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Web Camera-Based Gamified Rehabilitation System for Improving Fine Motor Skills: Pilot Study

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ABSTRACT

The system integrates a Python-based hand tracking module using a standard webcam with Unity, enabling real-time calculation of finger range of motion (ROM) angles and virtual hand visualization within interactive games. The pilot study was conducted with 40 healthy participants (aged 19–25) to evaluate usability and feasibility, while ROM measurements were validated against goniometer readings in a test with four participants. The system assessed distal interphalangeal (DIP), proximal interphalangeal (PIP), and thumb interphalangeal (IP) joints. To ensure consistency, participants gripped predefined cylindrical objects during measurements, reducing variability. The system demonstrated strong correlations with goniometer measurements (r = 0.585–0.998), particularly for PIP joints (e.g., 0.998 for the ring finger). An average Usability test score of 82.69 indicated high usability, and low latency (<2 milliseconds) ensured smooth user interaction. These findings suggest that the system provides accurate ROM tracking and an engaging rehabilitation experience. While promising, further validation with larger datasets is required to confirm its reliability and explore its potential for clinical populations.

1. INTRODUCTION

Motor skill loss, particularly in fine and gross motor functions, significantly impacts an individual's quality of life, often resulting from conditions such as stroke, hand surgeries, or neurological disorders. These impairments can hinder essential activities, including grasping objects, writing, or even basic self-care tasks. For instance, stroke survivors frequently experience pronounced deficits in hand mobility, with challenges in thumb and finger movements leading to reduced independence and functionality [1]. Such limitations highlight the urgent need for effective rehabilitation strategies aimed at restoring motor skills, enhancing daily living capabilities, and ultimately improving patient well-being.

Fine motor skills, involving precise movements like finger dexterity, are crucial for tasks requiring coordination and small-scale manipulation, such as typing or buttoning a shirt. On the other hand, gross motor skills encompass larger hand and arm movements essential for activities like reaching or lifting. Loss of these abilities can severely disrupt a person's autonomy, emphasizing the necessity of targeted rehabilitation approaches. Traditional methods, such as physiotherapy and occupational therapy, have demonstrated success in addressing motor impairments. These typically involve repetitive, task-specific exercises aimed at retraining neural pathways and strengthening muscle coordination [2]. However, their effectiveness often depends on patient compliance and motivation, which can wane over time due to the monotonous nature of these exercises.

In addition to conventional approaches, surgical interventions may be employed in severe cases to address structural impairments or nerve damage. Technological advancements have further expanded the toolkit available for rehabilitation, introducing innovative solutions such as robotic-assisted devices, virtual reality environments, and sensor-based systems. These technologies offer precise monitoring and adaptive feedback,

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enhancing the rehabilitation process by making it more engaging and tailored to individual needs [3].

The integration of technology into rehabilitation has brought numerous benefits, particularly in improving accessibility and effectiveness. Gamified rehabilitation systems, for example, leverage interactive exercises to maintain patient engagement while delivering therapeutic benefits. Real-time feedback provided by such systems enables patients to monitor their progress and make adjustments, fostering a sense of accomplishment and motivation.

This pilot study proposes a gamified hand rehabilitation system that leverages technological innovations to address the limitations of traditional rehabilitation methods. The system employs advanced hand-tracking technologies with Unity and Python, offering real-time feedback and interactive, gamified exercises designed to improve both fine and gross motor skills. By combining the strengths of gamification and computer vision technologies, this system provides a flexible and accessible home-based rehabilitation solution tailored to individual patient needs. Additionally, to the best of our knowledge, this is the first study to calculate users' finger ROM angles using a webcam. The system has been tested on healthy individuals, and future studies aim to validate its accuracy and effectiveness by conducting further ROM tests and evaluations on patients.

Accordingly, the general framework of this paper, Section 2 presents a detailed review of the related studies, specifically in technology's influence on motor skill recovery as well as examining comparable solutions. Meanwhile, Section 3 concentrates only on technological application of similar studies. This entails various types of technologies such as cameras, Kinect, Leap Motion Controller, and others which have been closely surveyed in this regard. Moreover, this section highlights and details thoroughly the project's development processes. . This section also describes the steps taken to produce the hand tracking module, design the user interface and develop the required scripts. Additionally, details the test and evaluations conducted. Finally, Section 4 presents the results of usability and ROM accuracy.

2. LITERATURE REVIEW

This section details and reviews the literature on the use of web cameras in rehabilitation, gamification as rehabilitation technique, and Hand Gesture-Controlled Games for Rehabilitation. These studies highlight the pivotal role of technology in enhancing rehabilitation processes, emphasizing its potential to improve accessibility, patient engagement, and therapeutic outcomes. Through this review, we aim to underline the significance of integrating innovative technological solutions into rehabilitation, showcasing their effectiveness and adaptability in addressing motor impairments and promoting recovery.

2.1. Web Camera in Rehabilitation

Rungruangbaiyok et al. [4] provide a Shoulder Angle Measurement (SAM) system that uses computer vision and a web camera to meet the rehabilitation demands of patients with shoulder movement limitation. The system recognizes arm movement in photos and determines the active shoulder angle. A correlation investigation comparing SAM readings to those from the ATAN Scale and a goniometer revealed strong Pearson correlations, with maximum full-scale errors of 5.03 and 3.69, respectively. The study underlines the need for affordable and accessible rehabilitation options, providing doctors with a tool for remotely monitoring and evaluating patient progress, potentially improving treatment planning and outcomes.

Furthermore, Liu [5], [6] et al. offer a framework for hand rehabilitation activities designed to suit the growing demand for home-based care options. The system includes a 3D hand model, an animation framework for exercise design, and a hand tracking application for performance monitoring. Their segmentation method, which uses a perception-based color space, proved stable under a variety of situations, while hand tracking was accomplished using unique versions of CAMSHIFT and contour analysis methods. University students evaluated the framework's ability to accurately reconstruct hand configurations and track hand movements, with satisfactory performance across a variety of lighting situations and real-world backgrounds. The system has the potential to enable remote rehabilitation monitoring and evaluation, hence improving the accessibility and effectiveness of home-based care initiatives.

2.2. Gamification in Rehabilitation Techniques

Then et al. [7] found that gamification helped patients heal from metacarpal fractures more quickly. There were 19 participants in the study, which was an exploratory, presumptive two-group randomized controlled experiment. These individuals were split into two groups at random: the intervention group, which received gamified therapy, or the control group, which received standard physiotherapy. Participants performed simultaneous flexion and extension of their long fingers to move the cursor and puzzle pieces on-screen in order to finish a schematic or photo. The goal of the game is to use color-coded gloves to identify specific finger gestures. Each session started with measurements, and they were repeated after two, four, and eight weeks of training. There was a substantial difference in PRWHE ratings and adherence between the gamification-treated group and the control group, with the first group benefiting more from the intervention. The gamification group performed significantly better in PRWHE scores and adherence, PRWHE score: 3.44 vs. 8.45, p =.038. Compared to the control group, the gamification group's adherence rate was noticeably greater. The group members also conveyed their happiness and gratitude for the system.

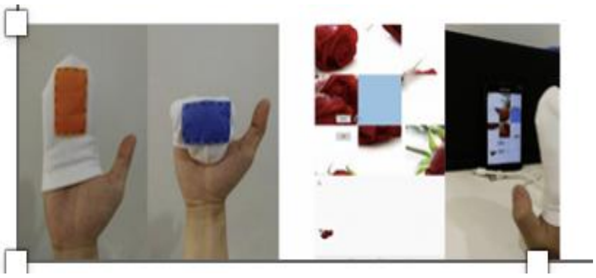

Figure 1. Color-coded gloves to enhance accuracy of motion tracking [7].

Moreover, In a study undertaken by Nasri et al. [8], they aimed to harness the recent AI advancements to enhance the interactivity between humans and machines, particularly for individuals with disabilities, specifically in the area of rehabilitation. They applied an approach that is innovative by application that is surface electromyography (sEMG) aimed at a 3D game, which utilized a deep learning-based architecture for the real-time recognition of gestures. The researchers were building a dataset with 7 gestures using the Myo armband aimed to be the main training subject for the developed deep-learning model. And finally, a field study was made to evaluate the usability and user experience with the game component of the rehabilitation system and participants gave their remarks on their experience with the game. The results presented important findings in this regard, depicting the efficacy of the method proposed through technology-driven interventions for recovery of motor skills, with training accuracy and validation accuracy high around 99.8% and an average of 99.48%, respectively.

The study conducted by Gabele et al. [9] was a significant one, involving 83 individuals who had suffered brain injuries and cognitive deficits. Group A and Group B, two distinct therapy procedures, were used to investigate these patients. Patients in Group Received cognitive training enhanced with game components, while those in Group A received cognitive training that was not gamified. The two groups' training durations did not significantly differ, according to the data. On the other hand, the majority of training was given to those who engaged with the gamified metaphor and NPC (Non-PlayerCharacter) (median=267.5 minutes, Range=792). Group B's primary and non-primary socializers showed a significantly different training duration (t=-2.19206; p=0.037176). Regarding effort and competence, there was no discernible difference. Nonetheless, primary socializers were found to derive more enjoyment from the gamified training, while primary achievers reported feeling more competent. These findings underscore the potential of gamified cognitive training in enhancing motivation and promoting engagement.

2.3. Hand Gesture-Controlled Games for Rehabilitation

Firstly, Yeng et al. [10] developed an interactive game-based system using hand gesture tracking and recognition technology for hand rehabilitation. This system was designed to increase patients' interest and engagement during hand exercises in physiotherapy sessions. In the study, a system supporting hand rehabilitation using the popular game "2048" was created. Hand movements were detected and recognized using the MediaPipe Hands algorithm. By mapping hand gestures to a predefined set, users were allowed to control the game by performing hand movements. The experimental results highlighted the critical importance of the appropriate distance between the computer monitor and the user for this system. The normal distance range (0.52 to 0.73 meters) enabled successful hand detection and tracking regardless of indoor or outdoor environments. The system performed well even at long distances (approximately 1.83 meters) for bedridden patients in indoor settings but occasionally failed to detect hands when the webcam-to-hand distance exceeded 2.5 meters.

Moreover, the aim of Pereira et al. [11] was to develop a Virtual Reality (VR) game to enhance traditional physiotherapy in hand rehabilitation, focusing on addressing recurring limitations reported in most technological solutions: limited support for diverse movements and exercises, complex calibrations, and exclusion of patients with open wounds or other hand disfigurements. The system was evaluated by seven physically healthy participants using a semi-structured interview targeting three evaluation categories which are hardware usability, software usability, and improvement suggestions. The study focused on conceptualizing and implementing VR games to improve hand function after injuries, wounds, or traumatic events. The game immersed patients in rehabilitation exercises and movements like those offered in physiotherapy sessions. The VR simulation was implemented using the Unity3D game engine, and evaluation was conducted with Oculus Quest. According to the results, the Usability test score was determined to be 84.3. This score is a standard measure to assess the overall usability of a system and is rated out of 100. The evaluation also revealed a Learn ability score of 82.1 and a Usability score of 84.8 for the system. The standard deviation was calculated as 6.9. These values indicate that the system is generally easily learnable and usable by users.

3. MATERIALS AND METHODS

This section outlines the hardware and software technologies utilized in the development of the proposed system for gamified rehabilitation. These components were carefully selected to ensure real-time interaction, precision in motion tracking, and an engaging user experience.

3.1. Hardware Components

The hardware setup of the proposed system includes multiple devices that facilitate accurate motion tracking and seamless interaction between users and virtual environments. At the core of the system is a standard webcam, which captures hand movements and provides video input for detecting joint coordinates. Furthermore, Webcams facilitate interaction with computers for users. Users can interact with their computers directly using their built-in webcams without needing to purchase additional hardware [12]. Webcams are widely accessible and capable of capturing high-resolution images, making them an ideal choice for home-based rehabilitation systems.

In addition to the webcam, the system integrates more advanced devices such as the Kinect sensor and Leap Motion Controller to enhance motion tracking capabilities. The Kinect [13], originally designed for gaming, includes RGB cameras, infrared projectors, and depth sensors, allowing it to generate depth images through structured light or time-of-flight calculations. These features enable real-time gesture recognition and skeletal tracking, making it a versatile tool for rehabilitation applications. The Leap Motion Controller [14] complements this setup with its ability to detect fine hand movements using infrared sensors. This device maps hand gestures into a real-time digital simulation, supporting detailed interactions in virtual environments.

For certain configurations, the system also incorporates data gloves equipped with motion-detecting sensors. These gloves track finger flexion and overall hand movement, providing precise input for virtual reality-based rehabilitation tasks. Such devices allow for enhanced immersion and responsiveness, making them suitable for tasks requiring high levels of precision. Together, these hardware components form the foundation of the system, enabling reliable motion tracking and interaction.

3.2. Workflow and Design

This section presents the proposed system's requirements, workflow, and design, visualized through sequence and use-case diagrams. The system (see in Figure 2.) is planned to be compatible with any PC, leveraging Unity and OpenCV frameworks to ensure cross-platform functionality. It will detect and track hand movements in real time, utilizing advanced computer vision and machine learning techniques for recognizing subtle gestures. To enhance user engagement, gamified interactive exercises tailored for hand rehabilitation will be incorporated. These exercises will adapt dynamically to users' hand movements, providing a personalized rehabilitation experience.

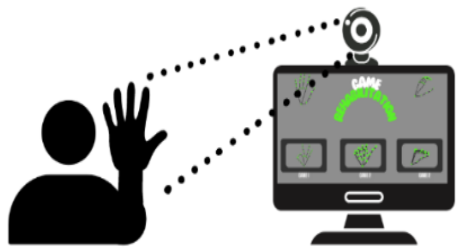

Figure 2. The system setup for game rehabilitation.

Performance and usability are key priorities. The system is expected to launch within 20 seconds, minimizing user waiting time. The interface will be designed for simplicity, enabling navigation and interaction with no more than two mouse clicks. Accuracy will be critical; the system aims to ensure that the Mean Absolute Error (MAE) between PIP ROM angles measured in the game and a goniometer does not exceed 10 degrees. Latency is targeted to be less than 2 milliseconds for real-time interaction and smooth gameplay.

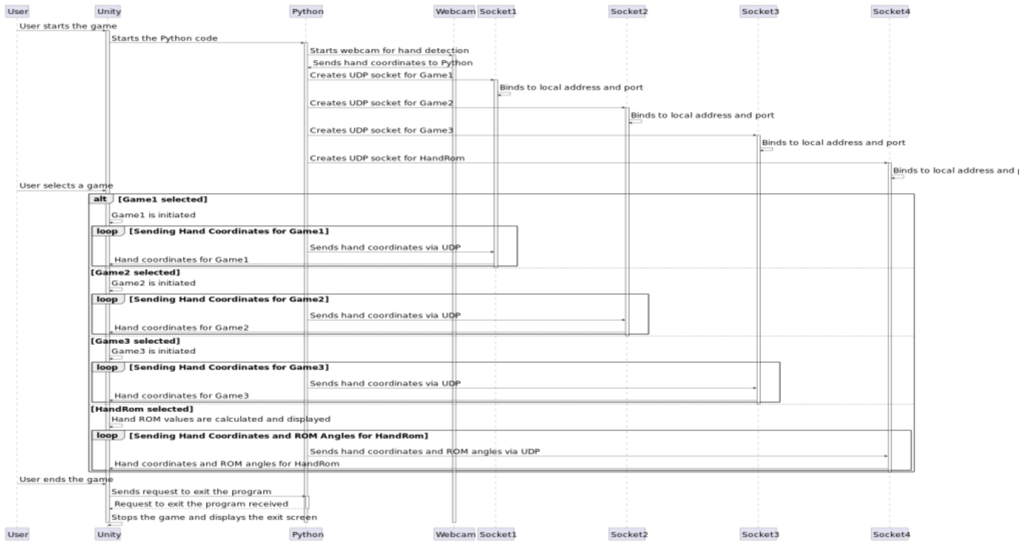

Figure 3. Sequence diagram of the system

The workflow of the system, as depicted in the sequence diagram (see in Figure 3.), outlines the following steps: Users will begin by selecting and launching a game, after which Python code will use a webcam to detect hand coordinates and send this data via UDP to sockets. The processes for starting and stopping games will also be represented. Unity will handle user interactions, offering options such as HandROM, Game 1, Game 2, and Game 3. Based on the user's selection, the respective game or process will be launched. For instance, selecting Game 1 will initiate its setup, and the same procedure will apply to Games 2 and 3. The HandROM option will provide real-time feedback on the user's hand range of motion.

Finally, users will be able to exit the system at any point. This step will include terminating Python processes and closing the Unity project to ensure resources are freed appropriately. This comprehensive design aims to provide an engaging, user-friendly experience while achieving high performance and accuracy in rehabilitation tasks.

3.3. Software Framework

The system consists of three main components: the Hand Tracking Module, the User Interface (UI), and the Game Logic, all working together to create an interactive rehabilitation experience.

The Hand Tracking Module has been implemented using Python, allowing users with a standard webcam to interact with the system without the need for expensive hardware. The module utilizes OpenCV for motion detection and MediaPipe for advanced gesture recognition, ensuring precise and real-time hand movement tracking (see in Figure 4.). The webcam is initialized at a resolution of 640x480 pixels for optimal video capture, and the HandDetector class from the CVZone library tracks up to two hands simultaneously with a confidence threshold of 0.8. Hand movement data is extracted and sent to the game engine using UDP sockets. A total of four distinct UDP sockets are utilized, each assigned to different ports to send hand movement information to various game modules simultaneously. Additionally, angles between defined hand landmarks are calculated and transmitted for visualization in the HandROM feature, providing insights into the hand's range of motion.

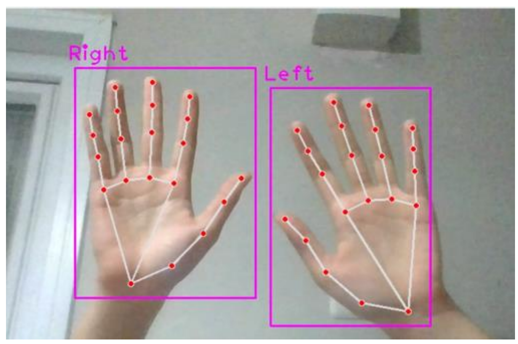

Figure 4. Hand detection program output from the camera.

The User Interface (UI) has been carefully designed using Unity to ensure ease of navigation and accessibility (see in Figure 5.). The main menu serves as the starting point, offering users options to access Games 1, 2, 3, or the HandROM feature. Each game has its interactive elements tailored for hand rehabilitation, and the system provides a "How to Play" video panel to guide first-time users. The UI elements include large, simple buttons with visual representations to ensure usability, especially for users with limited motor dexterity.

Three mini games have been implemented: Balloon Popping, Fist Basketball, and Puzzle. The Balloon Popping game allows users to move a balloon using their hand gestures. When a balloon is popped, its size changes randomly to simulate various hand dexterity challenges. The First Basketball game allows users to shoot a basketball into a hoop by clenching their hand, with trajectory lines visualized to mimic the motion. The Puzzle game challenges users to piece together a bridge image by dragging and dropping puzzle components, improving fine motor coordination. Each of these games relies on UDP sockets to receive real-time hand motion data, which determines object movement and game interaction.

The system's backend includes scripts that facilitate menu interactions, real-time hand tracking, and video feed control. The RunPythonScript class ensures that Python-based hand tracking is managed in the background without interfering with the Unity project. Similarly, menu navigation scripts like MenuController handle user interactions, enabling users to switch between games or exit the application. Additional scripts like UDPReceive, HandTracking, and VideoPanelController ensure asynchronous data processing, real-time feedback, and smooth user interaction.

In the HandROM feature, a simple user interface allows users to input their username and calculate their hand's range of motion in real-time. This data is visualized in the system interface and logged to CSV for further analysis. The HandTrackingROM script manages user input, processes UDP data streams, and updates hand landmarks accordingly. Real-time feedback is achieved by continually monitoring received UDP data and updating the visualization using the received coordinates.

These combined components, driven by advanced computer vision, real-time motion tracking, and interactive game design, form a smooth and responsive rehabilitation system. The interactive approach makes the system engaging, motivating users to perform exercises while simultaneously tracking their progress and providing insights into their hand recovery journey.

Figure 5. The User Interfaces of the main menu and the games

3.4. Testing

The proposed hand rehabilitation system was evaluated to assess its usability, accuracy, and performance. Testing was conducted under controlled conditions with healthy individuals to ensure consistency. The Usability Test was used to evaluate the system's ease of use and navigation. 40 participants aged 19 to 25 interacted with three mini-games: Balloon Popping, Puzzle, and Fist Basketball. After the interaction, they completed a Usability Test questionnaire, with an average score of 82.69. The game-specific usability scores were Balloon Popping at 86.75, Puzzle at 91.67, and Fist Basketball at 78.85. Additionally, all participants were able to navigate and start a game within two clicks, highlighting the simplicity of the interface.

To evaluate the system's accuracy, the Range of Motion (ROM) angle calculations were compared with a traditional goniometer using four healthy participants. Measurements were taken for the PIP, DIP, and thumb IP joints. Participants were instructed to hold spherical objects to stabilize hand movements during measurements. The correlation results for the ROM angles were high, with values such as 0.998 for the ring finger's PIP joint and 0.997 for the pinky finger's PIP joint. Strong correlations were also observed in the DIP joints, including 0.929 for the index finger and 0.883 for the ring finger, though not all correlations were statistically significant. For the thumb IP joint, the correlation was 0.934.

The system's performance was assessed by measuring the delay in updating game objects and the frame rate during gameplay. The delay consistently remained under 2 milliseconds. The system maintained an average frame rate of 30 frames per second.

4. RESULT

The results of this pilot study evaluating the usability, accuracy, and performance of a gamified hand rehabilitation system are promising, though they also point to areas for improvement. The system, combining Unity, Python, and a webcam for real-time hand tracking, was tested on 40 healthy participants, aged 19 to 25, with a Usability Test yielding an average score of 82.69 (see in Figure 6.). This indicates that the system is user-friendly and accessible. Notably, the Balloon Popping and Puzzle games scored highly on usability (86.75 and 91.67, respectively), whereas Fist Basketball, with a score of 78.85, pointed to the need for refinements in its control mechanisms. Feedback from participants indicated that Puzzle was the most enjoyable and user-friendly game, emphasizing the importance of intuitive design in rehabilitation systems.

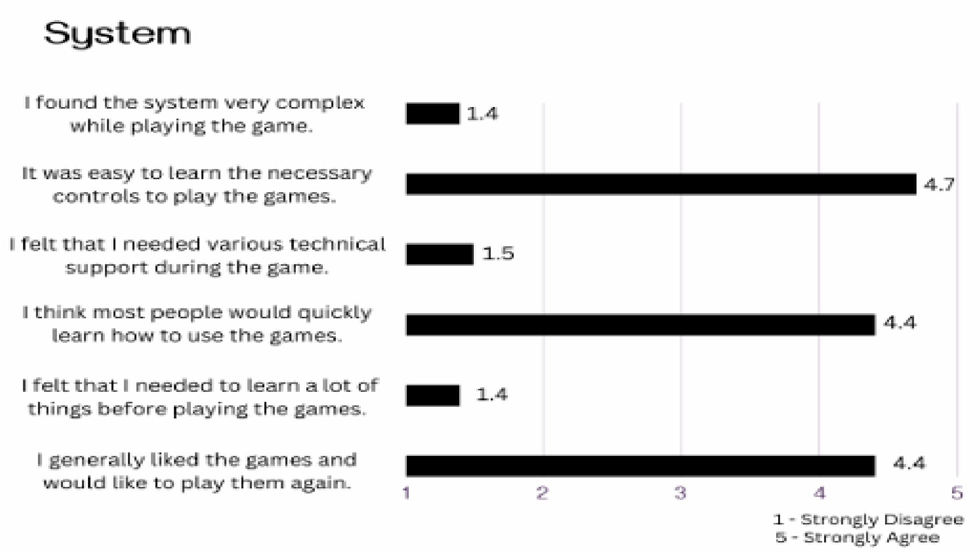

Figure 6. Graph for System Usability Test Result

The ROM angle calculation test, conducted with four healthy participants, showed strong correlations between the system's measurements and those obtained with a traditional goniometer, particularly for PIP joints. The system demonstrated correlations as high as 0.998 ($p = 0.002$) for the ring finger's PIP joint and 0.997 ($p = 0.003$) for the pinky finger, while the DIP joints and thumb IP joint showed somewhat weaker, but still notable, correlations (0.929 and 0.883 for DIP joints, 0.934 for the thumb IP joint). These results suggest that the system offers reliable ROM measurements, particularly for PIP joints, which are crucial for hand rehabilitation. However, the reliance on 2D hand projection can lead to inaccuracies if the hand is not positioned correctly relative to the camera, limiting the system's accuracy when hand alignment is not optimal. This issue underscores the need for further development to provide feedback on hand positioning and improve measurement consistency.

The system's performance was assessed by measuring the delay in updating game objects and the frame rate during gameplay. The results showed minimal delay, with a consistent frame rate of 30 frames per second and a delay of under 2 milliseconds, ensuring smooth and responsive interactions during gameplay. This is critical for maintaining real-time feedback, which is essential for user engagement in rehabilitation exercises. These findings demonstrate that the system performs well technically, making it suitable for use in gamified rehabilitation settings.

In conclusion, this study demonstrates the feasibility of using a gamified rehabilitation system that combines interactive games with hand tracking to enhance the rehabilitation process. The system's usability, particularly in the Balloon Popping and Puzzle games, highlights its potential for engaging patients in rehabilitation exercises. The accuracy of the system, particularly in measuring ROM for PIP joints, suggests that it could be a reliable tool for monitoring progress in hand rehabilitation. However, issues with hand positioning and the need for refinement in certain game controls were identified. To enhance the system's reliability, further development is necessary, including improving hand positioning feedback and expanding the dataset to validate its performance across diverse populations. Despite these challenges, the system holds significant potential for both clinical and home-based rehabilitation programs, offering a dynamic and accessible approach to physical therapy through gamification.

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