Virtual Reality-Based Adapted Handball Serious Game for Upper Limb Rehabilitation in Spinal Cord Injured Patients

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Abstract: In this paper, we present a virtual reality-based serious game that simulates the training of a wheelchair handball goalkeeper. It is designed to complement traditional therapy for upper limb rehabilitation and trunk mobility improvement in spinal cord injury patients. The proposal is underpinned by a multi-layered architecture that provides a therapeutic environment that enhances patient motivation and satisfaction through gamification techniques. The architecture also provides precise kinematic recording during exercise performance, since the recorded data is essential for therapists to objectively assess each patient's progress. Particularly, the recorded can be used to assess the extent of movement, how fast and smooth it is, the number of repetitions and their consistency, as well as the accuracy and precision of movements, balance, and posture control. The serious game was tested in the Hospital Nacional de Parapléjicos de Toledo, involving patients and healthcare professionals. The collected data are publicly available. This preliminary evaluation has been focused on assessing its functionality and safety. Following the exercise sessions, all participants were asked to complete a short questionnaire to measure their motivation, sense of achievement, satisfaction and overall comfort and well-being in the virtual environment. Future plans include expanding the patient sample and monitoring the long-term progress and impact of VR therapy on the recovery of mobility in the affected limbs.

1 INTRODUCTION

Individuals with spinal cord injury (SCI) confront substantial physical challenges daily. Annually, between 250,000 and 500,000 people worldwide sustain a spinal cord injury, predominantly due to preventable circumstances such as road traffic accidents, falls, or violence (WHO, 2021). A significant number of individuals with SCI often rely on wheelchairs for mobility, depending on the severity of their injury and the resulting impairment in leg function, and they may often experience limited mobility in their trunk, arms, and hands. These limitations further complicate daily activities, posing challenges for independent living and overall quality of life.

In this sense, rehabilitation plays a crucial role in enhancing the quality of life for individuals with SCI. Through consistent and targeted rehabilitative exercises, it is possible to regain some degree of mobility, improve motor functions, and promote overall physical well-being (Spooren et al., 2011). Persistence in rehabilitation is vital; a committed approach can facilitate more effective recovery, helping individuals navigate their daily lives with increased confidence and capability. Traditional therapeutic approaches, while fundamental, often involve repetitive and routine exercises, which can, over time, diminish a patient's motivation and engagement to rehabilitation programs. This drawback can adversely impact the consistency of practice, which is essential for recovery and improvement in individuals with SCI (Shahmoradi et al., 2021).

Recognizing this challenge, there has been a progressive introduction of technology in the field of rehabilitation in recent years. The integration of innovative therapeutic strategies, such as adaptive sports and technology-augmented exercises, can further enrich the rehabilitation process, making it more engaging and sustainable for SCI patients (Herne et al., 2022). Technological integration aims to mitigate the monotony of traditional therapy, incorporating engaging, varied, and personalized exercises to main-

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tain patients' interest and commitment. By enhancing the appeal and interactivity of rehabilitation activities, technology facilitates a more patient-centered approach, promoting improved consistency and outcomes in the recovery process (Doumas et al., 2021).

Building on the technological advancements in rehabilitation, serious games and exergames have emerged as one of these innovative therapeutic strategies (Proença et al., 2018). These applications use gamification principles, incorporating elements of play into the rehabilitation process to create an immersive and motivating environment for individuals with SCI. They enrich the therapy experience, transforming conventional exercises into interactive and purposeful activities, and promote a sense of achievement and progress, encouraging patients to actively participate in their recovery process (de Los Reyes-Guzmán et al., 2021). By transforming therapeutic tasks into game-like experiences, these approaches facilitate higher levels of patient engagement and satisfaction, which are essential for maintaining consistency and enhancing the effectiveness of rehabilitation programs.

The success of rehabilitation relies not only on consistent practice, but also on performing exercises accurately, which requires the therapist's guidance. In addition to enhancing motivation, incorporating advanced technologies offers benefits like precise recording of the patient's tracking. Hence, the obtained data is highly valuable for the patient to perform the exercises accurately, and for the therapist to objectively analyse the rehabilitation sessions and the patient's progress (Herrera et al., 2023a).

Within the diverse spectrum of technologies used for serious games and exergames, Virtual Reality (VR) holds a distinctive place, offering immersive environments that can be tailored to meet the individual needs and rehabilitation goals of persons with SCI (Herrera et al., 2023b). VR creates dynamic, customizable spaces, allowing therapists to adjust the complexity and type of exercise, as well as accurate recording of kinematics during execution. In particular, sport-based VR rehabilitation is a transformative approach to the rehabilitation of individuals with SCI (de Los Reyes-Guzmán et al., 2021). This approach combines the advantages of VR with the benefits of physical activity to create an engaging and personalized therapeutic environment. In recent years, sport-based VR rehabilitation has incorporated various sports, however, there has yet to be a development in adapted handball exercises within this innovative form of therapy. Adapted handball, particularly oriented towards the training of goalkeepers, inherently exercises the trunk, arms, and hands. Its unique nature encourages enhanced trunk stability (especially in patients with injuries to the C5, C6, and C7 cervical levels) and improved mobility in arms and hands, making it an ideal component for upper limb rehabilitation.

Our proposal aims to fill this gap by designing and developing a VR-based serious game specifically for the training of goalkeepers in adapted handball, which also serves as an adjunct to traditional rehabilitation methods. The system allows the patient to perform exercises without additional components attached to hands and arms, and to interact with virtual elements through their hands. The proposal encompasses accurate kinematic recordings, allowing therapists to objectively analyze patient progress using supportive data. This development has been incorporated into the Rehab-Immersive platform used at the Hospital Nacional de Parapléjicos de Toledo (HNPT). The platform hosts a collection of immersive serious games that support the upper limb rehabilitation process (Herrera et al., 2023a) (Herrera et al., 2023b).

Experiments conducted in a real-world setting, such as the HNPT, focused on evaluating functionality with patients and therapists. The results show the system's ability to record movements made during therapeutic exercises, offering the capability to individually analyze the mobility of the left and right hand, arms, and head, thereby inferring trunk mobility. Additionally, a progressive improvement in performance is observed among individuals as they become more accustomed to the virtual environment.

The rest of the paper is structured as follow: Section 2 reviews some of the relevant previous works related to the main topic addressed in this paper. Section 3 introduces the adapted handball solution based on VR for upper limb rehabilitation. Section 4 describes the experimentation and results obtained. The paper concludes with conclusions and future work in Section 5.

2 PREVIOUS WORK

Recent advancements in game-based virtual reality (VR) have significantly impacted upper-limb rehabilitation post-stroke, combining gamification elements with therapeutic exercises. A systematic review and meta-analysis of 20 clinical trials highlighted the effectiveness of game-based VR in improving motor function and quality of life in stroke survivors, indicating a promising direction for rehabilitation practices (Domínguez-Téllez P, 2020). Complementing this, a study involving the Microsoft Xbox 360 Kinect system integrated with conventional therapy showed notable improvements in upper limb motor functions in subacute stroke patients, suggesting an added value of interactive gaming in rehabilitation (Ikbali Afsar et al., 2018).

Pereira et al.'s exploration into VR for hand rehabilitation physiotherapy further underlines the diversity of approaches being explored in this field, emphasizing on the adaptability of these systems to different patient needs, based on a study with able-bodied participants testing the hardware and software's usability (Pereira et al., 2020).

Meanwhile, the efficacy of VR in sports training, particularly in handball, has been explored by Vogt et al. in the context of balance training and musculoskeletal injury rehabilitation. Although VR showed positive effects in healthy adults, it did not significantly outperform traditional balance training in rehabilitation settings, pointing to a nuanced understanding of VR's role in sports-focused rehabilitation (Vogt et al., 2019).

The broader applicability of VR and gaming interventions in enhancing upper extremity function post-stroke is evident in studies that have reported a 28.5% average improvement in motor functions, with a 10.8% greater benefit observed when gaming elements were incorporated compared to visual feedback alone (Karamians et al., 2020). This is supported by another study involving VR training with upper extremity tasks using the HTC Vive HMD, where patients demonstrated significant functional improvements and high satisfaction, affirming the feasibility and effectiveness of fully immersive VR rehabilitation (Lee et al., 2020).

Feedback from physiotherapists and game designers has been instrumental in shaping VR game content, as seen in a study involving chronic stroke patients. This study reported significant improvements in shoulder, wrist, and elbow movements, though not uniformly across all tested ranges, suggesting the potential of VR games in enhancing specific motor functions (Shahmoradi et al., 2021).

The role of serious games in upper limb rehabilitation is further emphasized by Provença et al., who analyzed 38 studies on technological gaming platforms for patients with neuromotor disorders. Although only a fraction of these studies reported improvements, this emerging paradigm in rehabilitation signifies a shift towards integrating serious gaming technologies into therapeutic practices (Proença et al., 2018). This is corroborated by another review that found serious games to be more effective than conventional treatments in upper limb recovery post-stroke, highlighting their long-term effectiveness in maintaining improvements (Doumas et al., 2021).

Exploring serious games further, a randomized controlled trial using the Leap Motion Controller for patients with multiple sclerosis demonstrated significant improvements in coordination and dexterity, illustrating the potential of these technologies in diverse patient populations (Cuesta-Gómez et al., 2020). In a similar vein, Herne et al.'s assessment of stroke survivors' engagement with a VR-based serious game underscored the importance of feedback and personalized experiences to optimize engagement (Herne et al., 2022), while Baluz et al.'s development of the Rehabilite Game received positive feedback from both physiotherapists and patients, pointing to its suitability as a complementary therapy tool (Baluz et al., 2022).

Innovative approaches like the wearable multimodal serious games for hand movement training in stroke patients, which combine various sensor technologies for movement classification, have shown an 81.0% accuracy rate and heightened patient enthusiasm compared to conventional methods, further indicating the growing potential of such tools in rehabilitation (Song et al., 2022). Finally, a study on a VR prototype using hand gestures for interaction in upper limb rehabilitation revealed a preference for hand-based interaction among participants, especially those with motor problems, suggesting its potential in enhancing motivation and facilitating home-based exercise therapy (Juan et al., 2023).

3 ADAPTED HANDBALL SERIOUS GAME FOR UPPER LIMB REHABILITATION

3.1 Architecture

A schematic overview of the developed system architecture for upper limb sports practice and rehabilitation is presented in Figure 1. It features a multi-layer architecture, each layer being independent, serving a clear function, and interconnected within the overall system.

The system involves two main actors: patients and therapists who supervise the rehabilitation process. The top layer, or presentation layer, is where patients directly interact. Patients can immerse themselves in a virtual environment using a VR headset, specifically the Oculus Quest 2 model. This device allows patients to experience a realistic recreation of a sports hall and a visual interface to configure training that includes a series of exercises. The layer also facilitates training calibration by allowing patients to stretch their

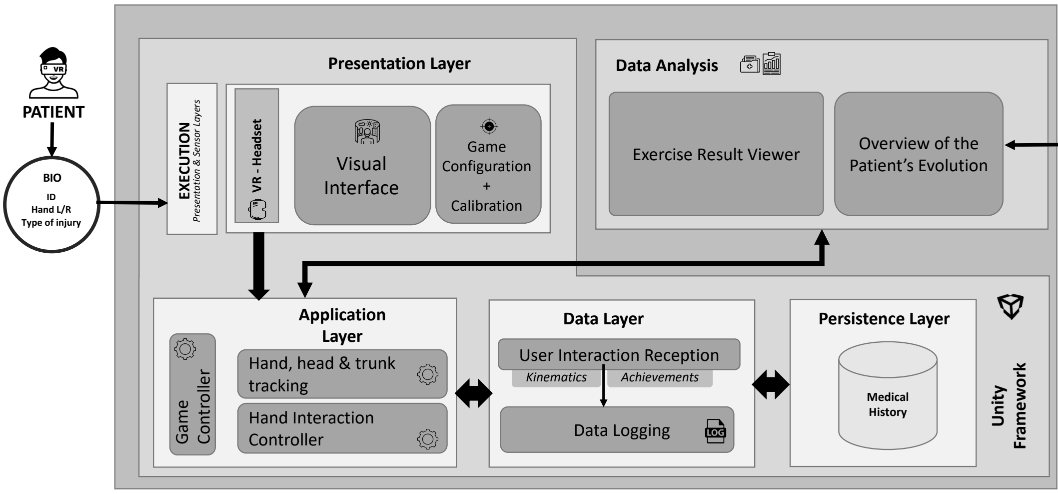

Figure 1: General architecture of the developed system.

arms fully, marking the maximum horizontal and vertical reach, with the system subsequently adapting ball throws to the patient's limits. Virtual worlds' significant advantage is the ease of creating accessible spaces tailored to each patient's unique needs.

On the other hand, the application layer manages the control logic, comprising various controllers: a) The Game Controller oversees the game dynamics and overall training, controlling the virtual environment elements and interacting with the physics engine. b) The Hand Tracking module accurately tracks the patients' hands. Most VR headsets have associated controllers equipped with accelerometers and gyroscopes, enabling precise hand movement registration. However, for patients with spinal cord injuries, using these controllers is not feasible due to motor limitations and grip difficulties. Therefore, hands-free interaction and accurate hand tracking during exercises are essential. Moreover, the system continuously monitors head position, determinable through the VR headset sensors, and infers the trunk position through inverse kinematics. c) The Hand Interaction Controller is crucial for modeling the real hand's interaction with virtual elements, like the thrown balls, necessitating the determination of intersections between hands and balls, representing a save to be counted.

This layer communicates with the data layer, which receives information from the tracking module and virtual element interactions, recording kinematics during exercises and achievements made during training. All this information becomes part of the patient's clinical history in the persistence layer.

Lastly, in a separate application, the therapist can analyze all recorded data, objectively determining the patient's progress in the rehabilitation process. This analysis involves evaluating performance based on achievements and a detailed examination of the three-dimensional space kinematics of hands, head, and trunk.

3.2 Immersive Environment for Exercise Execution

In the design of the virtual training space, achieving an appropriate level of realism is crucial to ensure that the patient experiences an almost full sense of immersion. This aims to give the patient the feeling of being transported to a typical environment where handball sports practice takes place. In such a setting, lighting is essential, especially considering that ball throws occur and the objective is to intercept as many as possible. Thus, the illumination of moving objects and shadow projections should be optimized to provide clear visibility for the participant undergoing the exercise. Adequate visibility empowers the user to precisely ascertain the position and distance of the target.

A handball court was designed in accordance with the official dimensions specified by the International Handball Federation (IHF), measuring 40 meters in length and 20 meters in width (see Figure 2). Traditional handball goals have dimensions of 2 meters in height and 3 meters in width. However, the handball goal featured in the virtual environment adheres to adapted handball standards, measuring 1.60 meters in height and 3 meters in width, catering to users who engage in the sport from a wheelchair (see Figure 3).

Regarding illumination, *Baked Lightmaps* have been implemented in Unity. *Baked Lightmaps* is a rendering technique used to enhance realism and ef-

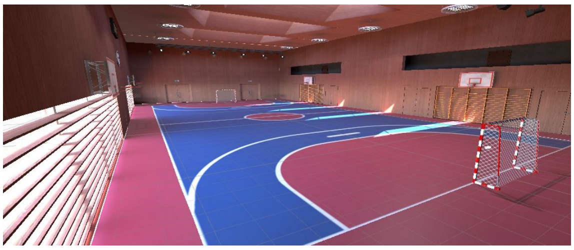

Figure 2: Design of the immersive training environment.

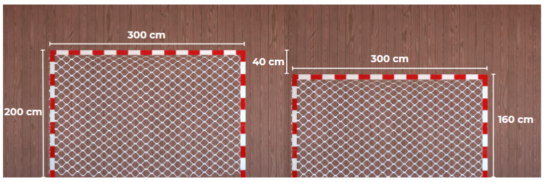

Figure 3: Comparison of handball and adapted handball goals.

ficiency in representing lighting in 3D scenes. These *lightmaps* store precomputed lighting information and apply it to the scene. The primary advantage of this lighting technique is its ability to reduce the computational load on the CPU and GPU in real-time. As the lighting is precomputed and stored within the *lightmaps*, there is no need to perform intricate lighting calculations for every frame, thus enhancing game performance.

Additionally, *Dynamic Lights* have been incorporated, which are computed for every frame and respond in real-time to changes in the scene. A series of *Spotlights* have been introduced and emit light in a specific direction, forming a cone of light. These lights are ideal for simulating light sources with a defined direction, such as the spotlighting in the scene. The use of these types of lights has been minimized to prevent excessive resource consumption that could lead to a decline in application performance. An unwanted decline in system performance may lead to observable disruptions, such as dropped frames and interrupted playback. These technical inconsistencies not only hamper the smooth operation of the application but also induce physical discomfort in users, manifesting as sensations of dizziness or disorientation. Such adversities compromise the immersive quality of the user experience, detracting from its overall enjoyment and appeal.

3.3 Throwing and Interception of Virtual Balls

The developed system features two game and training modes for physical exercise practice: a) Maximum Number of Saves; in this mode, players are challenged to make as many saves as possible within a fixed time limit. The patient's skill is gauged based on the quantity of saves achieved during this period, providing a measure of their performance. b) Maximum Time; this mode sets a limit on the number of goals that can be conceded. The focus here is on the length of time the patient can keep playing before reaching this limit. The duration of the exercise session extends with each successful save, turning the number of saves into a determinant of the overall exercise time.

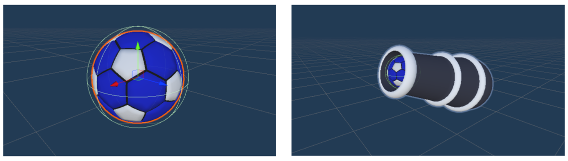

Figure 4: Ball and cannon prefabs designed in the application.

In all these training modes, there are two fundamental aspects for them to take place: i) the throwing of balls and ii) the interaction between the patient's real hands and the virtual balls, an event translated as a goalkeeper's save. For these two aspects, there are three key components: a) cannons responsible for throwing the balls, b) the virtual balls, and c) the user's hands performing the exercise.

The system represents several moving cannons positioned on the handball court in the classic positions where real players usually stand. At this point, it is worth introducing the concept of a *prefab*. A *prefab* is a type of resource that allows creating, configuring, and reusing objects in a Unity scene. Using *prefabs* is ideal when the same object needs to be used multiple times. *Prefabs* ensure that objects sharing the same *prefab* have the same properties and configurations. Handball balls and the cannons that will propel these balls are managed using *prefabs*. Figure 4 displays the designed *prefabs*.

The ball throws are determined by the trajectory drawn between a cannon, whose position determines the starting point, and an endpoint calculated from one of the shooting areas. As illustrated in Figure 5, the upper half of the goal is divided into an array of regions or zones, spanning from the base of the player's trunk to their head. These zones are labeled from A1 to A5 and B1 to B5. The regions located at the extremes: A1, A5, B1, and B5, require greater trunk mobility. Recording saves and goals in each of these zones allows the therapist to identify strengths and weaknesses in the patient's limb movements, differentiating between the left and right hand and arm.

To draw the ball throwing trajectory, a subroutine in Unity has been implemented, utilizing the *Lerp*

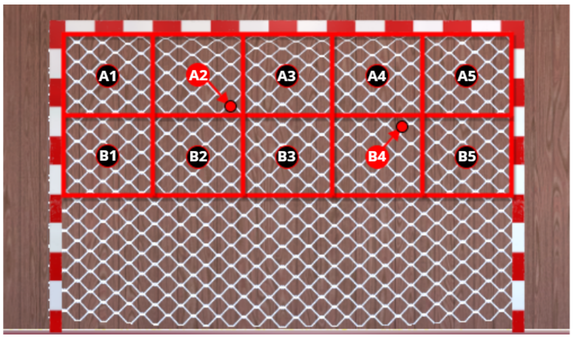

Figure 5: Target points where the ball throws are directed.

function. The *Lerp* function (meaning linear interpolation) is a useful tool for interpolating between two values over a period of time. The algorithm 1 shows a simplified implementation of the *Lerp* function for trajectory animation. In the *Lerp* function, each argument represents:

- **Starting Point:** represents the cannon's position from which the throw is made.
- **End Point:** represents the throw's final position at the goal.
- **t:** represents the interpolation value. A value of 0 represents the **Starting Point**, a value of 1 represents the **End Point**, and any value between 0 and 1 produces an interpolation between the two values.

Data: Starting point, End point, Movement speed, Total distance
Result: New position after interpolation
Initialization: Set initial value for *distanceTraveled*;
while *Update is called* **do**
  distanceTraveled += *movementSpeed* * Time.deltaTime;
  float t = *distanceTraveled* / *totalDistance*;
  Vector3 *newPosition* = Vector3.Lerp(*startingPoint*, *endPoint*, t);
  transform.position = *newPosition*;
end

Algorithm 1: Simplified use of the Lerp function.

On the other hand, the handball ball's *prefab* contains a vital component for game logic. This element is the *Collider*. A *Collider* defines a *Game Object*'s collision shape, in this case, the ball. It is used to detect collisions and trigger events when other objects come into contact with the *Collider*. The handball used in this project implements a *Sphere Collider*, attaching a spherical collision shape to the ball.

Finally, the user's hands in the handball scene are represented by the *Custom Hand* component. This component, in turn, consists of a *Collider* that will be set up to manage interaction with the balls. In the *Collider*, the *isTrigger* property is activated so that the *OnTriggerEnter* function always runs when there is a collision with another *Collider*. It is necessary to ensure in the *OnTriggerEnter* function that the colliding *Collider* is the handball. To address this issue, Unity tags are used to distinguish between virtual components. Thus, only the intersections between the virtual hands (which match the real ones in position and rotation) and the virtual ball are counted as a new save. If there is an intersection with an object that has a different tag, it does not trigger the event, and therefore, it does not result in the recording of a new save

The user interacts at all times through their hands, without the need to hold joysticks or external controllers. This forms a natural mode of interaction, closely mimicking real sports practice. This detail is crucial for patients with spinal cord injuries who have motor limitations and difficulty in executing grips correctly. Some patients even have serious difficulties in lifting weights, making hand-free interaction a top priority requirement.

3.4 Recording of Kinematics

In the realm of rehabilitation and therapeutic exercises, leveraging advanced technologies such as computer vision algorithms from the Meta API and Oculus Quest 2 has revolutionized the capture of detailed kinematic data. This sophisticated approach employs deep neural networks to predict and locate the positions of a person's hands and other significant landmarks like the joints of the hands. The resultant data is a comprehensive 3D model that encapsulates the nuanced configuration and surface geometry of the hands and fingers, offering a 26 degree-of-freedom pose reconstruction.

This tool facilitates a recording of movement and orientation of various body parts, providing therapists with a profound window to analyze the exercises executed by patients. Such precise data aids in delivering an objective evaluation of a patient's progress, bridging the gap between subjective observations and quantifiable metrics.

In our proposal, the dataset generated is rich and multifaceted, encompassing several relevant components that contribute to a comprehensive understanding of the user's movements. Fundamental variables such as *Frame* and *Time* establish a foundational context, anchoring each data point within a coherent sequence.


Figure 6: Patient and therapist testing the developed software during the experimentation session.

For capturing the intricacies of head movements, variables like *HeadPosition_x*, *HeadPosition_y*, *HeadPosition_z*, *HeadRotation_x*, *HeadRotation_y*, and *HeadRotation_z* are employed. They detail both the spatial position and the angular orientation of the user's head during the interaction.

On the other hand, the intricate movements and orientations of the user's hands are captured using a series of variables. For the right hand, aspects such as its detection, position in space, orientation, velocity, and wrist rotation are detailed by *HandDetectedR*, *HighConfidenceR*, *RHandPosition_x*, *RHandRotation_x*, and *RWristTwist*, among others. The left hand's kinematics mirror this structure, with variables like *HandDetectedL*, *LHandPosition_x*, and *LWristTwist* playing analogous roles.

4 EXPERIMENTATION

The experimental session conducted at the HNPT involved a total of 9 participants, consisting of 3 SCI patients and 6 healthy individuals (HNPT staff).All the patients had a chronic cervical SCI (more than one year after the injury). Additionally, the patient with ID:1 regularly engages in adaptive sports, ensuring a commendable overall mobility.

Before starting the experimentation, participants were thoroughly briefed on the nature of the exercises. Subsequently, with the VR headset on, they underwent an initial immersion into the virtual world to get acquainted with it, without any data being recorded yet.

Each participant, seated in a traditional chair or wheelchair, underwent individual assessments and participated in exercises designed to measure their progress. The primary objective was to prevent a specified number of shots from becoming goals. The goalkeeper, whether a patient or a therapist, aimed to maximize their successful saves. The system tracked the duration the goalkeeper remained active. The exercise persisted until the predetermined number of goals were conceded by the goalkeeper (15 in particular). As the goalkeeper's duration in the exercise extended, due to successfully preventing goals, the difficulty level progressively heightened with balls launched at faster speeds and greater frequencies.

On the other hand, the healthy individuals participating in the study are experienced in rehabilitating SCI patients. They are professionals specializing in fields such as biomedical engineering, occupational therapy, and physical therapy. The gameplay mechanics and objectives for these individuals were identical to those applied to the patients, maintaining a consistent approach across all participants in the study.

4.1 Sample Description

This section outlines the data pertaining to the participants, including their age, patient type, and type of injury. Table 1 summarizes the general characteristics of each participant.

Table 1: Participant data in the HNPT study.

ID	Age	Type	Injury
1	47	Patient	SCI
2	31	Healthy	-
3	24	Healthy	-
4	20	Patient	SCI
5	45	Healthy	-
6	44	Healthy	-
7	29	Healthy	-
8	23	Healthy	-
9	22	Patient	SCI

Two groups of subjects are distinguished: 88.9% of the participants had occasionally used VR devices previously. Furthermore, 11.1% used them frequently. 100% of the subjects had used a VR device at some point. It is also noteworthy that 33.3% of the study participants were HNPT patients, and the remaining 66.6% were healthy individuals.

44.4% of the participants were aged between 20 and 25 years, 44.4% were between 25 and 30 years old, 11.1% were between 30 and 40 years old, and the remaining 33.3% were above 40 years old.

4.2 Results

After conducting the study, the results obtained are displayed in Table 2. This table presents the duration times of each participant in each of the two series conducted, along with the number of saves made in each series. The longer the duration time, the better the performance. The last column displays the percentage of improvement or worsening that the participants achieved in the number of saves made. Finally, the last row presents the arithmetic mean of all the measurements recorded.

As can be seen in the table, the degree of improvement is positive in 8 out of 10 cases, with an overall average improvement of 29%. Only two subjects, 5 and 8 (both healthy subjects), showed worse performance and results after the second session. The main cause was fatigue after a short time elapsed between sessions S1 and S2. In the case of SCI patients, subjects 1, 4 and 9, the degree of improvement was 42.8%, 31.2% and 33.3% respectively, the arithmetic mean being 35.7%.

On the other hand, it was observed that the average time taken in S1 was 80 seconds, whereas in S2, it averaged at 90 seconds. This indicates an overall increase in time, showing a progression from S1 to S2 and, in consequence, a better performance. Among the patients, particularly subjects 1, 4, and 9, there was a variance in the degree of time growth noticed. The patients exhibited a diverse range of time increments, with a mean growth of approximately 31.84%. Specifically, P1 showed an increase of 27.27%, P4 had an increase of 53.97%, and P9 recorded a growth of 14.29%.

In Figure 7, a mosaic layout presents the kinematic recordings for each of the subjects who participated in the study. The red dots represent movements of the right hand, the blue dots denote movements of the left hand, and the yellow dots depict head movements. Among the subjects, those identified by IDs 1, 4, and 9 are patients with SCI, while the rest are healthy participants. This visual representation serves to compare and contrast the motion patterns and tendencies between the two groups.

In general, it appears that patients with spinal cord injuries tend to demonstrate a higher concentration of movements in the center of the chart for both hands, potentially reflecting a limitation in the range of motion. Additionally, their head movements display a notable restriction in breadth, focusing their attention on specific areas without encompassing the full visual field. On the other hand, healthy participants exhibit a broader dispersion of movements with both hands, suggesting an enhanced capability to respond to stimuli from various directions. Their more dispersed head movements indicate an aptitude for actively tracking the trajectory of the ball across diverse directions and elevations.

All data collected during the experiment are publicly available in the GitHub repository: https://github.com/AIR-Research-Group-UCLM/Rehab-HandballVR. The repository is organized into nine folders, each corresponding to an individual participant in the experiment. Each folder contains a `Historical.CSV` file detailing the number of throws, saves, and goals detected, as well as a `TrackingData` subfolder, which includes a CSV files with the kinematics recorded for each exercise performed.

4.3 Participant Feedback

At the end of the exercise sessions, each participant was asked to complete a simple questionnaire consisting of three questions designed to measure their motivation, sense of achievement and satisfaction, and comfort/well-being in the virtual space.

Q1 - ”After playing, I feel motivated to continue playing or to return to the game at another time.” Participants could respond with a value between 1-5, where 1 signifies ”strongly disagree” and 5 the opposite.

Q2 - ”I have experienced a sense of accomplishment and satisfaction upon completing the exercises.” The response format is the same as Q1, with a value between 1-5.

Q3 is designed to measure the user’s degree of comfort and well-being: ”I have experienced dizziness, disorientation, or balance difficulties while playing.” Possible answers are: a) I have not experienced any symptoms at all, b) I have experienced mild symptoms, c) I have experienced moderate symptoms, d) I have experienced significant symptoms, e) I have experienced very intense symptoms.

Figure 8 graphically summarizes the responses to the above questions. Regarding motivation, 7 out of 9 participants gave the highest score for motivation level, while 2 rated it 4, still above the average. In response to Q2, 5 of the 9 participants experienced the highest level of achievement and satisfaction, 3 rated it 4, and only one rated it 3. Finally, the results for Q3 indicate that the immersive experience was highly enjoyable, with only one participant experiencing a moderate sensation of dizziness during the exercises.

Table 2: Summary of the evaluation session at HNPT.

Identifier	Time S1 (seconds)	Saves S1	Time S2 (seconds)	Saves S2	Degree of Improvement
1	99	49	126	70	42.8%
2	100	38	102	49	28.9%
3	96	45	108	54	20%
4	63	16	97	37	31.2%
5	96	51	65	20	-31.4%
6	77	28	122	56	100%
7	64	19	68	23	21%
8	74	25	66	21	-16%
9	56	12	64	16	33.3%
Average	80	31	90	40	29%

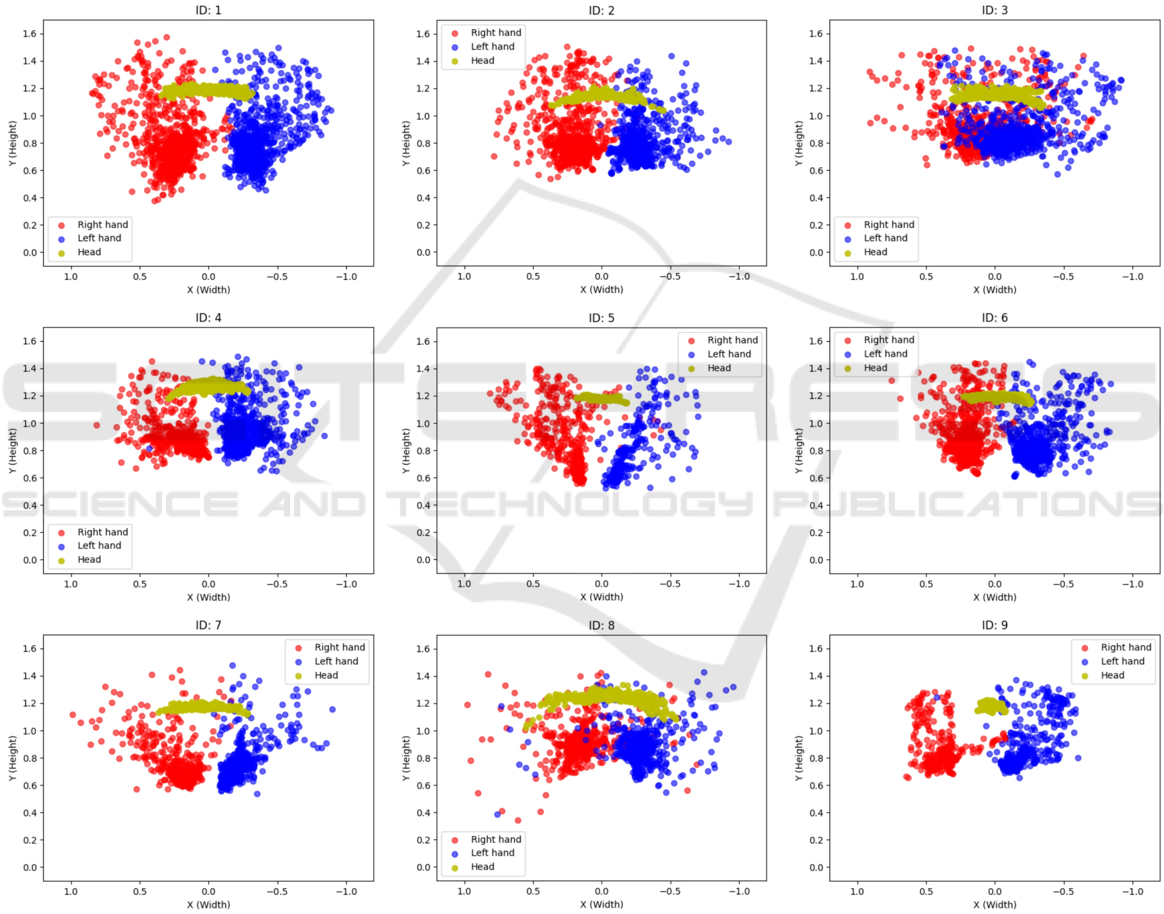

Figure 7: 2D representation of participants' hand and head positions during the second training session.

5 CONCLUSIONS

This paper presents a VR-based serious game designed for upper limb rehabilitation, replicating handball goalkeeper training for wheelchair users. It acts as a complement to traditional therapy methods, providing patients with a more appealing and motivational environment for exercise.

A key strength of this work is the accurate recording of kinematics during exercise performance. The data gathered are crucial for therapists to objectively assess patient progress. Parameters such as range of motion (ROM), movement speed and smoothness, repetition count and consistency, as well as the ac-

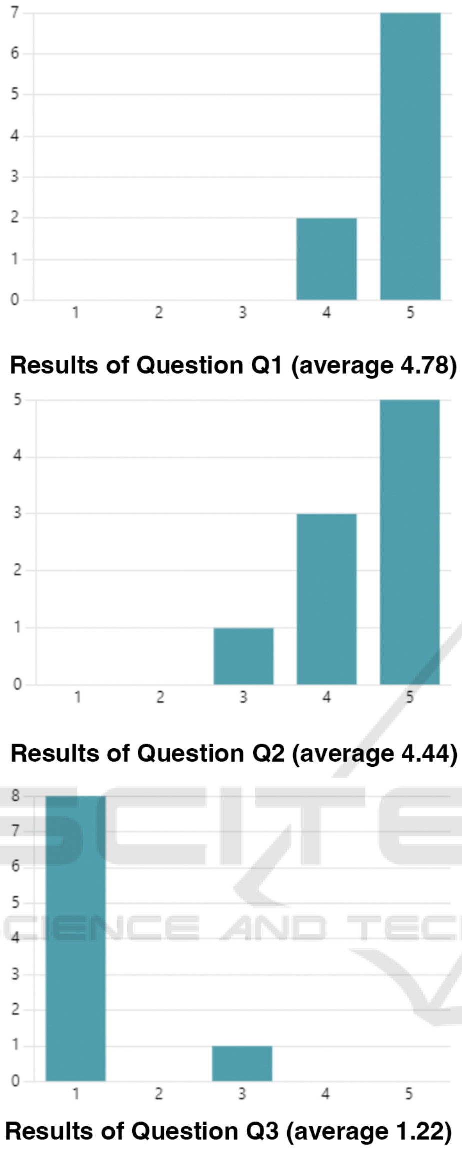

Figure 8: Graphical representation of the responses provided by participants regarding motivation, sense of achievement and satisfaction, and comfort/well-being.

curacy and precision of movements, balance, or postural control can be calculated from this data. For patients, this information is invaluable as it informs them whether they are performing the movements correctly, a vital aspect since the success of rehabilitation partly relies on exercise precision.

The system has been tested in a real-world setting at the Hospital Nacional de Parapléjicos de Toledo with SCI patients and has also been validated by therapists. The conducted experimentation has some limitations, such as a small participant sample and a single exercise session in one day. However, the initial goal of this preliminary work was mainly to analyze the correct functionality of the system and ensure it provides a safe testing environment for patients.

After verification by the HNPT staff regarding the system's safety for patients and the reliability of the data collected, future sessions are planned to involve larger patient samples and regular repetitions to evaluate the effectiveness and impact of the proposal on mobility recovery.

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REFERENCES

Baluz, R., Teles, A., Fontenele, J. E., Moreira, R., Fialho, R., Azevedo, P., Sousa, D., Santos, F., Bastos, V. H., and Teixeira, S. (2022). Motor rehabilitation of upper limbs using a gesture-based serious game: Evaluation of usability and user experience. *Games for Health Journal*, 11(3):177–185.

Cuesta-Gómez, A., Sánchez-Herrera-Baeza, P., Oña-Simbaña, E. D., Martínez-Medina, A., Ortiz-Comino, C., Balaguer-Bernaldo-de Quirós, C., Jardón-Huete, A., and Cano-de-la Cuerda, R. (2020). Effects of virtual reality associated with serious games for upper limb rehabilitation in patients with multiple sclerosis: Randomized controlled trial. *Journal of neuroengineering and rehabilitation*, 17:1–10.

de Los Reyes-Guzmán, A., Lozano-Berrio, V., Alvarez-Rodriguez, M., Lopez-Dolado, E., Ceruelo-Abajo, S., Talavera-Diaz, F., and Gil-Agudo, A. (2021). Rehabhand: Oriented-tasks serious games for upper limb rehabilitation by using leap motion controller and target population in spinal cord injury. *NeuroRehabilitation*, 48(3):365–373.

Domínguez-Téllez P, Moral-Muñoz JA, S. A. C.-F. E. L.-A. D. (2020). Game-based virtual reality interventions to improve upper limb motor function and quality of life after stroke: Systematic review and meta-analysis. *Games for Health Journal*, 9(1):1–10.

Doumas, I., Everard, G., Dehem, S., and Lejeune, T. (2021). Serious games for upper limb rehabilitation after stroke: a meta-analysis. *Journal of neuroengineering and rehabilitation*, 18:1–16.

Herne, R., Shiratuddin, M. F., Rai, S., Blacker, D., and Laga, H. (2022). Improving engagement of stroke survivors using desktop virtual reality-based serious games for upper limb rehabilitation: A multiple case study. *IEEE Access*, 10:46354–46371.

Herrera, V., Reyes-Guzmán, A., Vallejo, D., Castro-Schez, J. J., Monekosso, D. N., González-Morcillo, C., and Albusac, J. (2023a). Performance analysis for upper limb rehabilitation in non-immersive and immersive scenarios. In *International Conference on Enterprise Information Systems, ICEIS*, pages 231–242.

Herrera, V., Vallejo, D., Castro-Schez, J. J., Monekosso, D. N., de los Reyes, A., Glez-Morcillo, C., and Albusac, J. (2023b). Rehab-immersive: A framework to support the development of virtual reality applications in upper limb rehabilitation. *SoftwareX*, 23:101412.

Ikbali Afsar, S., Mirzayev, I., Umit Yemisci, O., and Cosar Saracgil, S. N. (2018). Virtual reality in upper extremity rehabilitation of stroke patients: A randomized controlled trial. *Journal of Stroke and Cerebrovascular Diseases*, 27(12):3473–3478.

Juan, M.-C., Elexpuru, J., Dias, P., Santos, B. S., and Amorim, P. (2023). Immersive virtual reality for upper limb rehabilitation: comparing hand and controller interaction. *Virtual Reality*, 27(2):1157–1171.

Karamians, R., Proffitt, R., Kline, D., and Gauthier, L. V. (2020). Effectiveness of virtual reality- and gaming-based interventions for upper extremity rehabilitation poststroke: A meta-analysis. *Archives of Physical Medicine and Rehabilitation*, 101(5):885–896.

Lee, S. H., Jung, H.-Y., Yun, S. J., Oh, B.-M., and Seo, H. G. (2020). Upper extremity rehabilitation using fully immersive virtual reality games with a head mount display: a feasibility study. *Pm&r*, 12(3):257–262.

Pereira, M. F., Prahm, C., Kolbenschlag, J., Oliveira, E., and Rodrigues, N. F. (2020). A virtual reality serious game for hand rehabilitation therapy. In *2020 IEEE 8th International Conference on Serious Games and Applications for Health (SeGAH)*, pages 1–7. ISSN: 2573-3060.

Proença, J. P., Quaresma, C., and Vieira, P. (2018). Serious games for upper limb rehabilitation: a systematic review. *Disability and Rehabilitation: Assistive Technology*, 13(1):95–100.

Shahmoradi, L., Almasi, S., Ahmadi, H., Bashiri, A., Azadi, T., Mirbagherie, A., Ansari, N. N., and Honarpishe, R. (2021). Virtual reality games for rehabilitation of upper extremities in stroke patients. *Journal of bodywork and movement therapies*, 26:113–122.

Song, X., van de Ven, S. S., Chen, S., Kang, P., Gao, Q., Jia, J., and Shull, P. B. (2022). Proposal of a wearable multimodal sensing-based serious games approach for hand movement training after stroke. *Frontiers in Physiology*, 13:811950.

Spooren, A. I. F., Janssen-Potten, Y. J. M., Kerckhofs, E., Bongers, H. M. H., and Seelen, H. A. M. (2011). Evaluation of a task-oriented client-centered upper extremity skilled performance training module in persons with tetraplegia. *Spinal Cord*, 49(10):1049–1054.

Vogt, S., Skjæret-Maroni, N., Neuhaus, D., and Baumeister, J. (2019). Virtual reality interventions for balance prevention and rehabilitation after musculoskeletal lower limb impairments in young up to middle-aged adults: A comprehensive review on used technology, balance outcome measures and observed effects. *International Journal of Medical Informatics*, 126:46–58.

WHO (2021). Spinal cord injury. Accessed: 17-Oct-2023.