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Review

Virtual reality as a non-conventional rehabilitation for stroke: A comprehensive review

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ABSTRACT

Stroke survivors often experience debilitating neural, physical, and cognitive impairments, particularly affecting upper limb functions. Conventional rehabilitations, though effective, are perceived as slow and monotonous by stroke survivors. This review explores the potential of Virtual Reality (VR) as an engaging rehabilitation approach to address such limitations. Our findings show that VR-based rehabilitations can be beneficial in restoring post-stroke upper limb functions and improving routine life of survivors. Moreover, VR offers adaptability, and user-friendliness across age groups. However, further research with larger sample size studies and stronger evidence base is needed to definitively establish the effectiveness of VR in post-stroke rehabilitation.

1. Introduction

Cerebral circulation, the blood flow within the brain is crucial for maintaining the proper functioning of human tissues, limbs, and organs. Interruption of this blood flow can result in unconsciousness and irreparable damage to brain cells known as neurons.[1] This cessation of blood flow can lead to a stroke, also known as Cardiovascular Accident or Brain Attack, characterized by either reversible or irreversible paralysis. Additional symptoms of stroke include dizziness, loss of consciousness, coma, physical disruption (such as muscle weakness, changes in movement, and coordination issues), cognitive deficits, visual disturbances, urinary complaints, and in severe cases, death.

A stroke can be classified as either ischemic i.e., caused by a disruption in blood flow to the brain due to thrombus or embolus) or hemorrhagic involving the leakage and accumulation of blood in localized areas.[2] Stroke represents a medical emergency that often correlates with advancing age, hypertension, high blood cholesterol, and diabetes mellitus. Approximately 20% of acute stroke patients may succumb within a month, and at least 50% of stroke survivors may experience prolonged physical disabilities.[3] The effects of stroke are particularly pronounced in the upper extremities (UE) including the upper arm, lower arm, and the hand.

Stroke survivors undergo a variety of progressive and dynamic rehabilitation aimed at restoring their neural, physical, and, cognitive functions. These rehabilitations are diverse and often

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combine autonomous learning processes[4] including restoration, switching and restitution. Consequently, a ‘one size fits all’ rehabilitation approach may not be suitable for every survivor. Instead, a combination of conventional and non-conventional rehabilitations[5] may be a more prudent option for managing post-stroke complications.

Rehabilitation plays a crucial role in maintaining or enhancing the functioning and independence of stroke survivors thereby promoting overall health.[6] While conventional rehabilitation approaches are effective for many, they are often perceived as monotonous, slow, and exhausting by some users. Recently, Virtual Reality (VR) based rehabilitations have demonstrated their effectiveness in enhancing upper limb (UL) motor functions and activities of daily living (ADL). This is attributed to their innovative approach, flexibility, real-time feedback, and user-friendly interface. VR is perceived as more responsive and interactive by stroke survivors due to its closer resemblance to physical reality.

This review, broadly discusses different types of conventional rehabilitations (CR) and non-conventional rehabilitations (NCR) aimed at restoring post-stroke UE functions. However, the primary focus of this review is on VR based rehabilitations in the form of combination of guided VR and CR, immersive VR, haptic feedback, and VR games all aimed at restoring various aspects of post-stroke UE functions, such as physical impairments, neuronal/cognitive rehabilitation, motor functions, gait disorders, attention deficits, mental perception, anxiety, etc.

2. Post stroke rehabilitations

2.1. Conventional rehabilitations (CR)

CR are normally free of medications, surgeries and sophisticated equipment i.e., electronics, diagnostic tools, etc. CR cover a wide range of post-stroke restorations such as language and/or speech disorder[7,8] with ‘Speech Therapy’, physical and functional movements[9] through 'Physical Therapy', and motor functions and individual skills[10] by 'Occupational Physical Therapy' (Fig. 1).

While CR can be effective, their effectiveness may be limited by emotional strain, physical demands, fatigue, unrealistic expectations, boredom, and the need to commute to and from therapists.[11] Additionally, a significant number of post-stroke survivors discontinue these rehabilitations due to a decline in determination, morale and will-power.[12] Therefore, considering NCR becomes essential.

2.2. Non-conventional rehabilitations (NCR)

NCR encompass a range of approaches targeting autonomous, cognitive, and neural aspects, including motor and gait functions, attention levels, and mental perception, These rehabilitations involve methods such as knowledge acquisition and information recall using robots, mirrors, electrical or magnetic stimulations, neural feed-back, electromyography (EMG), VR, etc (Fig. 2).

2.2.1. Robotic rehabilitation (RR)

The development and utilization of RR were driven by a shortage of therapists and other allied factors.[13] These robots, including assistive, resistive, passive, and proportional types (Fig. 3). Assistive robots, like the Manus ARM (Assistive Robotic Manipulator), use bulky actuators to provide external force for tasks impossible for stroke survivors, but they are unsuitable for in-home use due to their weight and cost.[14–17] In contrast, resistive robots offer cost-effective in-home rehabilitation by applying resistance based on the user's capacity using lightweight actuators.[18,19] Passive robots, utilized for one-sided hemiplegia, execute pre-determined patterns to reduce

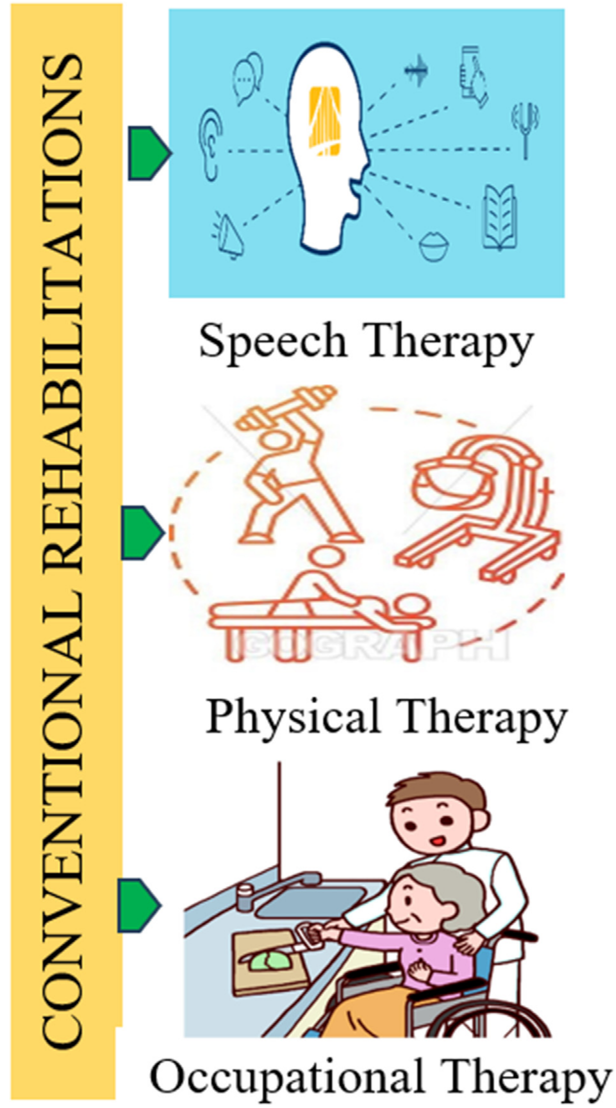

Fig. 1. Conventional rehabilitations.

muscular stiffness and spasms without user effort.[20–22] Proportional robots, extracting signals from muscles like biceps and triceps, provide adjustable support within a comfort zone for precise positioning and grasping to prevent objects from dropping.[23–25]

2.2.2. Mirror therapy (MT)

MT is a cost-effective and drug-free rehabilitation that enhances neural illusion. It involves the affected limb mimicking the movements of the unaffected limb, improving control over the impaired limb.[26,27] This therapy positions the unaffected limb in front of mirrors to create a mirror image, enhancing the illusion.[28] Advanced MT uses a brain-computer interface (BCI) with electroencephalogram (EEG) signals, motors, and accelerometers to compensate for positional status (Fig. 4). However, the effectiveness of this rehabilitation is limited to UL specifically the impaired hemisphere and motor functions.

2.2.3. Graded motor imagery (GMI)

GMI differs slightly from MT. It is a sequential treatment procedure that includes left/right image discrimination, imagined movements and MT.[29] GMI has proven effective in treating Complex Regional Pain Syndrome (CRPS), in individual users.[30]

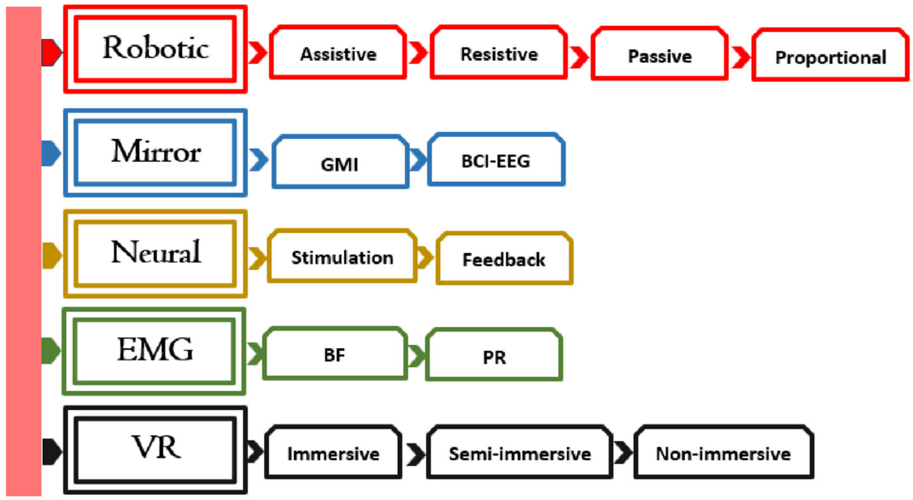

Fig. 2. Non-conventional rehabilitations. BCI-EEG, brain–computer interface-electroencephalography; BF, biofeedback; EMG, electromyography; GMI, graded motor imagery; PR, pattern recognition; VR, virtual reality.

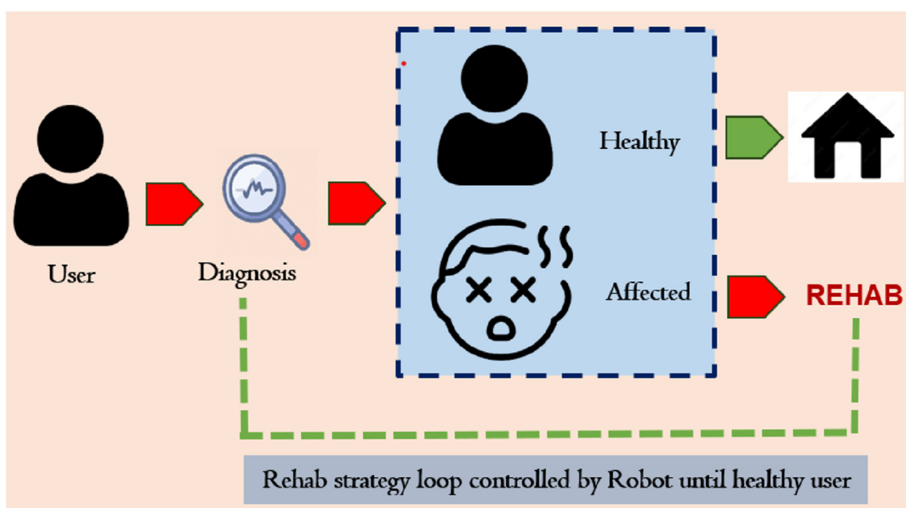

Fig. 3. Schematic of robotics-robotics based rehabilitation.

2.2.4. *Neuro-stimulations and feedback*

Neuro-stimulations modulate pain signals and deliver precise electrical or magnetic stimuli to specific neurological sites, employing both invasive and non-invasive methods.[31] Neuro-feedback (NF) leverages the brain's neuro-plasticity to re-organize cortical connections, offering innovative avenues for post-stroke rehabilitation.[32] NF interacts directly with the brain extracting information from the Sensory Motor Rhythm (SMR) to effectively modify the user's brain signals and achieve desired effects (Fig. 5).

2.2.5. *Electromyography (EMG)*

EMG offers an effective and innovative approach in post-stroke rehabilitation.[33] EMG involves the use of electrodes to record muscle electric impulses which are then converted into a visual or auditory representation. These rehabilitations can be non-invasive such as surface EMG (sEMG) which is commonly used for UL movement assessment and rehabilitation.[34,35] Invasive methods, like intramuscular EMG (iEMG), provide more accurate signals but are less accepted due to their invasive nature.[36,37] EMG signals are processed in both frequency and time domains with the choice depending on the information needed.[38] For simple muscle activation profile, time domain information is sufficient. EMG-Biofeedback (EMG-BF) allows modification of sub-conscious body processes for conscious control aiding in UL function recovery.[39] EMG Pattern Recognition (EMG-PR) helps detect direction errors in muscle movements, offering efficient functional recovery[40] when intended and actual movements do not align (Fig. 6).

2.2.6. *Virtual reality (VR)*

VR creates a stereoscope (3-D) environment through computer graphics, enhanced by machine interfaces like glasses, screens, projectors, gloves, helmets, and virtual environments (Fig. 7). In post-stroke rehabilitation, users easily recognize these simulated environments.[41] VR can be immersive (no real-world reference), semi-immersive (partial real-world reference), non-immersive (complete real-world reference), and haptic (involving touch sensation and vibration).

3. Review methodology

Almost 50% of stroke survivors experience prolonged physical disabilities and motor impairments, with 30% suffering from

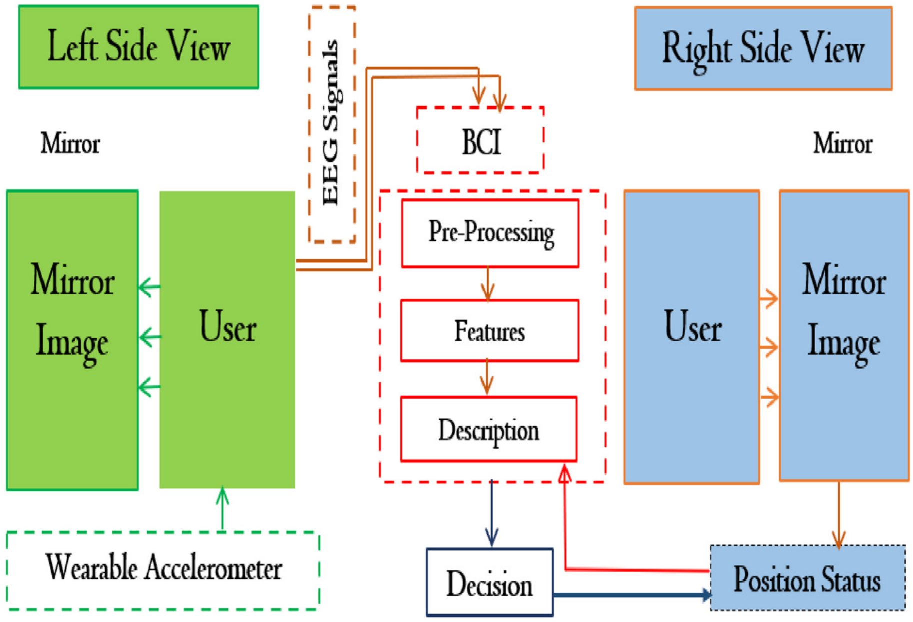

Fig. 4. Mirror therapy-(MT) based rehabilitation with a brain–computer interface (BCI) and accelerometer.

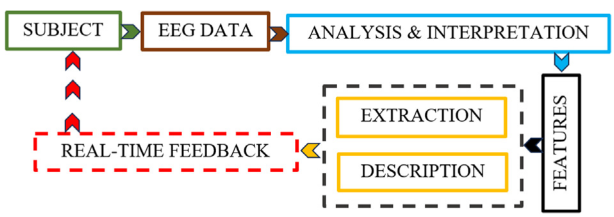

Fig. 5. Neurofeedback (NF) training loop.

hemi-paralysis of the UL.[42,43] Emotional strain, physical demands, fatigue, and other factors often accompany these conditions necessitating attention.[44–46] VR is an NCR that can address to these challenges through tailored education, training and assessment.[47] This review explores VR for restoring post-stroke UE functions, including disruptive motor functions, neural rehabilitation, gait disorders, attention deficits from traumatic brain injuries (TBI), mental perception, and anxiety, by comparing with CR in terms of fatigue, monotony, boredom and user-friendliness. The following sections outline the review methodology, including guidelines, data collection methods, and variables such as types of disorders, rehabilitation areas, types of VR rehabilitations and tools utilized.

3.1. Review guidelines, approach and data

This review adheres to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines.[48] It includes literature published from 2001 to 2023 in reputable peer-reviewed forums such as Springer, PubMed, IEEE, Science-direct, etc., using specific keywords like stroke, VR rehabilitation, neural rehabilitation, motor impairments, CR, cognitive domain, etc. Articles applying VR rehabilitation to conditions other than stroke are excluded (Fig. 8).

3.2. Review variables and features

For this review, we considered variables such as the type of survivors/disorders including asymptomatic, stroke, perinatal

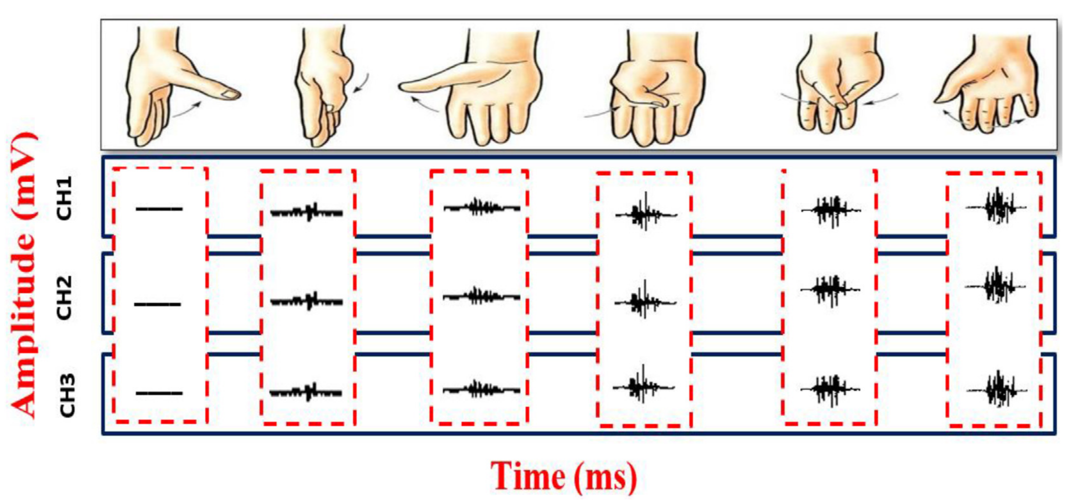

Fig. 6. EMG and kinematic data of hand patterns.

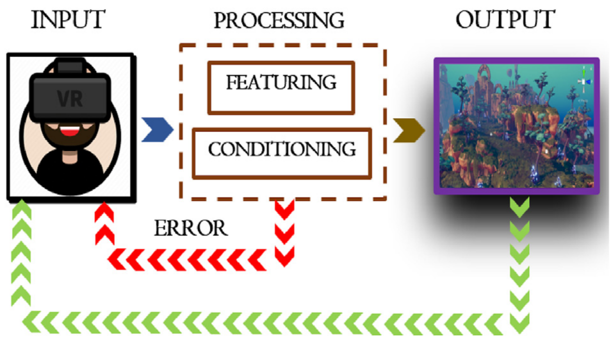

Fig. 7. Virtual reality (VR) machine interface.

stroke, motor functions, neural rehabilitation, gait disorders, attention deficits, mental perception, anxiety, TBI,[49] etc., VR tools/models (e.g., Play-Station, X-box 360, 3D glasses, projection screens, helmets, gloves, Unity platform, Motion Tracking Sensors, etc.), and the rehabilitation area (specifically UL).

3.3. Review scope (sub-heading added)

This review explores three aspects of VR based rehabilitations for maximizing post-stroke rehabilitation of UE (Fig. 9) including combined effects of guided VR and CR, the role of immersive VR and haptic feedback and the contribution of VR games.

4. Review of VR based rehabilitations

Following sections cover in detail the VR based rehabilitations for post-stroke restoration of UE.

4.1. Guided VR and CR

Training of stroke survivors through a structured educational process is crucial for effective VR utilization. Guided VR education can enhance rehabilitation outcomes and serve as a universal language for stroke prevention. A pioneering study[50] explored the impact of guided VR education and visualizations using Head Mounted Display and X-box 360 on four stroke survivors from 2012 to 2017. The findings underscored the significant contribution of guided VR education in maximizing rehabilitation outcomes and preventing recurrent stroke. Moreover, the study highlighted the synergistic effects of VR rehabilitations and standard physiotherapy in neuro-rehabilitation of UL motor functions and TBI. Proper VR training and education can also benefit users with attention deficits due to TBI. Another study[51] evaluated user performance in vigilance task using head-mounted displays, tracking (head, hand, and leg), and laptops in two clinical trials. Similarly, research[52–54] investigating the combined effects of VR and CR on UL motor recovery neuro-rehabilitation indicated supplemental benefit for stroke patients than the same amount of CR alone except in[55] as there were no significant differences in improvement between both groups including VR group (VR + CR) and control group (CR only). However, the participants found VR training useful and enjoyable, with no serious adverse effects reported.

The assessment of time taken by users to perform a task is crucial for evaluating smooth muscle movement. Completing a task quickly indicates improved smoothness in muscle movements and restoration of UL motor functions. A study[56] demonstrated significant recovery in UL motor functions and movement smoothness for three users using a ‘Pick and Place’ task in a VR environment created with Microsoft Visual C^{++}. Another study[57] established a

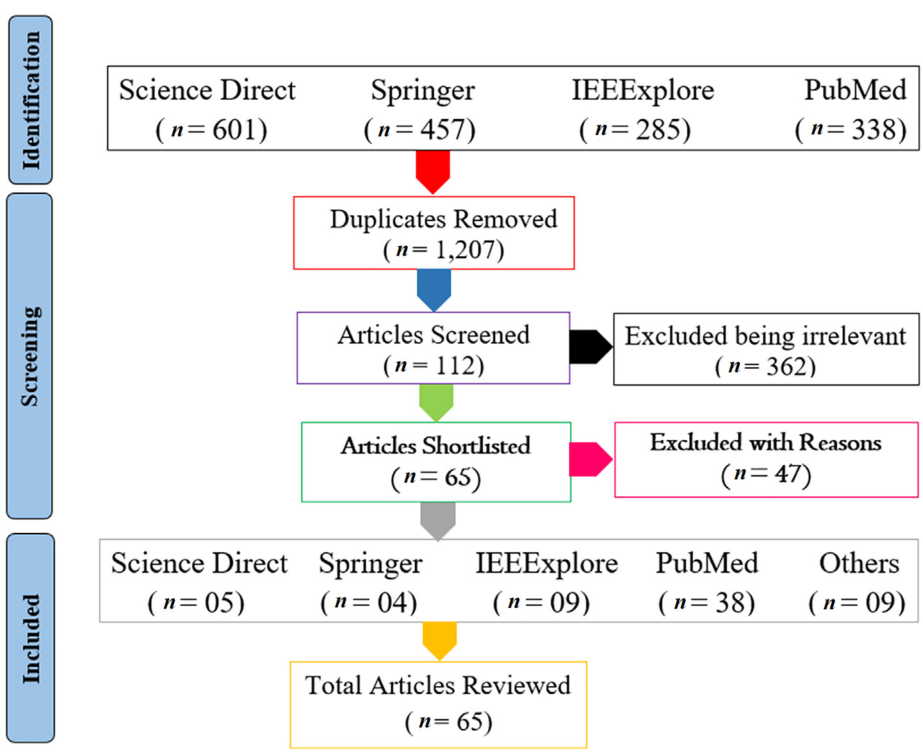

Fig. 8. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) – Review Guidelines.

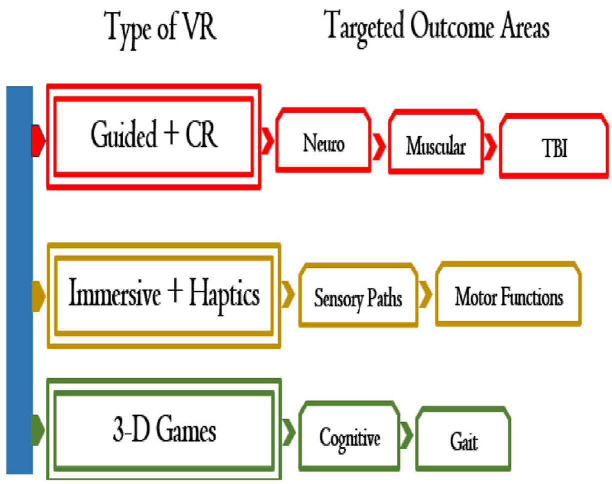

Fig. 9. VR features and their targeted outcomes. CR, conventional rehabilitation; TBI, traumatic brain injury.

significant relationship between training time and movement frequencies of users, aiding in the assessment of UL movements. This study successfully evaluated the benefits of VR using Jintronix Inc., Microsoft Kinect II camera application, and Fugl-Meyer Assessment Upper Limb (FMA-UL).

4.2. Immersive VR and haptic feedback

The utilization of immersive VR and haptic feedback can significantly benefit individuals in their daily lives, overall heath, and rehabilitation progress.[58] Immersive VR adaptations, completely engross users in a virtual 3D environment, potentially aiding in the restoration of motor functions and cognitive abilities. The immersive VR-based exercise system is a potentially effective, safe and acceptable approach for supporting post-stroke motor rehabilitation.[59] Research by Rachel et al.[60] demonstrated neurological rehabilitation benefit for stroke and spinal cord injury survivors using various virtual rehabilitations through Gesture Xtreme VR applications Similarly, studies[61,62] reported positive outcomes from an immersive VR rehabilitation using the Unity game engine and Kinect-based game system in addition to CR. Furthermore, glass-free systems with Leap Motion Controller (LMC) have shown promise in real-time feel provision during VR training, effectively capturing hand and finger motions and aiding in restoring UL motor functions, as demonstrated in.[63]

In chronic upper limb complications, even minor muscle movements are often restricted hindering muscle recovery.[64] Virtual haptic effects can help overcome these limitations by simulating force, torque, and position gradients. A study involving[65] three users utilized ankle-based haptic feedback VR interaction using joysticks to generate low-level (impedance, stiffness and vibrations) and task-level (simulations, jolts, and turbulence) haptic effects. Furthermore, mental perception plays a crucial role in an individual's behaviour and understanding of objects or events, affecting sensory or cognitive responses. Designing an efficient haptic interface is essential for reliable perception, as demonstrated using Sensable Phantom haptic device. Critical variables such as direction, force magnitude, and the ability to measure the minimum difference between stimuli (e.g., base and increment/decrement) were considered.[66]

4.3. VR games

Mobile health (mHealth) technologies offer a cost-effective, easily accessible approach to supporting health and healthcare. Incorporating human factors engineering and user-centered design can significantly enhance the effectiveness and efficiency of mHealth technology.[67] The number of health-care VR applications[68] has been steadily increasing since 2016 (added input from two papers i.e., 106–107 in the manuscript based on the guidance provided by the worthy reviewer). VR games have introduced an engaging, innovative dimension to post-stroke UE restoration. A task-oriented VR gaming system[69] using a CCD camera, data gloves and optic fiber on the Torque Game Engine demonstrated benefits in restoring UL motor and cognitive functions while improving the ADL. Lin et al.[70] explored the prospective use of an interactive, feedback-based VR gaming system based on C programming, motion tracking devices, EEG and the unity game development tool for post-stroke UL restoration. This system was successfully tested on fifteen users divided into three groups. Additionally, the effectiveness of a mobile, time efficient, user-friendly, VR based game program for UL rehabilitation using tablet PC displays and built-in smartphone motion sensors has been reported.[71] This program provides guided VR therapy under clinical guide from any remote location due to its mobile architecture.

Shahmoradi et al.[72] developed five VR games using the Unity game development tool and Kinect motion tracking sensor to explore the potential of VR games in post-stroke rehabilitation, aiming to improve UE performance. The game contents were designed based on expert feedback from physiotherapists and game designers, gathered through a literature-based survey. VR games can also benefit individuals with TBI and gait disorders. For this purpose, an accurate assessment of balance and correct posture is crucial. A gaming system utilizing force platforms, balance boards, and wireless bluetooth data protocols has been developed to calculate an individual's center of pressure.[73]

5. Discussion

After reviewing selected articles, the impact of VR rehabilitations for restoring post-stroke UL complications has been established. CR are progressive, dynamic, and repetitive which can lead to fatigue, monotony, and boredom. However, virtually none of the users reported any complaints regarding these aspects when using VR based rehabilitations. VR adaptations are typically highly user-friendly, allowing individuals of any age group to easily adapt to its requirements. The findings suggest that VR can be an effective, interactive, and intelligent NCR for restoring post-stroke UL complications. These findings are consistent with previous studies.[74–78]

Stroke-survivors typically receive information about stroke either after experiencing it or upon hospital admission.[79] However, achieving desired awareness at this stage may be challenging due to affected cognitive domains, emotional stress, and mental strain. Early education for care-givers can partially compensate for this lack of awareness.[80] The time taken by users to perform specific task is a crucial indicator of movement smoothness.[81] This time can be significantly reduced through coordinated movement between various muscles, such as shoulder and elbow, as well as through greater intensity and duration of training.[82] As a result, users may experience improvements in grasping, lifting, carrying and eating with their hands.

Our findings indicate that the combination of VR and CR is more effective than conventional programs alone in restoring UL motor functions,[54,56,57] including arm movements, smoothness, shoulder abduction & adduction, and wrist and elbow flexion. However, achieving these aspects can be further enhanced through VR education, which requires prior guidance and training. This approach can lead to improved user satisfaction, better understanding of stroke risks, reduced anxiety, and no reported side effects.

Attention deficits due to TBI are a significant health concern across all age groups particularly in the elderly, as they may lead to dementia.[83] In addition to the elderly population, assessing and rehabilitating attention deficits in children is crucial for educational activities, decision making, cognitive learning, problem solving, perceptual processing, and memory development. However, accurate assessment and rehabilitation of attention deficits are limited by cost and time constraints. Highlighting the need for a natural and attractive clinical model[84] and health economic evaluations (HEE) to understand the value of the required intervention.[85] Such a model should efficiently challenge and target various types of attention levels, including focused, sustained, selective, alternating and divided attention. A combination of VR and CR has been found to be more effective than CR alone.[52–54] However, inconclusive results have also been found in this regard.[55]

Human haptic perception is directly related to the direction and quantum of force while the hand is in motion. Translating the human haptic system to measure the minimum difference between stimuli such as direction and force magnitude, is crucial for reliable perception. However, achieving this using VR and haptic displays, poses a major technical challenge.[86] Additionally, friction between the user and the haptic interface can disrupt the minimum threshold of human perception.[87] Therefore, designing and implementing a friction controlled haptic interface is necessary to achieve perceptual transparency. Several studies[65,66] have demonstrated the effectiveness of VR immersion and haptic feedback in functional recovery of UL, including improvement in balance, mobility, posture, situational presence, muscle strength, and cognitive functions. Moreover, none of the users reported any adverse reactions or difficulties in using either immersive or haptic VR platforms.

While VR systems improve UL functions and ADL in post-stroke users, their effectiveness in restoring hand functions is unsatisfactory.[76] Despite the use of VR gadgets with built-in sensors, the complex anatomy of the hand presents challenges in accurately capturing and simulating hands and finger movements.[88–90] As a result, users experience delayed and imprecise response from the VR system, leading to inconclusive outcomes.[91] However, the use of LMC based VR training systems[92] can accurately capture and simulate hand movements leading to improved individual evaluation scores.[93] Additionally, a significant correlation has been established between personal and FMA-UL scores[60,61,63] when assessing functional recovery of UE using immersive VR.

Previously, functional recovery of motor functions was not considered for chronic TBI survivors,[94] as it was primarily focused on acute patients with limited postural stability and gait disorders.[95] However, functional recovery is also achievable for chronic TBI survivors[96,97] using VR games. The effectiveness and duration of a rehabilitation routine can influence an individual's attitude and interest. Performing the same activity repeatedly over a long period may lead to a negative attitude among users. VR games can improve an individual's attitude towards rehabilitation and its effectiveness.[98–100] While customized VR games are effective, commercial games can also be used for rehabilitation,[101–103] although they may not target the desired part of the UE. VR games can aid in improving range of motion, memory and attention levels[104–106] by providing real-time feedback on muscle movements, enhancing learning and task execution, boosting motivation,[107] diverting attention from reality, and improving performance and efficiency better than CR.[108,109] Users can choose options, actively participate, enjoy, and play longer with VR games.[110] Moreover, VR games can motivate users to continue their rehabilitation routines by providing continuous and positive feedback through points and sounds while playing.[111,112]

Mobile, task-oriented, VR gaming systems, along with force platforms and feedback-based approaches, are effective in rehabilitating UL functions such as shoulder abduction & adduction, wrist flexion and elbow movements, as well as TBI. These games are designed based on expert feedback i.e., physiotherapists and game designers, gathered through an intelligently drafted literature-based survey. Our findings[69–73] also align with these aspects.

In the studies reviewed for this manuscript, most users found VR based rehabilitations useful and reported increased satisfaction with its various adaptations and visualizations. Additionally, very few users experienced or reported any negative side effects. A significant advantage of VR based rehabilitations is their acceptance and adaptability among users of all ages thanks to their engaging virtual environments that closely resemble reality.

The core constraint of this review was the smaller sample sizes of post-stroke survivors in many studies and the low to moderate evidence base of the selected articles. Future effort will aim to conduct reviews with larger sample sizes and higher evidence bases. Additionally, there is a need to explore the use ability of home-based UL tele-rehabilitation[113] i.e., smart reminder type wearable devices to reduce rehabilitation costs and long waiting times associated with CR.

6. Conclusion

Based on the comprehensive literature review and ensuing findings, it is established that disabilities resulting from stroke notably impact the UE. Given the limitations CR, VR based rehabilitations such as guided VR education, immersive environments, haptic feedback and gaming adaptations present a viable, intelligent, and interactive alternative for UL functions, These VR adaptations are characterized by user-friendly interfaces, making them accessible and adaptable across a wide range of age groups.

Nevertheless, it is prudent to consider a combination of CR and NCR to effectively minimize, restore, and improve post-stroke complications. Future research endeavors should focus on studies with larger sample sizes of stroke survivors and higher levels of confidence in the evidence from available literature. This approach will undoubtedly enhance and build upon the current findings.

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None.

Authors' contributions

Muhammad Altaf Hussain, Asim Waris, and Syed Omer Gilani were involved in the literature search and review process. They conducted comprehensive searches in relevant databases, identified key studies, and reviewed the literature on stroke-induced disabilities, rehabilitation interventions, and the application of virtual reality in post-stroke upper extremity restoration.

Shafaq Mushtaq, M. Ijaz Khan contributed to the critical analysis and synthesis of the reviewed literature. They analyzed the findings of the selected studies, identified common themes or patterns, and provided interpretations and insights regarding the effectiveness of virtual reality adaptations for post-stroke upper limb functions.

Amit N. Pujari and **Gulrux Daminova** emphasized the methodological aspects of their review article, ensuring that it adhered to relevant guidelines and frameworks. They also carefully examined and addressed any methodological limitations and biases present in the studies they reviewed.

Niaz B Khan: As the corresponding author and lead researcher, Niaz B Khan oversaw the entire review process. He coordinated the efforts of the research team, supervised the literature search and review, ensured the quality and accuracy of the information presented, and facilitated the collaboration among the authors. He is also one of the key-person who design the structure of the article.

Mohammed Jameel designed the structure of the review article and also assigned the task to each author. He also provided expertise and insights related to the clinical aspects of stroke rehabilitation. Also, he contributed to the interpretation of the findings in terms of their practical implications for stroke survivors and the healthcare professionals involved in their care. Overall, he was responsible to ensure the coherence in the study.

All authors contributed to the study conception and design. Material preparation, data collection and analysis. All authors read and approved the final manuscript.

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Declaration of competing interest

The authors declare no conflict of interest.

Data availability statement

All data generated or analyzed during this study are included in article.

Ethical approval

Not applicable.

Informed consent

Not applicable.

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