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A Standalone Immersive VR System for Upper Limb Stroke Rehabilitation

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***Abstract*—Stroke is a leading cause of long-term disability worldwide, frequently resulting in upper limb motor impairments that reduce patients' independence and quality of life. Effective rehabilitation requires intensive, repetitive, and task-specific training, which is often difficult to sustain due to limited accessibility and low patient motivation. This paper presents a standalone immersive virtual reality (VR) system designed to support upper limb rehabilitation through gamified activities of daily living. The system runs on a Meta Quest 3 headset and leverages controller-free hand tracking to enable natural interaction without external devices. It integrates task-oriented exercises inspired by established rehabilitation programs and provides real-time visual and auditory feedback to enhance engagement. A preliminary evaluation with stroke patients in a clinical setting assessed usability and feasibility. The evaluation demonstrated high user satisfaction and good tolerability, with no significant adverse effects, supporting the feasibility of the proposed approach. These findings suggest that immersive VR systems can complement traditional rehabilitation by improving motivation and adherence, highlighting the need for further large-scale studies.**

***Index Terms*—Hand Tracking, Serious Games, Stroke Rehabilitation, Upper Limb Rehabilitation, Virtual Reality**

I. Introduction

Stroke is the second leading cause of death in Europe and worldwide [27], and one of the primary causes of adult disability, particularly affecting individuals over the age of 55 [17]. Among its different forms, ischemic stroke is the most common, resulting from the partial or complete blockage of cerebral blood vessels. This interruption of blood flow prevents brain tissue from receiving adequate oxygen and nutrients, leading to rapid cell death and potentially severe long-term consequences if not promptly treated. Although approximately 70% of stroke patients survive, only a minority achieve full recovery, while the majority require prolonged rehabilitation. Motor impairment is among the most prevalent outcomes, with upper limb dysfunction affecting a large proportion of stroke survivors [1]. These impairments significantly hinder the ability to perform activities of daily living (ADL), such as reaching and grasping objects, due to reduced coordination and grip control [2]. In addition to motor deficits, conditions such as unilateral neglect may further compromise patients' ability to interact with their environment.

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From a neurological perspective, stroke can disrupt the primary motor cortex and parietal regions involved in movement planning and execution, as well as alter proprioception and the perception of peripersonal space [22]. These alterations affect the patient's ability to perceive and control limb movements, often resulting in a reduced sense of embodiment of the affected limb. Consequently, many stroke survivors experience difficulties in performing self-care activities independently, increasing reliance on caregivers and reducing overall quality of life. For these reasons, effective rehabilitation is essential to promote motor recovery and restore functional independence. In particular, repetitive, task-specific training has been shown to play a key role in improving motor performance [28]. However, traditional rehabilitation approaches often require significant time, resources, and sustained patient motivation, which can limit long-term adherence. Recent advances in Virtual Reality (VR) technologies offer new opportunities to address these challenges by providing immersive, interactive, and engaging rehabilitation environments. VR-based systems can support repetitive training while enhancing motivation through gamification and real-time feedback. In this context, this paper presents a standalone immersive VR system designed to support upper limb rehabilitation through natural interaction and activities inspired by daily life.

II. Background & Motivation

A. Stroke Rehabilitation

Post-stroke neurorehabilitation aims to restore functional independence through multidisciplinary interventions that address motor, cognitive, and psychosocial impairments [19]. In addition to physiotherapy focused on mobility recovery [4], rehabilitation programs usually include speech and cognitive

therapy, pain and stress management, and emotional support. For upper limb recovery in particular, rehabilitation is typically based on intensive, repetitive, and task-specific sensorimotor training designed to improve motor coordination and sensory integration [21]. Effective motor rehabilitation also depends on multisensory stimulation, immediate feedback, progressive difficulty adaptation, and personalization according to each patient's functional abilities [13]. These elements are essential both to maximize therapeutic benefit and to sustain motivation during prolonged rehabilitation. Engaging training experiences have been associated with better outcomes, but personalization must be carefully balanced because stroke and acquired brain injury survivors may present altered sensitivity to sensory stimuli [9].

Several well-established therapeutic approaches target upper limb recovery. Environmental enrichment strategies recreate familiar daily-life settings, such as kitchens or other domestic spaces, to encourage physical, cognitive, and social activity [10]. Constraint-Induced Movement Therapy (CIMT) is another major approach and remains one of the most effective treatments for paretic upper limbs; it is based on intensive use of the affected arm and on reducing reliance on the unaffected limb [8]. Mirror therapy has also been used to address unilateral neglect by providing visual feedback that promotes activation of the affected limb through the mirror neuron system [29]. In addition, Functional Electrical Stimulation (FES) can support rehabilitation by stimulating paretic muscles and facilitating movement, although it is generally used as an adjunct rather than a standalone treatment [5]. Despite their effectiveness, traditional rehabilitation approaches have some practical limitations. They often require substantial therapist involvement, dedicated environments, and sustained patient effort over long periods. Because rehabilitation exercises are inherently repetitive, adherence may decrease over time, particularly when activities are perceived as monotonous or disconnected from meaningful activities of daily living. As a result, there is growing interest in technology-based solutions that can deliver engaging, intensive, and potentially home-deployable rehabilitation experiences.

B. Virtual Reality for Neurorehabilitation

VR has emerged as a promising approach for stroke rehabilitation because it can provide engaging, interactive, and feedback-rich training environments. Early work on VR in rehabilitation dates back to the 1990s, and more recent studies have explored both non-specific VR systems, such as commercial gaming platforms, and rehabilitation-specific VR solutions designed to promote motor recovery [14]. Compared with conventional therapy, VR can support intensive and task-oriented practice while increasing motivation through immersion, gamification, and real-time feedback. VR systems for neurorehabilitation can be broadly divided into non-immersive and immersive approaches. Non-immersive VR typically presents the virtual environment on a monitor and relies on cameras or wearable devices to capture movement, whereas immersive VR uses head-mounted displays (HMDs) to increase presence and embodiment. In principle, immersive solutions better maintain engagement, while non-immersive systems often offer lower cost and simpler access [14]. However, the degree of immersion is only one design factor, as the tracking mode, adaptability, portability, and clinical feasibility also strongly influence the usefulness of a system.

C. Related Studies

Several studies have explored VR-based systems for upper limb stroke rehabilitation, particularly using immersive setups based on devices such as HTC Vive. For example, Ogun et al. [16] and Huang and Chen [12] reported improvements in motor performance when VR was combined with conventional therapy, highlighting the potential of immersive training. Other approaches have focused on more specialized rehabilitation designs, such as mirrored training for severely impaired patients [6] or task-specific exercises targeting joint range of motion [3]. While these systems demonstrate promising results, they often rely on external sensors, controllers, or additional hardware, which increases setup complexity and limits scalability. Moreover, some solutions require close therapist supervision or are designed for specific impairment levels, reducing their applicability in more flexible or home-based contexts.

Other works have focused on non-immersive or hybrid rehabilitation platforms. Rogers et al. [11] studied the *Elements* system, a tabletop interactive environment that combines tangible objects with augmented visual and auditory feedback. Their results suggested improvements in motor and cognitive performance, but the system is expensive, clinic-bound, and cumbersome to deploy. Qiu et al. [20] proposed the Home based Virtual Rehabilitation System (HoVRS), a home-oriented platform using a computer and Leap Motion Controller. HoVRS demonstrated good long-term adherence, algorithm-based difficulty adjustment, and remote data collection, but it lacks immersion and is less suitable for patients with severe impairments. Nourouzi-Gheidari et al. [18] evaluated the Jintronix system, a Kinect-based non-immersive rehabilitation platform, finding it feasible and safe but with inconclusive efficacy results and limited hand-tracking capability.

Prior work suggests that VR can increase engagement, provide meaningful feedback, and support upper limb rehabilitation after stroke. Nevertheless, several limitations remain recurrent across existing systems: non-immersive platforms are often affordable and adaptable but lack the sense of presence that may sustain long-term engagement, while immersive solutions frequently depend on external sensors, PCs, controllers, or other specialized hardware, thereby reducing portability and limiting deployment outside clinical settings. Furthermore, many systems do not adequately support fine hand movements, and several studies remain based on small samples or preliminary protocols. These gaps point to the need for more portable and accessible immersive solutions that combine natural controller-free hand tracking, task-oriented rehabilitation inspired by activities of daily living, and reduced setup complexity suitable for both clinical and potential home

use. The system presented in this paper was developed to address these needs through standalone headset-based VR and built-in hand tracking, without requiring external sensors or tethered hardware.

III. System Design

A. Concept and Design Rationale

The aim of this work was to develop a VR application to support upper limb rehabilitation after stroke as a complement to conventional physiotherapy, suitable for both supervised clinical use and unsupervised home-based rehabilitation. ReFlex VR is designed to encourage functional use of the paretic upper limb through repetitive, task-oriented exercises involving reaching, arm extension, and coordinated movements. These activities aim to promote upper limb mobility, movement coordination, movement speed, and active use of the affected limb during functional tasks. Rather than targeting muscle strength or fine grip control directly, the system focuses on movement patterns commonly incorporated into upper limb rehabilitation programmes.

A standalone VR headset (i.e., Meta Quest 3) was selected as the target platform to ensure portability, affordability, and ease of deployment, minimizing the need for external hardware or technical assistance. This choice is supported by prior work highlighting the benefits of immersive VR in promoting neuroplasticity and motor recovery through enriched multisensory feedback and a heightened sense of presence. To meet the constraints of standalone hardware, the application was designed to be lightweight and self-contained, avoiding reliance on external computation or cloud-based services. The system, named ReFlex VR, was designed as an immersive rehabilitation experience centered on repetition, motor engagement, and functional movement, with the goal of improving both user motivation and therapeutic outcomes.

B. Design Principles and Target Users

The design of ReFlex VR was guided by three main principles: ecological validity, accessibility, and engagement. Rehabilitation tasks were designed to closely resemble activities of daily living (ADLs), as familiarity has been shown to improve user acceptance and engagement [7]. Accessibility was addressed by eliminating the need for external controllers and minimizing setup complexity, allowing users to interact naturally using their hands. Engagement was supported through immersive environments, structured progression, and continuous feedback.

The system targets individuals with upper limb impairments resulting from stroke or traumatic brain injury. However, users are required to retain sufficient mobility to perform basic arm movements and to tolerate VR exposure. The application is not recommended for individuals with severe cognitive impairments or disorientation, as these conditions may be exacerbated by immersive environments. To address both motor and cognitive aspects of rehabilitation, the system includes different levels of guidance. A guided mode provides step-by-step assistance to support motor recovery, while a reduced-assistance mode encourages users to recall task sequences independently, introducing an additional cognitive component.

C. Interaction Design and Rehabilitation Tasks

ReFlex VR is structured as a set of goal-oriented scenarios within a domestic environment, each representing a sequence of activities of daily living. The application includes three main scenarios: a kitchen (Fig. 1), a coffee preparation area (Fig. 2), and a living room (Fig. 3). Across these scenarios, users perform a series of functional activities involving reaching, object manipulation, and coordinated upper limb movements to encourage active use of the paretic limb. Interactions were designed to be as natural as possible, relying on direct hand input rather than abstract controls. Activities such as picking up and placing objects promote shoulder and elbow range of motion, movement coordination, and active use of the paretic limb, while manipulating kitchen utensils, rotating handles, and pressing buttons encourage controlled grasping, wrist and forearm movements, and movement precision. These exercises provide repetitive, task-specific practice within meaningful everyday contexts, supporting improvements in upper limb mobility, movement coordination, and movement speed. Each scenario is organised as a sequence of subtasks that must be completed in order, providing a clear sense of progression. Upon completion, users receive performance feedback through a scoring system that reflects both task execution and movement quality. This is further translated into a star-based evaluation to provide an intuitive summary of performance and encourage continued engagement.



Fig. 1. Kitchen scenario illustrating task-oriented rehabilitation.

D. User Interface, Environment, and Feedback

The user interface combines traditional menu elements with in-world guidance mechanisms to maintain immersion while ensuring usability. In addition to standard UI panels, the system incorporates diegetic elements embedded within the environment, such as task boards that display objectives and



Fig. 2. Coffee preparation task. The user inserts the capsule, positions the cup, and operates the machine through natural hand interactions.

progress. This approach reduces cognitive load while preserving the sense of presence within the virtual environment. Feedback plays a central role in the interaction design. Visual cues, such as arrows and object highlights, guide the user through tasks, while auditory feedback provides confirmation of successful actions and corrective prompts when necessary. Background audio was intentionally minimized to avoid distraction, allowing users to remain aware of their physical surroundings. The level of guidance can also be adjusted, including a mode with reduced or no assistance, to support users with varying levels of ability and promote progressive independence.

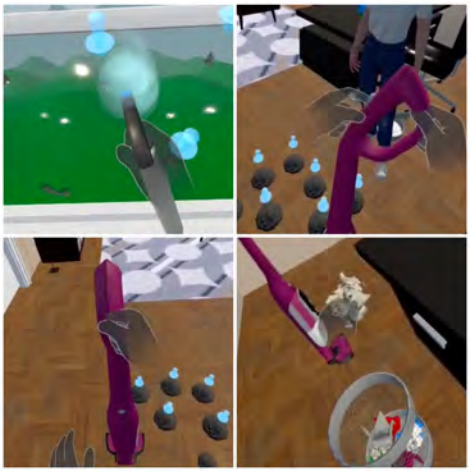

Fig. 3. Living room scenario focusing on reaching, object manipulation, and coordinated movements.

IV. System Implementation

A. Platform and Technical Framework

ReFlex VR was developed using the Unity game engine and the C# programming language, with the Meta XR Interaction SDK providing the foundation for user interaction. The application was designed to run on a standalone head-mounted display, specifically the Meta Quest 3, leveraging its integrated tracking capabilities to eliminate the need for external sensors or controllers. To ensure smooth performance on standalone hardware, the system was optimized through a combination of low-polygon assets, baked lighting, and efficient scene management. 3D models were either created using Blender or adapted from external repositories and subsequently optimized to reduce computational load while maintaining visual coherence. These design choices allowed the application to operate entirely on-device, improving portability and simplifying deployment.

B. Interaction and Task Implementation

User interaction is based on real-time tracking of hand and head movements using the headset's built-in sensors. The Meta Interaction SDK enables these inputs to be translated into intuitive actions, allowing users to interact with virtual objects through natural gestures such as grasping, pressing, and rotating. Rehabilitation tasks are implemented as structured sequences of actions that users must complete in order. Task progression is guided by system checks that determine whether each step has been performed correctly, based on object interactions, spatial positioning, and timing. More complex activities, such as tool use or continuous manipulation, are supported by monitoring user movements over time. This approach allows the system to provide realistic and responsive interactions while remaining adaptable to differences in user ability and performance.

C. Performance Evaluation and Data Management

The system evaluates user performance based on task completion, execution time, successful completion of arm extension and contraction movements, and use of the paretic limb, which is identified during system configuration by the therapist. Arm extension and contraction are detected by computing the Euclidean distance between the tracked hand position and the headset position using the Meta Quest's built-in hand-tracking capabilities. This distance is compared against a configurable threshold to determine whether the required movement has been successfully completed. The resulting measures are combined to generate a performance score and provide feedback that encourages continued use of the affected limb. No additional preprocessing or filtering was applied beyond the tracking provided by the Meta XR SDK.

User data, including scores, preferences, and configuration settings, are managed through a centralized component that persists information across sessions. Data are serialized into individual JSON files and stored locally on the device, with one file created for each user. This persistent storage allows the application to retrieve user progress across sessions while maintaining lightweight and platform-independent data management. Because the data are stored as standard JSON files, they can also be accessed outside the Unity application for inspection or further analysis if required. Performance

outcomes are represented through a point-based system that is converted into a star rating, offering users an immediate and intuitive understanding of their progress.

D. Feedback and Guidance Mechanisms

A multimodal feedback system was implemented to support both usability and engagement. Visual guidance is provided through dynamic cues such as arrows, highlights, and contextual indicators, which direct the user's attention and structure task execution. Auditory feedback complements these cues by providing confirmation of successful actions and corrective instructions when necessary. The guidance system is adaptive and can be adjusted based on user needs. In addition to fully guided interaction, a reduced-assistance mode removes or limits feedback elements, requiring users to rely more on memory and task understanding. This flexibility allows the system to accommodate a wide range of motor and cognitive abilities while maintaining a consistent interaction framework.

V. Evaluation

A. Usability Assessment

Before deploying the system with patients, a preliminary usability assessment was conducted to identify potential issues that could affect safety, clarity, or ease of use during rehabilitation sessions. The evaluation was carried out by a usability expert using the Nielsen Norman Group Heuristic Evaluation Workbook, based on Jakob Nielsen's ten usability heuristics. Although heuristic evaluations are ideally performed by multiple experts, for the scope of this work a single-expert review was considered sufficient to identify the most critical issues prior to patient testing. Overall, the expert's assessment was highly positive, with a mean score of 4.6/5 (standard deviation: 0.66) across the ten heuristics. The system scored particularly well in visibility of system status, match between the system and the real world, consistency and standards, recognition rather than recall, flexibility and efficiency of use, aesthetic and minimalist design, and help and documentation. These results reflected the clarity of the interaction flow, the realism of the scenarios, the consistency of the user interface, and the presence of multimodal guidance throughout the experience.

B. Preliminary Clinical Evaluation

For the clinical evaluation, 13 participants were divided into two groups: a control group of 7 participants, who continued their conventional rehabilitation program, and a VR group of 6 participants, who combined standard therapy with two ReFlex VR sessions per week over a five-week period. Group allocation was based on participant availability and the rehabilitation centre's scheduling constraints, resulting in a slight imbalance in group size (7 control, 6 VR). Clinical assessments were administered immediately before and after the intervention period in order to explore whether the VR-based training could produce measurable benefits. The selected outcome measures were the Fugl-Meyer Assessment [24], Motor Activity Log-28 [25], Action Research Arm Test [15], Naturalistic Action Test [23], and Stroke Impact Scale 3.0 [26].

During each VR session, participants were seated in a clear area and completed one or more scenarios depending on the training week. The progression of content was organized by level, with the kitchen level introduced first, followed by the coffee scenario, and later by the living room scenario. Sessions ended with a short debriefing in which participants could report discomfort, fatigue, or suggestions. Minor usability issues emerging during the study, such as reachability of some objects for wheelchair users, were corrected between sessions. In addition to the clinical measures, in-game performance data were recorded manually, including task scores and completion times. Across sessions, several participants showed gradual improvement in their level scores, suggesting increased familiarity and better performance over time. However, these gains were modest and not statistically significant. A similar pattern emerged in the pre- and post-intervention clinical measures: both groups showed some degree of improvement in motor ability and participation, and the VR group tended to perform slightly better overall, but the differences were not large enough to support statistically significant conclusions.

C. Discussion of Findings

Although the intervention did not produce statistically significant improvements in motor outcomes, the study yielded useful evidence regarding feasibility, usability, and acceptability. Patients accepted the technology well, required little setup support, and generally found the experience engaging and motivating. These aspects are particularly important in rehabilitation, where long-term adherence is often a major challenge. Several factors likely contributed to the lack of significant clinical effects. First, the recruited participants were in a chronic stage of impairment, where recovery tends to plateau and additional gains are more difficult to obtain. Second, the VR exposure may have been too limited: sessions were organized around level completion rather than fixed duration, resulting in relatively short training times compared with the longer sessions commonly reported in the literature. Third, only two VR sessions per week were delivered, and the overall intervention period lasted five weeks, which may have been insufficient to produce measurable changes.

VI. Conclusions and Future Work

This paper presented ReFlex VR, a VR application designed to support upper limb motor rehabilitation for stroke survivors. The system aims to provide an accessible, engaging, and practical complement to traditional physiotherapy, with the long-term goal of enabling patients to continue rehabilitation independently in home settings. While further longitudinal studies are required to rigorously assess the clinical effectiveness of the proposed rehabilitation approach, including its impact on sustained user engagement, adherence to therapy, and functional recovery over extended intervention periods, the results of this study indicate that the application is well accepted by users, easy to deploy, and does not produce significant adverse effects.

From a system development perspective, several extensions could further enhance the application. Additional scenarios could be introduced to broaden the range of rehabilitation tasks, including both everyday household activities (e.g., cleaning, folding clothes) and more complex or hobby-oriented interactions (e.g., assembling objects or using tools), improving long-term user engagement. Incorporating automatic performance tracking and feedback mechanisms such as recording completion times alongside scores could further enhance user awareness of progress and introduce additional motivational elements. Finally, expanding the system's gamification strategies could make it more appealing to a wider range of users. While the current design primarily emphasizes goal completion and performance improvement, future versions could incorporate elements tailored to different player motivations, such as exploration, collaboration, or competition. In particular, cooperative or competitive multiplayer scenarios could enhance both engagement and social interaction, although their implementation would require careful consideration in clinical and home-based settings. In conclusion, this work highlights the feasibility and usability of VR as a tool for upper limb rehabilitation. Although more research is needed to establish its clinical impact, the results support the potential of immersive technologies to complement traditional rehabilitation approaches and contribute to more engaging and accessible therapeutic experiences.

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