Performance Analysis for Upper Limb Rehabilitation in Non-Immersive and Immersive Scenarios

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, U.K.*

Keywords: Virtual Reality, Immersive Environments, Upper Limb Rehabilitation, Hand Tracking, Free-Hand Interaction.

Abstract: In recent years, new technologies have contributed to an improvement in the upper limb rehabilitation process as a complement to the conventional therapy received by patients. In this context, technologies should facilitate accurate monitoring of the hands and serve to collect data on patient performance during functional tasks in order to objectively assess the patient's potential evolution. Mechanical and wearable devices provide greater accuracy in measurements. However, the physical limitations of patients requires the use of hands-free solutions. This article investigates controller-free hand technologies for accurate hand tracking in the Box and Block test (BBT) benchmarked against the real test, validated and standardized in the context of the Hospital Nacional de Parapléjicos (Toledo, Spain). In particular, the performance in the execution of therapeutic exercises is analyzed in three different scenarios: i) physical environment without the use of technologies, ii) non-immersive virtual environment and, finally, iii) fully immersive virtual environment. The results demonstrate the similarity between therapies developed in physical scenarios without the use of technologies, and those carried out in virtual reality-based scenarios.

1 INTRODUCTION

The interdisciplinary use of new technologies has favored their expansion into areas not originally designed for. Robotics as an aid to physical movement (Mekki et al., 2018), robots that interact with the patient, wearable devices (Bravo and Muñoz, 2022), serious games (Pereira et al., 2020), and even the combination of several of them (Guillén-Climent et al., 2021) has become an increasingly widespread practice to help improve patients with different physical or psychological pathologies. A clear example is the case of video games and virtual reality, whose purpose originally intended for entertainment, has resulted in great interest in fields such as education, health, or digital marketing. In particular, the use of virtual reality in medicine and rehabilitation is increasingly employed in hospitals and other health centers. One main reason is the results obtained through non-immersive, semi-immersive, and immersive applications in patients affected by a wide range of problems: neurological problems (Lamash et al., 2017), eating disorders (Clus et al., 2018), phobias, or spinal cord injuries (de Araújo et al., 2019), among others. It is the case of the Hospital Nacional de Parapléjicos de Toledo (Spain)[1], a center specializing in patients with spinal cord injuries. The hospital employs an interdisciplinary team to evaluate, analyze, intervene, and guide the patient to achieve the highest degree of recovery and independence.

Spinal cord injury (SCI) affects conduction of sensory and motor signals across the site(s) of lesion(s), as well as the autonomic nervous system (Rupp et al., 2021). This type of injury can be caused by trauma or

[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

[1]https://hnparaplejicos.sanidad.castillalamancha.es/

Herrera, V., Reyes-Guzmán, A., Vallejo, D., Castro-Schez, J., Monekosso, D., González-Morcillo, C. and Albusac, J.
Performance Analysis for Upper Limb Rehabilitation in Non-Immersive and Immersive Scenarios.
DOI: 10.5220/0011711800003467
In *Proceedings of the 25th International Conference on Enterprise Information Systems (ICEIS 2023) - Volume 2*, pages 231-242
ISBN: 978-989-758-648-4; ISSN: 2184-4992

medical conditions such as degenerative diseases, tumors, or infections. The incidence rate of SCI patients has been increasing and ranges from 13,019 per million to 163,420 per million people worldwide (Kang et al., 2017). Most patients with SCI have impaired function of the upper limbs (Wyndaele and Wyndaele, 2006). In this context, one of the most common consequences after injury is loss of muscle strength and numbness, increased muscle tone (spasticity) (Hodkin et al., 2018), weakness or paralysis. Thus, rehabilitation is essential to improve muscle strength and hand/arm function in both early and chronic stages. Rehabilitation aims to improve the patient's quality of life so that he or she can perform activities of daily living autonomously or at least achieve the highest degree of autonomy possible (Spooren et al., 2011).

Specifically, occupational therapy focuses on the patient's ability to cope with most everyday tasks. A team of functional rehabilitation specialist, physiotherapists, and other specialists plan treatment tailored to the needs of each patient. Rehabilitation begins at an early stage and can last for life, so it is important to maintain the patient's motivation and involvement. The repetition of inadequate movements has a negative impact on recovery, and it is necessary to prevent the patient from performing compensatory movements with other parts of the body. Furthermore, the repetition of compensatory movements prevents strengthening the area to be treated.

In accordance with the above problems, new technologies can help capture each patient's kinematics with the dual objective measuring movements and evaluation of the execution of each exercise. There are different alternatives for motion capture: 2D or 3D cameras, magnetic sensors, mechanical skeletons, and inertial sensors, among others. Some systems provide complete solutions, such as virtual reality headsets. They are Head Mounted Display (HMD) combined with IMUs (Inertial Mesure Unit) that allow the user to immerse in virtual worlds and interact with the elements of the 3D environment. Some of the best-known are Oculus Go, Oculus Rift, Oculus Quest, Oculus Quest 2, HTC Vive Focus, HTC Vive Pro 2, HTC Vive Focus 3, among others. In this type of device, the main form of interaction is via controllers. However, some of these HMDs, thanks to the cameras and sensors they integrate, are beginning to provide libraries that allow the development of applications. The main form of interaction is made through the movement and gestures of the hands. This is the case of Meta Quest 2 VR headset.

However, not all VR-based technologies are suitable for use in this type of patient. The use of elements such as controllers limits the functional movements and grasps that can be performed by humans (Everard et al., 2022). In addition, virtual applications with controllers cannot be used by a large number of patients with SCI with affecting the upper limbs. These patients generally, do not have sufficient strength or mobility. Also the use of controllers do not allow the natural movements and grasps of the hand to be performed freely. These movements include: flexion-extension of the wrist, flexion-extension of the index finger, gripping ability, hand and arm movements and end-terminal pinches.

There are different tests to assess the grasp function of the hand. In rehabilitation and occupational therapy, the Box and Block test (BBT) is widely used because it allows unilaterally measuring the degree of manual dexterity (Oliveira et al., 2016).

This article uses the BBT in three different scenarios. First, a physical scenario without the use of technologies. Secondly, a non-immersive virtual environment in which the Leap Motion Controller (LMC) sensor is used for hand tracking and a screen to display hands and objects virtually. Finally, the last scenario is fully immersive and uses the Oculus Quest 2. Virtual reality scenarios are tested by therapists and clinical staff in charge of rehabilitation sessions for patients with spinal cord injuries affecting the upper limbs. These tests are carried out thanks to the joint development with the Hospital Nacional de Parapléjicos de Toledo in Spain. The study described in this article stands out from others because the comparison between the different environments (real, non-immersive and immersive) is performed with the same parameters and sample. In both virtual environments, the interaction is executed with one's own hands, ruling out possible biases introduced by the use of controllers or other devices. In addition, although the objective of the test is to count the number of blocks moved correctly, certain variables of interest have been included for further study. On the other hand, unlike other implementations, immersive VR-BBT is performed using hand tracking provided by the virtual reality device itself, thus achieving a more realistic immersion.

The rest of the article is structured as follows. Section 2 sets the context of the problem. Section 3 presents different scenarios and immersive and non-immersive methods employed to support upper limb rehabilitation. Section 4 describes the clinical study and the results obtained. Finally, the article ends with Section 5 where the conclusions are presented.

2 PROBLEM CONTEXT

2.1 Upper Limb Rehabilitation and Occupational Therapy

Occupational therapy plays a significant role in the rehabilitation of patients with spinal cord injuries. Therapists assess the most appropriate treatment according to each individual's needs and functional goals. The therapy aims to achieve as much independence as possible for the patient in daily living activities like eating, turning lights on and off, dressing, or writing.

The recovery process of patients with SCI is linked to early mobilization and a multidisciplinary approach. To achieve improved and optimized long-term outcomes, it is necessary to involve experts in nutrition and physical and occupational therapists. Hence the importance of having an interdisciplinary team from the beginning of rehabilitation in the hospital.

2.2 Upper Limb Exercises

One of the types of exercises used in upper limb rehabilitation focuses on improving manipulative skills. The aim is to achieve the highest possible degree of hand functionality. In its execution, the hand(s) to be rehabilitated must be able to grasp and manipulate objects of different sizes.

Based on the above, there are different classifications of the movements and grasps required for the hand to be functional. One such grasp is described by (Vergara et al., 2014). The classification is based on the common grasps used by adults during the performance of activities of daily living: cylindrical grasp (the palm is involved and the thumb is in abduction or neutral), oblique palmar grasp (the thumb is adducted), hook grasp (palm and thumb are not involved), lumbrical grasp (thumb and proximal part of the fingers), intermediate power-precision grasp, pinch (thumb and fingertips), lateral pinch (lateral part of fingers and usually the thumb), special pinch and non-prehensile grasp (without grasping).

Another type of grasp that is widely used in patients with tetraplegia is the so-called tenodesis grasp. This is made by actively extending the wrist, and then the passive tension of the flexor muscles puts them under tension, generating a grip between the thumb and fingers (Jung et al., 2018).

Patients with SCI often need external aids to hold certain objects, such as a toothbrush or cutlery. In addition, the supervision by a specialist is essential when performing the exercises. Incorrect execution can lead to non-optimal rehabilitation and even to other secondary problems. These characteristics and limitations must be taken into account in the development of VR applications for rehabilitation.

3 REHABILITATION THROUGH VIRTUAL REALITY THERAPY

Virtual reality is an emerging tool that is becoming increasingly widespread in the field of rehabilitation. Studies corroborate the positive effects of this technology in patients with different types of diseases. Due to the diversity of existing pathologies and the goals to be achieved, it is difficult to unify the benefits of virtual reality rehabilitation, although it is worth highlighting the following: improvement in motor functions and quality of life (Toldo et al., 2021), cognitive functions (Maggio et al., 2018), muscle strength (Lee et al., 2016) and increased motivation (Dias et al., 2019).

Depending on the part of the body to be rehabilitated, the devices and virtual environments must comply with some characteristics. In the case of upper limb rehabilitation, it is essential that the user can move his/her hands freely. Virtual applications that need controllers to interact with virtual elements do not simulate natural grasping. Thus, it is necessary to rely on an efficient hand tracking system from which it is possible to obtain:

- The position of the hand and fingers in 3D space with the least possible error.
- The interaction of the hand on the virtual objects in the environment.
- An objective measurement of the degree of mobility and achievements of the patient.

In order to meet these needs, the following issues must be resolved: the first is the modeling of the different grasp types and their recognition by the system. The second is the grab, displacement and release of the virtual objects. And last, the objective measurement of the results using a standardized test such as the BBT.

3.1 Modeling Grasp Types

As described in the previous section, various functional grasp allow humans to grasp and move virtual objects. In the case of virtual reality, this problem is solved by using a virtual 3D hand that internally relies on an associated bones and joints (see Figure 1), similar to that of a human. In this way, the type of grasp can be recognized according to the direction vector of

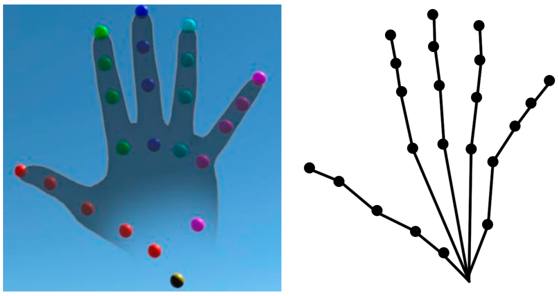

Figure 1: Virtual hand in immersive environment with associated skeleton for accurate finger position detection.

the bones, position and rotation of the individual fingers in relation to each other or in relation to the palm of the hand.

In addition to pose recognition, it is also important to detect the level of effort. The effort of each patient can be key in determining when an object is considered to be attached to a virtual hand. Effort can be defined as the distance between two or more bones involved in the grasp. Above a certain threshold, contact is considered to exist between two or more fingers or between the fingers and palm. On the other hand, below a certain threshold, it is considered that they is no contact at all. In the case of grasping a given object, it is necessary to take into account both the contact distance between fingers (or fingers and palm of the hand) and the distance between the hand and the object. If a grasp pose is recognized but the object is not within reach, then the grasp will not be executed.

In the case of non-prehensil movements used to lift an object, it is necessary to know the orientation of the hand, as it must be placed with the palm facing the ground.

3.2 Holding of Virtual Objects

In order to simulate, in a virtual environment, the human ability to grasp and release objects, it is necessary to evaluate the shape and position of the object in relation to the hand with which it interacts within the 3D environment.

First of all, the interactive elements of the scene must be defined along with the kind of interaction. For this, the physical properties of the object, its weight or gravity, the collision area of the object and the state of the object from the interaction point of view must be specified. The states related to the interaction are as follows: *non-selectable* (it is away from the hand), *selectable* (the hand can interact with it), *grabbed* (it is attached to the hand and follows the movements of the hand) and *released* (it will be subject once more to the established physical principles).

In order to recognize the different types of grasps with respect to the object, the collision area of the object has to be considered. This area can be the same size as the object or vary slightly whether a more fluid interaction is required.

Once the object is considered to be grabbed, it is dependent on the actions of the hand. When grasp strength is detected to be less than a certain threshold, the item will behave according to its physical characteristics.

3.3 Box and Block Test (BBT)

Once the different types of grasping and the interaction of the hands with objects in the virtual world have been established, it is necessary to determine how the manipulative ability of a user can be measured. There are different scales and tools to measure motor dexterity, such as the Gross Motor test, the Movement Assessment Battery, the Action Research Arm Test (ARAT), or the Motor Assessment Scale (MAS) (Carr et al., 1985).

Particularly, in order to assess manipulative dexterity, BBT is widely used by patients with different diagnoses: spinal cord injury, geriatrics, multiple sclerosis and fibromyalgia, among others. Therefore, in this work, BBT has been performed in three different scenarios: a) real physical environment without the use of technologies, b) non-immersive environment with virtual elements and, finally, c) immersive environment based on virtual reality. In scenarios b) and c), technological solutions have been adopted so that the user does not need to have their hands occupied with a controller device or attach wearables to the body.

3.3.1 Scenario 1: BBT in Physical Environment

The BBT, requires a 53.7 cm x 25.4 cm x 8.5 cm wooden box divided into two compartments of equal size. Initially, 150 blue, yellow, or red wooden blocks with a dimension of 2.5 cm are placed in one of the compartments. This configuration depends on the hand to be assessed: if it is the right hand, the blocks are initially placed in the right compartment; if the dexterity of the left hand is to be measured, the blocks are placed in the left compartment.

The patient is seated in front of the box and has to move as many blocks as possible from one compartment to another within 60 seconds (Mathiowetz et al., 1985). In order to perform the test, the patient is first given 15 seconds to trial period. Once the test has started, the examiner must count the displaced blocks correctly: only one block can be carried in each movement (otherwise, only one is counted), the patient's

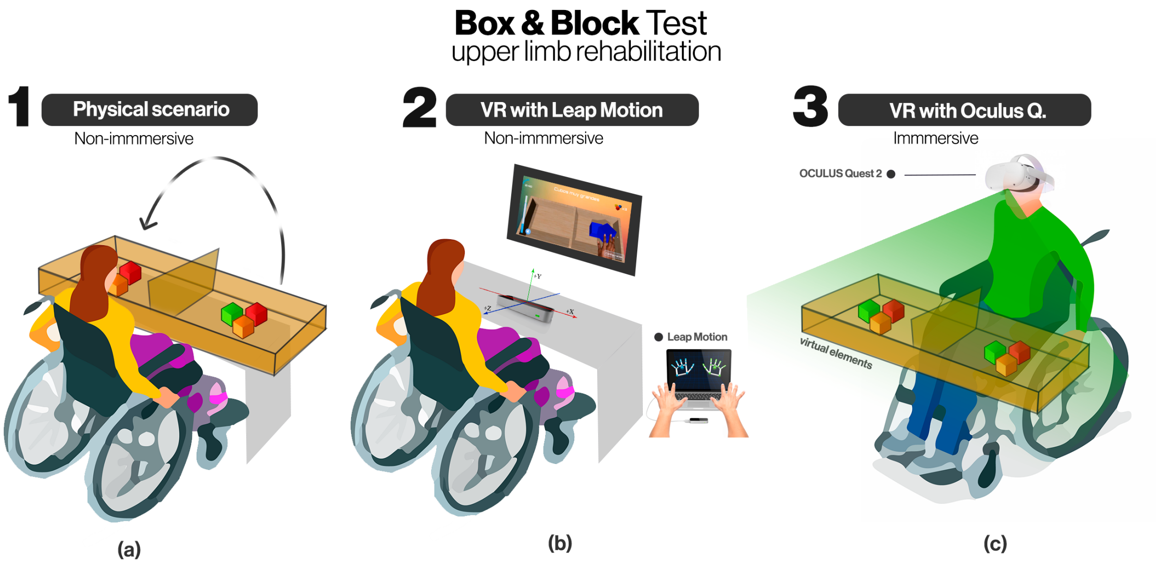

Figure 2: Analysis of hand movement accuracy and performance in the execution of therapeutic exercises using the Box and Block test in three types of scenarios: a) physical scenario without the use of technologies, b) use of virtual components in a non-immersive scenario and, finally, c) use of virtual components in a fully immersive scenario.

hand must pass over the partition of the box and release the block when it is in the target partition.

BBT is a simple test, portable, efficient, and inexpensive to perform. It provides information on the speed of performance but not on other aspects such as the quality of the performed movement (Alt Murphy et al., 2015). There is no single trajectory to perform the exercise, apart from the different initial positions of the cubes in the box. In recent years, new technologies have been adopted to mitigate the disadvantages derived from the test, so that objective measurements of the user's movements can be obtained. One of them is the modified BBT which allows the assessment of movement in upper-limb impairment with the help of motion capture techniques, and may help measure the effect of interventions to improve upper-limb function (Hebert et al., 2014). Other studies make use of wearable sensors to obtain, among other things, information on the speed or time spent moving each block (Zhang et al., 2019).

3.3.2 BBT with Virtual Reality (Scenarios 1 and 2)

Recently, and thanks to the rise of virtual reality, applications have begun to be developed to simulate BBT to exploit the advantages of the virtual world with an accurate capture of movements.

In tests conducted by Gieser et al. (Gieser et al., 2016) the number of blocks moved in the real BBT was much higher than those achieved with the non-immersive VR-BBT. Hashim et al. (Hashim et al., 2021) in their study with an immersive VR-BBT supports this result, although this number of achievements increases in line with the number of training sessions. Other studies, such as those conducted by Onat et al. (Oña et al., 5 13) have shown that these differences are reduced when the environment is immersive, and no additional controllers are used.

This paper presents two solutions to VR-BBT: non-immersive and immersive. The implementation of the virtual world has been developed following the guidelines of the clinical experts of the Hospital de Parapléjicos de Toledo. To this end, the physical characteristics of both the box and the blocks, as well as the colors used, have been taken into account to eliminate possible biases in the results obtained with traditional BBT and virtual BBT.

Both solutions were developed in Unity[2]. The wooden box and blocks were designed following the guidelines of the real test. A virtual object is modeled and instantiated as many times as necessary at runtime to represent the cubes. Each cube has two basic elements: *Rigidbody* and *Box Collider*. The first one allows the cube to act under the control of physics, defining mass and gravity, among others. The second is a box collider that simulates physical collisions with other elements. In order to be faithful to the real model, the color of each cube is determined randomly, according to the colors used in the BBT test: red, blue, or yellow. The position in the scene is also set randomly, and inside the zone of origin (right side for the right hand or left side for the left hand).

In both proposals, audio and graphical aids have

[2]https://unity.com/

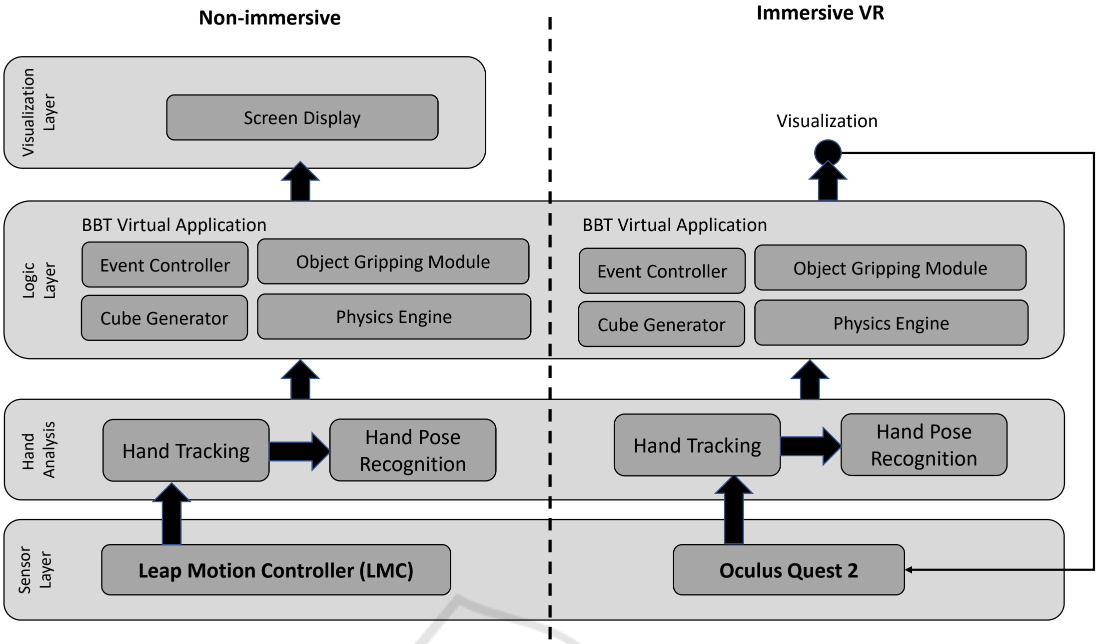

Figure 3: Multilayer architecture of the two proposed solutions for virtual BBT. Main hardware components, software and connection between modules.

been added to help the patient to know the state of the interaction. Both immersive and non-immersive solutions have a sound when the cube is grabbed and another one when the cube is released. In addition, when a cube is grabbed then it changes to a greyish colour.

Moreover, both virtual solutions have a pre-calibration phase to adjust the object grip. In the event that a user/patient has severe movement limitations, the test is run in "autogrip" mode. In other words, the cube is automatically grasped by proximity to the hand and will be released when it comes into contact with the target compartment.

Each of the two VR-based solutions mentioned above is described in more detail in the following section. Figure 3 shows a multilayer architecture of the two solutions developed. On the left a VR-based and non-immersive solution, on the right the solution is fully immersive. The design is divided into four main layers. The lowest level layer captures the movement of the hands through a set of sensors. This information is processed at a second level to track hands and recognize grasping gestures. The information generated at the second level progresses to the logic layer, where the most significant processing load is located. In the logic layer, there is a module for generating BBT cubes, the module that determines the grip between hands and virtual objects, the event controller module (any given situation in the virtual environment), and the physics engine to provide the virtual elements with realistic behavior. Once all the information has been processed, the last layer is responsible for displaying the changes in the virtual environment. The major difference between the two solutions is that in the non-immersive solution the changes are displayed on a screen and the user does not stop perceiving the real world at any time. In contrast, the second solution feeds back to the first layer, as the changes are displayed again in the VR goggles and the user is completely isolated from the real world.

3.3.3 Scenario 2: BBT in a Non-Immersive Scenario With Virtual Reality

In a non-immersive scenario, the patient interacts with his/her own hands and the results of the actions are displayed in real-time on a screen. In the non-immersive virtual BBT presented in this paper, Leap Moption Controller (LMC) has been used for hand motion capture (see Figure 4). The Leap Motion Controller is an optical hand-tracking module to capture hand and finger movement. It is a small size and low-cost sensor with two cameras and infrared LEDs. The connection is made via USB 2.0, it has two 640x240-pixel near-infrared cameras with infrared-transparent typically operating at 120Hz, but the hardware is capable of 240+ (lea, 2022). LMC can track both hands simultaneously, recognizing gestures and allowing real-time interaction: pushing, pinching, grabbing, etc. Besides, Ultraleap offers an API for different programming languages and supports integration with both Unity and Unreal engines for building real-time 3D projects.

Figure 4: BBT in a non-immersive scenario using LMC and on-screen display.

The different functional hand grasps are detected when they come into contact with the collision area defined in the cube. For this implementation (see Figure 4), the methods provided by the API were used to determine the grab strength and pinch strength. Firstly, we calculate the strength of a hand grasping posture based on how close the hand is to being a fist. Secondly, the pinch strength indicates the holding strength of a pinch hand (between the thumb and another finger of the same hand). In both cases, the domain of definition of the variable is a numerical value belonging to [0,1]. The value 0 indicates no grip, whereas the value 1 refers to the highest strength.

A set of variables that inform about the execution of the exercise is stored in real-time. These variables are: *hand used*, *reliability* (degree of confidence of the hand), *palm position* (X,Y,Z), *palm position in magnitude*, *hand speed*, *grasp capacity* understood as opening and closing the hand (grasp strength) [0-1], *thumb grip capacity* with any of the other fingers (grip strength) [0-1], *wrist flexion* expressed in degrees ($arm.Direction.AngleTo(hand.Direction) * 180/(float)\pi$) and the *pronation* of the forearm from the hand's roll angle($normal.Roll * 180/(float)\pi + 90$).

Finally, it is worth mentioning that the application has an initial menu to select the difficulty level according to time, size, and the number of targets depending on the pinch or grip performed. The menu design contemplates accessibility aspects so that patients with physical limitations can interact without external assistance.

3.3.4 Scenario 3: BBT in Immersive Environment with Virtual Reality

In immersive VR-BBT, the patient is completely immersed in the virtual world (see Figure 5). The environment that the user views and feeds back to is isolated from the real world. Moreover, unlike other proposals, the solution presented here uses the patient's hands as a natural form of interaction. It should be noted that hand tracking is performed by the virtual reality device itself, Oculus Quest 2. Unlike other developments in which was used with virtual reality glasses (Oña et al., 5 13), the immersive VR-BBT we propose uses the device's own hand tracking. From the clinical study carried out in this work, it was found that Oculus Quest 2 offer better tracking accuracy compared to the LMC. This fact results in improved patient performance as will be discussed in future sections.

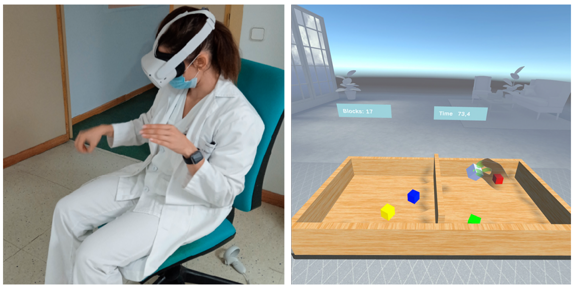

Figure 5: BBT in an immersive scenario in which the patient perceives only virtual elements.

Oculus Quest 2 is a Head-Mounted Display (HMD) with 6 DoF inside-out via four integrated cameras for tracking and allows interaction with the immersive world through the dynamic controllers and the user's hands. Hand tracking has been significantly improved in the new version 2.0 (April 2022), which allows faster movements and solves occlusion issues, so more applications integrating this type of interaction are starting to emerge. Meta[3] provides developers with SDKs for integration into both Unity and Unreal engines.

The VR-BBT immersive has been developed in Unity (v.2020.3.23f1) and uses the Hand Tracking API v2.0. The SDK allows the configuration of certain parameters; one of the most relevant is the tracking rate that can be low, medium or high. The latter reaches 60 Hz and is the one used in our VR-BBT application.

The development of the virtual environment has been implemented following feedback from clinical specialists. Special attention has been paid to provide the VR-BBT with a high configurability so that a wide variety of patients can use it. The primary considerations taken into account to adapt to each patient's needs are listed below.

- Recognition of any possible grasp, including tenodesis grasp and release. The block grasp is performed by proximity to the hand in case no func-

[3]https://www.meta.com/

tional grasp detected.

- Initial configuration of the positioning of the box. This static element can be adapted to each patient, i.e., its position in the three axes (X, Y, Z) can be modified before starting the BBT. The box containing the blocks must be positioned at a suitable height, i.e., the patient must remain seated, with the box in front of him/her and a 90° angle must be formed between the arm and forearm. This avoids forced shoulder, arm, and forearm positions and even prevents some of the blocks from being inaccessible. For this reason, the location of the box can be configured from the menu, adapting it to each patient.
- Configuration for patients with severely reduced mobility. The calibration stage, in which the patient tries to grasp a sample block in any possible way might be advisable. The application runs in "autogrip" mode if no grasp is detected. Concerning the difficulty of the game, two forms, "normal" and "easy"', have been created, which are linked to the separator between the two areas of the box. Some patients cannot perform arm lifts, but with this configuration it is possible, in easy mode, to correctly score when the hand crosses the separator between the two cubicles. These options allow testing with a wider range of patients.
- Visual and audio feedback: in addition to the elements discussed in section 3.3.2 the immersive environment has the following elements to support interaction. The fingertips change to purple when starting to grasp a block and to green when it is grabbed by the hand. In addition, the correct movement of a block is accompanied by a sound. A different sound is played when the block has been moved incorrectly or placed outside the target partition.
- The initial menu is easily accessible. The buttons are large and can be pressed with the whole hand. Interaction can be done either with the hands or with the controllers.

During the execution of the VR-BBT a dataset is stored to facilitate a possible a posteriori evaluation of the performed exercise: the number of frames since the beginning of the exercise, time measured in seconds, hand detected/not detected, the degree of confidence and position in 3D space of the hand, pinch detection (true/false), palm grip detection (true/false), force realized the thumb with the rest of the fingers ([0-1]), the strength of each finger with respect to the palm ([0-1]) and HMD position (x,y,z). With these elements, it is possible to determine the number of correctly performed grips, the type, and the exerted force. Furthermore, it is possible to detect false negatives due to inefficient hand tracking thanks to the degree of hand confidence. One of the variables described above is worth mentioning, the HMD position. This value is stored to report undesirable trunk compensatory movements. This is done thanks to the positioning of the HMD in 3D space. The patient's head and trunk performs a displacement when movement is detected in the Z axis of the HMD.

The feeling of complete immersion, the adjustments in the virtual environment according to the patient's needs and the variables stored at run-time provide a powerful tool for both the patient and the rehabilitators and therapists. The patient feels more motivated to perform the exercise, which is also adapted to his or her particular needs. Rehabilitation specialists have objective data on the performance of BBT and can evaluate not only the blocks moved but also the quality of each movement as well as the patient's evolution.

4 CLINICAL STUDY AND RESULTS

4.1 Participants

The technologies discussed throughout the article were initially tested on healthy patients. In later phases of the project, real patients will be included in the clinical study. Thus, ten healthy individuals (32.50±17.25 years) participated in the study. All of them were right-handed and performed the BBT task in three different experimental conditions with the dominant hand:

- The real environment.
- The virtual environment in a non-immersive condition by means of Leap Motion Controller.
- The virtual environment in an immersive condition by means of Oculus Quest 2

With the aim of controlling the order effects, individuals' performance in each condition was randomized. The clinical study was carried out at the Hospital Nacional de Parapléjicos (Toledo, Spain) and was approved by the local Ethical Committee.

All the subjects must have neurologically healthy condition. Exclusion criteria were: not signing the corresponding informed consent; having visual impairment or any impairment of upper limb function; having previous history of seizure or motion sickness.

4.2 Clinical Study Setup

Each participant performed all three experimental conditions on the same day in a single experimental session. The BBT in each experimental condition was performed seated in front of a height-adjustable table until the elbow was flexed 90º with the palm of the hand on the table. For the immersive VR condition, the table was removed and it was performed in the same chair as the other conditions.

Before performing the first trial within the both VR conditions, a preliminary trial was performed to familiarize with each virtual environment. In the case of the real BBT, no familiarization was considered needed with the exception of the 15 seconds allowed by the real test (Mathiowetz et al., 1985).

Three trials of each experimental condition were performed. The variable measured was the total number of cubes passed to the other side of the box in one minute. As the final result, the mean value of the three trials was considered for analysis for each condition.

4.3 Statistical Analysis and Results

The results of the variable analyzed were expressed as median and interquartile range. The Wilcoxon non-parametric test was applied to find possible differences between the three experimental conditions (see table 1). The relation between each pair of conditions was analyzed by the Pearson correlation coefficient.

The performance in the real BBT was significantly higher than in the both VR modalities (83.67 ± 16.75 in the real test vs. 69.17 ± 20.33 in the immersive VR version ($p < 0.05$) and 45.66 ± 16.84 in the non-immersive version ($p < 0.01$)) (see Figure 8). Moreover these results were statistically significant between the both VR modalities ($p < 0.01$) (see Figure 7). However, if we selected only participants with previous experience in virtual environments ($n = 8$), no statistically significant differences were found between the real BBT and the immersive VR version (see Figure 6).

The correlation between the real BBT and the non-immersive VR BBT was high (0.858, $p < 0.05$). This correlation was statistically significant ($p < 0.01$) between the real BBT and the immersive BBT (0.717) and between both VR conditions (0.763).

4.4 Limitations of the Study

The conducted clinical study has been oriented towards the evaluation of data acquisition and performance in relation to the BBT. This is an essential aspect when devising a system that allows autonomous

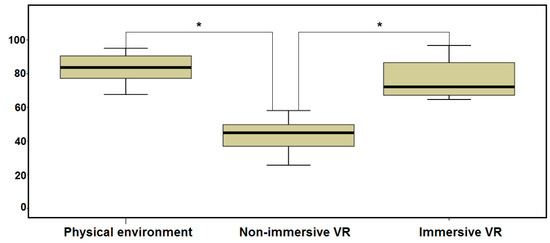

Figure 6: Box plot in relation to the cubes passed for each experimental condition with practice in VR environments (n = 8).

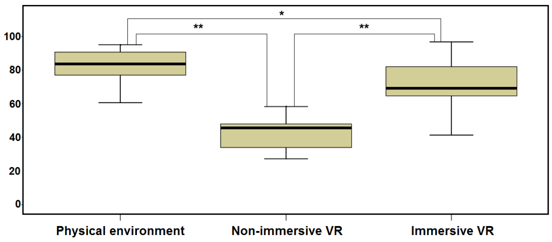

Figure 7: Box plot in relation to the cubes passed for each experimental condition and for all the participants (n = 10).

but guided rehabilitation. This first step is key before evaluating its usefulness with real patients who have suffered neurological conditions.

After this first step, a series of clinical studies to analyze if this trend is maintained in spinal cord injured patients will be conducted in a second phase. These are intended to be performed in the Hospital Nacional de Parapléjicos, where the system will be deployed.

The technological requirements of the discussed system are not high (VR headset and an standard laptop). The authors of this manuscript do not consider the system as high-cost, since it aims at improving the rehabilitation process and mitigating the lack of specialized staff, which is becoming more and more challenging from a global point of view (see (Alvarez-

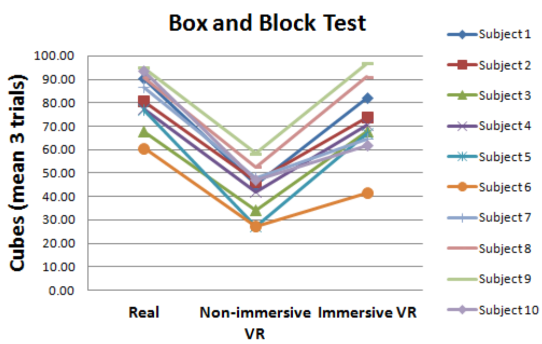

Figure 8: Performance of each participant within each experimental condition. All the participants maintain the same trend.

Table 1: Significant statistically differences between the three experimental environments analyzed by means of Wilcoxon test $(a, b(p < 0.05), c, d(p < 0.01))$.

Participants	Physical environment	Non-immersive VR	Immersive VR
All (n=10)	$83.67(16.75)^{a,c}$	$45.66(16.84)^{c,d}$	$69.17(20.33)^{a,d}$
With practice (n= 8)	$83.67(13.50)^{a}$	$45.66(15.50)^{a,b}$	$72.17(21.83)^{b}$

Sabín et al., 2017) for a related discussion that affects stroke rehabilitation in Spain). At this point, one of the pursued goals is to show the usefulness, and even the acceptance, of the system when performing rehabilitation. Particularly, the study and analysis the influence of motivation, in the short term, on the user's commitment has been considered.

Lastly, in a third phase, a clinical trial will be conducted to study the feasibility and effectiveness of the proposed system, considering its intended use during longer periods of time. The research hypothesis at this point would be the assessment and validation of effective, upper-limb rehabilitation through virtual reality at hospitals and rehabilitation centers. In this phase, functional resonance magnetic imaging (fRMI) will be included in the study for detecting signs of improvement after the rehabilitation treatment. This feature will allow us to design and describe a motor paradigm and the corresponding experimental protocol, suitable for all the participants, whether healthy or SCI patients. Finally, to extend the fMRI post-processing for analyzing voxel-based morphometry and voxel-based thickness of T1-weighted images.

5 CONCLUSIONS

This paper analyzes and compares technologies that facilitate hand tracking and are applied to upper limb rehabilitation. For this purpose, non-immersive and immersive virtual solutions based on virtual reality have been developed and applied in the context of the Hospital Nacional de Parapléjicos de Toledo (Spain).

The proposed solutions are integrated together with the BBT and three different scenarios are proposed: traditional physical scenario without the use of technologies, non-immersive scenario and virtual elements and, finally, fully immersive scenario based on VR.

The main novelty of the work lies in the simultaneous design of both non-immersive and immersive solutions that take into account the future limitations of patients. Precisely because of these limitations, we have opted for implementations in which patients can perform the exercises without the attachment of real physical controllers or the adhesion of wearables devices.

The starting hypothesis was that the conditions offered by immersive virtual environments can recreate scenarios and situations very similar to real ones, to which should be added the advantages of these virtual environments such as the elimination of physical barriers and the recreation of any type of object. In the context of rehabilitation, this factor is crucial since the precision with which therapeutic exercises are performed directly influences the recovery of damaged limbs.

Precisely, the results demonstrate this hypothesis. The number of blocks moved from the point of origin to the point of destination in the immersive environment largely resembles the data obtained in a traditional physical environment. This is due to a proper perception of the environment and the elements presented, the correct implementation of grasping pose recognition and, finally, the control logic that determines the adhesion of objects to the hands.

As future work, the use of devices that can measure the muscular activity exerted by the patient during virtual rehabilitation is proposed, using, for example, EMG-based controllers (Pleva et al., 2022). As well as mixed reality technologies that would allow for greater precision in measuring the patient's progress and better adaptation of the intensity and difficulty of the exercises to the individual needs of the patient.

ACKNOWLEDGMENTS

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

(2022). *Leap Motion Controller Datasheet*. Ultraleap.

Alt Murphy, M., Resteghini, C., Feys, P., and Lamers, I. (2015). An overview of systematic reviews on upper extremity outcome measures after stroke. *BMC Neurology*, 15(1):29.

Alvarez-Sabín, J., Quintana, M., Masjuan, J., Oliva-Moreno, J., Mar, J., Gonzalez-Rojas, N., Becerra, V., Torres, C., and Yebenes, M. (2017). Economic impact of patients admitted to stroke units in spain. *The European Journal of Health Economics*, 18(4):449–458.

Bravo, V. P. and Muñoz, J. A. (2022). Wearables and their applications for the rehabilitation of elderly people. *Medical and Biological Engineering and Computing*, 60(5):1239—1252.

Carr, J. H., Shepherd, R. B., Nordholm, L., and Lynne, D. (1985). Investigation of a new motor assessment scale for stroke patients. *Physical Therapy*, 65(2):175–180.

Clus, D., Larsen, M. E., Lemey, C., and Berrouiguet, S. (2018). The Use of Virtual Reality in Patients with Eating Disorders: Systematic Review. *Journal of Medical Internet Research*, 20(4):e7898. Company: Journal of Medical Internet Research Distributor: Journal of Medical Internet Research Institution: Journal of Medical Internet Research Label: Journal of Medical Internet Research Publisher: JMIR Publications Inc., Toronto, Canada.

de Araújo, A. V. L., Neiva, J. F. d. O., Monteiro, C. B. d. M., and Magalhães, F. H. (2019). Efficacy of Virtual Reality Rehabilitation after Spinal Cord Injury: A Systematic Review. *BioMed Research International*, 2019:e7106951. Publisher: Hindawi.

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.

Gieser, S. N., Gentry, C., LePage, J., and Makedon, F. (2016). Comparing objective and subjective metrics between physical and virtual tasks. In Lackey, S. and Shumaker, R., editors, *Virtual, Augmented and Mixed Reality*, Lecture Notes in Computer Science, pages 3–13. Springer International Publishing.

Guillén-Climent, S., Garzo, A., Muñoz Alcaraz, M. N., Casado-Adam, P., Arcas-Ruiz-Ruano, J., Mejías-Ruiz, M., and Mayordomo-Riera, F. J. (2021). A usability study in patients with stroke using MERLIN, a robotic system based on serious games for upper limb rehabilitation in the home setting. *Journal of NeuroEngineering and Rehabilitation*, 18(1):41.

Hashim, N. A., Razak, N. A. A., and Osman, N. A. A. (2021). Comparison of Conventional and Virtual Reality Box and Blocks Tests in Upper Limb Amputees: A Case-Control Study. *IEEE Access*, 9:76983–76990. Conference Name: IEEE Access.

Hebert, J. S., Lewicke, J., Williams, T. R., and Vette, A. H. (2014). Normative data for modified box and blocks test measuring upper-limb function via motion capture. *Journal of Rehabilitation Research and Development*, 51(6):918–932.

Hodkin, E. F., Lei, Y., Humby, J., Glover, I. S., Choudhury, S., Kumar, H., Perez, M. A., Rodgers, H., and Jackson, A. (2018). Automated fes for upper limb rehabilitation following stroke and spinal cord injury. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 26(5):1067–1074.

Jung, H. Y., Lee, J., and Shin, H. I. (2018). The natural course of passive tenodesis grip in individuals with spinal cord injury with preserved wrist extension power but paralyzed fingers and thumbs. *Spinal Cord*, 56(9):900–906.

Kang, Y., Ding, H., Zhou, H., Wei, Z., Liu, L., Pan, D., and Feng, S. (2017). Epidemiology of worldwide spinal cord injury: a literature review. *Journal of Neurorestoratology*, Volume 6:1–9.

Lamash, L., Klinger, E., and Josman, N. (2017). Using a virtual supermarket to promote independent functioning among adolescents with Autism Spectrum Disorder. In *2017 International Conference on Virtual Rehabilitation (ICVR)*, pages 1–7. ISSN: 2331-9569.

Lee, S.-H., Yeh, S.-C., Chan, R.-C., Chen, S., Yang, G., and Zheng, L.-R. (2016). Motor ingredients derived from a wearable sensor-based virtual reality system for frozen shoulder rehabilitation. *BioMed Research International*, 10(6). Publisher: Hindawi.

Maggio, M. G., De Cola, M. C., Latella, D., Maresca, G., Finocchiaro, C., La Rosa, G., Cimino, V., Sorbera, C., Bramanti, P., De Luca, R., and Calabrò, R. S. (2018). What about the role of virtual reality in parkinson disease's cognitive rehabilitation? preliminary findings from a randomized clinical trial. *Journal of Geriatric Psychiatry and Neurology*, 31(6):312–318. Publisher: SAGE Publications Inc STM.

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.

Mekki, M., Delgado, A. D., Fry, A., Putrino, D., and Huang, V. (2018). Robotic rehabilitation and spinal cord injury: a narrative review. *Neurotherapeutics*, 15(3):604–617.

Oña, E. D., Jardón Huete, A., Cuesta-Gómez, A., Baeza, P., Cano de la Cuerda, R., and Balaguer, C. (2020-05-13). Validity of a fully-immersive VR-based version of the box and blocks test for upper limb function assessment in parkinson's disease. *Sensors*, 20:2773.

Oliveira, C. S., Almeida, C. S., Freitas, L. C., Santana, R., Fernandes, G., Junior, P. R. F., and Moura, R. C. F. (2016). Use of the box and block test for the evaluation of manual dexterity in individuals with central nervous system disorders: A systematic review. *Manual Therapy, Posturology & Rehabilitation Journal*, pages 1–7.

Pereira, M. F., Prahm, C., Kolbenschlag, J., Oliveira, E., and Rodrigues, N. F. (2020). A virtual reality serious game for hand rehabilitation therapy. In *2020 IEEE 8th International Conference on Serious Games and*

Applications for Health (SeGAH), pages 1–7. ISSN: 2573-3060.

Pleva, M., Koarečko, v., Hladek, D., Bours, P., Skudal, M. H., and Liao, Y.-F. (2022). Biometric user identification by forearm EMG analysis. In *2022 IEEE International Conference on Consumer Electronics - Taiwan*, pages 607–608. ISSN: 2575-8284.

Rupp, R., Biering-Sørensen, F., Burns, S. P., Graves, D. E., Guest, J., Jones, L., Read, M. S., Rodriguez, G. M., Schuld, C., Tansey-Md, K. E., et al. (2021). International standards for neurological classification of spinal cord injury: revised 2019. *Topics in spinal cord injury rehabilitation*, 27(2):1–22.

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

Toldo, J. M. P., Arjona, M., Campos Neto, G. C., Vitor, T., Nogueira, S. A., Amaro, E. J., Saba, R. A., Silva, S. M. C. A., Ferraz, H. B., and Felício, A. C. (2021). Virtual rehabilitation in parkinson disease: A dopamine transporter imaging study. *American Journal of Physical Medicine & Rehabilitation*, 100(4):359–366.

Vergara, M., Sancho-Bru, J. L., Gracia-Ibáñez, V., and Pérez-González, A. (2014). An introductory study of common grasps used by adults during performance of activities of daily living. *Journal of Hand Therapy*, 27(3):225–234.

Wyndaele, M. and Wyndaele, J.-J. (2006). Incidence, prevalence and epidemiology of spinal cord injury: what learns a worldwide literature survey? *Spinal cord*, 44(9):523–529.

Zhang, Y., Chen, Y., Yu, H., Lv, Z., Shang, P., Ouyang, Y., Yang, X., and Lu, W. (2019). Wearable sensors based automatic box and block test system. In *2019 IEEE SmartWorld, Ubiquitous Intelligence Computing, Advanced and Trusted Computing, Scalable Computing and Communications, Cloud and Big Data Computing, Internet of People and Smart City Innovation (SmartWorld/SCALCOM/UIC/ATC/CBDCom/IOP/SCI)*, pages 952–959.