Towards a Modular XR Platform for Personalized Upper Limb Rehab

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Figure 1: Gameplay Overview along with hand mapping & positioning

Abstract

A modular, clinically informed XR-based rehabilitation platform is presented to support customizable therapy programs for upper limb conditions. Designed in collaboration with rehabilitation physicians, the system enables medical professionals to create, adapt, and deploy personalized therapy routines while monitoring patient progress remotely. The platform incorporates gesture-based exercises and personalized progression through two core mechanisms: (1) A tolerance adaptation algorithm is proposed to dynamically adjust evaluation difficulty based on user-specific parameters, including age, injury severity, and demographic profile. (2) A weighted gesture scoring model that prioritizes motion components most relevant to the therapeutic objectives of each exercise. Modular gameplay allows reconfiguration according to clinical prescriptions for various conditions, including Carpal Tunnel Syndrome, post-stroke upper limb recovery, and rotator cuff rehabilitation. All exercise-to-gesture mappings are derived from validated clinical documentation to ensure medical accuracy. This system establishes a foundation for a general-purpose, adaptable XR rehabilitation framework tailored to individual patient needs and therapeutic outcomes.

Index Terms: XR Rehabilitation, Gesture Accuracy, adaptive thresholding, personalized therapy, Mixed Reality

1 Introduction

Upper limb rehabilitation often relies on repetitive, non-personalized exercises that limit engagement and slow recovery. Existing XR solutions typically offer generic movements and lack mechanisms for clinical adaptability or dynamic progression tracking. The poster presents a modular Extended Reality rehabilitation platform, co-designed with healthcare professionals, that integrates gesture-driven therapy with real-time personalization. Unlike prior systems, ours includes clinically grounded movement mappings, tolerance algorithms enabling adaptive progression, a gesture-weighting model that allows condition-specific tuning and patient customisation. This enables tailored therapy plans with continuous performance feedback and remote physician monitoring.

2 Literature Review

Markerless hand-tracking and gamified XR technologies have advanced upper limb rehabilitation by enhancing engagement and autonomy. Camera-based systems like Gao et al. [4] enable fine finger tracking without gloves. Serious games improve motivation, as shown by Bressler et al. [3], who developed a high-usability VR therapy tool. Clinical outcomes support efficacy—Arman et al. [1] demonstrated that VR-based tendon gliding reduces CTS symptoms. Adaptive tele-rehabilitation approaches, such as Macaluso et al. [5]'s work on virtual therapist agents, highlight the growing personalization in MR therapies.

Yet, no current solution unites untethered tracking, clinical validation, patient customization, modularity, and adaptive progression which are features offered by the XRRehab system introduced in this study.

3 Methodology

The XR rehabilitation system was developed through an iterative process with expert input to design the gameplay to mirror the exercise flow of rehab programs. Initially, it focused on upper limb conditions such as Carpal Tunnel Syndrome. Each exercise was broken into sequential gesture units, and timers were used to ensure that the gesture units are performed accurately. This was done to ensure the exercises were performed in the prescribed manner.

Positional data of hand joints were captured using Unity XR Hands, enabling real-time computation of kinematic parameters such as wrist flexion angles, inter-finger distances, and hand orientation. This data was used in calculating the accuracy of the gesture being performed. The accuracy is a weighted sum of all these measures, and can change the weights according to which measure holds more importance in the exercise. After this, the patient performs a calibration session (Section 4.2).

In the beginning, the physician can choose the number of exercises and a set of exercises to be performed by the patient in their rehab journey. Exercises like flexions, extensions, glides, etc. predefined as a collection of gesture units. The game has attacks effective against certain kinds of enemies that can be assigned to any exercise, allowing modular, customisable rehab routines.

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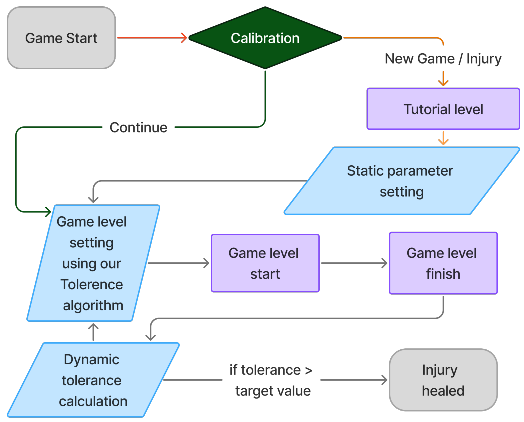

Figure 2: Gameplay and tolerance adjustment flow

Therapists can configure custom routines via a web-based dashboard, selecting gestures, adjusting thresholds used in the tolerance calculation, and specifying difficulty scaling profiles per patient. The system supports real-time progress tracking through metrics like tolerance, completion time etc., with performance logs uploaded to a secure backend for physician review.

4 System Overview

XR Rehab engages patients in an immersive mixed-reality shooter where each correct rehabilitation movement triggers a corresponding in-game action. Enemies spawn around the player's physical space, and the patient must execute prescribed exercise steps accurately to fire homing projectiles and survive.

4.1 Startup, Calibration & Spatial MR

From the main menu, the patient launches a short *Tutorial* that (1) teaches basic gestures, (2) records baseline performance, and (3) gathers data to compute initial accuracy thresholds T for each gesture, based on average accuracy during the tutorial. These thresholds set the minimum accuracy required for each gesture in the upcoming session. The system builds a real-time mesh of the user's room; later, enemy projectiles can destroy virtual wall segments in that mesh, revealing passthrough portals to the real environment and heightening immersion while promoting spatial awareness.

4.2 Core Interaction Loop

During each exercise wave, enemies fire projectiles and approach the player, while a HUD (Head-up display) canvas displays the current exercise step (e.g., "Median Nerve Glide 3/6") and the required accuracy (e.g., 80%). The patient performs the mapped hand gesture, if accuracy $\geq$ threshold T , a projectile is launched at the nearest enemy; otherwise, the player loses HP. Should HP reach zero, all enemies within a 5m radius are cleared and the current exercise step restarts. This loop repeats until the patient achieves the desired accuracy on every step of the prescribed exercise.

5 Tolerance Algorithm

To ensure safe but challenging progression, XR Rehab proposes a novel tolerance algorithm that recalibrates its accuracy threshold T for each gesture unit using tolerance τ after each exercise set using:

$$T = 1 - \tau$$

$$\tau_{\text{next}} = \tau_{\text{current}}\,(1-(1-c)\,P), \quad c \in (0,1], P \in [-1,1],$$

where $P = 1 - 2\,|\,actual\ accuracy - desired\ accuracy\,|$ is the patient's Performance score for each gesture unit and the adaptability coefficient c weighs clinical risk against demographic context:

$$c = w_d\,C_{\text{demo}} + w_s\,C_{\text{severity}}, \quad w_d + w_s = 1,$$

$$C_{\text{demo}} = w_{\text{age}}\,Age + w_{\text{gender}}\,Gender + w_{\text{eth}}\,Ethnicity$$

and C_{severity} the normalized injury severity at diagnosis. A higher P (good performance) or lower c (e.g., young age, mild injury) tightens tolerance (i.e. reduces τ, increases T), promoting incremental challenge, while lower P and higher c slow progression.

By logging $\{\tau, P, c\}$ each cycle, clinicians can visualize tolerance curves, track patient progress, and adjust weights, ensuring the game remains engaging and therapeutically effective.

6 Results

A preliminary evaluation was conducted with a senior rehabilitation physician. The expert provided positive feedback, highlighting the system's high degree of customization and its potential to increase patient motivation through gamification. The expert that the ability for clinicians to define exercises and tune difficulty parameters via the dashboard was a significant advantage over existing solutions. The physician validated the clinical relevance of the gesture-to-exercise mappings for Carpal Tunnel Syndrome and post-stroke recovery. We also emphasized the value of the tolerance algorithm for enabling safe, unsupervised progression in a home setting. The primary recommendation was to expand the library of predefined exercises to cover a broader range of upper limb conditions.

7 Conclusion

A modular and customizable XR rehabilitation system has been developed, integrating clinically validated upper limb exercises with an adaptive difficulty algorithm to support personalized therapy. The platform has been positively reviewed by a clinical expert for its potential to enhance patient engagement and provide valuable remote monitoring capabilities. Future work will focus on expanding the exercise library, conducting formal usability studies with patients, and undertaking a clinical trial to quantify the therapeutic efficacy of our approach compared to conventional rehabilitation methods. Future plan to incorporate established game design principles into future gameplay elements, drawing on frameworks such as Barrett et al. [2]. Our long-term goal is to establish this system as a versatile and effective tool for tele-rehabilitation.

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