Advanced VR Calibration for Upper Limb Rehabilitation: Making Immersive Environments Accessible

Vanesa Herrera[1][a], Ana Reyes-Guzmán[2][b], David Vallejo[1][c], José Castro-Schez[1][d],
Dorothy N. Monekosso[3][e], González-Morcillo Carlos[1][f] and Javier Albusac[1][g]
[1]*School of Computer Science, University of Castilla-La Mancha, Ciudad Real, Spain*
[2]*Hospital Nacional de Parapléjicos de Toledo, Toledo, Spain*
[3]*Department of Computer Science, University of Durham, Durham, County Durham, GB, U.K.*

Keywords: Upper Limb Rehabilitation, Virtual Reality, Dynamic Environment Adaptation, Free-Hand Calibration, Immersive Gamification.

Abstract: The creation of accessible spaces is essential for patients with motor injuries to conduct therapy safely and effectively. Disruptive technologies such as Virtual Reality (VR) are increasingly being used as a complement to traditional therapy, with excellent results. VR allows, among other things, the realistic recreation of physical spaces, so much so that it is relatively easy to run the risk of transferring physical barriers into the virtual space. This article proposes an innovative method of calibration in virtual environments that assesses the motor limitations of patients with cervical spinal cord injuries, doing so individually for each upper limb. The result is the dynamic adaptation of virtual environments to make them accessible and safe for rehabilitative therapy practices. This method has been integrated into the Rehab-Immersive platform, which hosts a series of serious games aimed at rehabilitating upper limbs, using immersive gamification techniques.

1 INTRODUCTION

In recent years, the use of Virtual Reality (VR) has spread to a variety of fields, including physical and psychological rehabilitation (Zhang et al., 2020; Cha et al., 2021). The application of VR in rehabilitation process has shown important benefits such as an improvement in mobility, balance and cognitive function (Park et al., 2020), as well as reducing the perception of pain in patients (Goudman et al., 2022; Mallari et al., 2019). Furthermore, the use of VR devices in rehabilitation programs improves treatment adherence and increases motivation (Dias et al., 2019), both important qualities for a successful rehabilitation process (Teo et al., 2022).

In particular, the technological advances that immersive VR devices have undergone in recent years have led to a new field in upper limb rehabilitation. Wearable devices, such as head-mounted displays (HMDs), provide users with immersive experiences in virtual environments through a viewer and controllers. More recently, this type of system has begun to offer hand tracking through the existing inside-out cameras in the headset (Khundam and Nöel, 2021). As a result, existing applications are being adapted or new ones are being developed. These applications allow the user to interact with the virtual world using his or her own hands, without the need for controllers or joysticks. This new form of interaction with virtual environments makes it more intuitive, natural and simple. In line with this, recent studies demonstrate the preference for this mechanism of interaction over controllers (Juan et al., 2023). Moreover, it opens new opportunities for people with reduced mobility in their upper limbs who, until now, have been unable to use these types of devices due to the need for fine motor skills to hold the controller and press the buttons. This technological progress has generated new possibilities in the development of applications for upper limb rehabilitation. In this context, it is essential for

---

[a] https://orcid.org/0000-0002-6187-4794
[b] https://orcid.org/0000-0003-2905-2405
[c] https://orcid.org/0000-0002-6001-7192
[d] https://orcid.org/0000-0002-0201-7653
[e] https://orcid.org/0000-0001-7322-5911
[f] https://orcid.org/0000-0002-8568-9542
[g] https://orcid.org/0000-0003-1889-3065

Herrera, V., Reyes-Guzmán, A., Vallejo, D., Castro-Schez, J., Monekosso, D., Carlos, G. and Albusac, J.
Advanced VR Calibration for Upper Limb Rehabilitation: Making Immersive Environments Accessible.
DOI: 10.5220/0012624600003690

In *Proceedings of the 26th International Conference on Enterprise Information Systems (ICEIS 2024) - Volume 2*, pages 378-389
ISBN: 978-989-758-692-7; ISSN: 2184-4992

patients to use their hands naturally, replicating traditional rehabilitation movements and grips.

Although hands-free interaction and accurate hand tracking is an important advance in the accessibility of immersive environments for people with motor impairments, it is still not sufficient for the proper development of rehabilitation therapies. The challenge of developing VR environments that are accessible and adapted to the different needs of end users and the specific characteristics of each application. VR makes it possible to simulate worlds and situations that are difficult to reproduce in real environments, which is a significant advantage, especially given the diversity of environments and the mobility constraints of certain users. This capability highlights the need for virtual environments to be accessible and adaptable to both user needs and application-specific requirements.

For users with special needs or disabilities, the creation of adapted, accessible, and inclusive VR environments is crucial (Soomal et al., 2020; Creed et al., 2023). This involves tailoring the type of interaction and the placement of interactive elements to suit each user's abilities. This is particularly important for patients with cervical spinal cord injuries (cSCI), who require exercises to be performed while seated, considering their upper limb mobility and gripping capabilities. Proper positioning of interactive elements in the VR environment is key to ensuring safety, prevent overexertion or unwanted compensatory movement. These compensatory movements, which are movement patterns adopted to overcome motor restrictions (Luo et al., 2023), while facilitating task performance, can sometimes lead to additional problems that negatively affect the rehabilitation process (see Figure 1).

One solution to address these challenges lies in the ability of VR systems themselves to capture and store relevant data. This includes data related to the kinematics of the body parts undergoing therapy, as well as the position of elements in the virtual scene and historical tracking of the patient's progress. In addition, the capture and storage of kinematic data is essential in the rehabilitation process. This practice provides healthcare professionals with a more objective and quantitative view of the patient's progress. This is exemplified in the study by Onitsuka et al. (Onitsuka et al., 2023), which highlights the significance of such data in monitoring and enhancing rehabilitation outcomes. This information is useful for adjusting and optimising rehabilitation programmes, ensuring their maximum effectiveness for the specific needs of each patient. Furthermore, the capture and analysis of this data not only facilitates the identification of the effectiveness of the exercises but also allows for the detection of possible unwanted compensatory movements.

In this context, leveraging VR capabilities, a practical solution for enhancing the accessibility and adaptation of virtual rehabilitation environments involves a calibration process before exercise execution. This calibration should focus on the specific motor conditions of the patient, taking into account their particular characteristics and limitations. This assessment allows for precise modifications to the positioning of the interactive elements within the virtual environment. Such an approach ensures that the virtual environment is not only accessible but also highly personalized, adapting to both the physical capabilities of the patient and their specific stage in the rehabilitation process.

On this basis, the article presents an advanced automatic calibration system adapted to upper limb rehabilitation in patients with cSCI. This system takes into account the physical characteristics of the patient and the specific requirements of the exercises to be performed. Thanks to this pre-calibration, it is possible to adapt the position of the elements in the virtual environment according to the specific characteristics of the exercise. For this reason, the range of movement is taken into account separately for each of the upper limbs, since the exercises can be performed with one or two hands. In addition to the optimal position, it is taken into account that the patients perform the exercises in a seated position, thus avoiding possible undesirable compensatory movements. It should be noted that the calibration is based on hand positions, without the need for external elements such as joysticks or controllers. As a result, patients perform the exercises in a more natural and ergonomic way, potentially improving the effectiveness of rehabilitation.

The calibration system, aimed at improving upper limb rehabilitation of cSCI patients, has been integrated into the Rehab-Immersive platform (Herrera et al., 2023). This integration facilitates design, implementation and testing. The Rehab-Immersive platform is currently developing a series of serious games. These games are adapted to specific therapies for the rehabilitation of upper limbs of ICSc patients. The collaboration with the Hospital Nacional de Parapléjicos de Toledo has been key in this development. This hospital is recognised as a reference centre for patients with SCI. The main objective of Rehab-Immersive is to create an environment that favours effective rehabilitation

The rest of the paper is structured as follows. Section 2 reviews related works. Section 3 provides context and background information. Section 4 describes

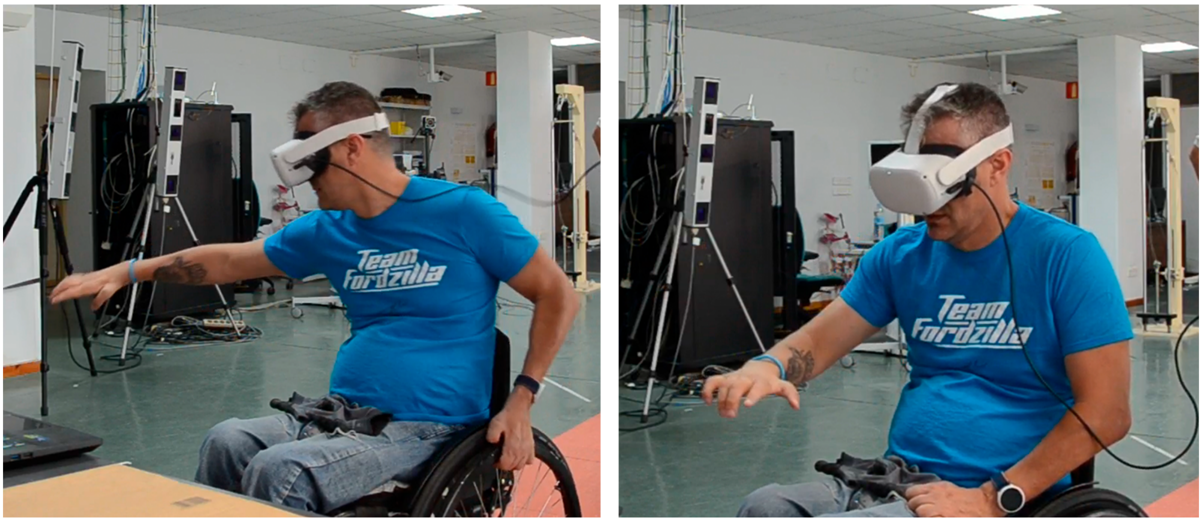


Figure 1: On the left, a patient performs compensatory movements, with trunk inclination and grasping the wheelchair with the left hand to achieve balance. On the right, due to a correct distribution of virtual elements, compensatory movements are not necessary.

the automatic calibration system. Section 5 presents the evaluation and the results obtained. Section 6 discusses the limitations and future work. Finally, the paper concludes with Section 7, which presents the conclusions.

2 RELATED WORKS

2.1 VR Rehabilitation for Upper Limbs

Several studies have focused on the rehabilitation of upper limbs using VR techniques. These works can be classified according to the degree of immersion and the main way of interaction. Depending on the degree of immersion, there are non-immersive and immersive applications and, the use of devices such as controllers or the user's own hands (hand tracking) can be considered.

Non-immersive and hand tracking upper limb VR rehabilitation studies include the work of Shahmoradi et al. (Shahmoradi et al., 2021), who used the Kinect sensor to rehabilitate the upper limb in stroke patients through a set of games. The results of the study indicated improvements in participants' range of motion in terms of horizontal shoulder abduction and adduction, elbow flexion, and wrist supination and flexion. The study by Reyes-Guzmán et al. (de Los Reyes-Guzmán et al., 2021) also uses non-immersive VR and hand tracking by means of a Leap Motion Controller (LMC), and focused on SCI patients. The conclusions of the study indicate that the LMC is suitable for a given sample of cervical patients for rehabilitation purposes.

Regarding studies with immersive VR and the use of controllers, the following can be found the study by Lim et al. (Lim et al., 2020) which investigated the use of VR in combination with conventional rehabilitation for upper limb rehabilitation in patients with SCI. The conclusion of the study is that VR training for upper limb function after SCI may be an acceptable adjunctive rehabilitation method without significant adverse effects. With this degree of immersion and type of interaction, the study by Everard et al. developed an immersive VR version of the Box and Block Test (BBT-VR) to assess manual dexterity in stroke patients and healthy participants. The aim was to evaluate the concurrent validity of the BBT-VR, highlighting the need for regular follow-up and kinematic assessments to objectively measure motor recovery after stroke. The study by Lee et al. demonstrates that a fully immersive VR rehabilitation programme with an HMD and controllers is feasible for upper limb rehabilitation in chronic stroke patients, without serious adverse effects.

In the field of upper limb rehabilitation using immersive VR systems and direct interaction with the patient's hands, is the study by AlMousa et al. (AlMousa et al., 2020). This study presents the development of a game designed for stroke patients requiring upper limb rehabilitation at home. The game uses the Oculus Rift HMD and the LMC hand tracker for a fully immersive virtual reality experience.

In the latter group, the combination of immersive virtual reality (VR) and hand tracking has proven to be most effective for upper limb rehabilitation.

This approach provides a more natural interaction, which is crucial for patients with motor limitations (AlMousa et al., 2020; Juan et al., 2023). In addition, non-immersive systems can limit depth perception due to their design for flat monitors, which negatively affects the user experience (Everard et al., 2022).

2.2 Adaptation of VR Environments for Rehabilitation

Adaptation in VR environments is essential to ensure accessibility and effectiveness in rehabilitation. Several studies have highlighted the accessibility challenges associated with these technologies, particularly for people with physical disabilities. Mott et al. (Mott et al., 2019) identify five key elements for the accessibility of VR content: accessibility of interaction, accessibility of devices, inclusive representations and diversity of applications. In addition, in a separate study conducted in 2020, (Mott et al., 2020) identified seven specific barriers for people with reduced mobility, one of which related to the preparation of VR peripherals and the definition of VR game boundaries.

The need to adapt virtual environments to the capabilities of rehabilitation patients is a topic widely supported in the scientific literature. One example is the study by Lagos Rodriguez et al. (Lagos Rodríguez et al., 2022) which highlights the importance of personalisation in VR environments, focusing on the specific needs of each patient. On the other hand, the study by Carrington et al. (Pei et al., 2023), allows wheelchair users to assess the accessibility of unfamiliar places remotely by exploring detailed digital replicas. The study introduces a VR technique called ‘Embodied Exploration’, which allows wheelchair users to explore high-fidelity digital replicas of physical environments. However, a limitation of the study is the need for users to provide accurate measurements of their biometrics.

3 BACKGROUND

Focused on the need to create patient-centred virtual environments for upper limb rehabilitation in patients with cSCI, the *Rehab-Immersive* (Herrera et al., 2023) project arises, coordinated with the Hospital Nacional de Parapléjicos (Toledo, Spain). In this project, a set of serious games is being developed to improve the mobility and manipulative skills of patients. Serious games in the context of *Rehab-Immersive* take advantage of the benefits of VR, such as motivation and reinforcement of the patient’s commitment, as well as accurate monitoring and evaluation of the evolution of the treatment by the specialist.

Through various analyses and tests conducted with patients and specialists, a key element has been identified in VR environments for the rehabilitation of cSCI patients: the significance of three-dimensional (3D) positioning of elements within the space that patients interact with.

In order to solve this problem, a manual calibration of the elements with which the patient interacts was implemented in two ways: with predefined positions (closer and further away) in the three axes, and through manual positioning of the object in 3D space.

However, moving barriers were found in the manual calibration. First, depending on the patient’s mobility, it can be a tedious process. This is the case when the elements with which the patient must interact are positioned too far apart, leading to a suboptimal interaction location. Additionally, complexity increases when there are numerous elements that require individual configuration. Second, there are patients who, given their conditions, cannot calibrate the elements well due to grip difficulties. In the case of predefined positions, these may not be adequately adapted to the optimum. Thirdly, this calibration has to be done for each element with which interactive element and for each serious set, which is a slow process.

Particularly in patients with limited or no functional grip, this approach presents a significant problem, making it necessary for the specialist to intervene by positioning the item. However, the specialist’s view of the 3D space is not through the VR HMD, but on a screen, which leads to a loss of depth sensation and can lead to errors in calibration.

4 CALIBRATION SYSTEM

In response to the challenges mentioned above, the calibration system proposed in this paper is tailored to the specific needs of cSCI patients. This system is designed to accommodate several factors to accomplish effective rehabilitation. To achieve this, both the calibration system and the BBT-VR have been developed using Unity[1] and the Meta XR Interaction SDK[2]. First of all, it takes into account the patient’s posture and limited mobility, since the exercises are performed sitting and without moving. This consideration includes

---

[1] https://unity.com/

[2] https://developer.oculus.com/documentation/unity/unity-isdk-interaction-sdk-overview/

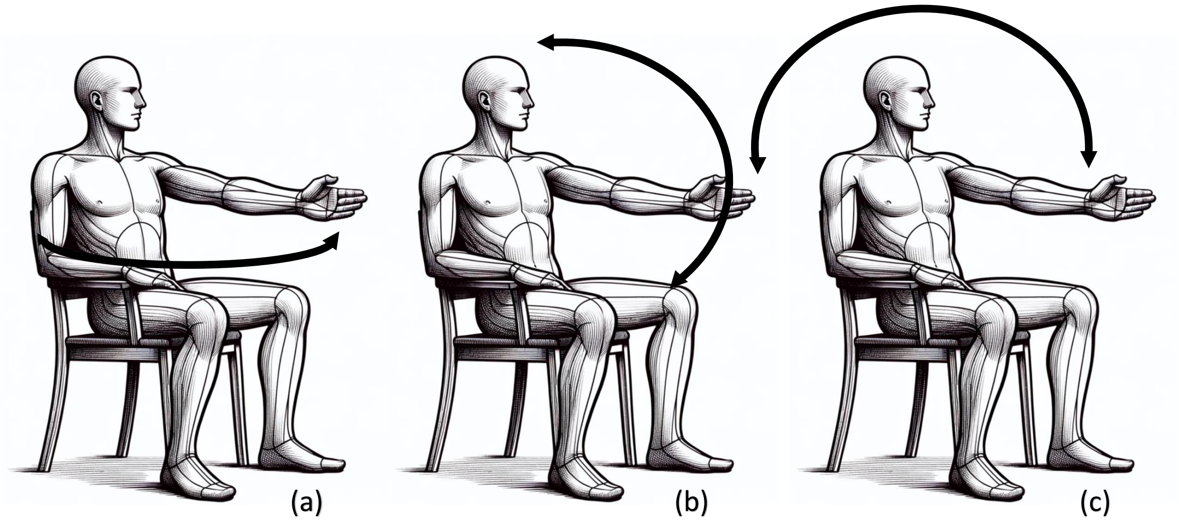


Figure 2: Movements to be reproduced for the calibration of the right and left arm in the three planes: (a) transverse plane, (b) sagittal plane, and (c) frontal plane.

the height of the items and the position of the patient's legs.

The system also provides individual calibration for each upper limb, adjusting the virtual environment to respect the limitations and capabilities of each side of the body.

In addition, the system is applicable to different games and interactive elements. It incorporates calibration data to adapt the interactive elements depending on the type of exercise, whether monomanual or bimanual, and whether it involves gripping or not.

A key feature of this system is its automation and customization capabilities. It automates the calibration process based on patient mobility and capacity data, facilitating accurate and efficient customization for each individual.

Thanks to this calibration, a safe VR environment is provided. Feature that helps prevent excessive efforts and compensatory movements that could be detrimental to the patient's health.

Finally, the system improves ease of use, improving patient autonomy in the use of VR.

In summary, the proposed calibration system aims to improve the patient's experience and optimize rehabilitation results, adjusting to the evolution of the patient's motor capacity and ensuring that the exercises are performed safely and effectively.

Additionally, the calibration system will be tested with one of the games implemented within *Rehab-Immersive*, specifically the BBT-VR. The BBT, is a manipulative dexterity test in which the patient must move as many blocks as possible from one compartment to another within a box, all within 60 seconds (Mathiowetz et al., 1985).

The implemented calibration system is designed to adapt the virtual workspace to fit the motor skills of each cSCI patient. This calibration process takes into account three aspects: i) head position, ii) elbow flexion and, iii) shoulder movements.

The initial state of the HMD is captured to determine the position and rotation of the head at rest. On the other hand, elbow flexion, with the hands hip-width apart, is used to determine the central area to the patient and the position of the hands in this pose, which is used for some therapeutic exercises. However, it is the analysis of the shoulder movements that plays a central role in this process, following the principles established by I. A. Kapandji (Kapandji, 1971). In this book, Kapandji details the complex movements of the shoulder in the sagittal, frontal and transveral planes, which include flexion and extension, abduction and adduction, and horizontal flexion and extension, respectively.

The objective of this calibration phase is to determine the maximum reach that a user can achieve with each hand in three planes. The kinematics of the shoulder are critical in this process, as the maximum reach is achieved with the arm and elbow fully extended. The use of ellipses, rather than circles, to define the workspace is adopted because of the potential mobility restrictions that patients may have. Ellipses offer greater flexibility to accommodate these limitations. Since users are seated and cannot perform the full circumduction movement, the workspace is ideally limited to the front and side areas, rather than extending behind the patient. In an optimal scenario, these ellipses will approximate to circles. Through various tests, it has been proven that using ellipses to

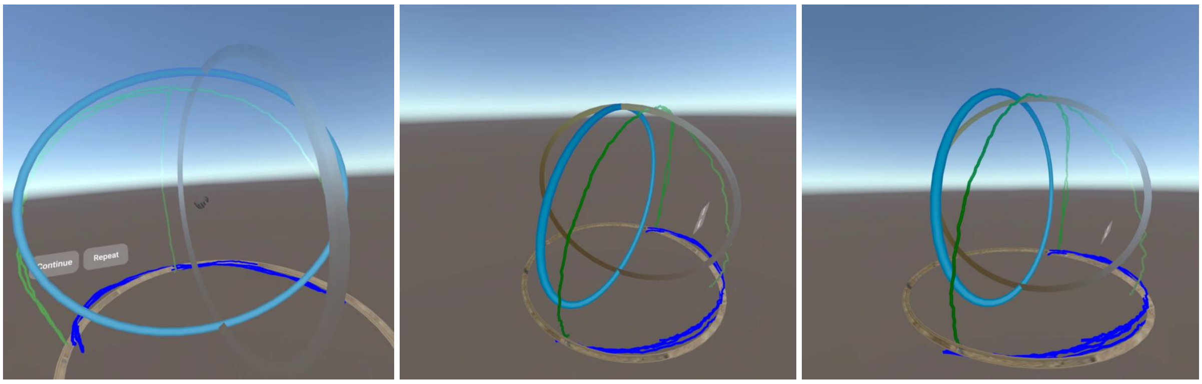


Figure 3: An example of sagittal, frontal, and transverse ellipses resulting from the calibration process. Images taken from different perspectives and decorative elements have been removed for clearer visualization.

define the workspace results in greater accuracy than using circles.

The calibration process has been designed in an intuitive and detailed way. Each phase of calibration is accompanied by an instructional video in which an avatar demonstrates the specific movements that the user must replicate. At the end of each instructional video, the application emits a sound to indicate that the user must begin to perform the movements or position themselves in the explained pose.

During the whole process, the user must keep his back well supported and without twisting his trunk. This requirement is essential in order to know the degree of mobility of the upper limbs without the intervention or influence of trunk movement.

In the first stage, the patient is instructed to look forward for a few seconds. This first step captures the position and rotation of the HMD, as its default position is not always aligned with the zero position on all three axes.

$$\textbf{hmdInitialPosition} = (x_{\text{hmd}}, y_{\text{hmd}}, z_{\text{hmd}}),$$
$$\textbf{hmdInitalRotation} = (\alpha_{\text{hmd}}, \beta_{\text{hmd}}, \gamma_{\text{hmd}}),$$

where $(\alpha_{\text{hmd}}, \beta_{\text{hmd}}, \gamma_{\text{hmd}})$ are the Euler angles.

The second stage is for the patient to bend his elbows 90 degrees while keeping his arms aligned across the hip, making sure his hands are above the knees. This position helps determine the central area and ideal position for many virtual reality games. An example of the importance of these positions is the BBT-VR. This calibration ensures that the box is placed in front of the patient at the correct height, aligning with the elbows bent at 90 degrees.

$$\textbf{centerPalmR} = (x_r, y_r, z_r),$$
$$\textbf{centerPalmL} = (x_l, y_l, z_l),$$

During the third step, the calibration process is further divided into two new phases. First, a detailed calibration of the upper limbs movements in three dimensional planes is performed.

In this new first phase, the avatar asks the user to fully extend the arm in the transversal plane and move the arm from one end of the X-axis to the other, keeping the arm above the knees (see Figure 2.a). This stage is designed to calibrate the range of motion in the horizontal plane and the patient's ability to reach laterally, thus capturing the range of possible movements in this plane.

The second part of the calibration relates to the frontal and sagittal planes. As in the previous stage, the patient is asked to fully extend the arm. After the avatar has shown the necessary movements, the calibration begins. These movements consist of extending the arm from one end of the X-axis to the other and moving it along the Y-axis (height) and Z-axis (depth) (see Figure 2.b and c). The trajectory of these movements simulates the drawing of a dome in the air. This process is designed to assess and calibrate the patient's ability to perform both vertical and depth movements. Figure 3 shows an example of ellipses formed in the sagittal, frontal, and transverse planes, outlining the patient's movement scope. Next to the ellipses, less firm traces, generated by the user during the calibration process, are visible.

Simultaneously, and transparently to the user, the system creates two lists of points during the calibration process. The first list, denoted as $(\mathcal{P}_{R_{XZ}})$, collects the points traced by the patient's arm in the XZ plane. This list encapsulates all the trajectories performed in the XZ plane.

The second list, $\mathcal{P}_{R_{XY/YZ}}$, consists of the points generated during movements in the XY and YZ planes.

These two lists, together provide a complete representation of the patient's arm movement capabilities in all three axes. This separation into two lists

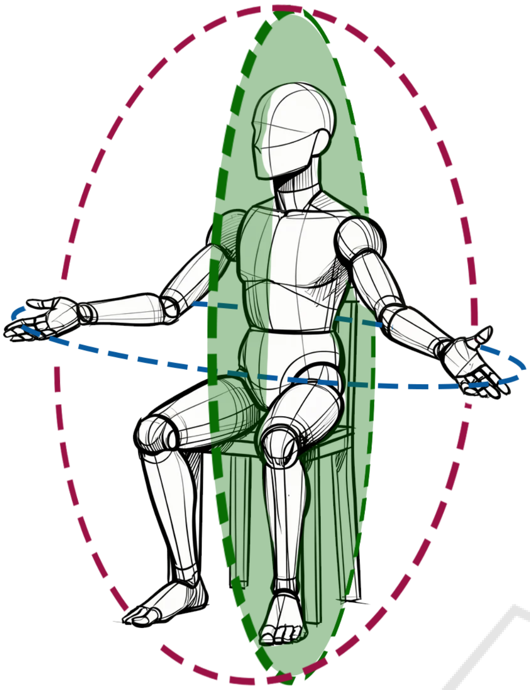


Figure 4: An example of sagittal, frontal, and transverse ellipses resulting from the calibration process.

allows a more detailed and specific assessment of the movement capabilities in different planes, facilitating a more accurate calibration.

The fourth stage shows the calibration results. After completing the calibration, the system draws three ellipses. Each ellipse corresponds to the range of mobility of the patient's arm in different planes: XY, XZ, and YZ. These ellipses are calculated based on the trajectory data ($\mathcal{P}_R$ and $\mathcal{P}_L$) collected for each arm, ensuring they represent the patient's actual movement capabilities. The ellipses are defined as follows:

1. The center of each ellipse, denoted as $\mathbf{C}$, is computed as the average position of the trajectory points within each plane:

$$\mathbf{C} = \left(\frac{1}{n} \sum_{i=1}^{n} x_i, \frac{1}{n} \sum_{i=1}^{n} y_i, \frac{1}{n} \sum_{i=1}^{n} z_i \right),$$

$$\text{for } (x_i, y_i, z_i) \in \mathcal{P}_R \text{ or } \mathcal{P}_L.$$

2. The radii of the ellipses are calculated based on the maximum distances from the center point to the points within each plane. For a set of points $\{(x_i, y_i, z_i)\}$, the radii in the X, Y, and Z directions are calculated as:

$$r_x = \max_{(x_i,y_i,z_i)\in\mathcal{P}} |x_i - x_{\mathbf{C}}|, r_y = \max_{(x_i,y_i,z_i)\in\mathcal{P}} |y_i - y_{\mathbf{C}}|,$$

$$r_z = \max_{(x_i,y_i,z_i)\in\mathcal{P}} |z_i - z_{\mathbf{C}}|.$$

To test the accuracy of the calibration, a virtual block is displayed at the center of the palm of the patient's hand (see Figure 5). The patient can move their hand freely, with the block remaining attached to the palm's center. The color of the block provides immediate feedback: it appears green if it is within the defined ellipses, signifying that the hand is within the calibrated workspace. If the block turns red, it indicates that the hand has moved outside the defined working area, surpassing the calibrated range of motion. To determine if a point is inside the calibrated workspace, defined by ellipses in the XY, XZ, and YZ planes, the following mathematical condition is used:

Let $\mathbf{O} = (o_x, o_y, o_z)$ represent the position of the object (e.g., virtual block) in 3D space, and let $\mathbf{C} = (c_x, c_y, c_z)$ be the center of the ellipses with radii r_x, r_y, and r_z in the X, Y, and Z dimensions, respectively. The point $\mathbf{O}$ is considered to be inside the calibrated workspace if the following conditions are met for each plane:

$$\text{Inside XY-plane:} \quad \left(\frac{o_x - c_x}{r_x}\right)^2 + \left(\frac{o_y - c_y}{r_y}\right)^2 \leq 1$$

$$\text{Inside XZ-plane:} \quad \left(\frac{o_x - c_x}{r_x}\right)^2 + \left(\frac{o_z - c_z}{r_z}\right)^2 \leq 1$$

$$\text{Inside YZ-plane:} \quad \left(\frac{o_y - c_y}{r_y}\right)^2 + \left(\frac{o_z - c_z}{r_z}\right)^2 \leq 1$$

Figure 5: Post-calibration environment with a cube attached to the hand, indicating boundaries in green (within limits) or red (outside limits).

Finally, the fifth stage involves the storage of the calibration data. Once the calibration is completed and verified for accuracy, the system stores the relevant data in a historical record. This allows for the calibration to be referenced or adjusted in future sessions, ensuring a tailored and efficient VR experience for each patient.

The stored historical data, used for game calibration, also presents another value for medical specialists. By regularly repeating the calibration process over time, changes in a patient's mobility can be closely monitored. This enables a more personalized rehabilitation approach, tailored specifically according to the evolving mobility data of each patient, thereby optimizing the rehabilitation process.

4.1 Application of Calibration Data in BBT-VR

In the specific case of the BBT-VR (see Figure 6), which is a monomanual exercise, the precise positioning of the virtual box is essential. The calibrated data is used to ensure that the box is placed in a comfortable position in front of the user, without requiring excessive arm extension.

Additionally, the height of the virtual box is carefully adjusted to be suitable for the patient's stature. It is positioned to avoid being too high or too low, which might interfere with the patient's legs, considering the seated position during the exercise.

Furthermore, the box is centered relative to the patient's midline, ensuring that the exercises are symmetric and balanced, regardless of which hand is being used.

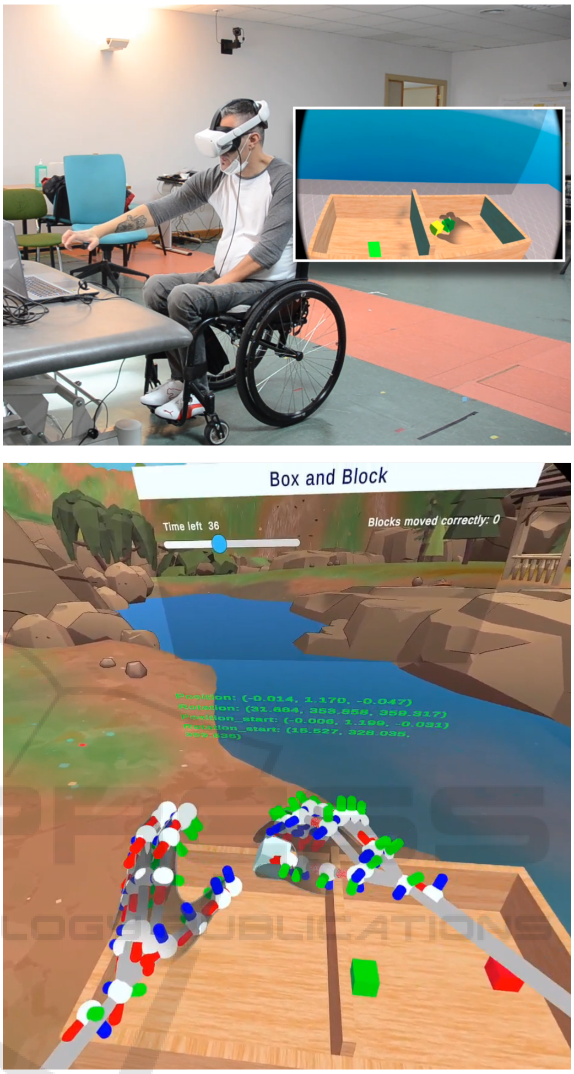
To facilitate these adjustments in BBT-VR, an option has been added to the configuration menu that allows users to choose between automatic or manual calibration. The manual option involves the user physically grabbing the box and moving it to the appropriate position. Additionally, while the box is ideally positioned in front of the user, the option for lateral positioning has been introduced. This lateral position will be to the right if the right hand is selected as dominant, and to the left if the left hand is chosen.

Depending on the selected configuration, the BBT-VR begins by placing the box either manually or automatically, and in the selected position, either central or lateral.

5 EVALUATION AND RESULTS

The evaluation was conducted with a diverse group of participants, including both men and women, aged between 20 and 43 years. All participants selected did not have any mobility issues in their upper limbs. The study was divided into two sessions: the first involved 6 participants, while the second included 9.

Initially, participants received a comprehensive briefing about the test session's procedures. The first part of the session focused on testing an automatic calibration system (see Figure 7). Participants were required to follow instructions provided by an avatar, mimicking the indicated movements. To correctly perform the calibration, participants were asked to keep their backs against the backrest and ensure all movements were made without twisting or shifting their torso. After calibration, they were asked to verify if the defined area appropriately adapted to the accessible area for them, without the need for excessive movements or trunk torsions.



```
Position: (-0.014, 1.170, -0.047)
Rotation: (31.684, 353.858, 359.317)
Position_start: (-0.006, 1.199, -0.031)
Rotation_start: (15.527, 328.035,
359.836)
```

Figure 6: BBT implementation in VR.

Subsequently, the participants were introduced to a BBT-VR application. In this part, they tested the automatic calibration, both in central and lateral positioning, for the right and left hands.

Finally, participants completed a questionnaire to gather their impressions and feedback on the experience. The questionnaire, which was explained to each participant before completion, comprised 10 questions. The initial set collected basic information, such as the participant's assigned identifier, age, height, and hand dominance. Question 4 asked about previous experience with immersive virtual reality (HMD) devices, asking: 'have you used immersive virtual reality HMD devices before?', with possible answers: 'Never (N)', 'Occasionally (O)' or 'Frequently (F)'. The following questions examined their experiences with the calibration system and the VR application, using a Likert scale for responses:

- **Q6:** did you find the automatic calibration system complex? Rate on a scale of 1 to 5, where 1 is not complex at all and 5 is very complex.
- **Q7:** after calibration, do you feel that the working area defined by the three ellipses adequately matches the range of motion limits of your upper limb? Please rate on a scale of 1 to 5, where 1 means 'not at all' and 5 means 'completely'.
- **Q8:** is the position of the box in the BBT-VR application, with automatic calibration in normal mode (centered to the user), correct for you?
- **Q9:** is the position of the box in the BBT-VR application, with automatic calibration in right lateral mode, correct for you?
- **Q10:** is the position of the box in the BBT-VR application, with automatic calibration in left lateral mode, correct for you?

For questions Q8, Q9, and Q10, participants rated the appropriateness of the box's position on a Likert scale from 1 to 5, where 1 indicates the lowest score (least appropriate) and 5 indicates the highest score (most appropriate).

Also, to facilitate observation and verification of the participants' movements and actions during the test, an external screen was used. This screen mirrored in real-time what the participants were seeing through the Meta Quest 3.

Figure 7: Moments captured during evaluation, while participants test the calibration method.

5.1 Results

The results obtained in the study were analyzed from two complementary perspectives. The first, a quantitative approach, focused on technical considerations related to the elliptical volume defined by ellipses in the XZ, XY, and ZX planes. For the central position of the box, it was verified that the center of the box was located within the elliptical volume, in relation to both the right and left sides of the upper limbs. For the lateral positions of the box, it was confirmed that the center of the box was within the control area defined by the corresponding elliptical volume (right or left).

The second perspective, with a qualitative approach, focused on the patient's viewpoint and perception. This subjective evaluation sought to understand the experiences and impressions of the participants regarding the calibration process and their interaction with the virtual environment. Analyzing the results of the VR experience questionnaire, we identified several significant trends that reflect participants' perceptions of the VR calibration system and its subsequent use in the BBT-VR application.

The data presented in Table 1 includes the responses to the questionnaire. To complete this overview, it is worth mentioning that for question Q5, all participants reported being right-handed. The ease of use of the calibration system is highlighted, as evidenced by the low average score of 1.07 in question Q6, with a standard deviation of only 0.26. This indicates that most participants found the system straightforward, with very little variation in their responses, reinforcing the notion of an intuitive and easy-to-manage design.

Regarding the accuracy of the working area (Q7), the high average scores of 4.27, with a standard deviation of 1.03, suggest that participants generally perceived that the defined working area aligned well with the movement limits of their upper limbs.

As for the appropriateness of the box's position in the BBT-VR application (Q8, Q9, Q10), the predominantly positive responses are reflected in the high average scores (4.73 for Q8, 4.33 for Q9 and Q10), with relatively low standard deviations (0.46 for Q8, 0.62 for Q9, and 0.49 for Q10). These figures indicate a generally favorable perception of the box calibration in all modes. However, it is interesting to note the trend of slightly higher scores for the box's central position (normal mode) compared to the lateral positions. This could suggest a perceived greater accuracy or comfort in the central setup, although the variations are not substantial.

To conclude, the study provides a comprehensive understanding of the VR upper limb calibration system and its integration into the BBT-VR, using both quantitative and qualitative approaches. From a technical perspective, the precise placement of the BBT-VR box within the elliptical volume was validated in both central and lateral positions, ensuring the correct execution of the exercises without excessive effort or compensatory movements. From a user perspective, the ease of use of the system and the positive perception of the accuracy of the workspace and box placement in the application were highlighted. These results underline the technical effectiveness of the system and its positive reception by users, highlighting its potential in precision-oriented VR applications while ensuring user comfort.

Table 1: Table summarizing the responses collected from the questionnaire on automatic calibration. The columns, from left to right, represent the participant ID, age, height, and responses to questions related to the automatic calibration system and the BBT-VR.

ID	Age	Ht	Q4	Q6	Q7	Q8	Q9	Q10
1	21	178	N	1	5	4	3	5
2	27	160	F	1	4	5	4	4
3	24	174	F	1	4	5	5	5
4	21	191	N	2	5	5	4	4
5	21	165	N	1	4	5	5	4
6	21	180	O	1	5	5	5	5
7	40	166	F	1	4	5	4	5
8	42	172	F	1	4	4	5	4
9	38	179	O	1	5	5	4	4
10	30	165	O	1	4	5	5	4
11	37	166	F	1	5	4	4	4
12	41	178	N	1	5	5	4	4
13	29	175	O	1	4	5	4	4
14	27	173	F	1	1	5	5	5
15	43	177	F	1	5	4	4	4

6 LIMITATIONS AND FUTURE WORK

Although the initial results of the calibration system are promising, further validation is needed to confirm its effectiveness. A larger study with a larger number of participants, including people with cSCI, is needed to confirm the preliminary results. Previous tests were conducted exclusively with healthy individuals, as the primary objective of this initial phase was to establish the system's safety before extending the testing to patients in subsequent phases. Additionally, storing other variables like the maximum degree of wrist flexion/abduction and arm rotation should be considered to enhance the calibration accuracy and applicability.

Following the study, there is a need to automate the implementation of the calibration system for each set. In the current iteration, specific values of the calibration data were manually selected and applied to correctly position elements in 3D space for the test set. The aim for future development is to automate this aspect so that the system can classify each set according to a set of parameters and automatically apply the calibration values in an efficient manner.

This will require a thorough study and ranking of the relevant parameters. These parameters could include factors such as whether the exercise is one-handed or bimanual, involves lateral trunk displacement or not, and requires centred positioning or positioning adapted to the range of motion of each arm. It will also be important to consider the plane of movement, whether vertical or horizontal. This second phase of implementation of the VR upper limb rehabilitation calibration system aims to facilitate its implementation in any game in a simple way.

7 CONCLUSIONS

This article presents an innovative calibration method for immersive spaces used in upper limb rehabilitation. The method particularly accounts for the motor limitations of patients with cervical spinal cord injuries who require rehabilitative therapy to regain mobility. A key novelty of the method is its consideration of the limitations of each limb individually, forming three ovals in the sagittal, frontal, and transverse planes. The set of generated ovals, along with the proposed methods, are used to reconfigure the virtual environment in which the patient exercises, ensuring that all objects they interact with are within reach based on the detected limitations. In other words, the environment adapts to become an accessible, suitable, and safe space for therapy.

The correct distribution of virtual components with which the user interacts, taking their limitations into account, also prevents more significant problems such as body compensations that could endanger the integrity of healthy parts.

Finally, the different calibrations performed by the same patient at different times, along with the recording of kinematics during exercise, provide therapists with a valuable tool for objectively measuring a patient's progress. In particular, comparing calibrations allows for the measurement of improvements in mobility.

ACKNOWLEDGEMENTS

This work has been founded by the Spanish Ministry of Science, Innovation and Universities under the Research Project: Platform for Upper Extremity Rehabilitation based on Immersive Virtual Reality (Rehab-Immersive), PID2020-117361RB-C21 and PID2020-117361RB-C22.

REFERENCES

AlMousa, M., Al-Khalifa, H. S., and AlSobayel, H. (2020). Move-IT: A Virtual Reality Game for Upper Limb Stroke Rehabilitation Patients. In *Computers Helping People with Special Needs: 17th International Conference, ICCHP 2020, Lecco, Italy, September 9–11, 2020, Proceedings, Part I*, pages 184–195, Berlin, Heidelberg. Springer-Verlag.

Cha, K., Wang, J., Li, Y., Shen, L., Chen, Z., and Long, J. (2021). A novel upper-limb tracking system in a virtual environment for stroke rehabilitation. *Journal of NeuroEngineering and Rehabilitation*, 18(1):166.

Creed, C., Al-Kalbani, M., Theil, A., Sarcar, S., and Williams, I. (2023). Inclusive AR/VR: accessibility barriers for immersive technologies. *Universal Access in the Information Society*.

de Los Reyes-Guzmán, A., Lozano-Berrio, V., Alvarez-Rodríguez, M., López-Dolado, E., Ceruelo-Abajo, S., Talavera-Díaz, 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.

Dias, P., Silva, R., Amorim, P., Laíns, J., Roque, E., Serôdio, I., Pereira, F., and Santos, B. S. (2019). Using Virtual Reality to Increase Motivation in Poststroke Rehabilitation. *IEEE Computer Graphics and Applications*, 39(1):64–70. Conference Name: IEEE Computer Graphics and Applications.

Everard, G., Otmane-Tolba, Y., Rosselli, Z., Pellissier, T., Ajana, K., Dehem, S., Auvinet, E., Edwards, M. G., Lebleu, J., and Lejeune, T. (2022). Concurrent validity of an immersive virtual reality version of the Box and Block Test to assess manual dexterity among patients with stroke. *Journal of NeuroEngineering and Rehabilitation*, 19(1):7.

Goudman, L., Jansen, J., Billot, M., Vets, N., Smedt, A. D., Roulaud, M., Rigoard, P., and Moens, M. (2022). Virtual Reality Applications in Chronic Pain Management: Systematic Review and Meta-analysis. *JMIR Serious Games*, 10(2):e34402.

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

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.

Kapandji, I. (1971). *The Physiology of the Joints, Volume I, Upper Limb*, volume 50. Churchill Livingstone.

Khundam, C. and Nöel, F. (2021). A Study of Physical Fitness and Enjoyment on Virtual Running for Exergames. *International Journal of Computer Games Technology*, 2021:1–16.

Lagos Rodríguez, M., García, A. G., Loureiro, J. P., and García, T. P. (2022). Personalized Virtual Reality Environments for Intervention with People with Disability. *Electronics*, 11(10):1586. Number: 10 Publisher: Multidisciplinary Digital Publishing Institute.

Lim, D. Y., Hwang, D. M., Cho, K. H., Moon, C. W., and Ahn, S. Y. (2020). A Fully Immersive Virtual Reality Method for Upper Limb Rehabilitation in Spinal Cord Injury. *Annals of Rehabilitation Medicine*, 44(4):311–319.

Luo, Z., Lim, A. E.-P., Durairaj, P., Tan, K. K., and Verawaty, V. (2023). Development of a compensation-aware virtual rehabilitation system for upper extremity rehabilitation in community-dwelling older adults with stroke. *Journal of NeuroEngineering and Rehabilitation*, 20(1):56.

Mallari, B., Spaeth, E. K., Goh, H., and Boyd, B. S. (2019). Virtual reality as an analgesic for acute and chronic pain in adults: a systematic review and meta-analysis. *Journal of Pain Research*, 12:2053–2085.

Mathiowetz, V., Volland, G., Kashman, N., and Weber, K. (1985). Adult norms for the box and block test of manual dexterity. *The American Journal of Occupational Therapy*, 39(6):386–391.

Mott, M., Cutrell, E., Gonzalez Franco, M., Holz, C., Ofek, E., Stoakley, R., and Ringel Morris, M. (2019). Accessible by Design: An Opportunity for Virtual Reality. In *2019 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)*, pages 451–454.

Mott, M., Tang, J., Kane, S., Cutrell, E., and Ringel Morris, M. (2020). "I just went into it assuming that I wouldn't be able to have the full experience": Understanding the Accessibility of Virtual Reality for People with Limited Mobility. In *The 22nd International ACM SIGACCESS Conference on Computers and Accessibility*, pages 1–13, Virtual Event Greece. ACM.

Onitsuka, K., Kubota, K., Yokoyama, M., Miyazawa, T., Hamaguchi, T., Taniguchi, H., Usuki, N., Miyamoto, S., Okazaki, K., Murata, K., and Kanemura, N. (2023). Clinical utility of markerless motion capture for kinematic evaluation of sit-to-stand during 30 s-CST at one year post total knee arthroplasty: a retrospective study. *BMC Musculoskeletal Disorders*, 24(1):254.

Park, J.-S., Jung, Y.-J., and Lee, G. (2020). Virtual Reality-Based Cognitive–Motor Rehabilitation in Older Adults with Mild Cognitive Impairment: A Randomized Controlled Study on Motivation and Cognitive Function. *Healthcare*, 8(3):335. Number: 3 Publisher: Multidisciplinary Digital Publishing Institute.

Pei, S., Chen, A., Chen, C., Li, F. M., Fozzard, M., Chi, H.-Y., Weibel, N., Carrington, P., and Zhang, Y. (2023). Embodied Exploration: Facilitating Remote Accessibility Assessment for Wheelchair Users with Virtual Reality. In *Proceedings of the 25th International ACM SIGACCESS Conference on Computers and Accessibility*, ASSETS '23, pages 1–17, New York, NY, USA. Association for Computing Machinery.

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.

Soomal, H. K., Poyade, M., Rea, P. M., and Paul, L. (2020). Enabling More Accessible MS Rehabilitation Training Using Virtual Reality. *Advances in Experimental Medicine and Biology*, 1262:95–114.

Teo, J. L., Zheng, Z., and Bird, S. R. (2022). Identifying the factors affecting 'patient engagement' in exercise rehabilitation. *BMC Sports Science, Medicine and Rehabilitation*, 14:18.

Zhang, W., Paudel, D., Shi, R., Liang, J., Liu, J., Zeng, X., Zhou, Y., and Zhang, B. (2020). Virtual Reality Exposure Therapy (VRET) for Anxiety Due to Fear of COVID-19 Infection: A Case Series. *Neuropsychiatric Disease and Treatment*, 16:2669–2675.