VR-ADAPT: An Immersive Learning and Training Environment for Wheelchair Users with Recent Spinal Cord Injuries

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Abstract: Each year, thousands of people worldwide suffer injuries that limit their mobility, affecting not only their ability to walk but also, in many cases, the functionality of their upper limbs. These conditions represent a drastic life change for patients, who must undergo an initial process of learning and adaptation to their new circumstances. To address this challenge, we present VR-ADAPT, an innovative virtual reality-based platform designed to facilitate the transition to a more autonomous life. VR-ADAPT integrates an advanced simulator for learning to operate electric wheelchairs and digitized environments based on domestic and workplace settings. These environments are gamified through serious games, allowing users to practice and develop essential skills for confidently navigating their daily lives. Additionally, the platform includes a kinematic recording and analysis module that collects detailed data during exercises. This functionality provides clinical teams with a valuable tool for objectively evaluating patients' progress, enhancing the personalization and effectiveness of therapies.

1 INTRODUCTION

Each year, between 250,000 and 500,000 new spinal cord injuries occur worldwide, significantly impairing mobility, affecting not only the ability to walk but also, in many cases, the functionality of the upper limbs. This impact radically transforms the lives of those affected, particularly in the early stages following the injury, when they face the challenge of adapting to new circumstances. This period is critical, as it involves not only accepting physical limitations but also learning skills that enable them to regain a degree of autonomy and improve their quality of life.

For instance, operating an electric wheelchair can become a complex and daunting task for someone who has never used such devices before. Controlling speed, making precise turns in confined spaces, or tackling everyday obstacles like ramps and curbs requires a learning curve that can be frustrating without proper guidance and practice. Similarly, daily tasks such as reaching for and handling objects in a home environment—like picking up a glass from a high shelf or opening a jar of food—can pose significant challenges. These difficulties not only test the patient's physical abilities but also their psychological and emotional resilience as they adapt to a new way of life.

The process of adapting to these new circumstances is fraught with challenges that extend beyond physical limitations (Herrera et al., 2025). The magnitude of change in patients' daily lives can lead to feelings of uncertainty and frustration, particularly when faced with tasks such as learning to operate an electric wheelchair or performing basic activities in the home and workplace environments. The lack of safe and controlled spaces where they can practice these skills exacerbates the situation, as mistakes during this learning period can result in accidents or reinforce insecurities, further hindering their progress toward autonomy (Arlati et al., 2019).

In this context, new technologies have proven to be effective tools for facilitating the adaptation process (Hoter and Nagar, 2023). Digital platforms, simulators, and interactive tools provide patients with safe and controlled environments that replicate real-world challenges. These solutions not only allow users to practice and refine specific skills without risk but also optimize learning by offering scenarios that can be tailored to their individual needs, promoting gradual and structured progress.

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Particularly, Virtual Reality (VR) stands out as a promising technology in this field. Its ability to create immersive and interactive environments enables patients to engage in simulations that replicate real-world scenarios (Genova et al., 2022), such as maneuvering in confined spaces, overcoming urban obstacles, or navigating a simulated kitchen or office. This provides them with a unique opportunity to develop essential skills in a gamified environment that transforms learning into a motivating experience.

Both the challenges and motivation described form the basis of our proposal: VR-ADAPT, a VR-based platform for learning and training aimed at individuals with recent mobility-limiting injuries, designed to support and complement their initial adaptation process. This project is a collaboration with the Hospital Nacional de Parapléjicos de Toledo (HNPT) and is funded by Indra and the Fundación Universia (supported by Banco Santander) through the 8th Call for Research Grants in Accessible Technologies. The platform includes an immersive simulator for operating electric wheelchairs, virtualization of supervised domestic and workplace environments, the integration of serious games within these spaces to perform daily tasks while simultaneously undergoing rehabilitative therapy to recover mobility, and, finally, the recording of kinematic data from sessions to enable therapists to objectively assess each patient's progress.

The implementation of VR-ADAPT is expected to yield multiple benefits for both patients and the clinical teams responsible for their rehabilitation. For patients, the platform offers a safe and controlled environment where they can progressively acquire essential skills without the risks associated with practicing in real-world settings. This not only facilitates the learning of practical abilities, such as operating electric wheelchairs and performing domestic and workplace tasks, but also boosts their confidence to face real-life situations, promoting greater independence in their daily lives. For clinical professionals, the platform provides an advanced tool for evaluating and personalizing therapies through the recording and analysis of kinematic data from each session. This approach enables objective monitoring of patient progress and allows therapeutic interventions to be tailored to individual needs, thereby optimizing treatment effectiveness and improving overall rehabilitation outcomes. Ultimately, VR-ADAPT has the potential to significantly enhance patients' quality of life by accelerating their adaptation to a new environment and reducing the barriers they face in their daily activities.

2 RELATED WORK

Wheelchair simulators have been established as effective and safe tools for training and assessment, offering controlled environments where users can develop essential navigation skills and perform complex tasks. Additionally, they are valuable for analyzing progress in physical and cognitive rehabilitation. Recent evidence highlights that these platforms not only enable the transfer of skills to real-world scenarios but also improve users' confidence and quality of life (Alapakkam Govindarajan et al., 2022), (Ortiz et al., 2021).

The sense of presence (SoP), defined as the subjective perception of "being there," is identified as a crucial factor for the effectiveness of simulators. Various studies have shown that the use of virtual reality (VR) technologies, such as head-mounted displays (HMDs), enhances immersion, although they can induce cybersickness symptoms, particularly in users with limited mobility (Vailland et al., 2020), (Arlati et al., 2019). The integration of multisensory feedback, including vestibular and haptic stimuli, improves both the user experience and SoP while minimizing adverse effects (Vailland et al., 2021).

These platforms have evolved to include digitized domestic and workplace environments, broadening their applications. For instance, the use of personalized environments enables patients with recent spinal cord injuries to learn specific functional skills and adapt to their new reality. Additionally, gamification and serious games have been employed to maintain motivation and promote physical recovery (Hoter and Nagar, 2023).

Kinematic recording stands out as a key component, providing objective metrics for evaluating and adjusting rehabilitation programs. Tools such as ViEW allow for the analysis of user performance in both simulated and real conditions, showing a positive correlation between acquired skills and their transfer to real-world contexts (Morère et al., 2018).

3 VR-ADAPT PLATFORM

Figure 1 provides an overview of the architecture of the proposed platform. From bottom to top, the VR headset allows the user to immerse themselves and interact with the virtual world. Within the virtual environment, users can navigate in a wheelchair using joystick controls or interact with virtual elements using their hands, free of any controllers. This latter functionality is utilized in the serious games integrated into the learning platform.

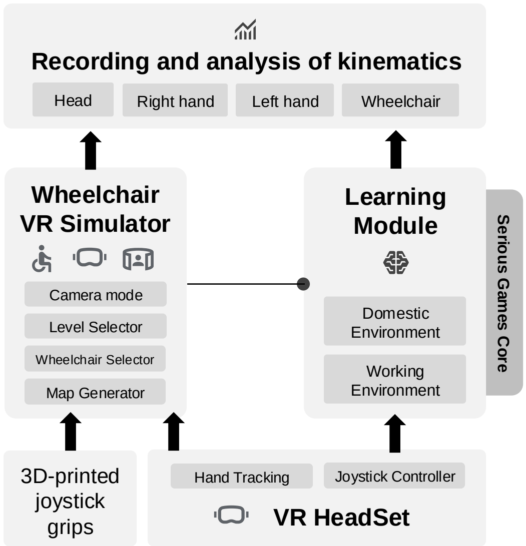

Figure 1: General architecture of the proposed platform.

To enable this, the headset itself includes a module that tracks the user's hands and head, as well as a joystick controller. For patients with spinal cord injuries affecting the upper limbs—particularly those who do not have mobility in the hands or fingers—the standard joystick associated with the VR headset lacks the necessary accessibility features, especially due to its small size. This creates the need to fabricate larger and diverse grips using 3D printing, which can be attached to the mini-joystick controller and simulate the grips typically found on electric wheelchairs. Further details on this topic will be provided in the next section.

On the other hand, the intermediate level consists of the wheelchair simulator. This simulator includes options for selecting the camera mode, choosing maps based on their level of complexity, selecting the type of wheelchair to emulate, and generating maps according to a set of predefined rules. The camera mode selector allows users to switch between different perspectives depending on their tolerance to movement in immersive environments. A higher tolerance enables a first-person view mode, while for users experiencing discomfort or motion sickness, a third-person mode with minimal camera movement may be more suitable. Regarding wheelchair selection, the main difference lies in the type of traction—front, central, or rear—which influences how the wheelchair turns. Additionally, users can train in predefined spaces approved by therapists or create new maps to practice in. There is a connection with the lower level, as the VR wheelchair simulator utilizes the VR headset, the controller, and the custom 3D-printed grip that has been attached.

At the intermediate level, there is also a learning module featuring the virtualization of domestic and workplace environments, allowing users to develop skills for navigating these everyday settings. The primary goal is to provide users with guided support to understand potential challenges they might encounter and how to address them, while simultaneously enabling hands-on practice. This module is connected to a core system that hosts various serious games designed to simulate daily tasks while also targeting hand and arm exercises, thus contributing to the patient's rehabilitation and improved mobility. Within the immersive space, different games are associated with specific zones, with each game's theme aligning with the characteristics of the corresponding area.

The wheelchair simulator is connected to the learning module, allowing the user to navigate through the virtualized environments using the wheelchair. It should be noted that the wheelchair simulator can also be used in open maps without being associated with domestic or workplace environments.

Finally, the upper layer focuses on kinematic recording. During user activity, whether in the wheelchair simulator or within the virtual environments of the learning module, the system records all spatiotemporal data related to wheelchair movement as well as hand and head tracking. These data, which can be represented in various formats, provide the clinical team with an objective means to assess the patient's progress.

3.1 3D-Printed Joystick Grips

In this project, we will use the Oculus Meta Quest 2 and 3 models for immersion in virtual spaces. The choice of these devices is based on a favorable balance between cost and quality, high versatility, a large user community, the availability of several units within the research group as laboratory equipment, and the team's experience with the Meta XR Platform SDK[1].

Both hardware and software resources support user interaction through external controllers (see Figure 2) as well as hand tracking for controller-free use. In both cases, the system provides high precision, with the latter offering a virtual representation of the hands and reliable tracking.

Real electric wheelchairs are operated using a joystick located on either the right or left armrest, depending on the user's most skillful hand. The interaction mode intended for implementation in the virtual

[1] https://developers.meta.com/horizon/downloads/package/meta-xr-platform-sdk/

Figure 2: On the left, the controller model used for the Oculus Meta Quest 2. On the right, the controller model for the Oculus Meta Quest 3.

Figure 3: Adapter designed for attachment to joysticks of Oculus Meta Quest 2 and 3. At the bottom, 3D-printable joystick handle models for mounting onto the adapter.

wheelchair simulator closely mimics this setup. However, as shown in Figure 2, the size of the joysticks is too small. This issue is particularly critical for patients with spinal cord injuries, whose upper limbs are affected and who face difficulties with gripping.

To address this problem, the project has set as one of its objectives the fabrication of larger, differently shaped grips using 3D printing, designed to be mounted onto the original controller. Since the original joystick can be removed (see Figure 3), the HNPT department responsible for designing and manufacturing adapters has developed a piece that attaches to the movable shaft of the original controller. Once the adapter is constructed, additional grip models in various shapes (see the bottom of Figure 3) are fabricated and mounted onto the intermediate piece, facilitating their attachment.

3.2 Wheelchair VR Simulator

The VR simulator for wheelchair operation is set in a sports hall with a spacious court measuring 45x25 meters (see Figure 4). Within this space, various elements are placed to represent the milestones the learner must reach, such as target points, zones to cross, or turning maneuvers around specific markers.

The simulator includes a variety of maps, designed in collaboration with the HNPT team, arranged by levels of difficulty to facilitate gradual and controlled learning. Additionally, the simulator implements three viewing modes:

- **First-Person View.** The VR camera is positioned directly at the patient's eye level, offering a fully immersive experience. The primary drawback of this mode is the potential for motion sickness caused by the sensation of movement while the body remains stationary. The simulator allows the wheelchair's movement speed to be adjusted according to the user's tolerance level.
- **Third-Person View.** The user sees the wheelchair from an external perspective. Camera movement is minimal and only adjusts when the wheelchair moves sufficiently far from the current view. While this mode is less realistic, it is designed for users who experience severe motion sickness in the first mode.
- **First-Person View Without VR Headset.** In this mode, similar to the first, the VR camera is positioned at the patient's eye level. However, the scene is projected onto an external monitor, and the patient does not wear a VR headset. This semi-immersive mode is specifically intended for users who cannot tolerate the other two modes.

Additionally, the simulator allows users to select and train with electric wheelchairs featuring different traction types: front-wheel, mid-wheel, and rear-wheel. The physics simulator included in Unity, utilized in this project, accurately replicates these behaviors. Traction primarily influences power delivery but, more importantly, affects the wheelchair's turning mechanism. Through this simulation, both the patient and the hospital's professional team can determine the type of wheelchair best suited to the patient's abilities.

Finally, two key components of the simulator deserve special mention: gamification and movement tracking. On the one hand, the simulator employs gamification techniques to enhance the patient's motivation. These include scoring systems, milestone completion tracking based on time, and visual and auditory feedback associated with specific events. On

Figure 4: Third-person view of the wheelchair simulator prototype developed to date.

the other hand, the simulator records spatiotemporal data of the wheelchair during activity sessions, enabling the evaluation of the patient's progress. This functionality will be discussed in greater detail later.

As we will see in the following section, patients also have the opportunity to practice their wheelchair skills in virtualized domestic or workplace environments, which more closely resemble the settings they encounter in their daily lives. These are typically smaller spaces, requiring a higher level of control over the wheelchair from the user.

3.3 Learning Module: Virtual Domestic and Working Environments

In addition to the wheelchair simulator, the platform aims to incorporate virtualized environments for learning and training. These primarily include domestic settings, such as the home, where patients spend a significant amount of time, and workplace environments where they might engage in professional activities. These spaces not only require wheelchair navigation but also encourage users to perform tasks that involve hand use. Basic functionalities are modeled in these environments, such as turning lights on and off, opening doors, or adjusting furniture height, among others. Additionally, various serious games are integrated into specific areas within these spaces. The gameplay mechanics themselves require users to achieve milestones, which, through gamification, enhance patient motivation and engagement.

One of the domestic environments already virtualized is the adapted apartment at HNPT. This physical space allows patients to practice and experience sensations very similar to those they might encounter at home. It includes a kitchen, a living room, a bedroom, and a bathroom. Figure 5 shows a digital version of the adapted apartment on the left and real photos of some areas on the right. The digitalization process was carried out using Polycam[2] software and LiDAR sensors from an iPhone 15 PRO. The model was refined in Blender[3] and subsequently integrated into a Unity 3D[4] project for visualization with Oculus Meta Quest 2 and 3 devices.

Throughout the virtual apartment, floating help buttons are distributed across different areas. At any time, the user can interact with them. When activated, a virtual monitor appears near the user (see Figure 6), playing a real video featuring a therapist or an experienced patient. In each video, the speaker provides the user with relevant information about the associated area and offers recommendations to overcome potential challenges.

On the other hand, as mentioned earlier, the virtualized spaces incorporate several serious games across the different rooms. All these games feature a scoring system, time tracking, and visual and auditory feedback to notify the user of each occurring event. In the specific case of the virtualized adapted apartment at HNPT, the following serious games are intended to be integrated:

- **Kitchen Cleaning.** The objective of this game is to collect plates and utensils from the countertop and load them into the dishwasher. This game involves arm and hand movements, as well as wheelchair navigation.
- **Recipe Preparation.** The game displays various ingredients on the kitchen countertop. The user must follow a specific sequence to prepare the meal. It requires arm and hand movements and wheelchair navigation, as some ingredients need to be retrieved from the refrigerator.
- **Box and Block on the Living Room Table.** Box and Block is a standard test used in upper limb rehabilitation. It consists of a wooden box divided into two sections. One section contains wooden blocks, and the patient must grasp and move them to the other side of the box. This serious game has already been developed and integrated (see Figure 7). It involves arm and hand movements without requiring wheelchair navigation.
- **Packing a Travel Suitcase.** This serious game is associated with the bedroom. The user must take clothes from the wardrobe in the bedroom and pack them into a suitcase on a table (see Figure 8). The game involves arm and hand movements and slight wheelchair navigation.
- **Tooth Brushing in the Bathroom.** The serious game simulates brushing teeth, requiring circular arm movements without the need for electric wheelchair navigation.

[2] https://poly.cam/

[3] https://www.blender.org/

[4] https://unity.com/

Figure 5: On the left side of the image, a digital version of the adapted apartment at HNPT is shown. On the right side, real photographs of the bathroom and kitchen are displayed.

Figure 6: Playback of real video on virtual screens, providing guidance and recommendations from therapists and experienced patients.

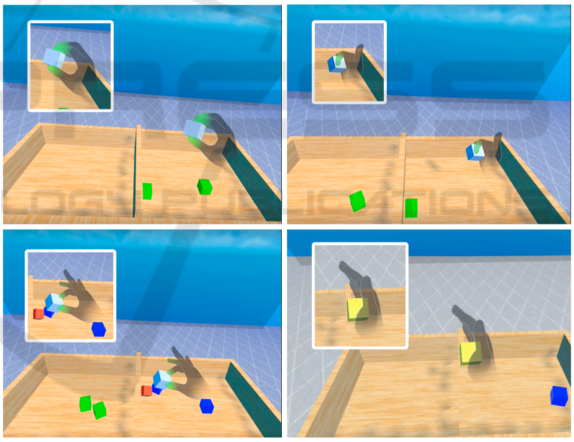

Figure 7: Virtualization of the standard Box & Block test for inclusion on the living room table. The graphical scheme also illustrates different types of grips for virtual objects, considering hands with motor limitations.

3.4 Recording and Analysis of Kinematics

A key feature of the proposed platform is the monitoring and recording of user activity, both during VR wheelchair simulator sessions and while engaging with the serious games integrated into the virtualized environments. Recording spatiotemporal data for the virtual wheelchair is relatively straightforward. Since the wheelchair exists entirely as a virtual entity (represented as a `GameObject`) within a three-dimensional virtual environment, it is possible to continuously track and record its position along the x, y, and z axes. The lower section of Figure 9 provides an example of a graphical representation of the movement of a virtual wheelchair in an open space.

In contrast, recording hand movements involves greater complexity. Oculus Meta Quest VR headsets are equipped with four external cameras featuring a 100-degree field of view. These headsets include a reliable tracking system capable of creating a virtual representation of the hands that accurately aligns with the position and orientation of the real hands. Once the hands are virtually represented, interaction with virtual elements becomes direct. It is possible to track the position and orientation of the hands, as well as detect any intersections with other objects. Ta-

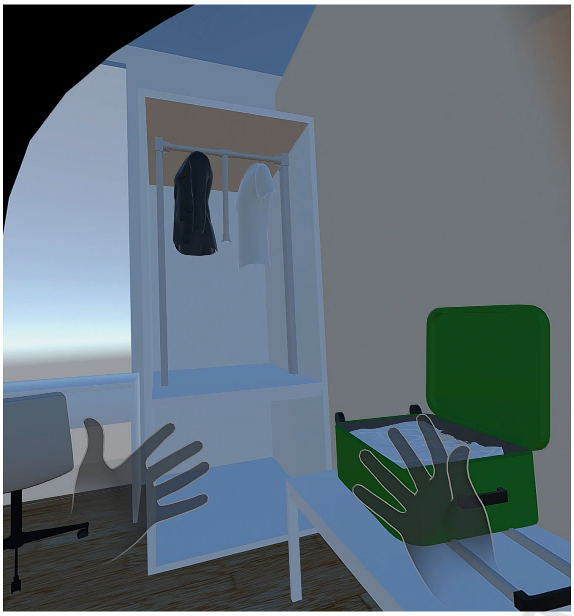

Figure 8: Serious game where the user must move clothes stored in the wardrobe and place them in a suitcase located on a table.

ble 1 lists the variables the system is currently able to record. The upper section of Figure 9 provides an example of graphical data representation for head movement and left and right hand movements.

From the collected data, metrics are defined to measure hand velocity, the concentration or density of recorded points (movement capacity), movement irregularity, maximum reach ranges, and response capacity, among others. Comparing these measurements across sessions over time provides therapists with objective tools for analyzing real progress.

4 DISCUSSION AND CHALLENGES

The VR-ADAPT platform represents a significant advancement at the intersection of clinical rehabilitation and immersive technology, offering a safe, flexible, and gamified environment to enhance the autonomy and quality of life of individuals with recent spinal cord injuries. However, the development and implementation of this solution present several key challenges that warrant discussion.

One major challenge is the acceptance of the system by both patients and clinical professionals. While gamification techniques and virtual immersion show promise for enhancing motivation, there is a risk that some users may perceive these technologies as complex or impractical compared to traditional rehabilitation methods. This underscores the importance of conducting additional studies focused on user experience and usability.

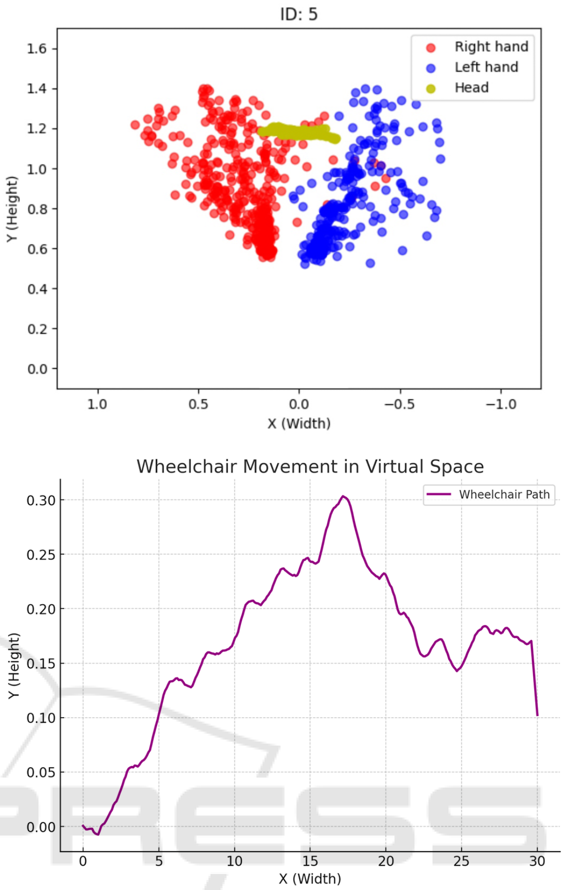

Figure 9: Movement tracking of the right hand (red), left hand (blue), and head (yellow). At the bottom, tracking of movements performed with a virtual wheelchair in an immersive space.

Another critical issue relates to patients' tolerance for simulated movement during virtual wheelchair navigation. Motion sickness in immersive environments can limit the effectiveness of learning and rehabilitation, particularly for more sensitive patients. Although different viewing modes are proposed, including first-person mode without VR headsets, careful design of simulation dynamics is required to minimize these adverse effects without compromising the immersive experience.

Finally, while the platform offers an innovative solution, its integration into clinical processes and validation in real-world settings pose operational challenges. It is essential to establish protocols that ensure the therapeutic effectiveness of exercises within a virtual environment and their positive impact on the transfer of skills to the physical world.

Table 1: Variables and spatio-temporal information related to kinematics.

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 the hand (detected or undetected)
3D position of hand	Vector	x, y, z coordinates	3D position of the hand in space
High confidence	Boolean	True or false	Confidence in hand tracking; if true, the confidence level is high
Hand velocity	Vector	x, y, z coordinates	Velocity of the hand in all 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)
Auto-grip	Boolean	True or false	Auto-grip mode status
Wrist twist force	Float	0 to 360	Degree of hand rotation relative to the wrist

5 CONCLUSIONS AND FUTURE WORK

This article presents VR-ADAPT, an innovative solution for the rehabilitation of individuals with recent spinal cord injuries, combining immersive environments, serious games, and kinematic tracking to support their transition to a more autonomous life. In the coming months, the development team will focus on completing the functionality of the wheelchair simulator, fully integrating the serious games into both domestic and workplace environments, and conducting studies with real patients at the Hospital Nacional de Parapléjicos de Toledo. These steps will enable the analysis of the platform's functionality and usability in a real-world setting, laying the groundwork for its clinical validation and future implementation.

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REFERENCES

Alapakkam Govindarajan, M. A., Archambault, P. S., and Laplante-El Haili, Y. (2022). Comparing the usability of a virtual reality manual wheelchair simulator in two display conditions. *Journal of Rehabilitation and Assistive Technology Engineering*, 9:20556683211067174.

Arlati, S., Colombo, V., Ferrigno, G., Sacchetti, R., and Sacco, M. (2019). Virtual reality-based wheelchair simulators: A scoping review. *Assistive Technology*, 32(6):294–305.

Genova, C., Biffi, E., Arlati, S., Redaelli, D. F., Prini, A., Malosio, M., Corbetta, C., Davalli, A., Sacco, M., and Reni, G. (2022). A simulator for both manual and powered wheelchairs in immersive virtual reality cave. *Virtual Reality*, 26:187–203.

Herrera, V., Albusac, J., Castro-Schez, J., et al. (2025). Creating adapted environments: enhancing accessibility in virtual reality for upper limb rehabilitation through automated element adjustment. *Virtual Reality*, 29(28).

Hoter, E. and Nagar, I. (2023). The effects of a wheelchair simulation in a virtual world. *Virtual Reality*, 27:407–419.

Morère, Y., Bourhis, G., Cosnuau, K., Guilmois, G., Rumilly, E., and Blangy, E. (2018). View: A wheelchair simulator for driving analysis. *Assistive Technology*, 32(3):125–135.

Ortiz, J. S., Palacios-Navarro, G., Andaluz, V. H., and Guevara, B. S. (2021). Virtual reality-based framework to simulate control algorithms for robotic assistance and rehabilitation tasks through a standing wheelchair. *Sensors*, 21(15).

Vailland, G., Devigne, L., Pasteau, F., Nouviale, F., Fraudet, B., Leblong, É., Babel, M., and Gouranton, V. (2021). Vr based power wheelchair simulator: Usability evaluation through a clinically validated task with regular users. In *2021 IEEE Virtual Reality and 3D User Interfaces (VR)*, pages 420–427.

Vailland, G., Gaffary, Y., Devigne, L., Gouranton, V., Arnaldi, B., and Babel, M. (2020). Power wheelchair virtual reality simulator with vestibular feedback. *Modelling, Measurement and Control C*, 81(1-4):35–42.