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Rehab-Immersive: A framework to support the development of virtual reality applications in upper limb rehabilitation

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ABSTRACT

In this article, we present a framework, called Rehab-Immersive (RI), for the development of virtual reality clinical applications as a complement to the rehabilitation of patients with spinal cord injuries. RI addresses the interaction of patients with virtual worlds, considering upper limb motor impairments. A preconfiguration allows customization for each patient's specific needs. RI also stores kinematics data, providing clinical staff with a valuable tool to evaluate progress and patient exercise performance. As an example, a virtual version of the Box & Block test is presented.

Code metadata

Current code version	1.0
Permanent link to code/repository used for this code version	https://github.com/ElsevierSoftwareX/SOFTX-D-23-00044
Permanent link to Reproducible Capsule	https://github.com/ArtificialIntelligenceAndRendering/RehabImmersive/tree/main/apk
Legal Code License	MITLicense
Code versioning system used	git 2.33.0
Software code languages, tools, and services used	C++, OpenXR Plugin 1.5.3, TextMeshPro 3.0.6, Meta Movement 1.3.2, Oculus Integration 46.0, JsonUtility, AndroidJavaClass, Unity 2021.3.12f1.
Compilation requirements, operating environments & dependencies	Oculus Quest 2, Unity 2021.3.12f1, OVRBuild APK (optional).
If available Link to developer documentation/manual	https://github.com/ArtificialIntelligenceAndRendering/RehabImmersive/blob/main/doc/DeveloperDocumentation.md
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1. Motivation and significance

Over the last decade, Virtual Reality (VR) has undergone significant developments. Its application has expanded to various fields of society thanks to technological advances and the availability of more affordable and user-friendly VR devices. These fields include leisure, industry, education, architecture, and healthcare [1–3]. In the latter, VR has been proven so far to be beneficial for patients with psychological, social, or physical issues [4–6].

Multiple studies support the use of VR in rehabilitation [7–9] as a complement of the conventional therapy received by patients. Virtual rehabilitation offers several benefits, such as increasing patient motivation and participation [10], improve motor function [11], reduce pain [12,13] anxiety and depressive symptoms [14], as well as providing objective monitoring and measurement of progress by the rehabilitator or therapist even remotely [15].

In this context, interaction methods are essential as they enable patients to engage with the environment and perform tasks within it. In a virtual environment, patients have access to various interaction methods, such as (i) tracking devices, such as gloves or suits equipped with sensors [16], (ii) controllers (joysticks,

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keyboards, or mice) [17–19], (iii) voice command control [20], and (iv) gesture and facial expression recognition [21].

However, not all interaction modes are suitable for users with motor impairments, such as individuals with spinal cord injury (SCI) who often have limited mobility in their hands. This can make it difficult to use controllers or tracking devices that require hand movement and limits the actual finger and grasp movements [22]. Fortunately, recent technological advances have led to the development of non-intrusive devices such as head-mounted displays (HMDs) that can track hand movements via external cameras integrated into the helmet. These devices provide an alternative means of interaction for individuals with SCI and other motor impairments [23].

In the context of upper-limb rehabilitation, reliable hand tracking is essential for effective rehabilitation. In addition to this requirement, the systems must be able to recognize both the types of grip and the limitations of each individual patient. This latter factor significantly influences the interaction between the patient and virtual targets, as well as the creation of accessible and adaptable virtual environments. Furthermore, the systems must have the ability to record all data generated during the performance of exercises. This data provides a fundamental means for therapists to make objective assessments of the patient's progress.

Existing studies do not cover all the aspects indicated. Some, such as those by Hashim et al. [24], use non-immersive VR. However, various studies support that the use of VR enhances three-dimensional perception of space, in contrast to non-immersive virtual reality [25]. Additionally, another advantage of immersive VR is the positive impact of VR immersion on the flow experience [26].

Other studies, such as [22] use controllers, which makes it difficult to accurately analyzing finger mobility, as they rely on the user's ability to manipulate them effectively. Some patients may not have the dexterity or strength to use controllers, which can limit the usefulness of this type of technology for rehabilitation. In the VR tool developed by Palaniappan and Duerstock [27], they propose a solution to the use of controllers among individuals with tetraplegia. Specifically, the controller is customized to be fastened to the arm via a velcro strap. They subsequently developed a pilot VR exergame with customizable gameplay parameters and an accessible interface [28]. Edwin et al. [29] uses an immersive VR system that utilizes HMD and Leap Motion Controller (LMC). This system eliminates the lack of depth by integrating the tracking performed by the LMC with a VR headset. However, this article does not mention the storage of critical information for the study of the exercise, the adaptation of the virtual environment to the patient, or other possible types of interaction. Also, studies such as [30] suggest that the technology provided by the Oculus Quest 2 is much more accurate than the single forward-facing sensor in the LMC.

The work of Pereira et al. [31] presents a serious game of VR using a HMD for hand rehabilitation therapy. This case is an immersive system, where the tracking is performed by the HMD itself. However, it has certain limitations, such as the type of interaction that the patient can perform: poke, single pinch, and multi-finger pinch. The software does not recognize other functional grasps (palmar pinches) or interaction of the raycast type.

Previous research has not identified a grasping or pinch type that does not involve direct touch. While some studies have recognized a pinch when the thumb fingertip touches another fingertip, this approach does not consider the volume of the object being grasped and does not accurately reflect the natural way in which an object is pinched. Additionally, these solutions do not adapt the configuration of the virtual environment to the individual needs of each patient. In contrast, our proposal addresses these limitations and provides a comprehensive approach to grasping and pinching in the virtual environment.

In this work, we present RI, that serves as a basis and support for the development of VR applications focused on the rehabilitation of the upper limbs (UL). The proposed software offers fundamental functions for manipulating objects in virtual environments, considering patient limitations, so that developers can focus solely on designing and developing new applications. In addition, RI also offers as a service the recording of kinematics during exercises. These data are accessible from the rehabilitation apps developed on RI and can be analyzed by therapists to objectively evaluate the progress of patients.

2. Software description

Fig. 1 illustrates a multilayer architecture in which the upper layer would house new applications for upper limb rehabilitation. These applications, especially developed with Unity 3D and C# for Oculus Quest 2, would be supported by RI, occupying the layers immediately below.

The layered set provides basic functionality to any hand rehabilitation software, and the construction of modular and scalable systems. Our proposal consists of three main layers: (i) configuration and calibration, (ii) hand interaction and (iii) data persistence.

First, the *configuration and calibration* layer plays a crucial role in ensuring that the virtual environment is customized to meet the specific needs of the patient. This layer is responsible for loading and storing the virtual environment preferences for each patient, as well as associating kinematic data from each session with the patient's identity. In this way, calibration is only required once per patient. The system recognizes the patient identifier and updates the scenario based on the stored configuration. This configuration remains unchanged unless certain characteristics of the patient are altered. For example, the autogrip function may be necessary at the outset, but after several sessions, the patient may be able to perform functional grasps, requiring a reconfiguration. By maintaining a historical log of this data, it is possible to track progress and make ongoing adjustments to the virtual environment, such as adjusting the size of objects, the distance between objects and the patient, or calibrating the grip to accommodate any limitations in hand movement.

Second, the *hand interaction* layer serves as the core of the system, responsible for modeling and detecting the various types of interactions that the patient can perform with the virtual environment. This layer also provides audiovisual feedback in response to these interactions, enhancing the immersive sensations for the patient. As the central component of the system, the hand interaction layer plays a key role in enabling the patient to interact with the virtual world in a meaningful and engaging way.

Finally, the *persistence* layer stores important information about the kinematics of the hand, arm, and head. This layer also maintains a history of executed applications and achievements, which can be used in conjunction with the kinematic data to track the patient's progress and analyze their evolution.

The following sections describes in greater detail each of these layers that are part of RI.

2.1. Configuration and calibration layer

This layer stores information on the user's preferences in a configuration file. This information represents the setting of various elements within the virtual rehabilitation application. Depending on the VR rehabilitation application, it is possible to configure different elements, such as:

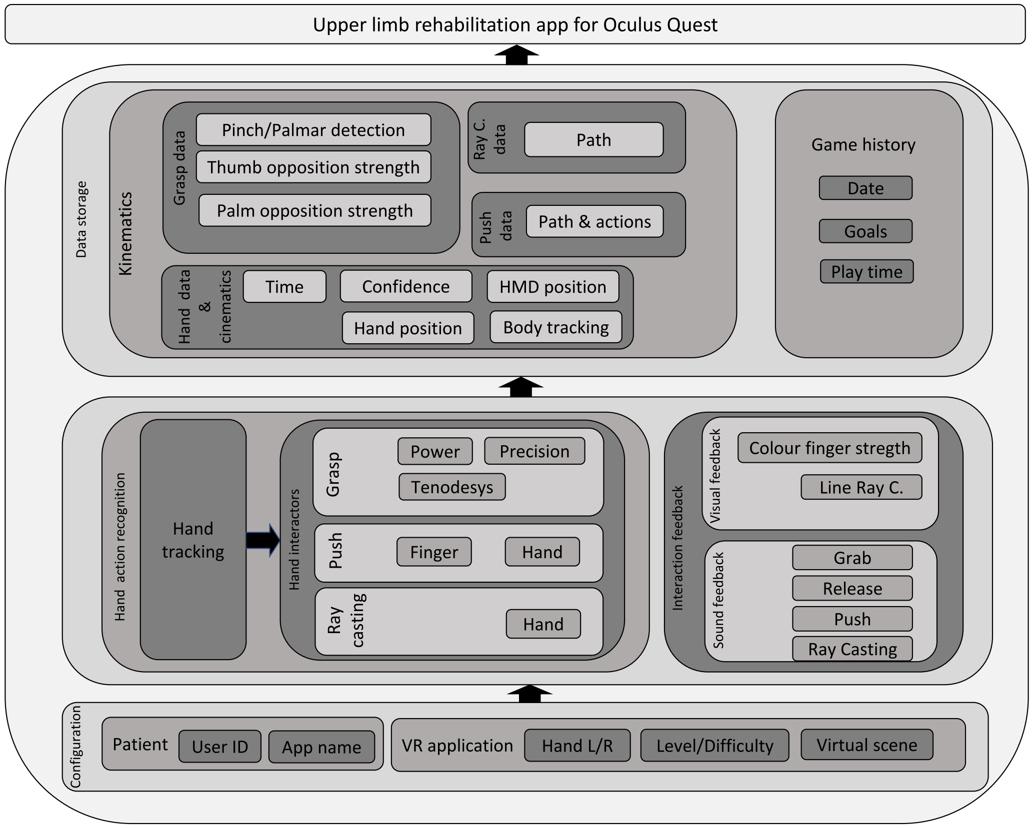

Fig. 1. Multi-layer architecture that supports RI for the development of virtual upper-limb rehabilitation applications.

- The hand which receives the UL treatment in function of the dominance (right-or left-handed).
- The location of objects with which the user can interact in the virtual space.
- The level of difficulty of the exercise.
- Grip calibration. Additionally, if the virtual rehabilitation application involves grip-based interactions, it may be necessary to conduct calibration to ensure the program is able to accurately detect various grips and pinches. If this is not possible, the exercise can be completed in "autogrip" mode, whereby objects are automatically grasped and released when they reach their designated target position.

2.2. Hand interaction layer

The middle layer of the system comprises three interconnected modules: (a) hand tracking, (b) hand interaction control, and (c) audiovisual feedback to enhance immersion.

The hand tracking feature is provided by Meta Quest Oculus software development kit (SDK). RI supported by this SDK offers three types of hand interaction: grasp, push, and ray casting. Grasp allows the user to pick up, hold, and release objects within the virtual environment. Push enables the user to press or activate certain elements in the virtual space, while ray casting allows the user to trace a virtual ray from the center of the hand to a specific object in the scene, that is intended to be interacted with. The system is capable of detecting a wide range of functional grasps, including both power and precision grasps (see Fig. 2). In addition to these commonly used grips, the system also supports the so-called tenodesis grasp, which is utilized by patients with spinal cord injuries (SCIs) who have limited finger function [32]. One notable feature of these grasping and pinching capabilities is that they have been modified to account for the volume of virtual objects. The degree of grasping or pinching is adjusted to mimic the natural grip on the virtual object, so it is not necessary to physically touch the elements of the hand (e.g. fingers and palm) but rather the volume of the object is taken into consideration.

In addition to grasp and pinch interactions, RI also supports a *Push* interaction that can be used in settings menus to allow users to access options by pushing a button when their hand passes over the surface (see Fig. 3). This simple interaction allows patients to interact with and operate VR applications independently, regardless of the severity of their hand impairments.

The final interaction mode supported by RI is *ray casting* (see Fig. 3), which can be used to track the movement of the hand in the virtual space, allowing the user to interact with virtual objects or perform certain tasks. This interaction is often used in rehabilitation exercises that focus on the wrist, arm, and/or forearm. In virtual interactions within a 3D environment, it is important for the patient to receive feedback on their actions. In VR environments, it is common to use haptic controllers as a feedback mechanism. However, RI does not utilize these controllers due to the physical characteristics of the targeted patients. Among the main reasons, it is worth mentioning the extra weight they would add and the requirement for external assistance in positioning these components. Additionally, many of these patients not only have limited finger movement but also experience a lack or decrease in tactile sensitivity. Instead, the current system has used audiovisual elements to support user interaction with virtual objects and actions. However, feedback from the virtual environment is crucial for the natural processing of actions. Therefore, this paper proposes to explore as future work the mixed reality as an alternative feedback and interaction method for virtual environments. As previously mentioned, the

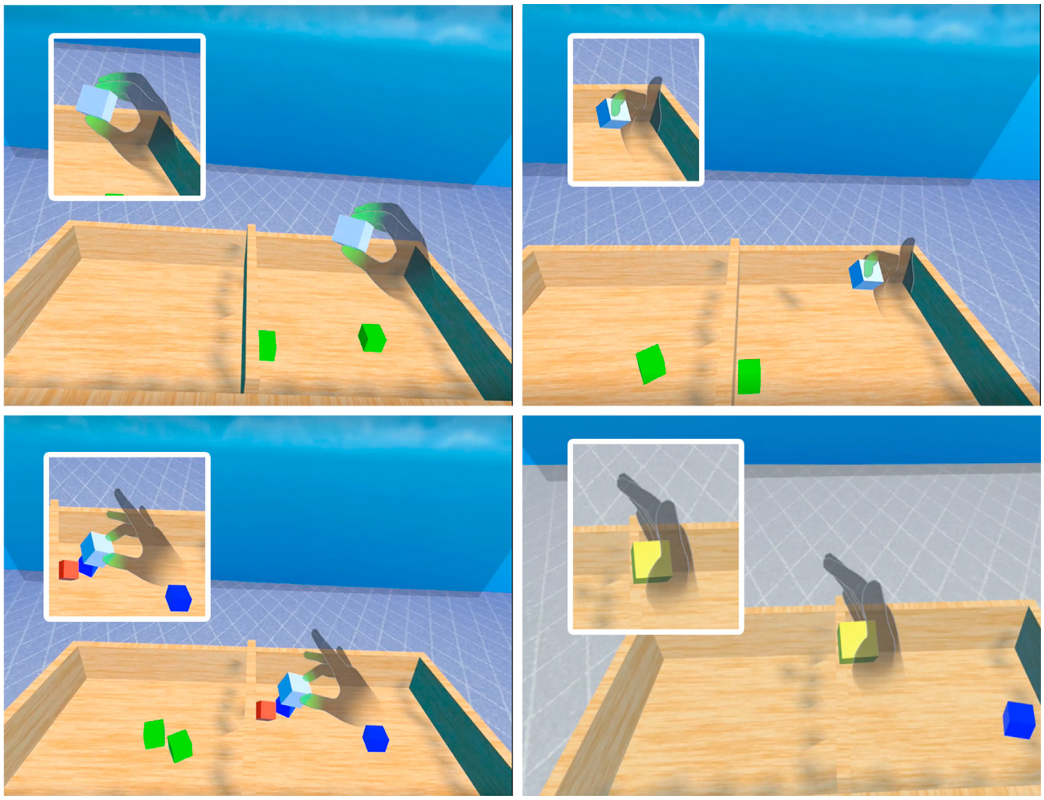

Fig. 2. Multiple types of grasps supported by the system. Top-Left: multi-finger pinch. Top-Right: palmar grasp. Bottom-Left: single pinch. Bottom-Right: autogrip.

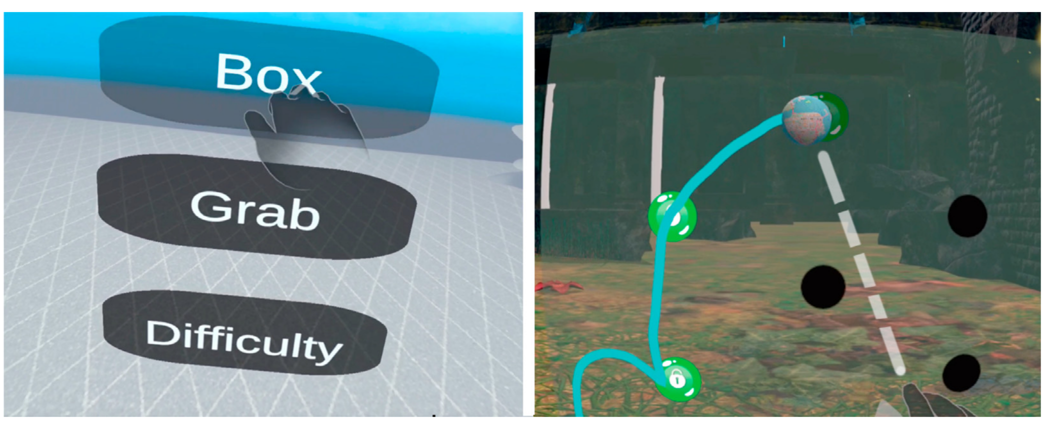

Fig. 3. Left: push interaction; Right: Ray Casting interaction. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

system provides visual and auditory support to provide feedback on patient actions and interactions in the virtual world. This feedback serves to inform the patient of the current state of the interaction and whether the exercise is being performed correctly. The feedback is associated with three elements: the hand or hands being used for interaction, the interactable elements within the virtual environment, and the success or failure of an exercise. Depending on the type of interaction, the feedback may vary for the first two elements:

- Grasp: When the fingertips approach an element that can be interacted with, they turn purple. When the object is grabbed, a sound is emitted, and while it is being held, the fingertips turn green and the object becomes gray.
- Push: When an element is pressed, a sound is emitted.
- Ray cast: A line is drawn from the center of the hand to visualize the emitted ray. If the ray passes through the objects in a correct path, the objects will change color.

2.3. Persistence layer

The *persistence* layer is essential for the analysis of exercise performance. By storing kinematic data and other relevant information, it enables posterior analysis to determine whether exercises were performed correctly. The stored data includes the variables shown in Table 1.

Together with these variables, grasp strength is an important factor in many tasks and activities. It is influenced by various factors such as muscle strength, dexterity, and cognitive function. With RI, we recorded the thumb's effort relative to the rest of the fingers (pinch) and the effort of each individual finger relative to

Table 1
Variables stored by the persistence layer.

Variable	Data type	Range of values	Description
Frame number	Integer	0 to *n*	The frame number from the start of the exercise
Time	Float	0 to *n* seconds	The time measured in seconds
Head position	Vector	*x*, *y*, *z* coordinates	Position of HMD in 3D Space
Hand detection	Boolean	True or false	Detection of hand (detected or undetected)
3D position of hand	Vector	*x*, *y*, *z* coordinates	3D position of the hand in space
High confidende	Boolean	True or false	Confidence hand tracking, if true then the confidence level is high
Hand position	Vector	*x*, *y*, *z* coordinates	Position of hand in 3D Space
Hand velocity	Vector	*x*, *y*, *z* coordinates	Hand velocity value in every directions
Pinch detection	Boolean	True or false	Detection of a pinch (true or false)
Palmar grasp detection	Boolean	True or false	Detection of a palmar grasp (true or false)
Autogrip	Boolean	True or false	Autogrip mode
WristTwist force	Float	0 to 360	Degree of hand rotation relative to the wrist

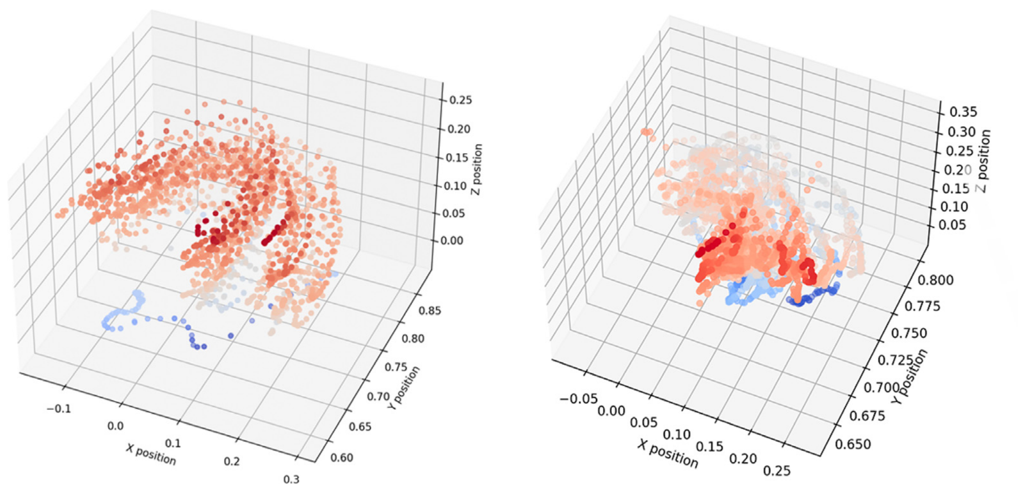

Fig. 4. 3D Heat Map depicting BBT performance by a healthy person (left side) and by a patient with cervical injury (right side). Upon visual inspection, it is evident that the pattern executed by the patient on the right side is more fragmented and lacks the rhythmic or cyclic quality observed in the healthy person on the left side. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the palm (palmar grip). Confidence degree data is used for the rejection of false negatives, providing information on the accuracy of hand tracking. Other data, such as the position of the head is used to detect compensatory movements that may hinder the rehabilitation process.

3. Illustrative example

To facilitate the reader's visualization of what RI offers, we have created a complementary video (https://youtu.be/FhzBlR0wGIY)that shows, from the perspective of the patient, the virtual world in which they would be immersed during upper limb rehabilitation. This video showcases the different types of pinchs and grips that RI supports.

Specifically, a VR Box and Block Test (VR-BBT) is presented. This test is widely used in rehabilitation and occupational therapy because it allows for the measurement of unilateral manual dexterity [33]. It is a simple test used in spinal cord injuries, fibromyalgia, geriatrics, and multiple sclerosis, among others.

To perform the BBT, a wooden box measuring 53.7 cm $\times$ 25.4 cm $\times$ 8.5 cm, divided into two equal compartments, is required. Initially, 150 blocks of wood, in the colors blue, yellow, or red, with dimensions of 2.5 cm, are placed in one of the compartments. The initial configuration depends on the hand being evaluated. The patient sits in front of the box and must move as many blocks as possible from one compartment to the other within 60 s [34] Figs. 2, 3 and the referenced video show images of a virtual implementation of the BBT developed on RI. On the other hand, Fig. 4 shows an example of a possible visual analysis from the kinematics recorded by the system.

4. Impact

This work was completed by a multidisciplinary team of researchers with backgrounds in computer engineering and biomechanics, in collaboration with clinical staff at the Hospital Nacional de Parapléjicos in Toledo, Spain. Fig. 5 shows a patient in such a hospital, during a rehabilitation session, using the proposed system. This collaboration allowed for the development of a user-centered methodology based on a co-creative approach involving researchers, clinicians, and patients. We believe that this approach has enhanced the quality of the proposed software architecture and increased patient commitment and motivation. The active participation of patients and clinicians was sought not only during the initial design phase, but also during concept testing and subsequent refinement. After each test, valuable feedback was collected on various aspects, including ease of use, depth perception, aesthetic elements and similarity of interactions to real-life scenarios.

This allows researchers who use the proposed system to align their own interests with the practical nature of the proposal. From a clinical perspective, researchers have a tool to complement and measure the effects of immersive VR-based rehabilitation therapy. From a technological development perspective, as previously mentioned, researchers and developers can also enhance the functional capabilities of the system and integrate additional exercises and grip modes.

The system is currently undergoing evaluation at the aforementioned hospital with patients suffering from spinal cord injuries who require upper-limb physical rehabilitation. This phase represents the step prior to a clinical trial with a representative

Fig. 5. Patient using the system in the Hospital Nacional de Parapléjicos in Toledo, Spain. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

sample of patients to validate aspects of functionality, usability, and clinical application on a larger scale.

This methodology will be tested during the next experimental phase that will be carried out on a sample of healthy individuals and a larger number of SCI patients. This experimental phase will last 2 months for each participant, with 3 weekly sessions of approximately 30 min each using the immersive VR applications developed.

5. Clinical study

RI was initially tested on healthy individuals. Therefore, ten healthy participants, aged between 15 and 39, were included in the study. The participants who took part in the BBT task were all right-handed and completed it under two distinct experimental conditions: the real environment and an immersive virtual environment facilitated by the Oculus Quest 2.

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

A preliminary trial was performed to familiarize participants with virtual environment. No familiarization was considered necessary for the real BBT, except for the 15 s allowed by the real test.

The performance in the real BBT was significantly higher than in the VR modality 83±17 blocks in the real test vs. 69±21 blocks in the immersive VR version ($p \prec 0.05$) (see Fig. 6). 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.

6. Conclusions

In this article, we have presented RI that aims to support the development of virtual reality (VR) applications for upper limb rehabilitation in a clinical setting. The creation of new VR-based technological solutions for upper limb rehabilitation can serve as a supplement to more traditional therapies. In this context, RI aids in the search for indicators related to the effectiveness of VR-based therapies, which are currently limited, as well as the analysis of the kinematic characteristics of rehabilitation movements performed by patients. RI has several benefits for different stakeholders.

For software developers, RI addresses fundamental issues such as hand tracking and interaction with virtual objects, taking into account the motor limitations of patients. This allows developers to focus on creating higher-level rehabilitation apps, knowing that the basic foundations are already in place. In other words, it is possible to utilize the natural interaction mechanisms and the various types of grips supported by the system to create applications with a broader scope in terms of physical rehabilitation.

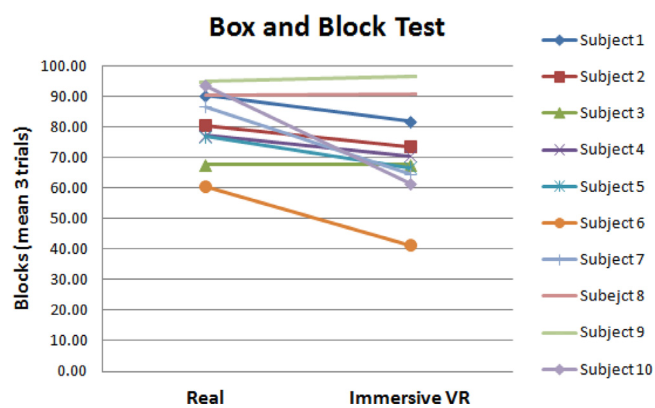

Fig. 6. Performance of each participant within each experimental condition. All the participants maintain the same trend. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

For therapists and patients, RI offers a range of benefits as well. Therapists can use the recorded and stored kinematic data to objectively evaluate the progress of their patients and make informed decisions about their treatment plan. They can also analyze the data over time to track the patient's evolution and identify areas of improvement. Meanwhile, patients can benefit from more precise and motivating rehabilitation tools, supported by RI. Overall, RI has the potential to enhance the rehabilitation experience for both therapists and patients.

Several improvements to the system are proposed for future work. Firstly, the use of mixed reality technology to allow patients to interact with real objects within a virtual environment, allowing them to manipulate and grasp tangible objects while enjoying the benefits of gamification and kinematic data storage. Secondly, attention will be paid to the automatic personalization of the virtual environment. Although user preferences are currently stored, prior calibration and subsequent manual adjustments are required to ensure an optimal user experience. To address this issue, an automatic adjustment of the level of interaction and virtual environment elements can be established based on the analysis of specific data such as trunk movement, arm supination or grasp strength. Finally, for future developments, voice commands will be used to perform certain actions, such as selecting options in the initial menu.

CRediT authorship contribution statement

Vanesa Herrera: Conceptualization, Methodology, Software, Validation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **David Vallejo:** Methodology, Validation, Investigation, Writing – original draft, Writing – review & editing, Funding acquisition. **José J. Castro-Schez:** Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Funding acquisition. **Dorothy N. Monekosso:** Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Ana de los Reyes:** Conceptualization, Software, Validation, Formal analysis, Investigation, Resources, Writing – review & editing. **Carlos Glez-Morcillo:** Conceptualization, Validation, Investigation, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Javier Albusac:** Conceptualization, Methodology, Validation, Investigation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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