Legato: Virtual Reality for Physical Rehabilitation of Patients in the Intensive Care Unit

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Abstract

Patients in intensive care units (ICUs) undergoing prolonged bed rest are at high risk of physical, cognitive, and psychological impairments due to immobility. While early mobilization protocols are critical for rehabilitation, the implementation is hindered by patients' restricted mobility and the complex ICU environment. To address these challenges, we present *Legato*, an immersive virtual reality (VR) game designed to enhance mobility activities for ICU patients. *Legato* offers a calming, customizable environment with thematic styles and music tracks, while providing real-time progress tracking and adaptive difficulty levels tailored to patients' hand movements. To evaluate its feasibility, we deployed *Legato* on Meta Quest 3 and conducted a pilot study with an ICU patient at Duke University hospital, demonstrating promising potential for improving rehabilitation outcomes.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Mixed / augmented reality;

1 Introduction

Patients in intensive care units (ICUs) with severe, life-threatening conditions require specialized care that includes continuous monitoring by healthcare professionals and advanced medical interventions. While ICUs are equipped to provide intensive treatment, including multiple monitors to track vital signs, prolonged bed rest—common during ICU stays—can result in significant muscle atrophy, weakness, and deconditioning. These factors contribute to ICU-acquired weakness [31], a condition that impairs patients' long-term motor recovery even in the absence of pre-existing neuromuscular disorders or direct nervous system injuries. To address these risks, clinicians implement early mobilization protocols to initiate physical rehabilitation for ICU patients. These protocols involve a progressive approach and require collaboration from a multidisciplinary team, including nurses, physical therapists (PTs), and occupational therapists, to tailor interventions to each patient's individual needs and abilities. Despite their importance, clinicians face considerable challenges in applying these protocols due to patients' limited ability to leave their beds and the presence of numerous medical devices and lines essential for monitoring their critical conditions. Furthermore, mobilization efforts must be customized to accommodate the diverse levels of acuity among patients.

(a)

(b)

Figure 1: VR for patients in the ICU with limited ability to get out of bed (a). In-game starting scene of our VR game, *Legato* (b).

Virtual reality (VR) technology has emerged as a promising tool for physical rehabilitation [12], particularly for patients experiencing prolonged bed rest (Fig. 1a). VR offers numerous benefits,

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including enhanced patient engagement, motivation, and compliance with recovery plans. Key determinants of motor recovery—–early intervention, task-oriented training, and high repetition intensity—– are effectively addressed by VR, as it immerses patients in task-specific motions that simulate real functional movements through interactive technology [30, 35]. Prior work demonstrates that VR has been successfully applied in physical rehabilitation, providing visual feedback to assist in movement correction and enhancing patients' sense of embodiment [3, 4]. However, applying VR in ICU settings presents unique challenges due to patients' extreme physical weakness, limited mobility, and the environment filled with essential medical equipment [22], resulting in a lack of VR-based interventions during hospitalization.

To address this challenge, we propose a patient-centered VR application designed to enhance the mobility activities of ICU patients while allowing clinicians to monitor and control patients' VR experience in real time. We assemble an interdisciplinary team involving PTs, critical care nurses, game designers, and computer engineers to develop *Legato* (Fig. 1b), a VR game that motivates ICU patients to engage in motor recovery movements by simulating joint progression rehabilitation through a collaborative design approach. *Legato* features a calming and realistic natural environment, enriched with sensory elements such as music tracks and visual cues, which serve as game mechanics to guide patients through mobility challenges. Recognizing the diverse levels of mobility and cognitive function among ICU patients, the application incorporates customizable settings for difficulty levels and progress tracking to support clinicians and address the individualized needs of patients. Additionally, by mirroring the VR environment to an external screen, clinicians can monitor and adjust the patient's experience in real time to ensure safety and optimize rehabilitation outcomes.

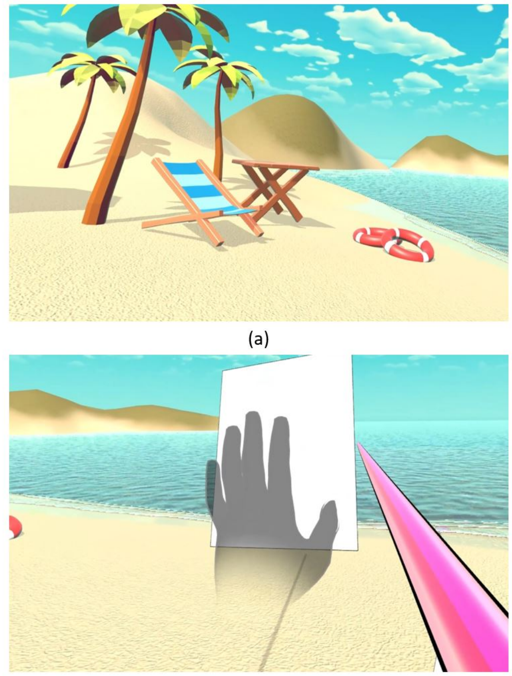
Our interdisciplinary team deployed *Legato* on the Meta Quest 3 platform and conducted a pilot study with an ICU patient to evaluate the feasibility of our VR game design. We report on the patient's experience and feedback, which informed our plans to incorporate more diverse game environments and refine the difficulty levels of mobility challenges. A demo video of *Legato* can be found here[1].

The remainder of this paper is organized as follows: Section 2 reviews related work. Section 3 details the design and development of the VR game, including mobility challenge levels, data collection metrics, and customization options. Section 4 presents the results of the pilot study conducted with an ICU patient. In Section 5, we discuss our ongoing user study plans and design refinements, followed by our conclusions in Section 6.

2 Related Work

The use of VR technology in physical rehabilitation offers numerous benefits, particularly in enhancing patient engagement, motivation, and compliance with recovery plans. The seamless transition between virtual and physical worlds afforded by VR can enhance the transference of knowledge gained during physical therapy to real-world activities [19]. Existing VR content for physical therapy and occupational therapy incorporates several key characteristics that improve patient participation and treatment effectiveness. Customization is a critical aspect, allowing therapists to tailor parameters such as body action speed and difficulty levels to align with each patient's abilities, ensuring both safety and accessibility [24, 30]. Gamification elements, including levels, points, timers, and rewards, create a challenging yet rewarding exercise environment that fosters motivation and continued engagement [3, 4]. The integration of therapeutic movements performed within a highly immersive, pleasant virtual setting culminates in a more positive rehabilitation experience for patients [35]. Additionally, the use of wearable devices with VR enables the tracking of user movements and physiological data, providing valuable insights for therapy optimization [2, 26].

[1]Link to a demo video: https://tinyurl.com/yr97yyww



(a)

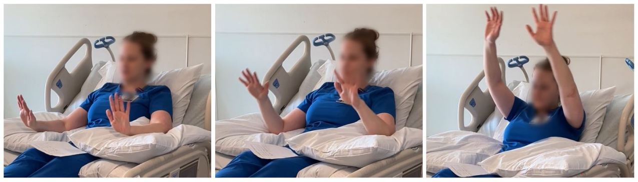
(b)

Figure 2: In-game screenshots of a sunny beach as the game environment (a) and visual cues for guiding patient's hand movement in the VR game (b).

Prior research has demonstrated the effectiveness of VR technology across various applications of exercise games (known as "exergames") to enhance physical engagement [6, 36], cognitive functions [1, 7, 23], and rehabilitation practices [11, 25]. Despite the clear benefits the VR brings, the latest studies of VR in the ICU are primarily in the feasibility and acceptability stage [10]. Existing studies typically assess the viability of VR interventions in a critical care environment by using metrics such as acceptance, satisfaction, immersion, and cybersickness [8, 13]. Few other studies have investigated the effectiveness of VR interventions in ICU towards understanding cognitive and emotional outcomes of using VR, particularly for post-traumatic stress disorder, sleep improvement [18], or long-term cognitive capabilities and emotional recovery [32]. However, a significant gap remains in studies investigating the delivery of VR interventions during hospitalization, with even fewer examining mobility-related outcomes [17, 34].

3 Game Development

Our game is designed to assist ICU patients undergoing prolonged bed rest in regaining strength and mobility. It serves as a therapeutic tool for clinicians, facilitating physical rehabilitation by promoting movement and interaction through an immersive VR experience, allowing patients to engage without leaving their beds. The main objective of the game involves patients using their hands to catch "musical notes" in synchronization with a playing music track and corresponding visual cues. At lower levels of difficulty, the game focuses on simple motions, such as finger and wrist movements. As patients progress, the game introduces more advanced motions and increased pace of these movements, including arm movements designed to enhance coordination and build strength in the elbows and shoulders. To advance through the levels, patients must meet specific accuracy thresholds, encouraging gradual improvement and sustained engagement. We selected the Meta Quest 3 for the implementation of our game due to its lightweight, tetherless design, built-in hand tracking for capturing hand movements, and support for pass-through functionality.



(a) (b) (c)

Figure 3: Different levels of mobility challenges in using hand and wrist (a), lateral movement using elbow (b), and overhead movement using shoulder (c), demonstrated by the PT in our team.

3.1 User Interface and Game Environment

The user interface (UI) of our game features different thematic styles. Patients can unlock different UI themes and game environments by earning "points" during the game. The game provides visual cues with different genres of music at each level. Those visual cues are displayed as a continuous line moving toward the patients and other feedback such as coins or scores on performance are displayed as feedback to patients. As the music track plays, the camera slowly pans through the game environment, providing the illusion of motion caused by the movements of the patient. Table 1 describes the difficulty levels of the game and required movements for each level. As the level of mobility challenges goes higher, the patient gradually builds strength and coordination for movement, starting with the distal extremities (i.e., hands and wrists), and moving towards the proximal extremities (i.e., elbows and shoulders).

3.1.1 Themes

The UI of our game incorporates various thematic styles to enhance patient engagement. By default, the UI features natural scenery elements, such as forests, plains, or rivers, with an example of a sunny beach theme showcasing ocean, sand, and trees, illustrated in Fig. 2a. Patients can unlock different themes by earning points in the game. Once a theme is selected, patients begin with a map tailored to that theme and their chosen difficulty level. Music genres and tracks remain customizable, allowing patients to select their preferred options independently of the chosen theme.

3.1.2 Game Character

To enhance interactivity and encourage patient engagement, we introduced a guiding character named Lumi to lead patients through challenges at each level. Designed to be approachable, ungendered, and race-neutral (as shown in Fig. 1b), Lumi embodies inclusivity and avoids any potential bias. During the interaction tutorial and gameplay, Lumi dances along and models movements for the patient, providing both guidance and motivation. Inspired by biophilic design, Lumi's wing pattern draws from the intricate structure of leaf veins, establishing a connection to the natural elements of the game's environments. Lumi's ability to fly allows it to seamlessly navigate the screen, capturing the patient's attention and directing their focus as needed. This design ensures Lumi is not only a friendly and engaging guide but also an integral game element that enhances the patient's focus and engagement throughout the mobility challenges.

3.2 Game Progression and Flow

Before starting the game, patients participate in a tutorial featuring slow, repetitive music designed to teach basic gameplay mechanics through simple, repetitive movements. Upon completing the tutorial, patients can choose a music track from various genres based on their preferences and progress through different challenges. Softer, calming music tracks are available at lower difficulty levels, while more dynamic and diverse tracks are unlocked as patients advance to higher levels of difficulty.

Table 1: Descriptions of varying game levels of joint progression rehabilitation in *Legato*.

Levels	Engaged Body Parts	Movement Locations	Movement Descriptions
1-6: Wrist	Hand/Wrist	In front	Move wrists a little
6-8: Elbow	Hand/Wrist + Elbow	In front + Lateral	Place both hands on the same side
9-10: Shoulder	Hand/Wrist + Elbow + Shoulder	In front + Lateral + Overhead	Put both hands up
11-12: Coordination	Hand/Wrist + Elbow + Shoulder	In front + Lateral + Overhead + Bilateral Coordination	Simple skillful coordinated movements
13+: Complex Coordination	Hand/Wrist + Elbow + Shoulder	In front + Lateral + Overhead + Bilateral Coordination	Hard skillful coordinates movements

3.2.1 Mobility Challenges and Customization

Physical therapy and rehabilitation in the ICU differ significantly from standard rehabilitation due to the critical condition of patients and the complexities of the ICU environment. ICU patients often require continuous monitoring and are connected to various medical devices, including tubes, intravenous lines, and catheters. These constraints, combined with physical weakness caused by prolonged bed rest, lead to ICU-acquired weakness, making even simple motions, such as moving the hands, highly challenging. To address these unique needs, our game incorporates a range of mobility challenges and tracks patient progress to ensure a personalized and effective rehabilitation experience.

To design the game, we recorded a series of motions demonstrated by the PT in our team on an ICU bed. These motions serve as references to customize game levels and generate visual cues. Fig. 3 shows a series of motions designed for ICU patients including an easy level of moving hand and wrist (Fig. 3a), using an elbow to perform lateral movements (Fig. 3b), and using shoulders to perform overhead and bilateral movements such as putting hands up (Fig. 3c). Using this as a reference, we developed five difficulty levels (Table 1), allowing patients to gradually progress from simple to more complex motions. At the initial levels, patients perform basic finger and wrist movements in a relaxed setting. As they advance, the tasks become increasingly challenging, involving coordinated arm movements, overhead poses, and bilateral actions requiring both hands. Visual cues are integrated at each level to guide patients through the corresponding movements, as shown in Fig. 2b.

The game leverages the built-in hand-tracking capabilities of VR headsets to monitor patient movements in real time. This functionality enables the game to compare the patient's hand motions with the visual cues for each level, providing immediate feedback and tracking progress. This real-time data supports customized rehabilitation plans tailored to the patient's abilities and recovery trajectory.

3.2.2 Score and Feedback on Performance

After each level, patients receive a performance score and reward points, which are accumulated throughout their gameplay. The score reflects the quality of the patient's movements based on various metrics, such as the similarity of their motion trail to the given cues and the accuracy of their motion range compared to the target. Utilizing the hand-tracking functionality of the Quest 3 headset, the system tracks the patient's hand joint positions and compares them to the visual cues in the game environment. Higher scores are achieved when patients keep their hands as close as possible to the targeted cues during gameplay. To advance to the next level, patients must meet a minimum accuracy threshold. Reward points, earned based on their scores, can be used to unlock new themes for game environments or different music tracks. These customization options are designed to motivate patients to continue engaging with the game, explore new challenges, and strive for higher levels of difficulty, fostering sustained participation in motor recovery.

3.2.3 Data Collection and Monitoring for Clinicians

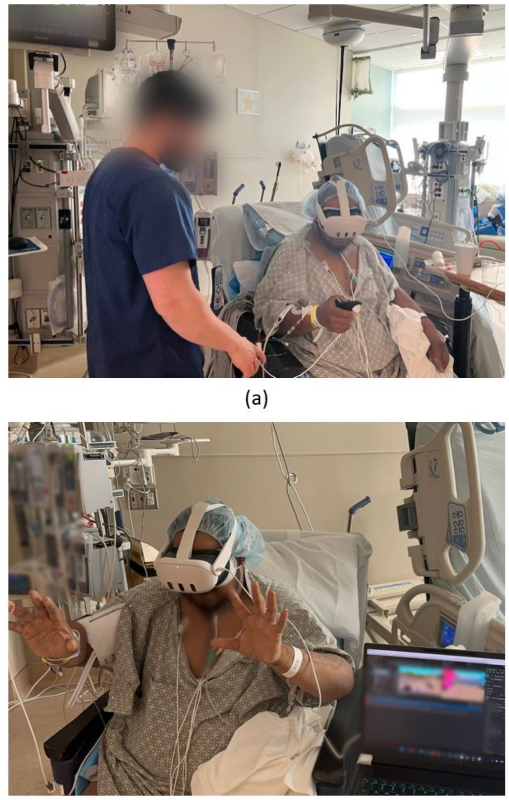
Given the critical condition of ICU patients, ensuring patient safety during rehabilitation is a top priority for clinicians. To address this, we integrated a mirroring feature into our game that allows clinicians to monitor patient progress and observe the VR environment in real time. The patient's virtual view on Quest 3 is mirrored wirelessly to an external device, such as an iPad or laptop. In addition, clinicians can use the Meta Quest Touch Plus controller to adjust the gameplay if patients encounter difficulties navigating the virtual environment.

Using the built-in hand and body tracking capabilities of Quest 3, we collect detailed motion data during each session. This includes 3D joint positions of the hands and arms, enabling the characterization of patient movements. Key metrics include the range of motion (e.g., how far the hands or arms extend laterally or overhead), total duration of motion, and the similarity of the patient's movements to the provided visual cues, analyzed using techniques such as dynamic time warping for time-series motion data [16, 21]. Additional metrics, such as the number of attempts to initiate motion, speed of movement, and the time spent in active (following visual cues) versus passive (resting between levels) movements, are also recorded. These metrics provide a comprehensive view of the patient's physical engagement and performance across different levels of mobility challenges. All motion data are stored locally on the Quest 3 in real time during gameplay and are downloaded for post-analysis after each session. These detailed analytics provide clinicians with valuable insights to patient progress, enabling a data-driven approach to tailor rehabilitation strategies for individual needs.

4 Pilot Study

The primary objective of this study was to evaluate the feasibility and applicability of *Legato*, with a particular focus on decision-making regarding the use of hand tracking versus controllers. Together with our team members at Duke University Hospital, we conducted a pilot study with an ICU patient in a cardiothoracic post-surgical ICU, as seen in Fig. 4. The study was conducted under the approval of the Duke University Institutional Review Board. The participant was a patient who had undergone a durable mechanical circulatory support device implantation (a mechanical pump inserted to assist the heart in pumping blood) 24 days prior to the pilot study. At the time of testing, the patient was connected to several invasive monitoring systems, including arterial blood pressure monitors, central venous access, electrocardiograms (for heart rate and rhythm), and oxygenation and blood pressure monitors. The combination of critical illness and intensive medical treatments contributed to the patient's ICU-acquired weakness.

The technical and clinical teams conducted a session in a tethered mode utilize the Quest 3 platform with wireless mirroring for improved deployment. The patient interacted with a game set in a sunny beach environment (Fig. 2), accompanied by classical music as the background audio. Gameplay involved difficulty levels ranging from 6 to 8 (Table 1), requiring the patient to perform hand, elbow, and shoulder movements in front, lateral, and overhead directions. The VR experience was displayed on a computer screen in real time,



(a)

(b)

Figure 4: ICU patient trying *Legato* during user testing with the help of clinicians to start the game (a), and performing the movement with both hands (b).

allowing clinicians to continuously monitor the patient's interactions and ensure safety throughout the session. Vital signs were closely monitored during gameplay to assess the patient's physiological response. After completing a brief session, the patient provided feedback on their experience, including suggestions for improving the game.

Overall, the patient expressed enthusiasm for the VR experience and indicated a willingness to participate in future rounds of user testing to support further development. He did not report any signs of cybersickness but noted that the Quest 3 headset felt slightly heavy. While he found the built-in hand tracking on the Quest 3 to be intuitive and smooth, he mentioned that using a controller required more time to adjust. Regarding the game environment, the patient described it as realistic but suggested several enhancements. He preferred a faster tempo for the music and expressed interest in music with lyrics. Additionally, he recommended incorporating alternative game environments, such as a jungle setting, and expanding the music genres to include pop, rap, and hip-hop. On a scale of 0 to 10, he rated the movement challenge as a 10, indicating it was very demanding. Although he appreciated the range of movements, he felt that the speed was too fast. He did not find the game duration exhausting but suggested shorter sessions with built-in breaks to allow for rest. Lastly, the patient requested more detailed scoring and feedback on his movement performance, specifically in relation to the visual cues provided during gameplay. Despite experiencing ICU-acquired weakness that limited his mobility, the successful completion of the movement challenge and the patient's enthusiasm towards the game demonstrate the potential of *Legato* as a tool for facilitating physical rehabilitation.

5 Current and Ongoing Work

We continue the development of *Legato* on Quest 3 to incorporate more diverse themes and music tracks based on feedback from the pilot study. Upon completing full development, we will conduct a randomized-controlled user study to assess the effectiveness of our VR game in physical and psychological engagement. We will randomize a cohort of adult cardiothoracic ICU patients with limited mobility and compare the control group (n=30) to the VR intervention group (n=30).

To assess the physical engagements of patients in *Legato*, we will collect patients' physiological data and evaluate patients' experiences with quantitative data measurements. Given that each patient's ability to perform movements may vary due to their medical condition, we will gather objective measures such as heart rate [33], blood pressure, and ECG [5], along with mobility data such as detailed measures of headset pose changes and the distance traveled by the patient's hands [29]. These metrics will be used to assess engagement, activity, and biometric feedback. Physiological data will be compared before and after the game to measure changes. Additionally, we will evaluate usability, the quality of the experience, and the game's effectiveness in promoting mobility through structured interviews and established questionnaires, such as the Game Experience Questionnaire [14], System Usability Scale [20], and the Physical Activity Enjoyment Scale [15].

Furthermore, we aim to evaluate psychological engagement by assessing changes in emotional states throughout gameplay. We hypothesize that *Legato* will reduce anxiety, depression, and loneliness in patients. To test this, we will use patient-reported measures such as the Hospital Anxiety and Depression Scale [37] and the UCLA Loneliness Scale [28], which are standard measures of psychological states used by clinicians, as metrics at baseline and day 10 after the intervention or the day of ICU discharge. Additionally, we will analyze blood biomarkers associated with depression and anxiety, including brain-derived neurotrophic factor [9] and tumor necrosis factor [27], to further quantify the psychological impact. All physical and psychological engagement data will be collected at baseline and at day 10 after intervention or the day of ICU discharge, whichever occurs first.

6 Conclusion

Due to the unique characteristics of ICU patients and the complexities of the ICU environment, clinicians face considerable challenges in implementing early mobilization protocols aimed at improving patient mobility. In this paper, we present the design and development of *Legato*, a VR game that provides an immersive experience by introducing various levels of mobility challenges. Our interdisciplinary team created a patient-centered VR game with features that allow customization of difficulty levels and enable clinicians to monitor and ensure patient safety by mirroring patients' VR experience. We also share feedback gathered from a pilot study with an ICU patient and outline future plans to evaluate both physical and psychological engagement using quantitative measurements.

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