzed for selection by four independent reviewers (D.M., A.I.M., I.C.C.B., E.B.B.). Potentially eligible studies were then studied in full text. Articles that did not meet the eligibility criteria were excluded from the research. The quality of the included studies in the systematic review was assessed using the PEDro scale (Table 1) [30]. This tool assesses the external and internal validity of randomized controlled trials using 11 criteria to help readers understand the confidence level they should have in a study's findings [30].

Table 1. The quality of the studies included in the review.

Section	D. Montoya et al. [23]	S. Hyeyoung Lee et al. [24]	M. Sebastián-Romagosa et al. [25]	N. Norouzi-Gheidari et al. [26]
1	YES	YES	YES	YES
2	-	YES	NO	NO
3	-	YES	-	-
4	-	YES	YES	YES
5	-	-	NO	-
6	-	NO	NO	YES
7	-	NO	NO	YES
8	YES	YES	YES	YES
9	YES	YES	YES	YES
10	YES	YES	YES	YES
11	-	YES	YES	YES
Total score	3/10	7/10	5/10	7/10

In addition to the PEDro scale, the Robvis tool (Table 2) was employed to generate risk-of-bias plots for this systematic review [31]. The Robvis tool is a widely recognized instrument designed to visually represent the risk of bias across domains within included studies. It provides a comprehensive overview of potential biases, allowing for a more precise assessment of the quality and reliability of the evidence [31]. The decision to use the PEDro and Robvis scales was made to ensure a more thorough evaluation of study quality. While the PEDro scale offers a structured approach to assess the methodological rigor of randomized controlled trials, Robvis complements this by offering a visual summary of potential biases, enhancing the ability to appraise and interpret the results of the systematic review critically. Utilizing both tools allows for a more nuanced and robust assessment of the studies, ensuring higher confidence in the findings presented.

Table 2. The Robvis tool of assessing risk of bias for methodological assessment.

Study	Random Sequence Generation	Allocation Concealment	Blinding of Participants and Personnel	Blinding of Outcome Assessment	Incomplete Outcome Data	Selective Reporting	Other Sources of Bias	Overall
Montoya et al. [32], 2022	Unclear	Unclear	High	Unclear	Low	Low	Unclear	High
Hyeyoung Lee et al. [33], 2018	Low	Low	Low	High	Low	Low	Unclear	Low
Sebastián-Romagosa et al. [34], 2020	Unclear	Unclear	High	High	Low	Low	Unclear	High
Norouzi-Gheidari et al. [35], 2021	Low	Unclear	High	Low	Low	Low	Unclear	Low

3. Results

3.1. Study Selection

The initial screening based on the key terms yielded 267 papers, out of which 189 were excluded following refinement based on the type of document analyzed and the identification of duplicates. The resulting 78 articles were analyzed and reviewed based on their titles, leading to the identification of 11 studies for further assessment based on their abstracts. Four studies, each of significant importance, were read in full and included in this literature review, as seen in Figure 1 (diagram). These studies focus on functional electrical stimulation in combination with virtual reality therapy for patients with limb sequelae following a stroke, providing valuable insights into this area of research.

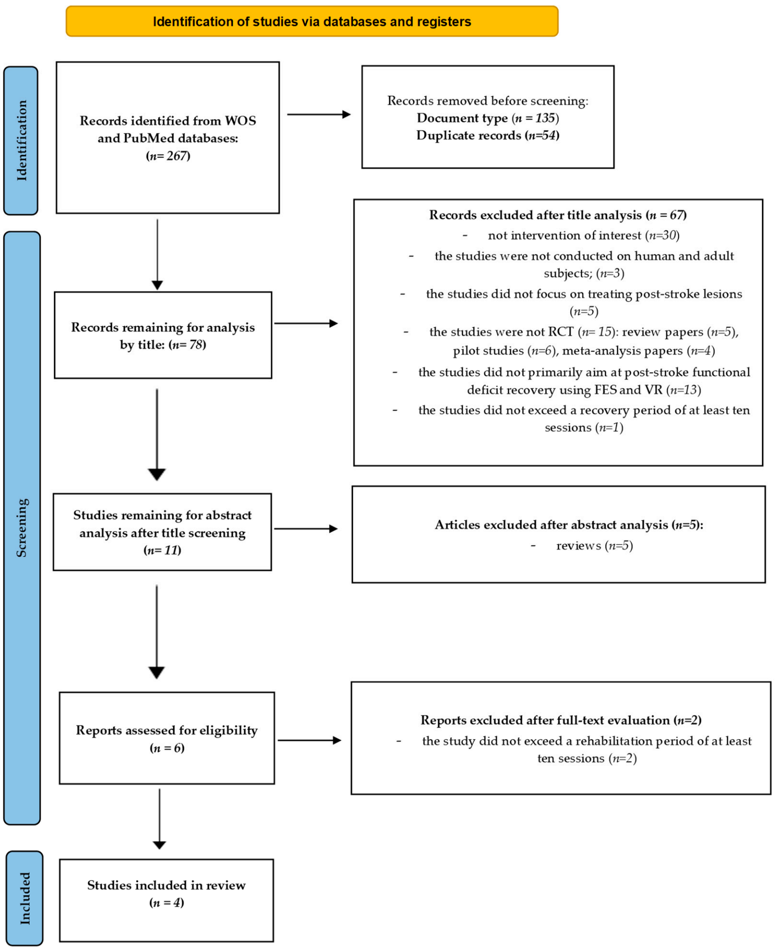

Figure 1. PRISMA diagram flow.

3.2. Main Characteristics of Included Studies

In the research, a total of 135 participants diagnosed with stroke were evaluated across 4 studies. The studies, published between 2018 and 2022, included various interventions for stroke rehabilitation. One study used multiple stimulation channels to the affected upper extremity. At the same time, the patient pedaled with the affected upper extremity on a bicycle and engaged in exercises through immersive virtual reality [32]. Another study utilized the RAPAEL Smart Glove gaming VR system, where patients interacted in a VR environment using a wearable glove-like device at the wrist joint. Each training session in this study involved three different VR training scenarios while the therapist manually operated the FES device [33].

Similarly, patients in another study underwent robotic therapy combined with VR intervention [34]. In a separate study, all patients underwent EEG during the rehabilitation session. Electrodes were applied to the extensor muscles of both hands for electrical stimulation, and patients were required to perform hand extension movements based on indications from a virtual reality system [35]. The researchers presented various options in their articles regarding comparison group interventions. Some studies did not include control groups, while others used electric stimulation through automatic cycling to induce muscle contraction or combinations of rehabilitation programs based on the upper limb's ability to function. The essential data, characteristics, and results from the studies have been carefully extracted for easy reference in Table 3.

Table 3. Characteristics of the randomized controlled trials.

Study, Year, and Design	No. of Participants	Interventions/Comparison Supervision	Assessment Methods	Key Results
Montoya et al. [32], 2022	- *N* = 13 - Age (years): *SG:* 56.61 ± 14.16 - sex: 4 F., 9 M - Time since Stroke: 1–4 years	**16 therapy sessions, 2/week, for 60 min/ session** During each session, two types of activities were performed: **(1)** Application of ***multi-channel FES*** in the paretic upper limb (wrist flexors, elbow extensors, shoulder flexors, and extensors using hydrogel electrodes) for 30 min. The FES therapy used a motorized upper limb cycle ergometer (MOTOMED Viva2 REck) and a 6-channel functional electrical stimulator (TRAINFES 6 channels) for active exercise; **(2)** Exercises through ***immersive VR*** (VR goggles) for 30 min, during which muscle groups of the affected upper extremity were trained;	A VICON system was used to assess movement on the following scales: (1) Sit-to-Stand Functional Reach Test; (2) Apley Scratch Test/Dawbarn Test—for evaluating the range of motion of the shoulder joint; (3) FMT; Furthermore, a comprehensive analysis was conducted, encompassing maximum joint angles (°), angular velocity (rad/s), and execution time (s)	The affected limb's movement consistently increased after therapy when the *p*-values were below 0.05 in the Wilcoxon test, with significant improvements noted in the: - maximum angles - range of motion - and angular velocities
Hyeyoung Lee et al. [33], 2018	- *N* = 41 - Age (years): *SG:* 49.5 ± 13.7 *CG:* 46.1 ± 13.0 - sex: 18 F., 23M.	**20 therapy sessions × 5 times/week × 30 min.** **Study Group (VR-FES):** The therapist used the RAPAEL Smart Glove gaming VR system on the wrist joint for 10-min training sessions. They manually operated the FES device to provide stimulation during wrist extension in the game. **Control Group (FES):** Electric stimulation through automatic cycling was provided to induce muscle contraction using biphasic pulsation (frequency 50 Hz, pulse duration 200 µs) for 6 s.	- FMT—UE; - WMFT—focuses on motor deficits assessed during ADLs; [20] - BBT; - JTT—for assessing distal upper limb ability; [21] - SIS—a questionnaire assessing disability and health-related quality of life after stroke; [22]	- compared to FES alone, VR-FES resulted in a more significant increase in FMA–distal score (p = 0.011) and a marginal improvement in JTT–gross score (p = 0.057); - VR-FES also led to more pronounced improvements in all other outcome measures, except in the SIS–ADL/IADL score; - VR-FES can improve specific gross motor functions by targeting the wrist and hand without requiring finger individuation;

Table 3. *Cont.*

Study, Year, and Design	No. of Participants	Interventions/Comparison Supervision	Assessment Methods	Key Results
Sebastián-Romagosa et al. [35], 2020	- *N* = 51 - Age (years): 60.52 + 16.7 - sex: 23 F., 28M.	**25 therapy sessions × 2 times/week × 30 min** All patients underwent EEG during the rehabilitation session. Electrodes were applied for electrical stimulation on the extensor muscles of both hands (frequency of 50 Hz and a rectangular pulse width of 300 µs), and patients were required to imagine performing the hand extension movement based on the indications of the virtual reality system.	- FMT—UE; - N–HPT; - BBT; - MAS; - Barthel Index; - Fahn Tremor Rating Scale; - Two-point Discrimination Test for evaluating sensitivity; - SCWT and MOCA to assess cognitive ability; - Self-assessment questionnaire of global post-stroke conditions;	- FMA-UE showed a significant increase in upper limb motor function by 4.68 points (SD = 4.92); - Improvements in finger and wrist spasticity were observed, correlating with performance in motor assessments like BBT and 9HPT; - There was no increase in spasticity in the months after completing the therapy;
Norouzi-Gheidari et al. [34], 2021	- *N* = 30 *Group with low potential for rehabilitation: N* = 18; *Group with good potential for rehabilitation: N* = 10;	**12 therapy sessions × 3 times/week × 1 h/session** **The group with low rehabilitation potential/Group performing movements only from the shoulder joint** received 60 min. of robotic therapy, and those who could mobilize their arm against gravity also received VR intervention (30 min. of robot therapy + 30 min. of VR therapy). **Group with good rehabilitation potential/Group performing movements from the entire upper limb** received approximately 30 min. of robotic therapy, followed by 30 min. of combined VR therapy with NMES. Electrodes were used to activate finger and wrist extensions during VR activities. Muscle stimulation was triggered when participants attempted to grasp objects on the computer screen.	- FMA-UE; - Abilhand Questionnaire; - MAL—a subjective test measuring the functional performance of an individual's upper limbs in real-life situations; [24] - SIS; - BBT; - Gross hand grip strength of the affected hand, measured with a dynamometer;	- The results showed that the intervention was safe and well-received by participants; - The study underlines that both robotics and VR activities are enjoyable and potentially beneficial;

SG: study group; CG: comparison group; F: feminine; M: masculine; VR: virtual reality; FES: functional electrical stimulation; FMT: Fugl-Meyer Test; WMFT: Wolf Motor Function Test; ADLs: activities of daily living; BBT: Box and Block Test; JTT: Jebsen Taylor Test; SIS: Stroke Impact Scale; N–HPT/9HPT: Nine-Hole Peg Test; MAS: Modified Ashworth Scale; SCWT: The Stroop Color-Word Test; MOCA: Montreal Cognitive Assessment; EEG: Electroencephalography; FMA-UE: Fugl-Meyer Test for upper extremity; MAL: Motor Activity Log; NMES: Neuromuscular Electrical Stimulation.

3.3. The Quality of the Studies

Our research, which has explored the integration of VR and FES into standard rehabilitation, has the potential to revolutionize patient care. Despite the lack of standardized protocols and the inclusion of a small number of patients in the studies, one of the aims has been to enhance patient engagement. This, in turn, could lead to higher commitment rates and potentially better outcomes. The immediate feedback provided by VR, coupled with the muscle re-education and strength improvement facilitated by FES, has shown promise.

The risk of bias assessment for the four studies included in this systematic review shows considerable heterogeneity in their methodological quality (Table 2). Two studies [32,35] exhibit a high risk of bias, particularly in critical areas such as blinding of participants and personnel and outcome assessment. This raises concerns about the internal validity of their findings, potentially limiting the generalizability of their results. In contrast, the other two studies [33,34] demonstrate a low risk of bias across most domains, suggesting a more reliable methodology and potentially stronger evidence.

The significant variation in study quality complicates the ability to draw definitive conclusions from the collective data. The high risk of bias in half of the studies could potentially skew the overall findings. Therefore, while the results provide some insights, it is crucial to interpret them with caution. Further research with more consistent and rigorous methodologies is essential to validate the effectiveness of virtual reality combined with functional electrical stimulation in rehabilitation.

3.4. Assessment Methods

Assessment tools, such as assessment scales, have consistently demonstrated subjective enhancements in outcomes following targeted treatments. In the selected studies, numerous assessment scales were used to identify and quantify the degree of motor deficit, providing valuable insights into the effectiveness of treatment interventions. Except for one study, all used the Fugl-Meyer Assessment for Upper Extremity (FMA-UE), developed by Axel Fugl-Meyer and his colleagues in 1975 [36]. This standardized method assesses stroke recovery through direct performance observation, determining disease severity, describing motor deficits, and planning and evaluating treatment. The FMA-UE is a widely accepted and validated tool in the field of stroke rehabilitation, making its consistent use in studies a significant factor in the reliability of the findings [37].

Montoya et al.'s [32], 2018, study involved 13 post-stroke patients in 16 therapy sessions with multi-channel FES and immersive VR exercises. The intervention significantly improved upper limb motor function, with FMA scores increasing by an average of 15 points ($p < 0.05$). Despite some limitations, such as a small sample size and a short follow-up period, which hindered the assessment of long-term effects, the study's findings are valuable. Similarly, the study by Hyeyoung Lee et al. [33], 2018, showed that VR-FES led to a more significant increase in FMA–distal score ($p = 0.011$) compared to FES alone. The other two studies also significantly increased upper limb motor function, expanding our knowledge about using the right assessment tool in stroke rehabilitation.

Hyeyoung Lee et al. [33], 2018, used the RAPAEL Smart Glove system and manual FES to demonstrate improvements in daily living activities by assessing the dexterity and coordination of the upper limb. Similar assessment tools were also used in studies conducted by Sebastián-Romagosa et al. [35], 2020, and Norouzi-Gheidari et al. [34], 2021. The studies presented a wide array of assessment tools, including the WMFT for upper extremity function, BBT for gross manual dexterity, the JTT for hand function, 9-HPT for finger dexterity, the Barthel Index for activities of daily living, the Abilhand Questionnaire for hand function, and the MAL for quality of movement, to develop the efficiency of the rehabilitation program. These diverse and comprehensive assessment tools across the reviewed studies have proven effective in evaluating the outcomes of VR and FES interventions. Each tool demonstrated significant statistical improvements, providing robust evidence of the efficacy of these combined rehabilitation approaches.

All these assessments aim to highlight the progression of motor and functional status and to correlate the results obtained based on the evaluation of motor deficits while performing tasks related to daily activities. Although the presented studies vary in the number of patients, period, type, and intervention method, they all share a common goal: integrating VR and FES in upper limb rehabilitation for stroke patients.

3.5. Limitations and Effectiveness of Combining VR and FES

3.5.1. Effectiveness of Combining VR and FES

I. Enhanced Motor Function and Dexterity

Integrating VR and FES has proven highly effective in enhancing motor function and dexterity in stroke patients. Notably, studies by Hyeyoung Lee et al. [33], (2018), Sebastián-Romagosa et al. [35], (2020), and Norouzi-Gheidari et al. [34], (2021) have reported significant improvements in clinical assessments such as WMFT, BBT, and 9 HPT. These improvements underscore the potential of the combined VR and FES approach to enhance gross and fine motor skills, making it a potent tool in neurorehabilitation.

II. Increased Patient Engagement and Motivation

VR's immersive nature creates an engaging and motivating environment for patients, which is critical for successful rehabilitation [38]. Montoya et al. [32], 2022, and Hyeyoung Lee et al. [33], 2018, highlighted high levels of patient engagement and adherence to rehabilitation programs. The interactive and adaptive VR systems kept patients motivated and committed to their therapy, which is essential for achieving significant functional gains.

III. Neuroplasticity and Brain Function Improvements

Sebastián-Romagosa et al. [35], (2020) demonstrated that integrating EEG with VR and FES improved motor function and enhanced neuroplasticity. EEG data showed significant changes in brain activity patterns, indicating that this combined approach could facilitate recovery. These results support other work that indicates that BCI can play an essential role in cortical reorganization underlying functional improvement [39–41].

3.5.2. Limitations of Combining VR and FES

I. Small Sample Sizes and Study Designs

One common area of improvement across the studies we reviewed is the small sample sizes. These limited sample sizes make applying the findings to a broader population difficult. For example, Montoya et al. [32], 2022, only included 13 participants, while Norouzi-Gheidari et al. [34], 2021, had 30 participants. The small sample sizes reduce the statistical power and the ability to make general conclusions. To address this issue, future research should focus on larger, multi-center, randomized controlled trials to validate these findings and gain a more comprehensive understanding of the effectiveness of the combined VR and FES approach.

II. Long-term Efficacy and Follow-up

Another significant limitation is the need for long-term follow-up data. The studies reviewed primarily focused on short-term outcomes, with few providing insights into the sustainability of improvements. Longitudinal studies are necessary to determine whether the benefits of VR and FES are maintained over time and to assess the long-term impact on functional independence and quality of life.

III. Standardization of Protocols

The VR systems and FES parameters used across different studies vary considerably. For example, the VR scenarios, frequency, intensity, and pulse width of FES varied significantly between Montoya et al. [32], 2022, and Hyeyoung Lee et al. [33], 2018. This lack of standardization makes comparing results and drawing definitive conclusions difficult. Developing standardized intervention protocols would enhance the reliability and reproducibility of research findings. Integrating VR and FES into standard rehabilitation protocols could potentially transform post-stroke rehabilitation by providing engaging and effective therapy options.

IV. Potential for Cybersickness and Discomfort

It is important to note that VR can sometimes lead to cybersickness, characterized by symptoms such as nausea, dizziness, and visual discomfort. This potential discomfort can be a limiting factor for patient participation and engagement [42]. While not extensively reported in the reviewed studies, it is crucial to acknowledge that designing more user-friendly and comfortable VR systems remains a potential challenge that needs to be addressed to ensure the successful implementation of the combined VR and FES approach. It is essential to highlight that those researchers did not observe any adverse reactions or dropouts attributed to challenges in using VR technology devices. These issues can be effectively alleviated with appropriate design and diligent patient monitoring.

4. Discussion

This review concisely summarizes the effects of integrating FES with VR treatments for stroke patients compared to conventional or no interventions. It is important to note that VR training for stroke patients has been integrated with traditional methods, including conventional exercises and more advanced approaches like robotic-assisted gait training and functional electrical stimulation, all aimed at enhancing motor function. Further examination of the integration of these various approaches is needed, underscoring the importance of additional research in this field.

This study reviewed four studies investigating rehabilitation systems using exercises tailored to each patient through the combination of virtual reality technology with functional electrical stimulation devices in motor rehabilitation enhancement. The studies conducted on stroke patients included a varied number of subjects, ranging from 13 to 51. The duration of these studies ranged from 12 to 25 therapy sessions, depending on the objectives pursued.

The selected studies utilized various assessment scales to evaluate motor deficits meticulously. The FMA-UE scale serves as a critical index for assessing sensorimotor deficiency in individuals with a stroke history [43]. Furthermore, the WMFT, BBT, JTT, 9-HPT, Barthel Index, Abilhand Questionnaire, and MAL were employed as additional evaluation methods to craft a comprehensive rehabilitation program. In the studies conducted by S. Hyeyoung Lee et al. [33], 2018, and M. Sebastián-Romagosa et al. [35], 2020, passive movement resistance was also evaluated using the modified Ashworth scale, which is an essential factor in assessing the degree of disability, with a significant impact on the rehabilitation process [44]. These rigorous assessments aim to meticulously monitor the progression of motor and functional status during activities of daily living.

Despite using different functional tests and scales, Christine Smith et al. [45], 2019, and Thomas Schick et al. [46], 2022, focus on upper limb rehabilitation for stroke patients. Their shared objective is to evaluate the effectiveness of functional electrical stimulation (FES) in restoring upper limb ability. This can involve achieving a more comprehensive range of movements, enhancing existing movements, or the ability to grasp various objects, all of which can significantly improve a patient's quality of life, enabling them to perform daily self-care activities and more, a crucial aspect of their rehabilitation journey.

The results of both studies were promising. In Christine Smith et al.'s study [45], 2019, video analyses showed a significant improvement in upper limb movement range, while Thomas Schick et al. [46], 2022, used specific tests such as the Fugl-Meyer Assessment Arm Section Score (FMA-AS), BBT, and SIS German version to assess patient progress.

These positive outcomes should inspire optimism about the potential of FES and VR therapy for stroke rehabilitation.

Furthermore, FES, which employs electrical stimulation to activate pathology-related muscles, has demonstrated potential in enhancing muscle control, strength, and coordination, thereby assisting in rehabilitating motor function [47]. Conversely, VR therapy entails using computerized simulated environments to deliver interactive and captivating experiences for patients during rehabilitation exercises [48].

In 2011, Saposnik and Levin conducted a study to assess the effectiveness of VR in post-stroke rehabilitation. They performed a meta-analysis of randomized clinical trials that investigated the use of VR in post-stroke rehabilitation, comparing VR therapy with other interventions or no intervention in control groups. The study measured improvements in motor function, cognitive abilities, and quality of life as primary outcomes. The meta-analysis found that VR therapy had a significantly positive effect on motor function in post-stroke patients, and there was also a trend toward improvement in cognitive abilities and quality of life. However, these results were not always statistically significant. The study provided valuable insights into the potential benefits of VR therapy in post-stroke rehabilitation, suggesting that it could be a useful component of treatment plans for these patients [49]. A comprehensive review by M. Soleimani et al. evaluates randomized controlled trials (RCTs) comparing VR-based interventions to conventional therapy for upper limb rehabilitation post-stroke. The significance of the article lies in its comprehensive analysis and solid evidence base, demonstrating that VR is a promising and potentially more effective method for upper limb rehabilitation in stroke patients than traditional therapy. By highlighting the advantages of VR, such as increased engagement, personalized interventions, and better accessibility, the study paves the way for a more optimistic future in clinical practice, aiming to improve patient outcomes and quality of life. It also underscores the variability in VR intervention designs and the need for standardized protocols to enhance the comparability and effectiveness of these therapies [50].

Our research thoroughly analyzes the effects of associating FES and VR therapy for stroke patients. It meticulously compares this innovative approach with traditional treatment methods or no intervention. It provides a detailed examination of how the incorporation of FES and VR can impact the rehabilitation process for stroke survivors. The report explores the comparative outcomes and demonstrates how this comprehensive approach could enhance rehabilitation and offer additional benefits in post-stroke care.

The four articles on upper limb rehabilitation in post-stroke patients reveal several noteworthy aspects:

In the study by Sebastián-Romagosa et al. [35], 2020, the use of FES and VR was combined in an innovative approach for upper limb rehabilitation in stroke patients. This combination aimed to maximize therapeutic effects, providing patients with a complex and stimulating method to regain motor function. VR was integrated to offer a captivating and personalized environment for therapy. Patients participated in virtual tasks and activities to engage in the interactive and motivating practice of upper limb movements. In parallel, FES was used to complement VR therapy. Applying electrical stimulation to the affected muscles encouraged patients to activate their upper limb movements while interacting with the virtual environment. This allowed for better muscle engagement and reinforcement of the connection between brain signals and movements performed in the virtual environment. This study's combination of FES and VR had several synergistic benefits. On the one hand, FES provided additional muscle stimulation and facilitated the generation of controlled movements of the upper limbs. On the other hand, VR created an interactive and captivating environment for therapy, encouraging patients to practice their movements in a more motivating and involved manner.

Norouzi-Gheidari et al. [34], 2021 and Montoya et al. [32], 2022 investigated the feasibility and effectiveness of a combined approach involving VR, robotic therapy, and FES in upper limb rehabilitation in post-stroke patients. Both studies demonstrated that this combination can significantly improve upper limb function and functional independence.

Hyeyoung Lee et al.'s [33], 2018 study explores the effects of rehabilitation therapy using VR combined with FES on upper limb function in chronic stroke patients. Participants were randomized into two groups: an intervention group receiving combined therapy (VR and FES) and a control group receiving conventional therapy. The intervention group showed significant improvements in movement performance and hand dexterity compared to the control group, with Fugl-Meyer Assessment (FMA) scores for the distal portion and Jebsen Taylor Test (JTT) scores increasing significantly, thus achieving a significant improvement in motor function.

These studies collectively underscore the potential of innovative technologies such as VR, robotic therapy, and FES in rehabilitating upper limbs in post-stroke patients. Combining these techniques can significantly enhance motor rehabilitation and functional independence, inspiring new perspectives in post-stroke rehabilitation therapies.

Certain limitations exist in this systematic review, and their potential impact on the field of post-stroke rehabilitation is significant. First, the small sample size, with only four studies involving 135 participants, limits the generalizability of the findings, necessitating further research with larger cohorts. Additionally, the variability in VR and FES intervention protocols across the included studies makes direct comparisons challenging, and the lack of long-term follow-up data prevents an assessment of the sustained effects of these therapies. The heterogeneity of stroke patients in terms of severity, time since stroke, and specific motor deficits introduces further variability that may impact the outcomes. Moreover, due to the inclusion criteria of English-language publications and specific databases, potential bias in study selection may have excluded relevant studies. The technological limitations, including differences in the quality and availability of VR systems and FES devices, also affect the findings, as does the high cost, which could restrict broader clinical application. Finally, the limited scope of outcomes assessed, primarily focusing on motor function, may overlook other crucial aspects of stroke recovery, such as cognitive function and psychological well-being. Addressing these limitations in future research is essential for enhancing the reliability and applicability of the results regarding the combined use of VR and FES in post-stroke rehabilitation.

5. Conclusions

Rehabilitation following a stroke is essential for enhancing the quality of life and restoring function and independence in patients. The combination of two technologies, functional electrical stimulation and virtual reality therapy, holds the potential for synergistic effects in post-stroke rehabilitation. By integrating these two methods, patients may benefit from the complementary effects of both technologies, offering an innovative, personalized, and practical approach to facilitating motor and cognitive rehabilitation. Their combination could amplify the benefits and prove to be a promising approach for improving patients' quality of life and independence after a stroke.

Additional research is required to thoroughly examine the potential benefits of combining FES with VR for stroke patients. Furthermore, it is imperative to investigate these two areas of study with larger groups of participants and over more extended periods to gain a more comprehensive understanding of their effects. However, further research is necessary to assess the impact of FES combined with VR on stroke patients. Moreover, it is crucial to approach these two topics in larger cohorts and with extended follow-up of participants.

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