VR-ADAPT: A Virtual Reality Environment for Skill Development in New Wheelchair Users with Spinal Cord Injuries

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DOI: *https://doi.org/10.17979/spu.23.c47*

Abstract: Annually, hundreds of thousands of individuals worldwide experience mobility-limiting injuries that compromise not only their walking ability but frequently the functionality of their upper extremities as well. Such injuries constitute a profound life transformation, necessitating an intensive period of learning and adjustment to new physical realities. We introduce VR-ADAPT, a novel virtual reality platform conceived to support this critical transition toward greater independence. The system comprises three integrated components: an advanced electric wheelchair operation simulator, immersive digital recreations of home and professional environments, and a suite of therapeutic serious games embedded within these spaces. Through gamification strategies, users can safely acquire and refine the competencies needed to navigate their everyday environments with confidence. A comprehensive kinematic capture and analysis module continuously records detailed performance metrics throughout training sessions, furnishing rehabilitation professionals with objective, quantifiable data to track patient advancement. This evidence-based approach enables more precise therapy customization and improved clinical outcomes.

1 INTRODUCTION

Worldwide, an estimated 250,000 to 500,000 individuals sustain spinal cord injuries annually, resulting in substantial mobility impairments that frequently compromise both ambulatory function and upper extremity dexterity. Such injuries precipitate dramatic lifestyle changes, with the immediate post-injury phase proving especially challenging as patients confront the dual burden of accepting their altered physical capabilities while simultaneously acquiring new competencies essential for regaining functional independence and enhancing quality of life.

Consider the task of mastering electric wheelchair operation, a seemingly straightforward activity that becomes remarkably complex for the uninitiated. Modulating velocity, executing precise maneuvers within confined environments, and negotiating commonplace barriers such as curbs and inclines demands substantial practice that, absent appropriate instruction and safe training opportunities, can prove deeply frustrating. Likewise, routine domestic activities (retrieving items from elevated storage, manipulating food containers, or managing household fixtures) present formidable obstacles. These challenges engage not merely the patient's residual physical capacity but equally test their psychological fortitude and emotional adaptability throughout this profound life transition.

The adaptation trajectory encompasses obstacles extending well beyond mere physical constraints Herrera et al. (2025). The sweeping alterations to patients' established routines frequently generate considerable uncertainty and frustration, particularly when confronting fundamental tasks such as wheelchair control or executing basic home and occupational activities.

The paucity of risk-free, supervised training environments compounds these difficulties, as errors committed during skill acquisition may culminate in injury or amplify feelings of inadequacy, thereby impeding progress toward autonomous functioning Arlati et al. (2019).

Within this landscape, emerging technologies have demonstrated considerable efficacy in facilitating patient adaptation Hoter and Nagar (2023). Digital platforms, simulation environments, and interactive training systems furnish patients with secure, controlled settings that authentically reproduce real-world demands. Beyond enabling risk-free skill practice and refinement, these solutions optimize learning trajectories by delivering customizable scenarios responsive to individual patient requirements, thereby supporting methodical, incremental advancement.

Virtual Reality (VR) technology exhibits particular promise within this domain. Through its capacity to generate fully immersive, interactive environments, VR enables patients to engage with high-fidelity simulations replicating authentic scenarios Genova et al. (2022), such as navigating cramped quarters, surmounting urban architectural barriers, or maneuvering through virtual domestic or professional spaces. This approach affords users distinctive opportunities to cultivate crucial competencies within gamified frameworks that transform rehabilitation into an inherently motivating endeavor.

These identified challenges and technological opportunities constitute the foundation for VR-ADAPT: a comprehensive VR-based learning and training platform targeting individuals with recent mobility-limiting injuries, designed to augment and support their initial adaptation journey. Developed through collaboration with Hospital Nacional de Parapléjicos de Toledo (HNPT) and supported financially by Indra and Fundación Universia (via Banco Santander) through the 8th Call for Research Grants in Accessible Technologies, the platform integrates four principal components: an immersive electric wheelchair operation simulator, digitally reconstructed domestic and occupational environments, embedded serious games facilitating simultaneous task performance and therapeutic upper-limb mobilization, and comprehensive kinematic recording capabilities enabling objective clinical assessment of patient progression.

VR-ADAPT implementation promises substantial advantages for both patient and clinical stakeholder populations. Patients gain access to protected training environments permitting progressive skill acquisition without the hazards inherent to real-world practice. Beyond facilitating mastery of practical competencies (wheelchair operation, domestic task execution, workplace activity performance), the platform cultivates self-efficacy for confronting authentic situations, thereby promoting enhanced daily autonomy. For rehabilitation professionals, the system delivers sophisticated evaluation and treatment personalization tools through granular kinematic data capture and analysis from each training session. This methodology supports objective progress monitoring while enabling individualized therapeutic intervention calibration, optimizing treatment efficacy and overall rehabilitation outcomes. Ultimately, VR-ADAPT holds potential to meaningfully elevate patient quality of life by expediting environmental adaptation and diminishing obstacles encountered in routine activities.

2 RELATED WORK

Wheelchair simulators have emerged as validated instruments for both training delivery and performance assessment, providing controlled experimental settings wherein users acquire fundamental navigation competencies and execute multifaceted tasks. Beyond skill development, these systems serve as analytical tools for monitoring advancement in physical and cognitive rehabilitation domains. Contemporary research demonstrates that such platforms not only facilitate successful skill transfer to authentic environments but additionally enhance user confidence and overall quality of life Alapakkam Govindarajan et al. (2022), Ortiz et al. (2021).

The construct of sense of presence (SoP), operationally defined as the subjective experience of "being there" within a virtual environment, has been identified as a critical determinant of simulator efficacy. Empirical investigations reveal that virtual reality (VR) technologies, partic-

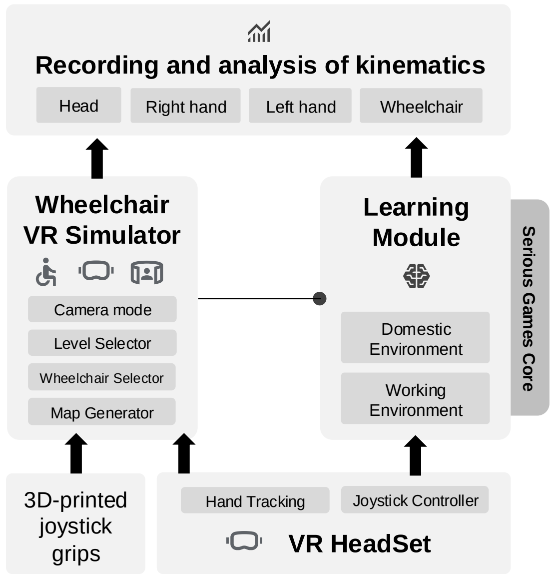

Figure 1: General architecture of the proposed platform.

ularly head-mounted displays (HMDs), substantially augment immersive experiences, though these devices may simultaneously precipitate cybersickness symptomatology, especially among users presenting mobility limitations Vailland et al. (2020), Arlati et al. (2019). The incorporation of multisensory feedback modalities (encompassing vestibular and haptic stimulation) has proven effective in elevating both user experience quality and SoP while concurrently attenuating adverse physiological responses Vailland et al. (2021).

Contemporary simulator architectures have expanded to encompass digitally reconstructed domestic and occupational environments, thereby extending their application scope considerably. Personalized environmental configurations enable individuals with recent spinal cord injuries to acquire domain-specific functional competencies while facilitating adjustment to their transformed circumstances. Furthermore, gamification principles and serious game methodologies have been strategically deployed to sustain user motivation and accelerate physical recovery trajectories Hoter and Nagar (2023).

Kinematic data acquisition represents a particularly salient system component, furnishing objective performance metrics essential for rehabilitation program evaluation and refinement. Platforms such as ViEW enable comprehensive analysis of user performance across both simulated and authentic conditions, with empirical findings indicating positive correlations between simulator-acquired proficiencies and their subsequent manifestation in real-world contexts Morère et al. (2018).

3 VR-ADAPT PLATFORM

Figure 1 presents the comprehensive platform architecture. At the foundational layer, the VR headset facilitates user immersion and interaction with the virtual environment through wheelchair joystick controls or direct hand manipulation for serious game engagement. The headset incorporates integrated tracking modules for hand and head position monitoring, complemented by joystick controllers.

The intermediate architectural layer encompasses wheelchair simulation and learning modules with integrated serious games. Functional connectivity between modules permits users to navigate virtualized environments via wheelchair control while engaging in rehabilitative tasks. The uppermost layer addresses kinematic data acquisition, continuously capturing comprehensive spatiotemporal data pertaining to wheelchair kinematics, hand trajectories, and head movement patterns throughout all training activities.

3.1 3D-printed joystick grips

This investigation employs Oculus Meta Quest 2 and 3 models, selected for their favorable cost-performance balance, versatility, and team expertise with the Meta XR Platform SDK. Both hardware and software architectures accommodate user interaction through external controllers and controller-independent hand tracking modalities.

For patients with spinal cord injuries affecting upper extremity function, the standard VR headset joystick proves inadequate due to its diminutive dimensions. To address this accessibility barrier, the HNPT department developed enlarged, morphologically diverse grips through additive manufacturing. An intermediate adapter piece affixes to the original controller's articulating shaft, enabling supplementary grip configurations in varied geometries to be mounted, replicating the grip characteristics of electric wheelchairs.

3.2 Wheelchair VR Simulator

The VR wheelchair operation simulator operates within a virtual sports facility featuring an expansive 45x25 meter court. This training environment incorporates diverse elements representing learning objectives, including designated target coordinates, transitional zones, and navigational markers for executing specific maneuvering patterns. The simulator comprises multiple map configurations developed collaboratively with HNPT clinical personnel, organized hierarchically by difficulty level to support progressive, controlled skill acquisition.

The system implements three distinct viewing modalities to accommodate varying user tolerance levels. First-person view aligns the virtual camera precisely with patient eye level, delivering complete immersive engagement, though the principal limitation involves potential motion sickness induced by visual motion cues while the physical body remains stationary. The simulator permits wheelchair velocity adjustment to accommodate individual tolerance thresholds. Third-person view enables users to observe the wheelchair from an external vantage point, with camera displacement occurring minimally and adjusting only when the wheelchair traverses beyond the current viewing frame. While this modality sacrifices realism, it accommodates users experiencing acute motion sickness during first-person engagement. Finally, first-person view without VR headset maintains camera positioning at patient eye level but projects visual output onto an external display, eliminating VR headset requirements for users intolerant of immersive modalities.

Additionally, the simulator enables selection and training across electric wheelchairs exhibiting distinct traction configurations (anterior-wheel, mid-wheel, and posterior-wheel drive systems). The Unity physics engine employed in this implementation accurately reproduces these behavioral distinctions. While traction type primarily influences power distribution, it more critically affects turning kinematics. Through systematic simulation exposure, both patients and clinical staff can identify wheelchair configurations optimal for individual patient capabilities.

Two simulator components warrant particular emphasis. First, the simulator deploys gamification strategies to augment patient motivation, incorporating performance scoring mechanisms, temporal milestone tracking, and multimodal sensory feedback (visual and auditory) associated with specific task events. Second, the system captures comprehensive spatiotemporal wheelchair data throughout training sessions, facilitating objective patient progress evaluation through detailed kinematic analysis.

Figure 2: 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.

3.3 Virtual Domestic and Working Environments

The platform integrates virtualized environments specifically designed for learning applications, encompassing domestic settings and occupational spaces where patients allocate substantial time. These environments necessitate wheelchair navigation and task performance involving manual dexterity, modeling fundamental functionalities including illumination control, door operation, and furniture height adjustment. Diverse serious games integrate into designated spatial zones, with gameplay mechanics requiring users to accomplish specific objectives that enhance motivation through gamification principles.

The HNPT adapted apartment represents a completed implementation enabling patients to practice in settings closely approximating residential environments. The space comprises kitchen, living area, bedroom, and bathroom. Figure 2 presents the digitally reconstructed apartment alongside photographic documentation of actual spaces. The digitalization workflow employed Polycam software with iPhone 15 PRO LiDAR sensors, refined in Blender, and integrated into Unity 3D for Meta Quest visualization.

Throughout the virtual apartment, interactive assistance interfaces manifest as floating activation buttons distributed across spatial zones. Upon activation, virtual displays present recorded video content featuring clinical therapists or experienced patients delivering contextually relevant information and strategic recommendations for navigating potential obstacles.

Five serious games integrate across different rooms with scoring mechanisms, temporal tracking, and multimodal feedback systems: (1) Kitchen cleaning requiring tableware collection and dishwasher loading with upper extremity movements and wheelchair navigation, (2) Recipe preparation with sequential ingredient manipulation and refrigerated storage retrieval, (3) Box and Block assessment (standardized upper limb rehabilitation instrument) requiring wooden block transfer without wheelchair navigation, with graphical implementation accommodating hands with motor limitations, (4) Suitcase packing extracting clothing from wardrobe storage with minimal wheelchair navigation, and (5) Tooth brushing simulating dental hygiene with circular upper extremity motions without wheelchair navigation.

Figure 3: Preliminary user testing sessions at Hospital Nacional de Parapléjicos de Toledo, featuring real patients and clinical therapists evaluating platform functionality.

3.4 Kinematic Data Acquisition and Analysis

A critical platform feature involves comprehensive monitoring and recording of user activity throughout all training modules. Spatiotemporal data acquisition for the virtual wheelchair proves straightforward, with continuous position tracking along x, y, and z axes providing graphical depictions of wheelchair trajectories.

Hand movement recording entails greater complexity. Oculus Meta Quest headsets incorporate four external cameras with 100-degree fields of view, featuring robust tracking systems generating virtual hand representations corresponding precisely to actual hand position and orientation. The system records multiple variables including temporal data (frame number, elapsed time), spatial variables (head position, hand detection status, 3D hand coordinates, tracking confidence), kinematic variables (hand velocity vectors), and interaction variables (pinch detection, palmar grasp detection, auto-grip status, wrist twist force measurements).

From accumulated data streams, derived metrics quantify hand velocity, spatial movement density, trajectory irregularity, maximum reach envelopes, and response latency. Longitudinal comparison across sequential sessions furnishes therapists with objective analytical instruments for evaluating patient progression, enabling data-driven therapeutic intervention refinement and personalized rehabilitation protocol optimization.

4 CONCLUSIONS AND FUTURE WORK

This article presents VR-ADAPT, an innovative rehabilitation solution for individuals with recent spinal cord injuries, synthesizing immersive environments, serious game mechanics, and kinematic tracking capabilities to facilitate transition toward enhanced autonomous functioning.

Preliminary validation sessions have been conducted with patient populations and clinical personnel at Hospital Nacional de Parapléjicos de Toledo (illustrated in Figure 3), yielding encouraging feedback regarding system usability, hardware ergonomics, and training protocol acceptability, proving instrumental in refining interaction paradigms and validating core design assumptions.

Forthcoming development priorities include completing wheelchair simulator functionality, achieving comprehensive serious game integration across domestic and occupational environments, and executing rigorous empirical studies with expanded patient cohorts. These initiatives will enable systematic functionality and usability analysis within authentic clinical contexts, establishing foundational evidence for clinical validation and subsequent implementation protocols.

Acknowledgements: *This work has been funded by the company Indra and the Universia Foundation through the VIII call for grants for research projects in accessible technologies, and by University of Castilla-La Mancha under Project ID 2023-GRIN-34400.*

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