

Dynamic Adjustment of Interactive Objects in Virtual Environments for Upper Limb Rehabilitation: A Patient-Centred Solution

V. Herrera¹  J. Albusac¹  S. Schez-Sobrinio¹  A. Reyes-Guzmán²  and C. Glez-Morcillo¹ 

¹Department of Technologies and Information Systems, University of Castilla-La Mancha

²Biomechanics and Technical Aids Unit. Hospital Nacional de Paraplégicos de Toledo

Abstract

Virtual reality (VR) is a promising technology that offers physical and emotional benefits for traditional rehabilitation. However, interaction with the virtual environment can be an obstacle for patients with reduced mobility, and even more so in the case of VR-based rehabilitation, where the movements required in traditional rehabilitation have to be simulated. This difficulty highlights the need to adapt the virtual environment to the capabilities of each patient. In this study, we present a novel system designed to automatically adjust the positioning of objects within the VR environment. The system, based on data from a previous calibration, is aimed at upper limb rehabilitation, especially in patients with cervical spinal cord injury (cSCI). It incorporates algorithms capable of detecting and relocating virtual objects used in various rehabilitation exercises, ensuring better localisation within the virtual space. The main objective of this system is to improve the effectiveness of rehabilitation treatment, while facilitating adaptation to individual patient needs and exercise characteristics. Preliminary results from a pilot test with healthy subjects are promising and support the efficacy of this system, laying a solid foundation for its implementation in patients with cSCI.

CCS Concepts

• **Human-centered computing** → *Virtual reality; Accessibility systems and tools; User centered design*; • **Applied computing** → *Health care information systems*;

1. Introduction

In recent years, the deployment of Virtual Reality (VR) within the healthcare sector has significantly expanded, particularly in the realm of rehabilitation. The integration of VR into rehabilitation practices has proven to offer substantial advantages over traditional rehabilitation methods, contributing positively to both physical and emotional aspects of patient recovery. Among these benefits are the improvement in the range of movement of the areas to be rehabilitated [SAA*21], the improvement of balance [FLL*19], as well as the reduction of pain perception in patients [MSGB19]. In addition, several studies support that the use of VR devices in rehabilitation programmes improves adherence to treatment and increases motivation [CAEMNP*21]. These are crucial factors for a successful rehabilitation process.

In patients with spinal cord injury (SCI), rehabilitation is crucial to improve quality of life and promote independence. The rehabilitation process in SCI can be extensive, demanding. It requires patience, motivation and a comprehensive approach that addresses both the physical and psychological needs of the patient [NYS*15]. In this context, the incorporation of VR in rehabilitation for SCI patients can offer significant improvements as a complementary tool.

For a successful adaptation, the first focus must be on the device itself used to interact with the virtual environment. Interaction with the virtual environment through direct use of the hands, without the need for controllers, is essential. Firstly, because of movement limitations and related problems such as spasticity [GF18], many patients are unable to properly grasp and use joysticks or controllers. Secondly, for VR-based rehabilitation to be successful, patients need to be able to exercise the grasps and movements they would perform in a physical environment. Thanks to advances in hand tracking used in HMD (Head Mounted Display) devices [Buc21], this first barrier has been eliminated, facilitating this natural and intuitive interaction.

In addition to the adaptation of the device used for interacting with the virtual environment, other adaptations of the application used for VR-rehabilitation are necessary. For upper limb rehabilitation in cSCI patients, the unique characteristics of their exercise execution are crucial. Considering that the patient performs the exercises in a seated position, it is necessary to adapt the location of the elements of the virtual environment, which the patient can manipulate with his or her hands, to a position in the virtual space that is accessible according to his or her capabilities and mobility. To address this problem, measuring user mobility within the virtual

environment offers an effective approach. Through an initial calibration, it is possible to determine the maximum distance at which virtual objects should be placed to facilitate their correct manipulation, thus avoiding overstraining and unwanted compensatory movements. Furthermore, taking into account the characteristics of patients cSCI, this calibration should be asymmetric, i.e. measure the range of motion (ROM) independently for the right and left side.

After this initial calibration, it is necessary to ensure that objects are correctly positioned in the VR environment, adapting to both the patient's motor skills and the specific requirements of each exercise. This research focuses on the post-calibration phase: how to use calibration data to ensure that VR elements requiring direct manipulation are placed within an optimal range for patient interaction. These algorithms ensure that the virtual elements are correctly positioned within the calibrated work area, adapted to the needs of each patient.

First, the detection algorithm evaluates the location of each virtual element in relation to the work area and the user's current position, identifying those objects that are not optimally positioned. Subsequently, the relocation algorithm adjusts dynamically the position of these elements, assigning them a new position in 3D space. This process is carried out considering both the exercise configuration and the new position of the user, to ensure that the virtual elements are always accessible and in locations that favour effective rehabilitation. Recognising that the ROM of the right and left upper limbs can differ significantly, and that exercises can be focused on a specific laterality (right or left) or performed in a central position, the algorithms distinguish between different work areas: right, left, central and global.

As a preliminary evaluation, algorithm performance is demonstrated in a simple virtual environment where the subject grasps multiple objects. The test is repeated after automatically relocating these objects according to set options and data from the initial calibration. The objective is to ensure the user can effortlessly grasp each item post-relocation without unnecessary movements.

The article is structured into distinct sections, starting with 'Related Work' to place the research in the context of existing literature, followed by 'Background' for foundational insights into upper limb VR rehabilitation in cSCI patients. Technical discussions are contained within 'Algorithms for Detecting and Relocating Virtual Elements in Upper Limb Rehabilitation for cSCI Patients' detailing the data informing the rehabilitation process. The methodologies and functionalities of the 'Dynamic Detection Algorithm' and 'Dynamic Relocation Algorithm' are detailed in later sections. The article culminates in 'Evaluation and Results', presenting the assessment of the algorithms' impact on upper limb rehabilitation, and concludes with 'Conclusion and Future Work', summarizing key findings and suggesting avenues for further research.

2. Related Work

2.1. VR and rehabilitation

Numerous studies have investigated the use of VR rehabilitation techniques, focusing on varying degrees of immersion and interaction modalities, ranging from non-immersive applications to fully

immersive experiences. These interactions occur through either direct device control, such as controllers, or through hand-tracking technologies.

Non-immersive and semi-immersive VR rehabilitation studies often utilize hand-tracking technologies for enhanced engagement. For instance, Shahmoradi et al. [SAA*21] employed the Kinect sensor to assist stroke patients in upper limb rehabilitation through interactive games, achieving significant improvements in patients' ROM. Other approaches employ Leap Motion Controller (LMC) hand-tracking technology for semi-immersive VR, capable of tracking hand movements. In the case of Tarakci et al, [TATK20] the study focused on children and adolescents with various physical disabilities, concluding that this technology is an effective alternative treatment option.

Concerning the use of LMC, the study by de Souza et al. [dSGC21] investigated the feasibility and accuracy of the LMC combined with serious games for upper limb rehabilitation. They discovered that while the controller generally tracked hand movements accurately and reliably, the workspace used in the experiments was relatively small when compared to the human upper limb's natural range. Therefore, careful consideration must be given to how the device is positioned relative to the patient's pose to optimize its effectiveness.

Considering the spectrum of VR immersion, a recent systematic review and network meta-analysis by Hao et al. [HHYR23] aimed to compare the effects of immersive and non-immersive VR on upper extremity function in stroke survivors. The review emphasizes the superior benefits of immersive VR over non-immersive VR systems and gaming consoles for the recovery of upper extremity motor functions.

Building on the advantages of immersive VR in rehabilitation, studies such as those described by Lim et al. [LHC*20] use HMDs and controllers to create fully immersive environments. Their study targeted SCI patients and documented notable enhancements in grip strength and functional mobility scores, showcasing the efficacy of immersive VR in rehabilitation. It's important to note that their study required participants to have sufficient hand grip strength to manage the controllers effectively.

Continuing with studies on immersive VR in rehabilitation, and adding more intuitive interaction through hand tracking, is the work of Mekbib et al. [MDZ*21]. This study presents a fully immersive VR environment for upper limb rehabilitation in stroke patients, focusing on the recovery of motor function. Unlike controller-based systems, MNVR-Rehab uses hand tracking to activate mirror neurons, which are essential for rehabilitation. It does this by employing a HMD, two HTC Vive tracking stations to track the user's exact location, and LMC technology to track upper limb movements and transfer them to a virtual limb in the virtual environment.

The study by Pereira et al. [PPK*20] also focuses on the use of immersive VR with hand tracking. It implements a serious rehabilitation game using the Meta Quest HMD as the only device, eliminating the need for additional trackers. With a system usability score of 84.3, the study confirms the potential of conceptual and technological approaches to improve hand rehabilitation therapy.

2.2. Adaptation of VR Environments for Rehabilitation

As VR becomes increasingly popular, the need for environments adapted to diverse motor and cognitive abilities becomes crucial. This section discusses previous research that underscores this importance. The focus is on creating inclusive and accessible VR spaces for people with different abilities. This approach is essential to ensure that VR technology benefits a broad spectrum of users, especially in fields such as rehabilitation, where personalised and adaptive environments can significantly influence treatment outcomes.

The study by Lagos Rodriguez et al. [LRGLG22] highlights this trend, showing VR scenarios as valuable tools in the rehabilitation process of people with disabilities. These VR environments allow patients to interact using their own hands, simulating everyday activities, thus facilitating the training of various physical and cognitive abilities.

Other studies, such as Mott et al. [MCGF*19], contribute to accessibility in VR environments. This study describes five areas: accessibility of VR content, interaction techniques, accessibility of devices and hardware, inclusive representations of users within VR environments, and the development of accessibility-focused VR applications.

The article by Dudley et al. [DYGK23] identifies three main challenges to achieving 'inclusive immersion' in virtual and augmented reality environments. These include the diversity of user needs, the lack of comprehensive guidelines and tools for developers, and the challenges associated with conducting empirical research in the field. The article highlights the need for customised systems, better developer resources and more structured research methodologies to advance the accessibility of VR/AR technologies.

Among the studies focused on interaction mechanisms in VR environments for people with upper body impairments is the work of Franz et al. [FYW23]. This study evaluates the accessibility of different locomotion techniques in VR for individuals with motor impairments in the torso and upper extremities. The results suggest the importance of offering a variety of techniques that are adapted to individual preferences and abilities, beyond considering accessibility alone.

3. Background

In the field of upper limb rehabilitation, the Rehab-Immersive platform [HVCS*23] is emerging as a comprehensive solution that addresses the critical limitations of previous approaches and prioritises patient-centred care. Developed in collaboration with the Hospital Nacional de Paraplégicos de Toledo (Spain), Rehab-Immersive leverages the benefits of immersive VR to create an engaging and accessible rehabilitation environment. Thanks to this collaboration it is possible to develop a system with continuous feedback from patients, cSCI experts, rehabilitation professionals and biomedical engineers. The platform integrates a number of serious games for rehabilitation using the Meta Quest 2 and Meta Quest 3 HMDs, using their internal hand-tracking capabilities (without controllers). In addition, accessibility to the VR environment is addressed from multiple angles, including accessible menus, user-friendly buttons,

exercises adapted to the rehabilitation process, recognition of different types of functional grasps [VSBGIPG14] according to the patient's motor skills, and audiovisual support for different interactions and achievements.

Despite these adaptations, fixed placement of virtual elements in 3D space may not meet the needs of all patients. On the one hand, given the needs of each patient according to the presented injury. On the other hand, it must be taken into account that rehabilitation is a dynamic process [CTA*22], which must be adapted and adjusted according to the evolution of the patient. To address this gap, manual calibration of certain objects within the scene was implemented. However, this process can present challenges for patients, requiring adjustments to each interactive element and within every serious game designed for upper limb rehabilitation. This situation underscores the necessity for an initial calibration that accurately reflects the ROM for each side of the body and the patient's central position. After this calibration, additional algorithms are applied to establish the desired position of the elements.

This article introduces dynamic detection and relocation algorithms tailored to the previously calibrated space, aiming to provide an effective and safe rehabilitation experience. These algorithms are a core component of our patient-centered solution for dynamically adjusting interactive objects in virtual environments, specifically designed for upper limb rehabilitation in cSCI patients.

4. Algorithms for Detecting and Relocating Virtual Elements in Upper Limb Rehabilitation for cSCI Patients

This section describes the process for the detection and automatic adjustment of virtual elements in 3D space within VR applications for upper limb rehabilitation. The procedure initiates with data acquired from a preliminary calibration phase. This initial stage employs ellipses to accurately assess the range of mobility in the upper limbs, addressing both the right and left sides independently to account for any asymmetry in movement capability. This approach draws on biomechanical principles outlined by I. A. Kapandji [Kap71], emphasizing the significance of shoulder circumduction and its complex motions across sagittal, frontal, and transversal planes.

Opting for ellipses over simpler geometric shapes like circles is driven by the need to accommodate patients' mobility restrictions. Since activities are performed seated, limiting the workspace to accessible frontal and lateral areas prevents extension beyond the patient's reach. This strategy not only conforms to current limitations but also anticipates workspace adaptation as mobility improves, aiming for ellipses to eventually resemble circles, indicating enhanced movement amplitude.

To calibrate the ROM for each side of the upper limbs, the user is instructed to move their hand with the arm fully extended in different planes: XY, XZ, and YZ (see Figure 1). This process results in an elliptical volume formed by these three ellipses.

After calibration, the methodology involves two principal algorithms. The initial algorithm detects a virtual element within a pre-defined work area, determined by various parameters. Subsequent to this detection, a second algorithm responsible for relocating virtual elements is activated.

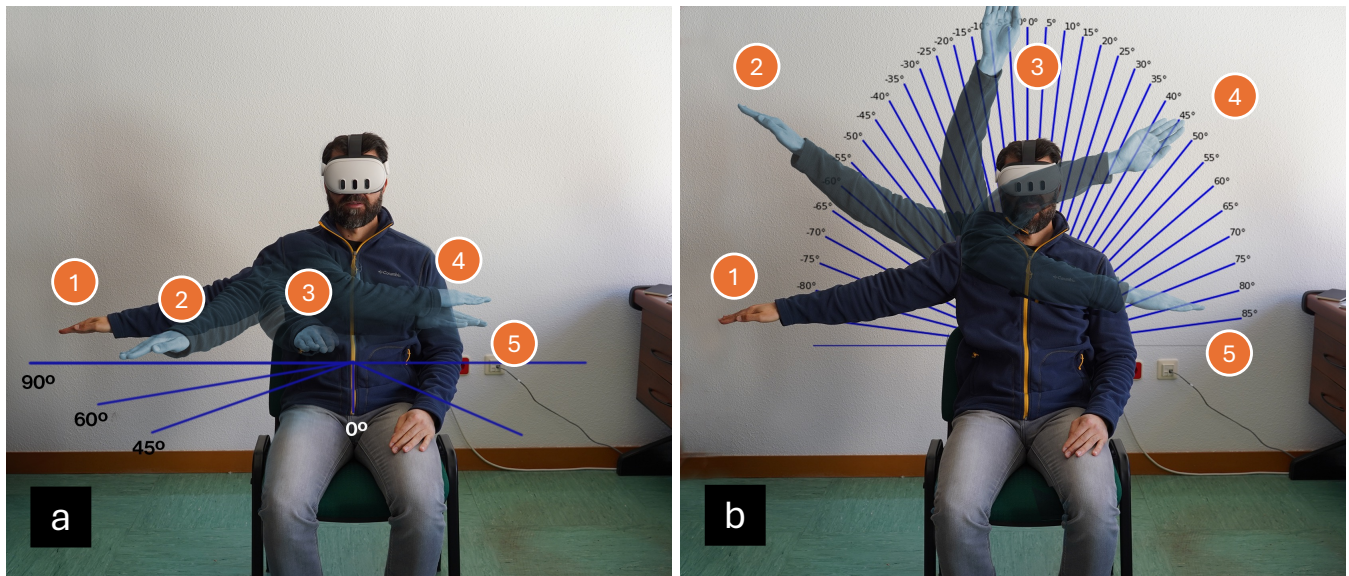


Figure 1: Movements performed during the calibration process to obtain the elliptical volume corresponding to the right-sided upper limb. (a) Calibration in the XZ plane. (b) Calibration in the XY and YZ planes.

4.1. Input Data for Algorithms

The algorithms employ a series of inputs designed to adjust VR environments to meet both user needs and application-specific requirements. Initial considerations involve data from previous calibration phases. This includes details on the position and rotation of the HMD during calibration and elliptical volumes that define the right and left work areas. Along with this data, the algorithms consider the ‘center position’, where users position their arms at hip width with elbows at 90 degrees and palms facing forward, serving as a reference for certain rehabilitation exercises. These inputs include:

- C_{HMD} : HMD position (P_{HMD}).
- C_R : Right elliptical volume in the XY, YZ, XZ planes.
- C_L : Left elliptical volume in the XY, YZ, XZ planes.
- C_C : Center defined by the hand positions.

The current HMD position ($P_{HMD_{current}}$) complements the calibration data, providing real-time context. This aspect is particularly important because the calibration process and its application might not always occur in the same physical setup. This component ensures the virtual environment adapts accurately, avoiding errors due to HMD or user movements.

Along with the previously described calibration data, additional parameters related to the specific characteristics of the exercise to be performed in the VR environment are considered. These parameters determine the area within the 3D space where the exercise will take place in the VR setting. A distinction is made between lateral exercises, which require that the elements interacted with by the user are located within the defined elliptical volume (right Z_R or left Z_L) (see Figure 2).

In addition to the lateral exercises, the system also includes those

performed in a center position relative to the patient (Z_{Center}). For these exercises, it is considered that the virtual object must be located within the defined center position (C_C), ensuring also that it is within one of the two elliptical volumes (C_R and C_L).

Finally, exercises that encompass the entire calibrated area, including both the right and left lateral zones as well as the center area, are considered. This category is named the complete zone (Z_C) and is designed for activities that require a more extensive and varied use of the 3D space in the VR environment.

Alongside these input parameters, a defined threshold for the workspace (U) is also included. This defines different levels and difficulties based on the location of elements in 3D space. This threshold allows for adjusting the boundaries of the reachable area, expressed as a percentage. A threshold of 100% would be equivalent to the limits established during calibration. Values below this percentage would imply a proportional reduction of the limits in all three axes. Conversely, a threshold higher than 100% is necessary for exercises requiring trunk movements. Therefore, the threshold provides a flexible tool for modifying the reach of the workspace, allowing adjustments tailored to the specific needs of the user and the exercise objectives in the VR environment.

In order to adapt the position of the elements according to the needs not only of the patient but also of the exercise, a Boolean constraint related to height is added, called R_{HLimit} . This parameter determines whether the virtual elements should be located above a specific height, in this case, the height of the seated user’s legs. This height is obtained from the Y position of the calibration data stored, referring to the position of the hands with the arms flexed at 90 degrees.

If R_{HLimit} is activated, the VR environment is adjusted so that

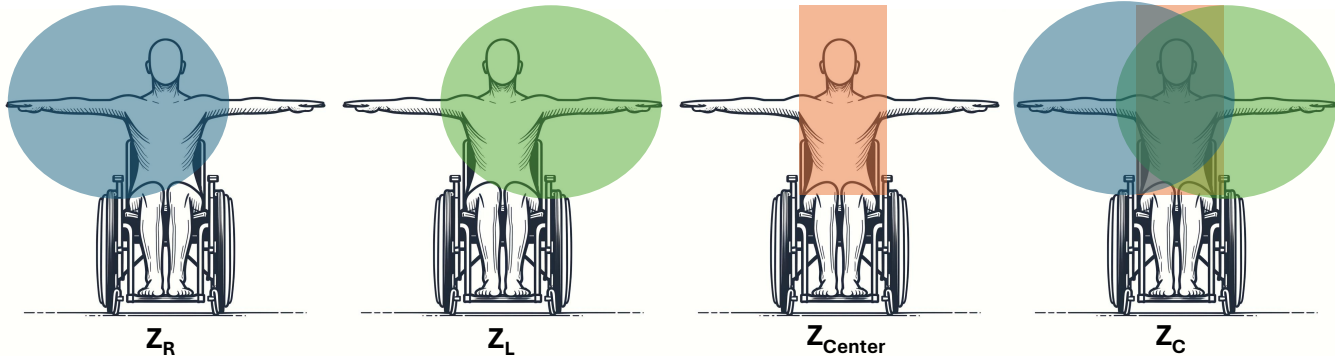


Figure 2: Representation of the different exercise execution areas in the virtual environment. From left to right: right lateral area (Z_R); left lateral area (Z_L); central area (Z_{Center}); and total area defined by the lateral and central areas (Z_C).

all virtual elements are placed above the minimum height defined by H_{limit} . Like the threshold, this parameter is necessary for those exercises that require trunk movement, in this case lateral.

Finally, the list of virtual objects (O) constitutes the last input parameter. Each object in this list contains a unique identifier, its original position, and, if the relocation algorithm has been applied, the adjusted position in 3D space.

Let $O = \{(ID(o_i), P(o_i), L(o_i)) | o_i \in \text{Virtual objects}, i = 1, 2, \dots, n\}$ represent the list of virtual objects in the VR environment, where each object o_i is defined by $ID(o_i)$, $P(o_i)$, and $L(o_i)$. Here, $ID(o_i)$ denotes a unique identifier of the object, $P(o_i)$ signifies the original position of the object in 3D space, and $L(o_i)$ corresponds to the modified position of the object in 3D space.

4.2. Preparation and Adaptation of the Workspace

Before running the iterative algorithms for detection and relocation in a virtual reality environment, a preliminary step is necessary. This step involves adapting the calibrated workspace to meet the specific requirements of the game and accommodate the user's new position. The process includes transferring the previously defined workspace to the potential new position of the user within the VR environment.

In the initial step, the parameters of the ellipses are adjusted, including their centers, radii, center position, and minimum height, according to the new location indicated by the current HMD position ($P_{HMD, current}$). This adjustment guarantees proper recalibration of the workspace to align with the user's present position.

The subsequent step includes an additional adjustment based on the predefined threshold (U). This adjustment enables modifications to the workspace to meet the dimensions needed for the particular rehabilitation exercise, thereby adjusting the difficulty level and accommodating the user's motor abilities. These adaptations guarantee that the VR workspace is accessible and ergonomically suitable for the user.

With these stages completed, the elements in the virtual space are configured to initiate the processes of detection and relocation.

Algorithm 1 Determining if an Object is Within a Specified Exercise Area

```

function ISOBJECTINAREA(objectPosition)
    isObjectInArea ← false
    switch CurrentExerciseArea do
        case Right
            isObjectInArea ← ISINSIDEELLIPSE(objectPosition, true)
        case Left
            isObjectInArea ← ISINSIDEELLIPSE(objectPosition, false)
        case Center
            isObjectInArea ← ISINSIDECENTER(objectPosition)
        case Complete
            isObjectInArea ← ISINSIDEONEELLIPSE(objectPosition)
    default
        isObjectInArea ← false
    if ConsiderHeightLimits then
        isObjectInArea ← isObjectInArea and heightLimit ≤
        objectPosition.y
    end if
    return isObjectInArea
end function

```

4.3. Dynamic Detection Algorithm

The detection algorithm assesses whether each object, contained in the list of virtual objects, is correctly positioned within the defined workspace. Objects that do not meet the location requirements are flagged as incorrectly positioned. To achieve this, it utilizes the *IsObjectInArea* method (see Algorithm 1), which evaluates the correct location of each object, considering two fundamental aspects: the height constraint (R_{HLimit}) and the specific exercise zone (Z).

Depending on whether the zone (Z_R for the right, Z_L for the left, Z_{Center} for the central area, or Z_C for the complete workspace area) the algorithm employs different methods to assess if an object is correctly positioned. For Z_R and Z_L , the *IsInsideEllipse* method is used to verify if the object is within the corresponding ellipse for the chosen laterality. In the Z_{Center} , the *IsInsideCenter* method evaluates if the object is positioned in the center zone defined during

calibration. Finally, for the Z_C , it checks if the object is within either of the two ellipses.

4.4. Dynamic Relocation Algorithm

Upon the completion of the detection algorithm, the relocation algorithm is initiated. This algorithm's primary objective is to reassign a new position to each element previously identified. The relocation process, similar to the detection phase, uses the recalculated coordinates and applied thresholds to determine the most appropriate and closest position within the designated working area. For each virtual object flagged as inaccurately positioned, the method `CalculateNewPosition` is invoked. This method, predicated on the exercise area configuration and the threshold, identifies the nearest compliant location within the work zone parameters.

Similar to the detection algorithm, the relocation strategy takes into account both the vertical restriction R_{HLimit} , if activated, and the VR environment's specified exercise zone (Z). Should the area be lateral (Z_R or Z_L), the `FindNearesInEllipse` method is employed to locate the nearest point on the elliptical volume's edge, whether right or left.

In instances where the object is to be relocated to the center area, the `FindNearesInCenterArea` method is utilized. This method is dedicated to finding the nearest point within the center zone, delineated by the calibrated center area. Given that this center area does not encompass the maximum depth but is defined by the hand positions with elbows bent at 90 degrees, it verifies that the relocated object in the X-axis falls within either the left or right elliptical volumes. If not, it calculates the distance to each lateral elliptical volume and selects the one with the lesser distance to the object.

The `FindNearestPointInGlArea` method is applied for exercises demanding the entire calibration area's utilization. This method identifies the closest point in the entire area by evaluating both the right and left elliptical volumes.

5. Evaluation and Results

To assess the effectiveness of the detection and adjustment algorithms for virtual elements within the upper limb rehabilitation environment, a pilot application has been developed. This application, like the preceding calibration algorithm, was developed using Unity [uni], the Meta XR Integration SDK [met], and tested on Meta Oculus Quest 3 [ocu].

The interface of the VR application is designed for accessibility, featuring a main menu with large buttons that accommodate activation via a single finger, multiple fingers, or the palm. This menu is divided into three primary sections: Calibration, Configuration, and Play. Selecting 'Calibration' triggers the process that captures data for the application's detection and relocation algorithms. The 'Configuration' (see Figure 3) menu allows for a tailored user experience by enabling the specification of detection and relocation parameters for virtual elements. This feature is designed to simulate the specific requirements of the exercise. Options within this menu include the designation of the exercise's execution zone, the

adjustment of the threshold for expanding or reducing the work area, and the implementation of a height restriction.

Upon selecting the 'Play' option, users are introduced to a new scene populated with five blocks within the virtual environment. Interacting with these blocks may necessitate considerable effort from the user, potentially leading to undesired compensatory trunk movements. The scene is also equipped with two interactive buttons: one for exiting and another for the automatic re-alignment of the blocks in alignment with the pre-configured settings. Furthermore, pressing the relocation button prompts the visualization of ellipses delineating the selected relocation area. The elliptical volume corresponding to the configuration of the complete area can be observed in Figure 4.

5.1. Evaluation

The evaluation was conducted with a diverse group of six participants, encompassing both men and women, aged between 21 and 44 years, and with heights ranging from 166 to 185 cm. All participants selected for the study had no mobility issues in their upper limbs and the study was carried out in a single session.

Before the testing began, each participant was thoroughly briefed on the procedure. Throughout the process, participants remained seated, and a re-centering of the HMD was performed before starting. The initial phase involved acquiring the calibrated area, during which the calibration process was explained in detail. Following this, it was confirmed that the defined area accurately matched the movements performed. After this setup phase, participants were asked to configure the mode in which the detection and readjustment algorithms would operate. To ensure uniformity in the setup, participants were instructed to set the complete area, adjust the threshold to 90%, and activate the height restriction to prevent blocks from appearing below leg height.

For the testing phase, participants were requested to try and keep their back against the chair at all times, and whenever the position of the object to be grasped allowed, to avoid excessive trunk movements.

During the test, data for each user were collected, including calibration details, selected configuration settings (area, threshold, and height restriction), the location of the blocks before applying the relocation algorithm, and their location after executing the algorithm.

Along with this information regarding calibration and virtual environment settings, two files containing relevant kinematic data are stored. One file pertains to the subject's kinematics before applying the algorithms, and the other after relocation. Among these data points, notable elements include the position and rotation of the HMD, the position and rotation of the hands, a boolean indicating if one of the hands is gripping an object, the fingers or palm involved in the grasp, the grip force within a range of [0-1], the name of the virtual object being grasped, and the velocity of each hand, among others. Depending on the area selected in the configuration, tracking of the right hand, left hand, or both is stored. Thus, for the case of Z_R , data pertaining to the right hand is stored, for Z_L , the data for the left hand, and for Z_C and Z_{Center} , bimanual exercises are considered, hence data for both hands are stored.



Figure 3: Menu of the VR application used to configure the work area. From left to right: submenu for selecting the exercise area; submenu for threshold selection



Figure 4: Elliptical volume corresponding to the complete exercise area (Z_C).

In the specific case of the test conducted for evaluation, selecting Z_C results in the storage of kinematic data for both hands. Furthermore, participants are asked to use one hand or the other depending on which side the blocks are closer to.

5.2. Results

This section details the results obtained from the tests conducted with the 6 subjects. The data stored regarding calibration, configuration, and block positions before and after the relocation process were analyzed. Euclidean distances between the original and relocated positions of five blocks for each of six participants. The

results are summarized in Table 2, which displays the Euclidean distances for each block and user, as well as the mean of these distances per user.

To assess the consistency of the relocation algorithm, the mean of the Euclidean distances for each user was calculated. The analysis reveals variations in relocation distances between users, with means ranging from 0.8422 to 0.9342, suggesting moderate variability in the relocation algorithm's effectiveness across different users. In all cases, it is observed that the algorithm relocates objects by attempting to respect the minimum distance from their original location as much as possible. This approach ensures that the spatial integrity and the relational positioning of the blocks relative to one another are maintained to a significant extent.

Figure 5.2 displays the original and relocated positions of blocks for User 1 within a three-dimensional space. Points denote the original positions of the blocks, and triangles signify the positions post-relocation. Gray dashed lines connecting the original to the relocated positions illustrate not only the direction but also the magnitude of movement for each block.

Following the analysis of Euclidean distances, we further investigated the spatial dynamics of participant movement by examining the head position data. The detailed analysis of head position data before and after the relocation of objects reveals notable changes in the range of movement across the X and Y axes, which are closely associated with lateral and frontal trunk movements, respectively. Such movements are essential for interacting with the virtual environment, indicating how participants adapt their physical engagement in response to the spatial rearrangement of objects.

The results, summarized in Table 1, highlight the shifts in participants' head positions, providing insights into their interaction with the virtual environment and the objects within it. This table captures the minimum and maximum positions on the X, Y, and Z axes, reflecting the spatial exploration and interaction behaviors of the participants with the environment and its objects. The data

Table 1: Minimum and maximum head positions on the X, Y, and Z axes before and after object relocation. The data represents the range of head movement, indicating spatial exploration and interaction behaviors of the participants.

User	X Axis		Y Axis		Z Axis	
	Before	After	Before	After	Before	After
User 1	-0.5128 / 0.2835	-0.1144 / 0.105	0.8806 / 1.2261	1.102 / 1.2144	-0.0446 / 0.3653	-0.0331 / 0.0738
User 2	-0.5642 / 0.3504	-0.0972 / 0.0709	0.7847 / 1.1117	1.0092 / 1.0806	-0.086 / 0.4451	-0.0903 / 0.0097
User 3	-0.5243 / 0.3759	-0.1433 / 0.1074	0.7318 / 1.1774	1.0795 / 1.1966	-0.0664 / 0.4967	-0.0444 / 0.0469
User 4	-0.4869 / 0.2888	-0.1466 / 0.1201	0.8722 / 1.1827	1.0293 / 1.1378	-0.0135 / 0.3894	-0.0102 / 0.0532
User 5	-0.4705 / 0.2993	-0.1611 / 0.1311	0.8731 / 1.1981	1.0835 / 1.1944	-0.0631 / 0.358	-0.1022 / 0.0473
User 6	-0.5053 / 0.3184	-0.0677 / 0.0987	0.7958 / 1.19	1.1468 / 1.1841	-0.0339 / 0.4045	-0.0499 / 0.0021

Table 2: Euclidean distances for blocks of each user. B1..B5 represents the 5 blocks identified in the scene.

User	B1	B2	B3	B4	B5	Mean
User 1	0.792	0.745	0.736	0.804	1.134	0.8422
User 2	1.041	0.912	0.739	0.810	1.169	0.9342
User 3	1.010	0.876	0.698	0.750	1.221	0.9110
User 4	0.831	0.969	0.630	0.687	1.461	0.9156
User 5	0.989	0.884	0.654	0.752	1.070	0.8698
User 6	0.853	0.910	0.829	0.916	0.972	0.8960

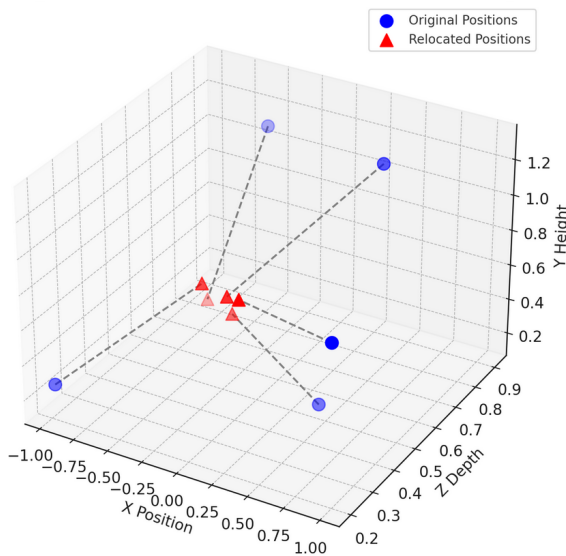


Figure 5: Original and relocated positions of blocks for User 1. Blue circles and red triangles represent the original and relocated positions, respectively. Gray dashed lines illustrate the movement trajectory of each block.

underscores the adjustments in movement dynamics resulting from the reconfiguration of object locations. A notable observation from the data is the significant decrease in movement amplitude along the X axis, indicating a marked reduction in lateral (side-to-side) trunk movements. This reduction points to a more constrained spatial interaction post-relocation, suggesting that participants adapted

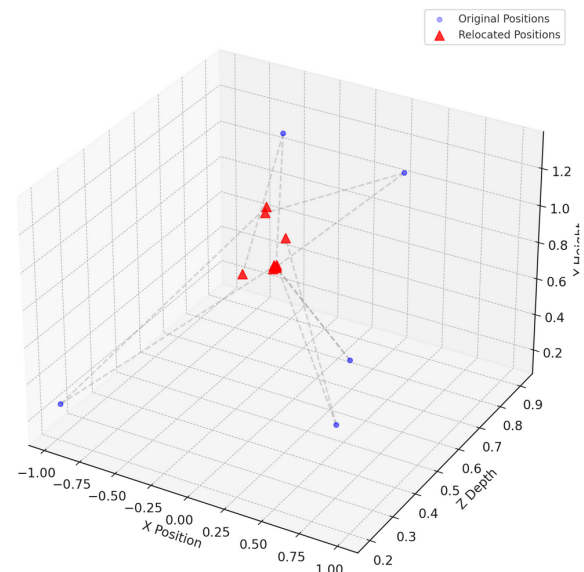


Figure 6: Enhanced 3D plot of original vs. relocated positions.

their movements to the newly configured object placements with lesser lateral exploration.

Moreover, the analysis delineates distinct patterns in the vertical (Y axis) and depth (Z axis) positions. An increment in the Z axis position, paired with a decrement in the Y axis position, specifically denotes forward trunk movements. This finding is particularly significant, as broader movements along the X axis typically signify more pronounced lateral trunk movements, which may serve as compensatory mechanisms, particularly within a rehabilitative framework. Conversely, the unique juxtaposition of an increased Z position and a reduced Y position highlights a forward leaning or reaching action, likely reflecting compensatory tactics employed by users to interact with objects that are positioned further within the virtual space or to navigate the spatial constraints imposed by the virtual environment.

Significantly, this study was carried out with a predefined threshold of 90 percent, indicating that the relocation of objects was designed so participants would ideally not need to engage in substantial trunk movements to reach these objects post-relocation. This strategic choice was aimed at ensuring that all interactable ob-

jects within the virtual environment fall within a comfortable reach for the users, effectively reducing the necessity for compensatory movements often associated with reaching for distant objects. However, if the nature of the exercise requires it, adjusting the threshold to allow for such displacements is feasible when they are not considered undesirable compensatory movements.

The analysis further quantifies the impact of object relocation on the participants' movement amplitudes. Table 3 presents the calculated amplitude of movement (difference between maximum and minimum positions) for each user along the X, Y, and Z axes, both before and after the relocation of objects. This quantitative assessment illustrates the spatial dynamics adjustments, demonstrating a more focused interaction pattern within the virtual environment post-relocation.

Table 3: Amplitude changes pre/post object relocation.

Usr	X (Pre/Post)	Y (Pre/Post)	Z (Pre/Post)
1	0.7963 / 0.2194	0.3455 / 0.1124	0.4099 / 0.1069
2	0.9146 / 0.1681	0.3270 / 0.0714	0.5311 / 0.1000
3	0.9002 / 0.2507	0.4456 / 0.1171	0.5631 / 0.0913
4	0.7757 / 0.2667	0.3105 / 0.1085	0.4029 / 0.0634
5	0.7698 / 0.2922	0.3250 / 0.1109	0.4211 / 0.1495
6	0.8237 / 0.1664	0.3942 / 0.0373	0.4384 / 0.0520

This table reveals a significant decrease in movement amplitude across all axes for each user, indicating that spatial interactions have become more restricted post-relocation.

In addition to the precise quantitative analysis of the recorded data, the evaluation is enriched by qualitative observations made during the evaluation process. Before the objects were relocated, it was observed that participants had to detach their backs from the chair and perform extensive trunk movements to reach the objects. However, after the relocation, a significant improvement was observed: no participant had to make extensive trunk movements to interact with any of the objects.

At the end of the test, participants were asked to report on their experience, specifically whether they found it easy to interact with the objects and whether they encountered any difficulties in reaching the blocks after applying the relocation algorithm. All participants responded positively to the ease of interaction and negatively to the second question, indicating no difficulty in reaching the objects. These responses not only attest to the effectiveness of the algorithm in terms of accessibility and user comfort, but also highlight its potential to enhance the interaction experience in virtual environments designed for rehabilitation or physical training.

This mix of quantitative analysis and qualitative observations provides a more comprehensive understanding of the impact of the displacement algorithm. While numerical data provide an objective measure of changes in movement dynamics, participants' perceptions provide valuable insights into the usability and perceived effectiveness of the reconfigured virtual environment. Such findings demonstrate the importance of considering both quantitative and qualitative aspects in the design and evaluation of interactive technologies for rehabilitation.

6. Conclusion and Future Work

In conclusion, this research contributes to the evolving field of upper limb VR rehabilitation by offering insights into the development of more adaptable, effective, and patient-centric VR environments. Preliminary data from the evaluation indicate that it is possible to establish a safe working area where patients do not have to exert excessive efforts or perform unwanted movements to interact with virtual environment objects. The dynamic adjustment algorithm ensures that virtual objects are always optimally positioned within the user's reach, considering both the exercise configuration and the user's current position.

This not only effectively removes one of the barriers encountered during the testing of serious games but also allows for the collection of a historical record of different calibrations. The data from these records offer therapists insights into mobility progress throughout the rehabilitation process. Importantly, this approach embodies a patient-centered focus, underlining advancements in patient mobility and aiding in a more customized therapeutic strategy. This aspect strengthens the core principle of our research, which is to prioritize the needs and experiences of patients throughout the rehabilitation process.

However, it is important to acknowledge certain limitations within our evaluation. One of the primary limitations is the number of participants involved in the evaluation. Expanding the participant pool and testing the algorithms with actual cSCI patients would provide more comprehensive insights into the effectiveness and applicability of our approach in real-world rehabilitation scenarios.

Furthermore, enhancing the algorithm's flexibility is important to meet a wider range of needs of patients with cSCI, as well as the type of exercise to be performed. Adopting an approach that accounts for an object's collider for relocation purposes, rather than its geometric center, could refine user interactions. Furthermore, introducing an independent threshold for height restriction could further tailor the virtual environment to individual users, accommodating variations in their physical capabilities and rehabilitation goals.

Our future work will aim to overcome these challenges by refining the detection and relocation algorithms, assessing the effects of varying object placement thresholds, and expanding the range of rehabilitation activities that can benefit from such adjustments.

Indeed, the integration of these algorithms within the Rehab-Immersive platform, specifically in the games designed for upper limb rehabilitation, demonstrates their practical utility. These games cover exercises both with and without requiring lateral trunk displacement, catering to mono-manual and bi-manual activities.

Acknowledgements

This work has been funded 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

- [Buc21] BUCKINGHAM G.: Hand Tracking for Immersive Virtual Reality: Opportunities and Challenges. *Frontiers in Virtual Reality* 2 (2021). URL: <https://www.frontiersin.org/articles/10.3389/frvir.2021.728461.1>
- [CAEMNP*21] CORONADO-AHUMADA K. J., ESTÁN-MÁRQUEZ A. F., NATERA-PANZA B., LARA R. A. D. L. H., SALAS-VILORIA K. E., CORONADO-AHUMADA K. J., ESTÁN-MÁRQUEZ A. F., NATERA-PANZA B., LARA R. A. D. L. H., SALAS-VILORIA K. E.: El Valor Agregado de la Realidad Virtual en Tratamientos de Rehabilitación Muscular. Revisión de Literatura. *Revista Lasallista de Investigación* 18, 2 (Dec. 2021), 239–257. Publisher: Corporación Universitaria Lasallista. URL: http://www.scielo.org.co/scielo.php?script=sci_abstract&pid=S1794-44492021000200239&lng=en&nrm=iso&lng=es,doi:10.22507/rli.v18n2a16.1
- [CTA*22] CRAIG A., TRAN Y., ARORA M., POZZATO I., MIDDLETON J. W.: Investigating Dynamics of the Spinal Cord Injury Adjustment Model: Mediation Model Analysis. *Journal of Clinical Medicine* 11, 15 (Aug. 2022), 4557. URL: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9369731/,doi:10.3390/jcm11154557.3>
- [dSGC21] DE SOUZA M. R. S. B., GONÇALVES R. S., CARBONE G.: Feasibility and Performance Validation of a Leap Motion Controller for Upper Limb Rehabilitation. *Robotics* 10, 4 (Dec. 2021), 130. Number: 4 Publisher: Multidisciplinary Digital Publishing Institute. URL: <https://www.mdpi.com/2218-6581/10/4/130,doi:10.3390/robotics10040130.2>
- [DYGK23] DUDLEY J., YIN L., GARAJ V., KRISTENSSON P. O.: Inclusive Immersion: a review of efforts to improve accessibility in virtual reality, augmented reality and the metaverse. *Virtual Reality* 27, 4 (Dec. 2023), 2989–3020. URL: <https://doi.org/10.1007/s10055-023-00850-8,doi:10.1007/s10055-023-00850-8.3>
- [FLL*19] FENG H., LI C., LIU J., WANG L., MA J., LI G., GAN L., SHANG X., WU Z.: Virtual Reality Rehabilitation Versus Conventional Physical Therapy for Improving Balance and Gait in Parkinson's Disease Patients: A Randomized Controlled Trial. *Medical Science Monitor : International Medical Journal of Experimental and Clinical Research* 25 (June 2019), 4186–4192. URL: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6563647/,doi:10.12659/MSM.916455.1>
- [FYW23] FRANZ R. L., YU J., WOBROCK J. O.: Comparing Locomotion Techniques in Virtual Reality for People with Upper-Body Motor Impairments. In *Proceedings of the 25th International ACM SIGACCESS Conference on Computers and Accessibility* (New York, NY, USA, Oct. 2023), ASSETS '23, Association for Computing Machinery, pp. 1–15. URL: <https://dl.acm.org/doi/10.1145/3597638.3608394,doi:10.1145/3597638.3608394.3>
- [GF18] GOHRITZ A., FRIDÉN J.: Management of Spinal Cord Injury-Induced Upper Extremity Spasticity. *Hand Clinics* 34, 4 (Nov. 2018), 555–565. doi:10.1016/j.hcl.2018.07.001.1
- [HHYR23] HAO J., HE Z., YU X., REMIS A.: Comparison of immersive and non-immersive virtual reality for upper extremity functional recovery in patients with stroke: a systematic review and network meta-analysis. *Neurological Sciences* 44, 8 (Aug. 2023), 2679–2697. URL: <https://doi.org/10.1007/s10072-023-06742-8,doi:10.1007/s10072-023-06742-8.2>
- [HVCS*23] HERRERA V., VALLEJO D., CASTRO-SCHÉZ J. J., MON-ÉKOSKO D. N., DE LOS REYES A., GLEZ-MORCILLO C., ALBUSAC J.: Rehab-immersive: A framework to support the development of virtual reality applications in upper limb rehabilitation. *SoftwareX* 23 (2023), 101412. URL: <https://www.sciencedirect.com/science/article/pii/S2352711023001085,doi:https://doi.org/10.1016/j.softx.2023.101412.3>
- [Kap71] KAPANDJI I.: *The Physiology of the Joints, Volume I, Upper Limb*, vol. 50. Churchill Livingstone, 1971. 3
- [LHC*20] LIM D., HWANG D., CHO K. H., MOON C., AHN S. Y.: A Fully Immersive Virtual Reality Method for Upper Limb Rehabilitation in Spinal Cord Injury. *Annals of Rehabilitation Medicine* 44 (July 2020). doi:10.5535/arm.19181.2
- [LRGLG22] LAGOS RODRÍGUEZ M., GARCÍA Á. G., LOUREIRO J. P., GARCÍA T. P.: Personalized Virtual Reality Environments for Intervention with People with Disability. *Electronics* 11, 10 (Jan. 2022), 1586. Number: 10 Publisher: Multidisciplinary Digital Publishing Institute. URL: <https://www.mdpi.com/2079-9292/11/10/1586,doi:10.3390/electronics11101586.3>
- [MCGF*19] MOTT M., CUTRELL E., GONZALEZ FRANCO M., HOLZ C., OFEK E., STOAKLEY R., RINGEL MORRIS M.: Accessible by Design: An Opportunity for Virtual Reality. In *2019 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)* (Oct. 2019), pp. 451–454. URL: <https://ieeexplore.ieee.org/abstract/document/8951960,doi:10.1109/ISMAR-Adjunct.2019.00122.3>
- [MDZ*21] MEKBIB D. B., DEBELI D. K., ZHANG L., FANG S., SHAO Y., YANG W., HAN J., JIANG H., ZHU J., ZHAO Z., CHENG R., YE X., ZHANG J., XU D.: A novel fully immersive virtual reality environment for upper extremity rehabilitation in patients with stroke. *Annals of the New York Academy of Sciences* 1493, 1 (2021), 75–89. eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1111/nyas.14554>. URL: <https://onlinelibrary.wiley.com/doi/abs/10.1111/nyas.14554,doi:10.1111/nyas.14554.2>
- [met] Meta xr all-in-one sdk. <https://developer.oculus.com/documentation/unity/unity-package-manager/>. Accessed: February 22, 2024. 6
- [MSGB19] MALLARI B., SPAETH E. K., GOH H., BOYD B. S.: Virtual reality as an analgesic for acute and chronic pain in adults: a systematic review and meta-analysis. *Journal of Pain Research* 12 (2019), 2053–2085. doi:10.2147/JPR.S200498.1
- [NYS*15] NAS K., YAZMALAR L., SAH V., AYDIN A., ONES K.: Rehabilitation of spinal cord injuries. *World Journal of Orthopedics* 6, 1 (Jan. 2015), 8–16. URL: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4303793/,doi:10.5312/wjo.v6.i1.8.1>
- [ocu] Meta oculus quest 3. <https://www.oculus.com/quest-3/>. Accessed: February 22, 2024. 6
- [PPK*20] PEREIRA M. F., PRAHM C., KOLBENSCHLAG J., OLIVEIRA E., RODRIGUES N. F.: A Virtual Reality Serious Game for Hand Rehabilitation Therapy. In *2020 IEEE 8th International Conference on Serious Games and Applications for Health (SeGAH)* (Aug. 2020), pp. 1–7. ISSN: 2573-3060. URL: <https://ieeexplore.ieee.org/abstract/document/9201789,doi:10.1109/SeGAH49190.2020.9201789.2>
- [SAA*21] SHAHMORADI L., ALMASI S., AHMADI H., BASHIRI A., AZADI T., MIRBAGHERIE A., ANSARI N. N., HONARPISHE R.: Virtual reality games for rehabilitation of upper extremities in stroke patients. *Journal of Bodywork and Movement Therapies* 26 (Apr. 2021), 113–122. URL: <https://www.sciencedirect.com/science/article/pii/S136085922030187X,doi:10.1016/j.jbmt.2020.10.006.1,2>
- [TATK20] TARAKCI E., ARMAN N., TARAKCI D., KASAPCOPIR O.: Leap Motion Controller-based training for upper extremity rehabilitation in children and adolescents with physical disabilities: A randomized controlled trial. *Journal of Hand Therapy* 33, 2 (Apr. 2020), 220–228.e1. URL: <https://www.sciencedirect.com/science/article/pii/S0894113018303442,doi:10.1016/j.jht.2019.03.012.2>
- [uni] Unity. <https://unity.com/>. Accessed: February 15, 2024. 6
- [VSBGIPG14] VERGARA M., SANCHO-BRU J. L., GRACIA-IBÁÑEZ V., PÉREZ-GONZÁLEZ A.: An introductory study of common grasps used by adults during performance of activities of daily living. *Journal of Hand Therapy* 27, 3 (2014), 225–234. 3