WheelUp! Developing an Interactive Electric-power Wheelchair Virtual Training Environment

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***Abstract*—Standard power wheelchair training is considered inadequate by clinicians and users due to insufficient means to evaluate user performance in varying environments. Virtual environment training offers a promising alternative by providing users with more practical opportunities while reducing the time demands on clinicians. However, there is a need to further explore and optimize game design elements and strategies to ensure engaging and effective training experiences for a diverse range of users. This paper presents our progress of *WheelUp!*, an open-source electric wheelchair virtual reality (VR) simulator. The simulator offers modularity for clinician-controlled difficulty adjustment, immediate visual and audio feedback, and a visualization tool to aid in clinical assessment and monitoring of progress. This is the first step to building an interactive platform to address the inadequacy of wheelchair training.**

***Index Terms*—Power Wheelchair Training, Virtual Reality (VR), Virtual Environment, Training Game**

I. Introduction

Standard power wheelchair training is often considered inadequate by both clinicians and users, as current assessment processes fail to evaluate user performance in varying environments, such as standardized hospital or home settings, and variable environments with changing obstacles like shopping centers or workplaces. In contrast, virtual wheelchair driving training provides users with more practice opportunities in a safe environment while reducing time demands on clinicians [1]. Moreover, digital environments offer customization and personalization to cater to users' preferences. A wheelchair training simulator can lead to increased retention and transfer of power wheelchair skills, resulting in improved real-life maneuvering, navigation capabilities, and confidence after virtual training [2], [3].

Virtual Reality (VR) technologies show promise for training games for phenomena closely tied to embodiment and interpersonal interaction. For example, the VR serious game "A Hole New Perspective" was designed to teach perspective-taking skills, and a preliminary study found a correlation between in-game performance and mental rotation ability [4]. In another study, a VR gaze-control training game was created for children with ADHD [5]. VR serious games can also be designed to provide real-time virtual social support/feedback for the training of public speaking skills [6]. Empirical research has shown that VR exergames can significantly enhance players' presence and motivation while reducing perceived exertion [7]. Yet, there has also been critique of contemporary VR experiences for a fundamental failure to consider disabled bodies [8]. There is a need to further explore VR design for wheelchair users and game design strategies in the field of power wheelchair training.

Here, we present *WheelUp!*[1], an open-source VR-based electric wheelchair simulator. *WheelUp!* uses the computing power of a standalone PC to render the simulation and stream the video to mainstream OpenXR-compatible head-mounted devices (HMDs). This guarantees that most HMDs can be used, regardless of their built-in computing power. *WheelUp!* offers both HMD and monitor-based rendering, allowing it to accommodate various levels of cybersickness susceptibility, as users have varying levels of susceptibility to cybersickness [9]. Unlike previous studies, which focused on developing virtual training environments for testing a specific input modality, our work proposes a versatile platform that allows research groups to test the mapping of input devices that adhere to the Human Interface Device protocol. *WheelUp!* incorporates modularity for clinician-controlled difficulty adjustment, immediate visual and audio feedback, as well as a visualization tool to aid in clinical assessment and monitoring of progress. Our preliminary user study indicated that wheelchair users appreciated the embodiment and fidelity of *WheelUp!*. Participants expressed a willingness to engage in virtual training in a safe environment when starting to use the motorized wheelchair.

II. System Description and Implementation

Through *WheelUp!*, we aim to create an open-source platform for realistic wheelchair driving experiences to facilitate clinical research. Powered by Unreal Engine 5 (UE5), the simulator features: A) **VR and non-VR Support** with automatic HMD device detection and render mode switching.

This work was supported in-part by UML-WPI Collaborative Seed Funding, Project ID R50220000054426. Correspondence can be sent to kelilah_wolkowicz@uml.edu.

[1]https://github.com/WPI-IDeaS/Wheel-Up

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Fig. 1. Photo of our preliminary study. A participant who uses a chin-controlled wheelchair is interacting with the VR training system and orally giving instructions to control the virtual wheelchair via our standard joystick.

B) **Drivable Virtual Wheelchair** with complex or idealistic physics models, various control methods, and collision detection. C) **Gameplay Features**, including custom maps for driving scenarios, customizable checkpoints with animated guides, and quick restart functionality. D) **Photo-realistic Rendering** utilizing UE5's lighting and rendering upgrades for realistic graphics. E) **User Testing Facilitation** with observer view, facilitator controls, data collection, and visualization tools. F) **Extensibility** through customizable maps, routes, input methods, and simulation properties.

A. Software, Hardware, and Virtual Reality

WheelUp! is a blueprint-based PC game built on Unreal Engine 5, optimized for head-mounted VR and compatible with regular monitors. *WheelUp!* runs smoothly on most modern desktop gaming PCs and can stream content to any OpenXR-compatible VR headset. It performs calculations on the PC rather than the HMD to enhance graphical fidelity, refresh rate, and response time, which can reduce cybersickness [9]. The VR features rely on UE5's OpenXR plugin. The simulator automatically detects connected HMDs and supports instantaneous VR and non-VR switching without losing user progress.

B. Drivable Virtual Wheelchair

1) Physics Simulation: A virtual wheelchair was built based on the Jazzy Select 6 Electric Wheelchair[2]. We implemented the UE5 Chaos Vehicle and Character Movement physics simulation models to balance realism and simpler movement.

The UE5 Chaos Vehicle system is a complex physics simulation that offers customization possibilities, such as motor torque curves and weight distribution. We implemented a vehicle that replicates the Jazzy Select 6 wheelchair dynamics, including weight, size, torque, wheel composition, and turning radius. However, physical realism introduced extraneous camera rotation and displacement on all three axes when turning and stopping, contributing to motion sickness in HMD VR. Camera stabilization was implemented to mitigate unwanted camera movement and physical effects of the Chaos Vehicle. Additionally, the standard UE5 Character Movement was customized for a simplified and idealistic wheelchair physics simulation, only applying rotation on the z-axis, resulting in less disturbing physical effects.

2) Collision: Multiple collision meshes were used to provide collision feedback. When a collision occurs, the screen briefly flashes red and a time-coded collision event is logged.

3) Movement Control: Input bindings and the UE5 raw input plugin were used to realize universal movement control. The player can control the virtual wheelchair via keyboards, standard gamepad controllers, paired VR controllers, or standard power wheelchair joysticks. A custom 3D-printed housing was designed to attach the power wheelchair joystick to the armrest of the participant's wheelchair. The joystick connects to the PC via a USB cable and the UE5 raw input plugin is used to establish its connection.

4) 3D Model: We modeled the Jazzy Select 6 Electric Wheelchair using polygonal modeling in Autodesk Maya and textured it using Substance Painter. This approach enabled quality control, generating a low-poly mesh and applying subdivision surfaces to achieve the desired level of detail. Texture painting in Substance Painter was applied to achieve highly realistic and immersive results. The model was then rigged in Blender for the Chaos Vehicle physics simulation.

C. Gameplay Features

1) Maps: Currently, *WheelUp!* consists of four maps; two maps were custom built and two were adapted from public third-party assets on the Unreal Marketplace. Maps can be modified separately from the core mechanics, making them flexible for additions and modifications. Different training goals can be achieved by using different maps to provide distinct user experiences, our approach is further documented in the User Studies section.

2) Tutorial: The player first meets a tutorial level that contains input instructions on how to use their controlling device to navigate and how the checkpoint system works. This map's visual style is futuristic and abstract, with the goal of having the player focus on the instructions instead of the environment.

3) Checkpoint System: Each level has a series of checkpoints to guide the player to complete training objectives. A checkpoint system was developed to enable non-technical experimenters to modify or add routes to existing or new levels easily. Checkpoint items can be added by dragging and dropping an Unreal actor onto a map. After modifying the links to the previous and next checkpoints, the system automatically establishes a dynamic goal chain and a progress indicator is shown in the player's view.

The current target checkpoint shows up as a green translucent cylinder to the player, while an animated guiding orb floats between the last checkpoint and the current target to get the player's attention and show the path. The granularity of guidance can be customized based on the number of

[2]https://www.pridemobility.com/jazzy-power-chairs/jazzy-select/

Fig. 2. Screenshot of the tutorial level from player view with instructions explicitly shown as a 3D text block and graphics on the wall.

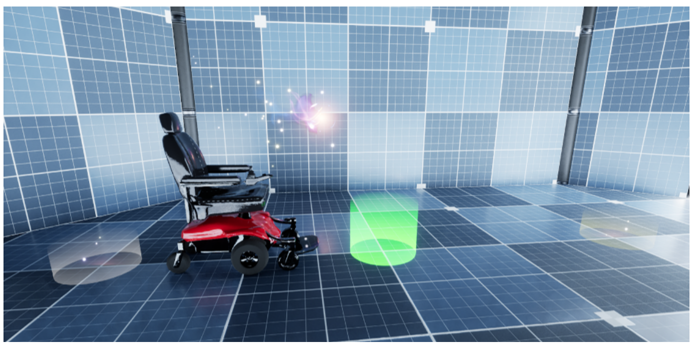

Fig. 3. Demonstration of the checkpoint system. The current target is shown in green, the completed checkpoints are shown in gray, and the remaining targets are shown in yellow. An orb floats between the last checkpoint and the current target to guide the player.

checkpoints provided. If the experimenter wants to provide more detailed instructions when navigating, they can set a checkpoint at each turn. Conversely, if the experimenter wants the player to explore possible routes to a specific location, they can place a checkpoint at the target location only.

During the training, if the participant appears to be stuck or lost, the experimenter can use a button to trigger a quick restart, which places the player back at the last checkpoint they reached. This action ensures that the player does not have to restart the entire level if they get stuck.

D. Photorealistic Rendering

WheelUp! utilizes UE5's optimized dynamic lighting features like Lumen and Virtual Shadow Maps to provide real-time global illumination, reflections, and shadowing. Our wheelchair model and maps also use high-resolution meshes and textures, as well as realistic styling, to contribute to the photorealism of the rendering. Rendering in *WheelUp!* is optimized for running natively on a PC with NVIDIA's RTX series dedicated graphics acceleration units. This ensures a balance between the graphical fidelity and responsiveness of the simulator while creating a believable world with minimum motion sickness caused by low response rates.

E. User Testing Facilitation

We implemented multiple features to facilitate clinical training and user testing.

1) Observer View: The experiment facilitators can observe the participant's behavior in VR in real time from an observer view displayed on a desktop monitor. This view helps the experimenter understand the current situation. For example, if the virtual wheelchair's foot pedal is stuck, they can provide assistance or instructions accordingly.

2) Experiment Facilitator Control: To mitigate distractions from experiment parameter configurations, facilitators can configure the simulator using keyboard shortcuts. Available functionalities include quick restart, level switching, VR and non-VR view mode toggling, and first- and third-person camera toggling. The experimenter can adjust the virtual camera height according to the player's seating or wheelchair height.

3) Research data collection: WheelUp! includes a data logging system that captures system statistics at every frame and logs events as they occur during gameplay. At every frame, the system records the frame number, system time, player location on the XY plane, their rotation in the Z-axis, as well as their movement input. Additionally, events such as collisions, quick restarts, level switching, and camera switching are logged into a separate file. The system stores the data locally and automatically appends it to external CSV files when a checkpoint is reached or when a new level loads.

4) Research data visualization: Using the online universal research data visualization tool *aniRGB*[3], created by one of the authors, data recorded in *WheelUp!* can be visualized in a single top-down image or real-time animations, showing selected segments or all of a playtester's path in a level. *aniRGB* is highly configurable and contains several presets, which include top-down map views as the background image, as well as each of the coordinate ranges for each level in the game for easy map selection and automatic coordinate adjustment.

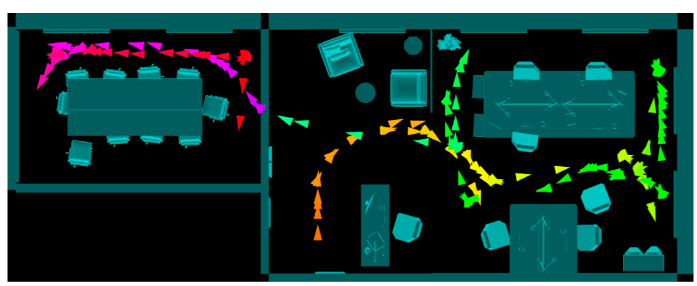

Fig. 4. Playthrough visualization example. Arrows point to the player's front direction at each location. The colors of the arrows begin with red and end with purple, following the sequential order of a rainbow, which reflects their chronological arrangement. The distance between two continuous arrows indicates the wheelchair's velocity (i.e. closer arrows represent slower movement).

[3]https://github.com/GP2P/aniRGB-Research-Data-Animator

F. Extensibility

WheelUp! is open-source and highly modular, thus easily extensible. Maps can be added by importing the new map into the Unreal project, visually configuring a keyboard shortcut to switch to the new map, dragging in checkpoints, and setting up their sequences. Routes and guidance granularity can be controlled with the amount and location of checkpoints. *WheelUp!* also supports the addition of alternative input devices without having to change the core mechanics of the wheelchair; changing the UE5 input setting or configuring raw input for the device will be sufficient. Changes to the wheelchair model or specifications can also be easily made by modifying the actor blueprint and its movement component's properties, depending on which physical simulation model was being used. With the platform's modularity and extensibility, we aim to create a universal open-source platform for VR wheelchair simulation training.

III. Community-Engaged User Studies

To gain early feedback about the simulator and our project, we conducted preliminary user studies with wheelchair users with real accessibility needs. Prior to commencing the user study, a physical assessment was performed to ensure the recruited users could engage with the simulated environment. We identified three wheelchair-bound participants and each was asked to complete the four maps that encompassed common maneuverability tasks first on the desktop version (approximately 15 minutes) and subsequently on the VR headset version (approximately 10 minutes). Then, they were interviewed for about 30-45 minutes about their virtual training experience. The interview questions can be grouped into three main categories: (a) the use of the simulated system and its components, (b) engagement with the virtual environment, and (c) reflections on design advocacy. We used an iterative team-based process to qualitatively analyze the interview data.

The interview questions included: "Is this your first time using a VR system? If not, what kind of experience have you had?", "Did you feel overwhelmed at any point? If so, when?", "Were there any moments you felt uncomfortable? What was the reason? Headset? Controller? Quality of the video or the background sound? Something else?", "Was the system responsive to what you wanted to accomplish in the simulation?", "Were there any helpful navigation cues within the simulation (directions, next steps, etc.)?", "Do you think users might need more navigational help within the simulation?", "Did the movements feel realistic? If not, which specific movements didn't feel realistic?", "Was the simulation able to give you the feeling that you were present in a different environment? If not, what could have helped to give that feeling?", "If the simulation could be redesigned, what kind of places would you choose as a possible setting? Why?", "Would you recommend this technology (in its current form or a developed version) to people using—or wishing to use—powered wheelchairs? Why, or why not?"

A. User Study Simulator Environment Levels

For the community-engaged user study, we developed three "levels" in addition to the tutorial level: an off-the-shelf office scene, a restaurant scene, and a custom-made office lounge scene. The training routes encompassed common maneuverability tasks, including driving and reversing the wheelchair in a straight line, driving and reversing the wheelchair into an enclosed space, and completing a 180-degree turn. During our user testing, we used a Windows 11 desktop PC equipped with a 12700F CPU and an RTX 3070 GPU, along with an Oculus Quest 2 HMD and a Ruffy HE2 joystick[4] connected via cables.

Fig. 5. Screenshot of the restaurant scene. The route aims at training how to navigate through a narrow aisle.

We designed each scene in *WheelUp!* to test different lighting and aesthetics. We imported a restaurant map from the Unreal Marketplace with intricate obstacles and complex, darker lighting. The map features a looped path that traverses the interior of a tight contemporary restaurant, forcing the player to navigate carefully while not having to worry about selecting a route. To enhance realism, the player needs to constantly adjust their angle and look at their wheelchair footrest to determine their distance from chairs and sofas, making the VR mode much more immersive compared to a fixed-perspective experience.

Another map we implemented is an office map that we created in-house. The entire design process of the office space was centered around emulating a rustic industrial aesthetic, while also incorporating warm colors to create a visually calming atmosphere in line with the technical aspects of constructing the wheelchair.

The most complex and photorealistic map we have is a workspace map from the Marketplace. It contains irregular workplace obstacles like shelves, potted plants, tables, and pushable chairs. The map includes two very tight paths and one blocked path to simulate the real-world experiences of wheelchair users. Players can elect to circumvent these paths,

[4]https://ruffycontrols.com/he2-series/

Fig. 6. Screenshot of our custom office lounge scene. The route aims at training how to navigate around coffee tables and armchairs.

Fig. 7. Screenshot of the workplace scene. The route aims at training how to avoid common obstacles and choose navigation paths.

just as they would in real life, in exchange for taking longer to reach their objective.

B. Preliminary Results

In the preliminary study, participants (N=3) found HMD provides higher embodiment compared to traditional displays because it allows them to look around when they move their heads. They also found the high-fidelity photorealistic graphics “really realistic”, and that the dynamic and accurate shadows were helpful in positioning the wheelchair in tight spaces.

Based on participant feedback, the tutorial level was deemed helpful as a learning phase for basic control. They expressed a positive response toward the contextual environment we created. The restaurant scene effectively portrayed the challenges of navigating through narrow paths. In addition, participants expressed a desire to incorporate several other contextual environments into the training simulators, such as a supermarket, hospital, and campus. They also noted that the presence of pedestrians would introduce an element of realistic uncertainty, mimicking true challenges encountered during wheelchair driving.

We also found that participants reported less cybersickness than was expected. We hypothesize that this may be due to users lowering their gaze to see the simulated wheelchair’s foot pedal to avoid obstacles. It has been studied that introducing a static reference (e.g. a virtual nose) can reduce cybersickness [10].

In addition, we learned from the wheelchair user community that current wheelchair training is inadequate. As a result, collisions with cabinets, walls, and even toilets occur as an individual learns to use a wheelchair in daily life. According to our participants, having a virtual wheelchair training simulator with real-life scenarios such as a restaurant and workspace would be helpful before they get an actual wheelchair.

IV. Discussion and Future Work

Practicing driving a wheelchair takes time and is often cut short due to the lack of adequate insurance coverage and a lack of varied training environments. In real life, people deal with narrow aisles in stores with bulky merchandise, aisles that are too narrow to navigate, and restaurants that are too crowded to maneuver past tables or through the entrance, despite advertising themselves as “accessible”. These situations cannot be easily replicated by physical therapists in clinical settings. *WheelUp!* is designed to provide users with training to maneuver a wheelchair in different contexts. Our virtual reality training simulator could be useful for patients and physical therapists to increase the person’s competence and safety. In our training simulator, we have included tasks such as turning left and right, navigating straight down a narrow hall, backing up in a straight line, and approaching obstacles and tight corners. Future work and iterations will include haptic feedback when encountering different terrains such as grass, traversing large thresholds, and navigating crushed stone or cobblestones. Additionally, it would be beneficial to introduce challenges such as crossing the street, going up and down ramps, and navigating tight shopping aisles.

Our preliminary study with the wheelchair user community validates the necessity of inventing the virtual training simulator. Through qualitative interviews, we have gained insights into the importance of incorporating more real-life scenarios such as supermarkets, hospitals, and campuses. However, the participants we invited for the preliminary study were experienced wheelchair users, which made them ineligible for the driving performance study. Future studies will invite novice wheelchair users and evaluate their performance before and after receiving the training. With a larger sample size, the data recorder and visualizer can become more useful.

While the virtual training simulator has a direct impact on wheelchair users, it can also facilitate physical therapists in administering the training in clinical settings. In our initial design, we included one physical therapist in designing the training goals. For our future work, we would like to conduct interviews with neurological physical therapists and assistive technology providers to learn about the specific types of training goals, as well as the time and space constraints in clinical settings.

An additional- limitation of *WheelUp!* is the sensory mismatch in motion, which is known to be an important factor that causes cybersickness [10]. Further research will include investigating whether a rotating motion platform and/or a vibrating gaming cushion could improve the immersive experience.

V. Conclusion

WheelUp! is a versatile VR-based electric wheelchair simulator that has the potential to address the inadequacies of the current standard for power wheelchair training. To optimize training experiences for users, *WheelUp!* incorporates tutorial and map sections, offering multiple options for learning and customizing training sessions. The photorealistic rendering of the simulator and real-life challenges such as navigating in an enclosed space, contributes to the sense of immersion and presence in the virtual environment, enhancing the user's experience. As *WheelUp!* offers both VR and monitor-based rendering, the choice of rendering platform is flexible and adaptable to individual users' susceptibility to cybersickness. Our preliminary findings suggest that the high-fidelity virtual environment is useful in motorized wheelchair training. With its user-centric design, *WheelUp!* has the potential to improve the way power wheelchair training is conducted, leading to improved skill acquisition and increased independence for wheelchair users.

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