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Review

Using Virtual Reality to Complement Traditional Wheelchair Skills Training Methods: A Literature Review

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Abstract: Training wheelchair skills are vital for enhancing independence and safety. Traditional training methods require significant time and resources, limiting accessibility. Virtual reality (VR) offers an innovative solution by simulating real-life environments for training, reducing risks and costs. However, the effectiveness of VR in complementing real-life training remains underexplored. This review investigates how VR can complement traditional wheelchair training by assessing the strengths and limitations of existing VR systems. A literature review of 28 studies on VR applications for wheelchair training from 2017 to 2024 was conducted, focusing on studies that detailed VR environments and training programs. It was found that most VR systems were designed for powered wheelchair users with joystick navigation. VR environments included tasks from basic navigation to complex real-world scenarios. While VR showed potential in improving skills and engagement, challenges included the lack of standard methods for evaluating effectiveness and cybersickness. Overall, VR can be a valuable complementary tool for wheelchair training, especially for powered users. Future research should standardise protocols, and address side effects.

Keywords: virtual reality; training; rehabilitation; disability; interaction devices; wheelchair

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1. Introduction

According to the World Health Organization (WHO), over 80 million people require the aid of a wheelchair (WC) to gain mobility [1]. In the UK alone, 1.2 million people are wheelchair users (WU) [2]. To maximise participation of individuals with restricted mobility, it is important they undergo some sort of training [3], especially during initial rehabilitation for new WUs [4]. This sort of training enables WUs to drive the wheelchair safely, to manage their daily activities and, therefore, to improve their independence [4–6]. Moreover, training enables WUs to avoid being placed in long-term care facilities [7,8], participate in society [7,9,10], and return to work [7,11]. A training system should be comprehensive, including everything from learning to drive a wheelchair to learning to drive an adapted car, both of which play a crucial role in making a positive change in one's life [12]. For example, some studies have shown that those who travel further and longer in a day with their wheelchair were more likely to be employed [13]. An appropriate training system may also reduce the physical risks someone faces when driving a wheelchair without prior experience. In fact, driving a wheelchair can lead to injury to self, due to prolonged seating or loss of balance, injury to others, due to collision, and the destruction of the wheelchair or nearby objects [14]. These physical risks further stress the importance of undergoing wheelchair skills training.

In this respect, various training methods have been developed, including training in real environments and in virtual reality (VR) environments [15]. To train a new wheelchair user in real life, programs include allowing the user to drive through various controlled environments such as obstacle courses or following a track on the floor [15–18], and through uncontrolled environments such as rehabilitation centres, homes, schools, outdoors, and having the user interacting with the environment, like approaching objects [15,19,20]. However, the training of WUs has also been standardised using the wheelchair skills training program (WSTP) [21]. The WSTP is a training method that provides a standardised way of enhancing and assessing the skills of a manual or powered wheelchair user; it tests the WUs on individual tasks (e.g., driving straight, backwards, through obstacles, turning, etc.), which allow users to deal with various real-life situations such as going shopping [21]. In this context, two review papers [22,23] analysed the effectiveness of the WSTP compared to other real-life training methods for both manual and power WUs.

Real-life training methods are often time and resource-intense [24,25], rarely allowing individuals to drive through uncontrolled environments, as would happen on a day-to-day basis, and encounter the danger of collisions. These limitations are something VR training can mitigate [24]. VR is a set of technologies that create a world beyond physical reality. Consumer-grade VR systems can deliver experiences that are: non-immersive (via monitor screens), semi-immersive (using systems which project virtual environments onto walls), or fully immersive (utilising head-mounted displays HMDs). HMDs can be mobile or stationary, and are typically controlled using handheld controllers [26]. In specialised contexts, such as those for wheelchair skills training, alternative VR controllers have been developed that are tailored to users' specific needs, including wheel-mounted sensors [27], eye-tracking devices [28], or electroencephalography (EEG) signals [29]. By aligning with an individual's motor abilities, these methods enhance accessibility for a wider range of users. Training wheelchair skills in VR environments can have a number of benefits: it can be more motivating, it has lower risks [30], it increases safe and independent learning opportunities, and it enhances engagement with tasks [24]. VR has also been successfully used to simulate the driving of other vehicles such as cars, trains, and aircrafts [31]. These are the reasons of its increasing popularity in the general rehabilitation field, together with its potential to overcome barriers present in other more traditional training methods such as high costs and lack of time [24]. VR can also be highly realistic through stimulating the users' senses to enhance the learning experience by targeting various feedback mechanisms such as auditory, visual, vestibular, and force feedback [31]. The immersion and involvement in a VR environment elicits the Sense of Presence (SoP), defined as "experiencing the computer-generated environment rather than the actual physical locale", which positively correlates with the effectiveness of VR-based training [31].

Two reviews have been published focusing on VR for wheelchair skills training [24,31]. Arlati et al. [31] specifically looked at the correlation between Sense of Presence (SoP) and the effectiveness of wheelchair training in VR. Lam et al. [24], on the other hand, provided an overview of the current VR technologies for wheelchair skills training. With the exponential growth of technology, VR methods are likely to increase in popularity although there are aspects of real-life training methods that might not be replaceable with technology. Thus, it is important to develop VR training systems which can best complement real-life ones. To do so, it is beneficial to identify how VR could support real-life training by reviewing the strengths and limitations of current VR training systems. Specifically, our review aims to answer the following question: How can VR be used to complement real-life training for wheelchair users? While, it has the following two main objectives: (1) to identify gaps of real-life training methods that can be addressed by VR; (2) to study the main features of VR training systems in order to identify their strengths and weaknesses. In order to answer our research question and address our objectives, our review investigates recent papers published in peer-reviewed journals from 2017 onwards about VR for wheelchair skills training (more details about the selection criteria can be found in Section 2) by extracting key information regarding their simulation hardware, their software features, their data analysis methods, their conclusions and limitations. This qualitative analysis of the included papers allows for a comprehensive overview of their developed systems, thus proving us with the information necessary to meet the aim of our paper. However, limitations of this analysis method may be a lack of comparison analyses between the papers and a quantitative evaluation of the effectives of VR systems.

2. Materials and Methods

To gain an overview of existing research about VR applications for wheelchair training, a range of papers were investigated and analysed in a literature review. We first reviewed two existing review papers on real-life training [22,23], which compare the effectiveness of the WSTP to other training methods used. Then, we reviewed two review papers on VR; the first one, published in 2018, includes articles from 1990 to 2016 with the objective to present the current state of knowledge regarding VR for wheelchair skills training [24]; the second one, published in 2020, focuses on articles from 2000 to March 2017 and aims to assess the extent of knowledge about sense of presence (SoP) and effectiveness of the systems in regards to VR-based wheelchair training programs [31]. Yet, due to the field's fast-growing pace, important and more recent papers needed to be studied, therefore, papers from 2017 onwards, together with the above-mentioned reviews, were analysed.

Inclusion/Exclusion Criteria and Data Sources

We included studies that met the following criteria: published from 2017 onwards, provided a comprehensive description of the virtual environment training features, published in peer-reviewed journals, published in the English language. According to this criterion, we excluded studies with the following specifications: published before 2017, discussed mainly the hardware (i.e., electronic and mechanical) side of their systems rather than the software features, were not published peer-reviewed journals, published a language other than English.

For our review, we searched in IEEE, PubMed, and Scopus with the keywords 'Virtual Reality' AND 'Wheelchair Training', for relevant papers dating from 2017 to 2024. A total of 47, 32, and 14 articles were found from the above-mentioned search engines, respectively; this led to 93 possibly useful studies. After reading their abstract, eliminating doubles, 41 were deemed to be relevant. A thorough review was done of the remaining 41 papers, which resulted in only 28 fitting the criteria of our study. A flow diagram of the study selection process can be seen in Figure 1, while a yearly distribution of the included studies is presented in Figure 2.

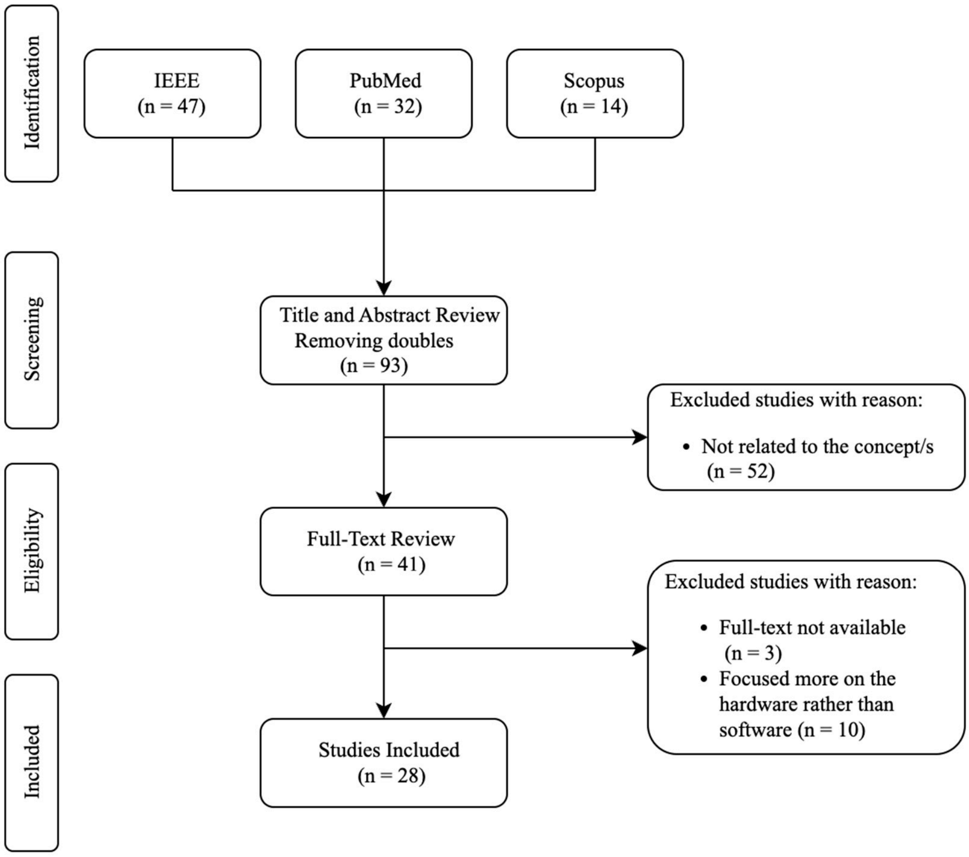

Figure 1. Study selection process flowchart.

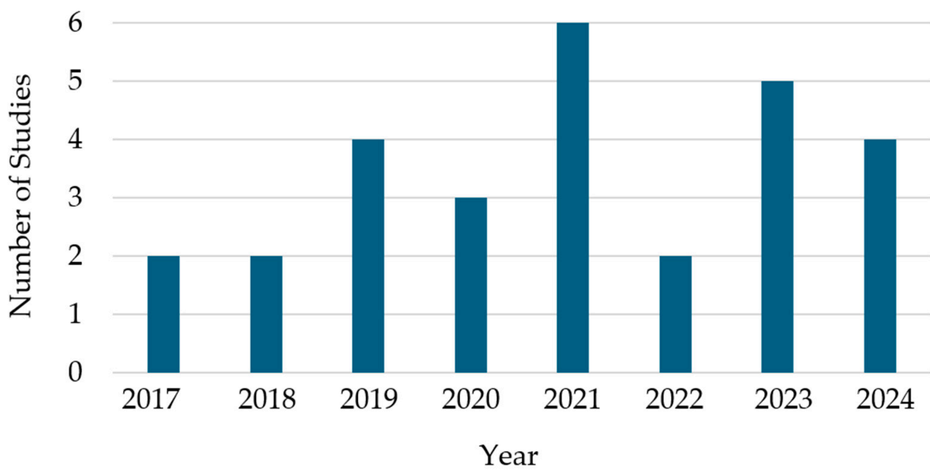

Figure 2. Yearly distribution of studies.

3. Results

The following data were extracted from the reviewed studies: overview of real-life training, simulator hardware of VR systems, software features of VR systems, data analysis performed by the studies, conclusions drawn by the studies, and limitations reported by the studies. A general discussion for each topic is provided in the respective subsections, with references to the two review papers [24,31], followed by a table presenting the data for each study.

3.1. Real-Life Training

Real-life wheelchair skills training can vary in nature, and often consists in completing tasks within controlled environments, such as obstacle courses, and measures speed and time completion to assess improvement [15]. Other methods, though less popular, are 'ecological' in nature where the user drives through real environments, while also interacting with them, such as schools and homes [15]; the interactions can mimic what someone would do daily like reaching for objects, writing, and opening doors [15]. Due to the heterogeneity of real-life trainings, a way to standardise them has been developed that is called the wheelchair skills training programme (WSTP) [21]. This programme can be used for manual and powered WUs and mobility scooters. The programme consists of a set of tasks that a person needs to successfully complete to be deemed able to drive a wheelchair independently. Specifically, it tests the WUs on individual tasks (e.g., driving forward, backward, through obstacles, and turning), with the aim of teaching users to deal with various real-life situations such as going shopping [21].

The efficacy of the WSTP was analysed by Tu et al. [23] who reviewed 10 randomised controlled trials (RCTs), and 7 non-RCTs to analyse the short-term and long-term retention of skills following WSTP. In the RCTs, participants undergoing the WSTP showed higher improvement in the short-term (immediately to one-week after) retention of skills than those undergoing other methods, for manual WUs. For long-term effects (after 3–12 months), instead, no significant difference was noticed compared to other training methods. In non-RCTs, instead, manual WUs undergoing the WSTP showed better improvement within 5 weeks as compared to other methods. Although the results show the effectiveness of the WSTP for short- and medium-term improvement of skills of manual Wus, insufficient evidence was reported for powered WUs as not enough studies reviewed by the authors investigated the effects of the WSTP in the acquisition of driving skills. A similar review was conducted by Keeler et al. [22], who reviewed 13 RCTs that used the WSTP to train manual and powered WUs, as well as mobility scooters. Keeler et al. concluded that the WSTP has a meaningful effect on the improvement of skills compared to no training or other methods [22]. Furthermore, in addition to being an effective training method, the WSTP consists in performing tasks in a safe and controlled environment, thus allowing WUs to be more confident during the training [22].

It must be stressed that the WSTP rarely contains tasks that mimic real-world driving experiences such as driving in different environments and interacting with them [15]. Importantly, real-life training requires a lot of time and resources which are not available to everyone [24]. Powered wheelchairs are also heavier than manual ones, and can go at moderately high speeds, thus incidents during real-life training can be very harmful and therefore training must be conducted in a careful manner.

3.2. Simulator Hardware of VR Systems

This section details the hardware used in the different systems to interact with the VR environments. These differ from one study to another, as shown in Table 1. Most studies, 20 out of 28, developed a VR system for powered WUs and thus used a joystick to conduct navigation [28–30,32–48]. These varied from a real powered wheelchair joystick to an adapted gaming joystick. Furthermore, some of the studies that used a joystick also had training groups using alternative ways to drive the simulation, such as eye-trackers [28,45] and BCI caps [49]. For manual WUs to drive the VR simulation, on the other hand, sensors attached to the wheels can be used, such as what was done by Li et al. [27] who placed VIVE trackers on the wheels to drive the simulation in VR; alternatively, the wheelchair can be placed on a platform that translates the movements of the wheel to the VR environment, such as the miWe simulator [50]. Regardless of the interaction method used in the various studies, each study took into account their end-user's motor abilities to determine the VR interaction method.

Table 1. Simulator hardware of VR system.

Study	Simulator Used
John et al. [42]	• The Microsoft Xbox One controller was used with a real joystick fitted on top of it. • Spectra XTR2 rear wheel drive wheelchair for real life driving.
Rodriguez et al. [45]	• The navigation was enabled by adapted joysticks, contactors and eye-trackers, all connected to the computer used for training.
Younis et al. [29]	• Two groups conducted the training using monitors, one using an Xbox controller with a regular desktop and the other using Emotiv Epoc+ as a controller with a brain-computer interface (BCI) desktop. • Two further groups used an HMD, one with an Xbox controller, and one with Emotiv Epoc+.
Bigras et al. [33]	• A real PW joystick.
Devigne et al. [37]	• The user is sitting on a real wheelchair placed on a mechanical simulation platform, which drives the VR environment. • The user navigates in VR with a joystick.
Salgado et al. [47]	• A real wheelchair joystick: the VR2 with haptic feedback was used.
Hernandez-Ossa et al. [28]	• One group used a real EPW with a joystick for movement in a HMD, another group used an EPW with eye-tracker for movement in VR which was shown on a LCD display.
Torkia et al. [48]	• A gaming joystick was used, connected to the monitor through a USB cable.
Nunnerley et al. [30]	• WUs remained seated in their own wheelchairs, but used a given wheelchair joystick for navigation. • Clinicians sat on an office chair at a desk and used the same joystick.
Day & John [36]	• Xbox controllers to control the VR environment. • A real wheelchair for the MR group.
Li et al. [27]	• The user sat on a wheelchair in a stationary position; HTC VIVE trackers were placed on the wheels to replicate movements in VR.
Thomas et al. [49]	• BCI cap
Vailland et al. [39]	• Quickie Salsa M2 power wheelchair
Chaar & Archambault [50]	• miWe simulator • Own manual wheelchair
Yan & Archambault [51]	• miWe • Own manual wheelchair
Yang et al. [52]	• Own manual wheelchair • Wheelchair ergometer
Mrityunjaya et al. [53]	• Simulation platform • Manual wheelchair
Salimi & Ferguson-Pell [54]	• Wheelchair ergometer • EON IcubeTM Mobile

Table 1. *Cont.*

Study	Simulator Used
Faure et al. [55]	• miWe simulator • Own powered wheelchair
Fraudet et al. [38]	• Powered wheelchair. • Multisensory mechanical platform
Araújo et al. [32]	• SM2 model powered wheelchair, with VR2 model joystick.
Kenyon et al. [43]	• Joystick or switch.
Zorzi et al. [34]	• Powered wheelchair with IMU sensor on joystick.
Zorzi et al. [35]	• Powered wheelchair with IMU sensor on joystick.
Gefen et al. [40]	• miWe simulator • Powered wheelchair
Martins et al. [44]	• Seat Mobile SM2 wheelchair • Joystick, EMG, eye-tracking
Salgado et al. [46]	• Powered wheelchair joystick
Gefen et al. [41]	• miWe simulator • Customized hybrid joystick (Penny and Giles JC-200 and the Logitech Extreme 3 D Pro)

Similar results were found by Lam et al. [24], in which the majority of studies used a joystick, and Arlati et al. [31], in which it was pointed out that all the studies using a power wheelchair used a joystick to control the VR environment. In those studies with manual wheelchairs, instead, the VR environment was controlled by a platform equipped with sensors, which were able to detect the movements of the actual wheelchair. Nevertheless, it is essential to note that powered wheelchair joysticks exhibit substantial variation across different wheelchair models, which can be a challenge when developing VR training solutions.

3.3. Software Features of VR Systems

This section gives an overview of VR environments developed for the studies we analysed, and highlights the software design requirements of a VR training system. VR, which can be non-immersive, semi-immersive and immersive, was mainly used with immersive (HMDs [27–30,34–36,38,39,42,46,47,49,53]), with only a few studies including semi-immersive (CAVE [37,54]) and non-immersive (monitor screen [33,42,45]) VR hardware in the analysed studies. Although HMDs provide a greater degree of immersion and SoP, compared to monitor screens [42], and are more effective in training skills transferable to real life, they cause cybersickness. Cybersickness is caused due to sensory conflict between vestibular and visual motion cues and leads to various discomforts such as nausea, disorientation, oculomotor disturbances, and drowsiness [56]. Nigel et al. [42] had participants split into three groups (a control group, a HMD group and a monitor screen group); the group using the HMD had the highest retention of driving skills which were transferred to the real world, even though participants showed more symptoms of cybersickness. Further, Hernandez-Hossa et al. [28], split participants into two groups, one using a HMD and one using just a projector screen; they found that the HMD group had a higher feeling of general presence, spatial presence and involvement. Similar results were shown by Govindarajan et al. [53], who found that HMDs resulted in a higher SoP, though they provoked more intense symptoms of cybersickness.

The features of the VR environments differ between various studies, as seen in Table 2. The tasks to complete in the different training environments normally have various levels of difficulties, some of which are relatively basic such as passing through doorways [36,41], mazes [34–36,42], or obstacle courses [29,32–35,37,38,42,44,46–51,54,55], while others are more complex such as collecting blue balls in a room while avoiding red balls to teach hand-eye coordination [42]. Salgado et al. [47] did not lay out any specific tasks, as the purpose of the study was to simply trial the training system; Rodriguez et al. [45] gave the user the option of roaming around freely in addition to its pre-defined paths. Interestingly, some studies included tasks inspired by the standardise assessment developed for real life training, namely the WSTP [34,35,40]. Similarly, Devigne et al. [37] used the WSTP as a pre-training assessment in VR prior to completing the actual VR training. Lam et al. [24], also highlighted a study [57] which used the WSTP as a baseline for its tasks. Regardless of the high variance between the tasks completed within studies, most of the studies attempted to teach real-life skills.

Table 2. Software features of VR systems.

Study	Software	Virtual Environment	Description of Task
John et al. [42]	Unity3D	• An HMD. • A monitor screen.	• Navigation through a maze. • Collecting blue balls by driving into them whilst avoiding collision with red ones. • Navigation in a crowded room. • Navigating through the track as quickly as possible while avoiding collisions with curbstones. • Ascending and descending the ramps.
Rodriguez et al. [45]	Unity3D	• A monitor screen.	• Practitioner chooses the environment, goal and speed which can be changed throughout the session. • Control device is chosen according to the user's needs. • Users are not required to follow a goal; they can freely explore several indoor and outdoor abstract environments.
Younis et al. [29]	Unity3D	• Oculus Rift HMD.	• A maze, a room with different obstacles, small rooms adjacent to each other, connected through doors and with obstacles, another maze • Following various paths in each scenario without hitting any obstacles. • Once all scenarios are completed, the user is tested on a real training environment.

Table 2. *Cont.*

Study	Software	Virtual Environment	Description of Task
Bigras et al. [33]	Not mentioned	• A computer screen.	• A total of five scenarios, based on different combinations of the above-mentioned parameters. • Moving through a hallway with width that changes, with 2–3 stationary obstacles and 2–5 moving obstacles. • Pressing the elevator button; Getting on and off an elevator with varying width.
Devigne et al. [37]	Unity3D, MiddleVR	• CAVE system with four screens surrounding the user.	• Driving through two obstacle courses with increasing levels of difficulty with and without assistance, not knowing if it was activated or not.
Salgado et al. [47]	Unity3D	• Oculus Rift HMD.	• Completing a predefined course with ramps, obstacles, and different directions to follow.
Hernandez-Ossa et al. [28]	Unity3D	• Oculus Rift DK2 HMD. • Projection screen.	• Driving in the VE following a laid-out path, which is a replica of the real-life training course.
Torkia et al. [48]	miWe-CC Software Program	• A PC monitor.	• Manoeuvring through a two-storey community centre with rooms, offices, a gym, a library, a cafeteria, and a courtyard; driving through hallways and doors, ramps, turning at corners, avoiding obstacles and parking. • Virtual characters that move unexpectedly when approached. • Activities are classified by three levels of difficulty.
Nunnerley et al. [30]	MTech Games Ltd.	• Oculus Rift HMD.	• Navigating around an environment representing the rehabilitation unit of an hospital centre.
Day and John [36]	Unity3D, Mixed Reality Toolkit	• Oculus Rift HMD for VR. • The Microsoft Hololens HMD for MR.	• For VR: driving through a maze and doorways. • For MR: navigating from one end of a room to another while avoiding virtual objects. • Visual and audio cues are given upon collision • A control group read through two guides about powered wheelchair safety.

Table 2. *Cont.*

Study	Software	Virtual Environment	Description of Task
Li et al. [27]	Unity3D	• An HMD.	• Manoeuvring through nine unique scenarios, a living room, bedroom, and an office which were automatically generated.
Thomas et al. [49]	Unity 3D 2021	• Meta Quest 2.	• A simulation of a large park within an urban city area with a few static obstacles, such as trees and flowers. • Environment can be changed depending on the stage of training and the hypothesis being tested. • Amount of auditory and visual stimuli can also be changed. • Either classical music, or a recording of common sounds heard in a city environment. • Can also have multiple 3D dynamic characters such as people. • High stimuli sessions had both music and common sounds playing throughout the experiment and 50 dynamic characters. • Low stimuli sessions contained no auditory stimuli or dynamic characters.
Vailland et al. [39]	Not mentioned	• HTC Vive Pro HMD.	• 3 different circuits with increasing difficulties. • Virtual circuit replica of the real one.
Chaar and Archambault [50]	miWe	• Monitor screen.	• Infinite sidewalk scenario with the following obstacles/tasks: (1) moving pedestrians (2) static pedestrians (3) static objects of varying size (4) slopes (5) street crossings. Presentation order of the obstacles was randomized.
Yan and Archambault [51]	miWe	• Monitor screen.	• Infinite sidewalk scenario with the following obstacles/tasks: (1) moving pedestrians (2) static pedestrians (3) static objects of varying size (4) slopes (5) street crossings. Presentation order of the obstacles was randomized. • Careful manipulation of VE obstacles.
Yang et al. [52]	Unity 3D	• HTC Vive HMD.	• Urban street scene, on both ground floor and uphill.

Table 2. *Cont.*

Study	Software	Virtual Environment	Description of Task
Mrityunjaya et al. [53]	Not mentioned	• Oculus rift HMD, Monitor screen.	• Participants were asked to perform the four following tasks: (1) Bathroom: use the access button to open door. Then, maneuver into the bathroom and position oneself parallel to the toilet. Finally, exit the bathroom by pressing the button. (2) Mall: Find the vending machine and "buy" a snack. Then, discard trash by finding the garbage can. Finally, exit the mall. (3) Street-Crossing: activate the first street crossing button. Then, move to the middle of the street within 15 s and activate the second street crossing button. Finally, move to the end of the street within 15 s to complete the scenario. (4) Elevator: Call the elevator. Then, maneuver into the elevator and press the button to go to the second floor. Finally, exit the floor. In all these tasks, buttons are activated automatically when the participant maintains a close distance for 5 s.
Salimi and Ferguson-Pell [54]	Not mentioned	• Projected on three screens.	• Three scenarios for basic skills training: obstacle course, accessibility ramp and elevators. • In the "obstacle course", L-shaped turns and 180° U-turns. In the "Accessibility ramp", narrow aisle, tight spaces, and side railings. In the "Elevators" scenario, two elevators with 90 cm spacing between them and partitions simulating a wall.
Faure et al. [55]	miWe	• Monitor screen.	• 6 ecological activities: crossing the street, going through a mall, using an adapted bathroom, taking the elevator, buying item in a supermarket, and going in and out an adapted van. • Users could choose activity and select the difficulty level. • Control group drove through an open-source kart-driving videogame, while avoiding obstacles and choosing from various levels of difficulty.

Table 2. *Cont.*

Study	Software	Virtual Environment	Description of Task
Fraudet et al. [38]	Unity3D	• HMD HTC Vive Pro.	• Virtual circuits. (C1) basic tasks such as driving forwards (10 m) and backwards (2 m), turning in place and while moving forwards (90°). (C2) more difficult tasks such as getting through hinged door, ascending and descending a 5° access ramp, rolling on soft surface (2 m), crossing doorstep and driving through narrow corridors. (C3) more difficult tasks such as avoiding a moving obstacle (manual wheelchair passing in front), ascending and descending a 10° access ramp.
Araújo et al. [32]	Not mentioned	• Monitor screen.	• 3 scenarios for basic skills training: obstacle course, accessibility ramp and elevators.
Kenyon et al. [43]	Not mentioned	• TV screen	• 8 progressive stages of learning. Stages 4–7 combine use of both the video-based gamified training modules and the mobility device, with four specific video-based gamified training: Bubble Pop, Panda Run, Arrow Hero, and Skills Drive.
Zorzi et al. [34]	Unity3D	• Meta Quest 2 HMD.	• Environment loosely based on the WSTP [22] and the design is a virtual replica of the laboratory room used for the real-life tasks. • 5 tasks: forward driving on a straight line, backward driving on a straight line, forward slalom course, backward slalom course, and a maze.
Zorzi et al. [35]	Unity 3D	• Meta Quest 2 HMD.	• Realistic VR environment is a replica of a building. Tasks loosely based on the WSTP. Participants completed 5 tasks: driving forward 10 m, driving backward 10 m, driving through 3 obstacles placed 1.5 m apart (forward and backward), and driving through a maze. • Gamified VR environment is a non-realistic environment, based on a space shuttle. loosely based on the WSTP. Participants completed 5 tasks: driving forward 10 m, driving backward 10 m, driving through 3 obstacles placed 1.5 m apart (forward and backward), and driving through a maze. Contained the following elements of gamification: a target collection system, positive visual feedback upon task completion, space shuttle background sound, and audio feedback upon collision.

Table 2. *Cont.*

Study	Software	Virtual Environment	Description of Task
Gefen et al. [40]	MiWe developed with Unity	• Monitor screen.	• Navigating an elevator or car ramp, driving in a supermarket or mall, entering a narrow room or crossing a street via a first person, non-stereoscopic viewpoint. • Pausing at a defined spot for several seconds (dwelling) activates an elevator button or used cashier services. • The tasks incorporated elements from the WSTP.
Martins et al. [44]	Unity 3D	• Monitor screen.	• Obstacle course (virtual cones and blue tape were used to delineate the course), climbing up and down a ramp (two segments with a 3-degree slope, turn on a raised platform and return down through the same two segments; arrows were placed to indicate the direction), entering and exiting the two elevators (first elevator, simulates an operator opening the door as soon as the wheelchair approaches it and keep it open as much as necessary; second elevator, the door opens and closes at regular intervals, and the user must be able to maneuver inward and outward). • At the end of the task, a screen is displayed with the results, such as the time spent completing the course, the number of collisions performed during the task and the number of commands sent to the virtual wheelchair.
Salgado et al. [46]	Unity	• Oculus Rift HMD and monitor screen.	• Obstacle course; (b) navigation ramps; (c) manoeuvring within elevators. • User sees the virtual wheelchair in the first view perspective in the simulation. • User has the freedom to move around and see all the aspects of the virtual wheelchair.
Gefen et al. [41]	miWe developed using Unity	• Monitor screen.	• Routes, including both indoor and outdoor segments, designed to correspond to the distances and levels of difficulty required by the physical driving tests such as passing through a doorway, driving up or down inclined sidewalks, turning right and left corners and managing a ramp.

All studies developed completely virtual environments, except one which also had a mixed reality environment [36], and most of the designs attempted to represent a realistic environment. Examples of these environments range from a simple laboratory room [35], to a virtual replica of a rehabilitation unit of a hospital [30]. Only one study, [45], purposely developed an unrealistic environment, because the target users for their platform were children with multiple disabilities and adding realism could have caused difficulties to the children's perception. A description of the environments, their respective tasks and the software used to develop them can be found in Table 2.

Furthermore, Lam et al. [24], pointed out that most studies did not explicitly describe the environment, rather they referred to images instead. The lack of detail in the developed environment makes it difficult for clinicians to understand which VE would be appropriate for their patients. In the papers we reviewed, the environments and their respective tasks were described in detail, thus allowing clinicians for an easier interpretation of the benefits of the VE. For studies to provide a solid base for future research, a standard for the description could be proposed, outlining the essential details a paper should include.

3.4. Data Analysis Performed by the Studies

It is important to highlight the ways the various studies measured the participants' performance, as improvements on these measures could be used to assess the success of their training system. In order to analyse the acquired data, which most commonly includes collision [27,29,33,36,37,42,47,53], completion time [27–29,32–39,41,42,44,47,53,55], joystick events [28,32,34,35,37,46,47], and cybersickness [34–36,38,39,42,46,47,53], the studies used statistical analysis, specifically most used the ANOVA test [27,33,34,36,42,43,46,50,53,54] which compares the means of different samples. Lam et al. [24], similarly to us, found that data were collected quantitatively mainly for task completion time, number of collisions, number of joysticks movements, cybersickness, and the user's SoP. The most used test to determine cybersickness is the Simulator Sickness Questionnaire (SSQ) [58], which asks participants to assign a score (from 0 to 3) to 16 possible symptoms of simulator sickness. The measures acquired in the different studies are reported in Table 3, together with the purpose of the studies to justify why specific data was collected. The most popular type of acquired data is quantitative, which can be objectively analysed and interpreted, however, at times, qualitative data collection is needed for a better understanding of the participants' subjective experience of the VR application. In fact, some of the studies [30,48,50,51] collected data in terms of interviews and focus groups for an in-depth understanding of the usability and feasibility of their developed system.

Table 3. Data analysis performed by the studies.

Study	Purpose	Analysis
John et al. [42]	• To determine if the VR simulator had any effect on learning the driving skills needed to safely operate a real PW.	• Completion time and collision within a real environment before and after training. • An ANOVA statistical analysis was conducted. • An SSQ was also completed by the group wearing an HMD.
Rodriguez et al. [45]	• To see if the important elements of the environment are perceived as well as if the users follow the predefined path or they choose an own path.	• A session recording tool was used, which analysed virtual movements of the users and their path.
Younis et al. [29]	• Evaluation of effectiveness of the systems with the different controllers and improvement.	• The participants completed the environment twice, and during the second time the data was collected. • Completion time, collision, improvement measure. • An analysis of the data was then conducted.

Table 3. *Cont.*

Study	Purpose	Analysis
Bigras et al. [33]	• To assess whether better learning can be achieved if augmented feedback is provided compared to when there is no feedback. • Whether motor skills learned in the VE improve PW driving performance in real life.	• Quantitative data was gathered such as mean and standard deviation of completion time, number of collisions, and distance to the elevator button. • Statistical analysis (ANOVA test) was conducted to the collected data. • Real PW driving was assessed before and after training.
Devigne et al. [37]	• To evaluate different wheelchair driving assistance solutions and assess the user quality of experience and satisfaction.	• The IPQ and the NASA task load index, were completed after the training. • Joystick signals, virtual wheelchair position, speed, collisions, data from virtual sensor, time completion.
Salgado et al. [47]	• To understand the influence of jerk on cybersickness and its relation to electrodermal activity.	• A post training questionnaire consisting of the SSQ, iGroup Presence Questionnaires (IPQ), the System Usability Scale (SUS), the SAM (a non-verbal assessment technique that measures the valence, arousal and dominance to person's reaction to stimuli) and the NASA-TLX assessment, was also conducted. • Electrodermal activity, motion data, joystick events, completion time, collisions. • A statistical analysis of all the gathered data was then performed.
Hernandez-Ossa et al. [28]	• To understand if the VR system mimics a real EPW, and if the users can learn or improve their EPW driving skills, and transfer the skills learned in VR to real life.	• The UEQ and IPQ were conducted. • Statistical tests to compare the participant's driving performance were conducted. • User experience, completion time, path following performance, number of movements of eye-tracker and joystick signals.
Torkia et al. [48]	• To determine if the system conveys a sense of presence by allowing the user to feel as involved and immersed as in the real world.	• Subjective user experiences through an interview guide composed of two sections was used, the first section being three open-ended questions that inquired about the participant's overall experience, and the second section consisting of structured questions based on the IPQ.
Nunnerley et al. [30]	• To better understand the WUs' and clinicians' experiences of the developed system.	• Qualitative data was gathered about the WUs' and clinician's opinion on the system. Focus groups and individual interviews were used to collect data and were conducted within one to two weeks after VR trials.

Table 3. *Cont.*

Study	Purpose	Analysis
Day and John [36]	• To determine the validity of the system and the usefulness of MR over VR and control.	• Completion time, collision, and deviation from path was measured in a pre-training obstacle course. • A time penalty of one second was added for each cone hit or deviation from path. • After training in VR and MR, users reran the initial obstacle course, and the same metrics were taken. • Statistical analysis (ANOVA) was used to measure the difference of the performance before and after the training. • To determine the reaction time an online tool called the Human Benchmark was used. • SSQ before and after the training was completed.
Li et al. [27]	• To verify the effectiveness of the developed VR training system.	• Obstacle collision and time taken for completion in a pre- and post-training evaluation study. • The ANOVA test was applied comparing pre-evaluation data and post-evaluation data.
Thomas et al. [49]	• To identify the best training method based on a simple task, in a simulated environment on a 2D display) and in a virtual environment using a HMD.	• EEG data in the different conditions which included two sets of 1.5-h training (offline) sessions and one active (online) testing session.
Vailland et al. [39]	• Compare user performance in two conditions as well as to assess the impact of the simulator on SoP and cybersickness.	• Before VR: MSSQ. • During VR: user head trajectory and virtual wheelchair trajectory, velocities and accelerations, completion time. • After VR: SSQ, IPQ. • After real life: USE Questionnaire. • As statistical tests the Wilcoxon Rank Sum test and the Kruskal–Wallis test were used.
Chaar and Archambault [50]	• The usability of the manual miWe simulator, and its potential influence on MW skills training, according to clinicians and expert WUs.	• IPQ and short feedback questionnaire (SFQ). • Clinicians also completed the ease of use questionnaire (EOU). • Short interview on the same topics. • Descriptive statistics (mean and standard deviation) for the IPQ, SFQ and EOU (clinicians only). • Homogeneity of variance using Levene's test for IPQ and SFQ results. • One-way ANOVA comparing the responses of clinicians and MW users. • Mann–Whitney U comparing the responses of clinicians and MW users for the SFQ.

Table 3. *Cont.*

Study	Purpose	Analysis
		• Separate analysis for each of the IPQ's subscales, comparing users, clinicians, participants of the previous study without haptic feedback, (one-way ANOVA, with correction for unequal groups). • Deductive analysis for interviews.
Yan and Archambault [51]	• To examine the effects of providing AF as well as its delivery schedule on motor learning, retention, and transfer of MWC propulsion technique as a novel motor skill.	• Biomechanical variables of contact angle, push frequency, velocity. • All three outcomes were tested for normality using the Shapiro–Wilk test. • To observe differences between baseline and short-term/retention/transfer as well as between groups, a repeated, mixed model analysis of variance was run for each of mean contact angle and push frequency with one between-subject and two within-subject factors. • Non-parametric tests were used to observe differences in proportion of contact angles in range between baseline and short-term/retention/transfer as well as between groups.
Yang et al. [52]	• To investigate the feasibility and efficacy of the VR stimulator, to compare the performance of wheelchair propulsion between real and virtual tasks using the HMD-based intuitive VR stimulator, and to gather feedback from their subjective preferences.	• User feedback questionnaire, Presence Questionnaire (PQ). • Individual semi-structured interview following the completion of the VR wheelchair manoeuvres about the participant's satisfaction and to express their views on the VR wheelchair manoeuvres. • Thematic analysis was used to analyse interviews. • Data from the wheelchair propulsion experiments. • Propulsion kinematic variables were averaged and a one-way repeated measures analysis of variance, followed by Bonferroni post-hoc comparison test, was used to determine whether the HMD-based intuitive VR stimulator modified the kinematic characteristics of the wheelchair propulsion. • Descriptive statistics for the PQ satisfaction level based: involvement, sensory fidelity, adaptation/immersion, and interface quality.

Table 3. *Cont.*

Study	Purpose	Analysis
Mrityunjaya et al. [53]	• To compare the usability and the sense of presence, in a wheelchair simulator with the two display conditions.	• Number of collision and the time of completion for each trial. • Virtual WC position at each time point, which was used to calculate the distance to objects in each task. • SSQ, IPQ, Short-Feedback Questionnaire (SFQ). • Paired *t*-tests to compare display conditions for performance, presence (PQ), and perception of VR activity (SFQ). • Repeated measures ANOVA for SSQ. • Display preference questionnaire through descriptive statistics only (distributions).
Salimi and Ferguson-Pell [54]	• To assess motion sickness and virtual presence of participants when performing wheelchair manoeuvres in three systems, in addition to assessing the effect of up to four training sessions in acclimatizing to motion sickness.	• Motion Sickness Assessment Questionnaire (MSAQ), IPQ. • Normality checked using Shapiro–Wilk test. • MANOVA to test the null hypothesis for normally distributed data. • Non-parametric methods to test the null hypotheses for non-normally distributed data. • Data for groups involved were checked for having similar distributions, and for satisfying the Assumption of Homogeneity of Variances (AHV). • If assumptions were met, Kruskal–Wallis method was used to find whether there were any statistically significant results.
Faure et al. [55]	• To assess the effectiveness of a home-based miWe simulator training compared with a control group receiving video game-based training, in terms of PW driving skills, skills use in a real-world setting, and driving confidence.	• Wheelchair Skills Test Questionnaire (WST-Q, version 4.1). • Completion time for each WST task. • Wheelchair Confidence Scale (WheelCon) version 2.0. • Assistive Technology Outcomes Profile for Mobility. • Life-Space Assessment (LSA). • Normality was tested for all outcomes using the Kologorov–Smirnov (KS) test. • Between-group comparisons were made using a linear mixed model, with subject as random effect, pre/post evaluation as fixed, repeated effect, and simulator training/control as fixed effect.
Fraudet et al. [38]	• To assess differences in driving performances, driving ability, usability, mental workload, cybersickness, sense of presence, between VR and real-life conditions.	• The number of collisions. • The driving speed estimated by the time of completion. • NASA-Task Load Index (NASA-TLX), Ease of Use Questionnaire (USE), IPQ, SSQ.

Table 3. *Cont.*

Study	Purpose	Analysis
		• Quantitative analysis of data was expressed as mean and standard deviation and median and inter-quartile range. • Normality of the data by the Shapiro test. • Real and VR conditions were compared using the Wilcoxon test. • Post hoc analysis to explore any unforeseen correlations or patterns among these variables.
Araújo et al. [32]	• To evaluate power WUs' driving performance, aiming to enhance therapeutic practices and inform the decision-making process for power wheelchair prescription	• Power Mobility Road Test (PMRT) [16], which corresponds to the user's ability to complete the task. • Total time, number of collisions and number of joystick commands. • The user's performance in each task was compared before and after the proposed protocol. • Descriptive statistics to analyse data from proposed protocol. • This descriptive analysis supported the evaluation of the participants' performance. • Normal distribution tested with the Shapiro–Wilk test.
Kenyon et al. [43]	• To explore the use of the system to provide skills training to the children and document parental satisfaction with system.	• Frequency counts to report categorical demographic variables. • One-way repeated measures ANOVA to assess differences in ALP and WSC. • Post-hoc paired samples two-tailed *t*-test with a Bonferroni correction were used as appropriate to assess mean differences. • Mean COPM Performance and Satisfaction scores were assessed via a paired samples two-tailed *t*-test. • Frequency counts for total CSQ-8 scores were reported.
Zorzi et al. [34]	• To assess a VR-based training system with low-cost control equipment.	• Completion time and length of movement of the joystick. • Heart rate. • WSTP type questionnaire, SSQ and IQP. • Paired *t*-tests for Ljm, Ct, WSTP style questionnaire to compare real-life results from before and after VR training. • Reference scores compared for the SSQ and the IPQ. • One-way Welch ANOVA test with a Games Howell post-hoc analyses was conducted to measure any difference in HR between tasks.

Table 3. *Cont.*

Study	Purpose	Analysis
Zorzi et al. [35]	• To compare effects on user performance and retention of skills in the real world, after completing training in a non-gamified environment to a gamified environment.	• Number of collisions, completion time, and the total sum of movements of the joystick, HR. • The WSTP-type questionnaire, the SSQ, and the IPQ. • Independent-sample Mann–Whitney U for completion time and sum of movements of the joysticks to compare between the two groups. • Independent t-tests for the WSTP-style questionnaire and the number of collisions, N_c.
Gefen et al. [40]	• To assess simulator-based PM training and to determine its effectiveness in comparison to traditional training.	• Pearson Chi-square test and the Fisher exact test for the categorical variables. • Mann–Whitney test or independent samples t-tests for ordinal or interval/ratio variables (respectively). • Wilcoxon signed rank test for outcome measures, practice effects overall and within group differences. • Mann–Whitney test for pre- and post-practice for between group differences.
Martins et al. [44]	• To evaluate through feedback from experienced EPW users the usability of the proposed system and to verify the possibility of learning and using the multimodal controls developed in ADLs.	• Completion time, number of collisions, number of commands given in a specific input control.
Salgado et al. [46]	• To evaluate the quality of experience of a VR wheelchair simulator.	• Physiological responses were collected by using the Empatica E4 wristband, blood volume pressure, interbeat interval, Heart Rate, electrodermal activity, XYZ raw acceleration and the skin temperature. The skin conductance response was extracted from the EDA during the experience. The blood volume pulse derived from heart rate variability. The peripheral skin temperature was used to check if the EDA signal oscillations were not affected by external temperature changes. • Post-experience questionnaire based IPQ and SUS. • Subjective reporting via the self-assessment manikin (SAM), NASA-TLX assessment. • The Simulator Sickness Questionnaire (SSQ). • Joystick events, completion time and the number of collisions.

Table 3. *Cont.*

Study	Purpose	Analysis
		• One-way ANOVA to examine the differences between the groups for the physiological data. • Kruskal–Wallis H test and Mann–Whitney U test for explicit and performance data.
Gefen et al. [41]	• To validate a modified version of the MiWe simulator for children (MiWe-C), by investigating the relationship between real world and simulator performance.	• Wilcoxon signed rank for differences between the driving. • Completion time and number of collisions.

3.5. Conclusions Drawn by the Different Studies

Table 4 discusses the conclusions extracted from the analysed studies. While all the studies claimed their research to be promising for wheelchair training, four studies explicitly stated that the skills acquired with their simulators can be transferred to real life [28,34,42,48]. We found that no two studies performed by different authors assessed their systems in the same way, which agrees with Lam et al. [24], who concluded that there was a lack of standard measures to determine the effectiveness of a VR training system. Zorzi et al. [34] have noticed this limitation in the research and have suggested standardised approaches to conduct VR training. Furthermore, some studies suggest that VR can be used to complement real-life training [32,50], rather than being used to completely replace real-life training.

Table 4. Conclusions drawn by the studies.

Study	Conclusions
John et al. [42]	• The skills acquired in VR can transferred to the physical world given that navigation performances are improved.
Rodriguez et al. [45]	• The children with different disabilities that participated in the study were interested and able to use the VE. • They were also able to express themselves and learn.
Younis et al. [29]	• The authors claimed that their VR system can be used to train people to control wheelchairs using EEG signals. • The VR system has a great positive impact and wheelchair navigation improves over time.
Bigras et al. [33]	• Augmented feedback has a small effect on the effectiveness of the training. • Training in a VR environment results in retention and transfer of PW skills.
Devigne et al. [37]	• The VR environment provided a good sense of presence, and its use requires low cognitive effort, thus potentially allowing those with cognitive disabilities to take advantage of the developed system. • The activation of driving assistance algorithms significantly reduces the risk of collision.

Table 4. *Cont.*

Study	Conclusions
Salgado et al. [47]	• A smooth transient period of starting and stopping wheelchair movements resulted in a lower simulation sickness score, whereas sudden movements have a higher incidence of simulator sickness. • While the skin conductance response increased for low jerk effect, the heart rate, which represents oculomotor symptoms, decreased. • A correlation between heart rate measures and simulation sickness scores during collision periods was also found. • It was concluded that the lower the jerk response the higher the arousal but the lower the simulator sickness.
Hernandez-Ossa et al. [28]	• Most people learned and improved their skills by driving the virtual PW. • Overall, the VE represented reality closely. • The authors claimed that the skills learned in the VE can be transferred to real life.
Torkia et al. [48]	• The results indicate that the developed VE produced a feeling of presence while stimulating enjoyment. • It was found that enjoyment had a close relationship with interactivity. • Interactivity, as well as adding sounds, was believed to contribute to the sense of presence. • The authors claimed that their system may facilitate the acquisition of PW driving skills which can be transferred to real life.
Nunnerley et al. [30]	• The VR environment allowed WUs to learn wheelchair skills in a safe environment. • Clinicians and WUs agreed that the VR system is effective in teaching skills, especially if the system mimics a familiar environment, a community setting and is personalised. • The participants preferred a simple and easily usable environment, rather than one with haptic and vibration feedback. • It is essential for the system to be fun and engaging.
Day & John [36]	• VR performed better in reverse parking manoeuvres compared to MR. • MR was better in slalom tasks compared to VR. • Use of MR also reduces the risk of experiencing cybersickness. • The authors claim that repeated training with MR would result in significant improvement of wheelchair skills.
Li et al. [27]	• The personalised VR environments improved the user's ability to accomplish the real wheelchair tasks efficiently, compared to not going through a VR training.
Thomas et al. [49]	• There was a statistically significant improvement for both groups of participants trained in the virtual environments compared to the real environment, suggesting that users who train in simulated environments are better prepared for using a BCI in an environment with multiple active stimuli. • The participants who completed the VR-2DD training showed a significant improvement in their performance during the training process compared to the simple task participants. • No significant improvement was found between the VR-HMD and VR-2DD participants.
Vailland et al. [39]	• Regular users are able to perform a clinically validated task in a similar way regarding the completion time, both with a VR based power wheelchair simulator and a real power wheelchair. • All the participants feedback regarding the simulator and overall study was positive which is promising for the future.
Chaar & Archambault [50]	• The results help validate the miWe as a tool, ideally, to complement real-life MW training, allowing additional practice time in a variety of conditions, possibly with less clinical supervision.

Table 4. *Cont.*

Study	Conclusions
Yan & Archambault [51]	• Provision of AF about propulsion biomechanics during MWC training in a VR simulator is critical for retention and transfer of appropriate propulsion technique.
Yang et al. [52]	• This study demonstrated the feasibility and efficacy of the HMD-based intuitive VR stimulator for wheelchair propulsion efficiency. • This VR simulator has benefits, such as safety, motivation, and a variety of experiences of wheelchair maneuverability, and provides a training tool for WUs in a risk-free environment without any physical limitations indoors and outdoors.
Mrityunjaya et al. [53]	• Participants viewed the HMD as more appropriate for wheelchair training purposes. • Improvement in performance when participants used the HMD in the more complex tasks, as compared to the CM display. • More cybersickness with the HMD than with the CM. • Both displays may be appropriate for training wheelchair skills, so users should start with the HMD and can then switch to a CM, if needed.
Salimi & Ferguson-Pell [54]	• The training sessions significantly reduced the gastrointestinal and central motion sickness, as well as the total motion sickness level.
Faure et al. [55]	• Both groups improved joystick manipulation skills and PW driving confidence. • Participants who received the miWe simulator training also demonstrated a modest post-training gain in their WST-Q capacity, approximately equivalent to an improvement in 2 additional wheelchair skills.
Fraudet et al. [38]	• The proposed simulator is suitable for driving task scenarios in simulation, and show the value of the simulator for driving training applications. • Mental load remains high during virtual immersion, thus individuals with cognitive disorders who may be in difficulty. • Simulator can be a useful tool for patients unable to safely drive a PWC in order to help them to acquire the necessary driving skills in safe, adaptable, and repeatable conditions.
Araújo et al. [32]	• The use of VR simulator can be a support to assist the future PW user in training the basic skills to drive the PW. • The use of VR simulators could be a complementary tool to the PW prescription task and could be a promising approach in rehabilitation centres, supporting the assessment of user performance before dispensing a PW for use in a real environment.
Kenyon et al. [43]	• All participants appeared made improvements in both understanding how to use a PWC and their execution of PWC skills, suggesting that the IndieTrainer may be a beneficial tool to support children's acquisition of PWC skills while safely seated in their own customized manual wheelchair or adaptive stroller.
Zorzi et al. [34]	• The results of our study support our two hypotheses that acquisition of wheelchair driving skills can be accelerated using VR and that affordable technology can be used to train in VR driving skills which are transferable to real life. • The results demonstrate that affordable and accessible VR for wheelchair skills training can be effective and safe to use. • The proposed protocol for the VR training, based on the renowned WSTP, enables the training to be standardised, which, may increase its reliability and popularity.
Zorzi et al. [35]	• Gamification was found to significantly reduce levels of perceived cybersickness and HR. Reducing cybersickness through gamification may enhance the usability and sustainability of the VR training by enabling users to repeat and enjoy the training as long as they need.

Table 4. *Cont.*

Study	Conclusions
Gefen et al. [40]	• Powered mobility simulators provide children and adults practice opportunities to achieve proficiency that may not be available otherwise due to the cost of a powered chair for training, therapy time and safety concerns
Martins et al. [44]	• The simulator has potential to be used as a tool for ADL training, in a safe situation and free from the inherent risks of improper driving. • Participants demonstrated more confidence and efficiency in the use of the simulator as the experiment progressed. • Improvement of participants on the proposed training activity was observed. This may suggest that the presented EPW simulator has the potential to be used to introduce the EPW to users with no previous contact with the device and has the potential to help individuals train and develop the required motor, cognitive and visual skills to properly drive the EPW, while providing a safe training environment. • The inclusion of alternative controls with biomedical signals for driving the EPW is essential so that individuals with severe motor disabilities can use the simulator, improve their skills, and be able to drive their own EPW. • The simulator is a tool that can be used in rehabilitation centers and even at the EPW user's home to assist in learning and improving the skills of driving an EPW. • The multimodal simulator promotes the inclusion of people and helps to improve the quality of life and independence of EPW users.
Salgado et al. [46]	• The simulator with a non-immersive setup (2D monitor display) provides lower levels of immersion (presence), usability scores, and arousal response according to the SAM questionnaire (subjective data) and the physiological data (EDA). However, it requires less cognitive load, which is essential to improve the user QoE. • The dynamic motion of acceleration and deceleration were not perceptive for the non-immersive setup (desktop group) but were for the headset groups (immersive environment). • The physiological response in terms of HRV and EDA were better for the headset groups. • The immersive set-up with a smooth change of acceleration (s-shape profile) provided a better physiological response among the groups. • The dynamic immersive simulator without adequate motion configuration may lead to an unpleasant experience with a high cognitive load.
Gefen et al. [41]	• Simulator is an affordable, user friendly interface based on hardware and simulation software that can be used anywhere including at home and in school. An additional advantage is that continual adult assistance is not needed, so children can be independent when practicing. Can provide additional practice when powered wheelchairs are not available or there are time constraints. Introducing a simulator for practice could be in addition to powered mobility practice or as a sole practice mode.

3.6. Limitations Reported by the Different Studies

The limitations of the studies we reviewed are reported in Table 5. Nine articles did not mention any limitations [29,32,35,37,38,45,49,52,54]. Common limitations mentioned are cybersickness, a very common side effect of VR [36,42], small participant sample size [30,33,34,40,44,46,50], and having participants who were non-WUs [34,46,51,53,55]; limitations were mentioned but they were specific to the individual study. The systematic reviews [24,31] did not explicitly report any limitations related to the studies they reviewed.

Table 5. Limitations reported by the studies.

Study	Limitations
John et al. [42]	• Cybersickness.
Rodriguez et al. [45]	• Not mentioned.
Younis et al. [29]	• Not mentioned.
Bigras et al. [33]	• The use of a desktop monitor to show the VE as it is non-immersive. • The limited set of metrics used to measure PW driving performance. • Small sample size.
Devigne et al. [37]	• Not mentioned.
Salgado et al. [47]	• Lack of different training tasks for participants. • Lack of user experience and feedback evaluation.
Hernandez-Ossa et al. [28]	• The increase in the family wise error rate across the statistical analysis, which is the probability of coming to at least one false conclusion when testing various hypothesis, since multiple statistical tests were conducted for the same data set.
Torkia et al. [48]	• The generalisability of the study due to the clinicians and participants being experienced in PW driving. • Lack of outdoor activities, sound, consequences upon mistakes, limited visual field and use of a non-typical PW joystick.
Nunnerley et al. [30]	• Small sample size.
Day and John [36]	• The small field of view of the Microsoft Hololens used for MR. • Cybersickness in VR.
Li et al. [27]	• The VR hardware constraints which make long-term training result in visual fatigue and possible loss of concentration.
Thomas et al. [49]	• Not mentioned.
Vailland et al. [39]	• Performance evaluation based only on completion time.
Chaar and Archambault [50]	• Low number of participants. • While participants experienced the forces required to go uphill in the simulator, they did not feel any tilt.
Yan and Archambault [51]	• Low sample size made of inexperienced, able-bodied participants aged between 18 and 35. • Study investigated the effects of propulsion and providing feedback on contact angle and push frequency only. • as many MWC users may face additional needs and challenges during motor learning and MWC propulsion.
Yang et al. [52]	• Not mentioned
Mrityunjaya et al. [53]	• Healthy adult participants. • Tasks may have been too easy for the users.
Salimi and Ferguson-Pell [54]	• Not mentioned

Table 5. *Cont.*

Study	Limitations
Faure et al. [55]	• WST-Q capacity score were unexpectedly high at baseline for both groups. • Low sample size made of inexperienced users. • Lack of long-term follow up. • Lack of control group driving in the real world.
Fraudet et al. [38]	• Not mentioned.
Araújo et al. [32]	• Not mentioned.
Kenyon et al. [43]	• Open-label, single-arm study design used • Lack of a control group and randomization in the study design. • Assessors were not blinded during administration of the outcome measures. • Short duration of the study. • Did not address intervention fidelity.
Zorzi et al. [34]	• Short study duration. • Small sample size made of non-disabled participants.
Zorzi et al. [35]	• Not mentioned.
Gefen et al. [40]	• Small sample size. • Some comparisons of the study did not survive this procedure, mainly for the ALP outcome measure.
Martins et al. [44]	• Small sample size. • Lack of appropriate skill analysis protocols. • The use of EPW model which does not have diagonal movements.
Salgado et al. [46]	• Imbalance in the participant small in terms of numbers and gender and the lack of participants with impairment.
Gefen et al. [41]	• Lack of a better evaluation. • Bias of evaluation.

4. Discussion

Our review presented the state-of-the-art of VR technology for training WUs, with the aim of finding how it can complement real-life training. Our first objective is to identify gaps of real-life training methods that can be addressed by VR. We found that real-life training is often very controlled, and rarely the user is exposed to environments that allow to practice everyday skills. In terms of standardised assessment methods, the WSTP has been proven to be more effective than other training programs, however the evidence only supports this for the case of manual WUs. There are fewer studies that used WSTP for powered WUs, therefore there is a need to do more research on training methods for this population. Furthermore, the WSTP does not train the user to navigate around real-life environments, and distractions and obstacles are minimal [21]. VR could mitigate these limitations given that it is a more resource efficient training system, through being more cost effective and allowing the training of driving skills in virtual "dangerous" environments without putting the user in danger. Furthermore, as the WSTP has been proven to be effective for manual WUs in particular [22,23], and most VR training systems are designed for powered wheelchairs, it is reasonable to suggest that VR training systems may more suitable for powered WUs. In this regard, VR could complement real life training by developing VR systems based on the WSTP [21] for powered WUs.

Our second objective is to understand the main features of the VR training system. These include the virtual environment design, the hardware and the way the effectiveness of the system is assessed. However, due to the high design heterogeneity amongst VR studies, including differences between tasks and assessment methods, it is currently unclear what methods are more effective than others. Importantly, the target audience needs to be kept in mind when developing a VR environment, in fact, different users may well have completely different disabilities and therefore needs. Nonetheless, the use of realistic VR environments is common, suggesting that realism is an important aspect to consider when developing VR training applications. This is the case unless the target audience requires an abstract environment due to other conditions they may have [45]. Further, making the VR environment more engaging is also important for the training experience to be more enjoyable [48]. Regarding the tasks to complete, some studies laid out specific tasks for the users to complete, normally ranging in complexity. These studies proposed various parameters to assess the user's performance improvements and therefore to test the success of a system. The hardware used in the different studies also varied significantly. However, most studies used a joystick [28–30,32–48] or similar, as a controller for the VR navigation, given that VR training systems are predominantly developed for powered WUs. Some studies developed more accessible controller hardware such as BCI [29], eye-trackers [28], sensors on the wheels [27], to find the requirements of their users.

Although all studies aim to use VR as a system to teach driving skills which can be transferred to real-life scenarios, only fewer studies directly tested this by having the user navigate in a specific real environment before and after the VR training [32–36,39,42]. It is our advice that any future research should implement real-life tests comparing pre- and post-training performances to provide evidence of transferable skills. Additionally, each study used its own measures and analyses on which to base its conclusions on the usefulness of its system. The use of different data analyses makes it challenging to compare the outcomes of different systems and, therefore, to design better ones in the future. Standardised assessments would be of great interest and can be achieved by identifying a list of parameters that can be measured by any VR system. Task completion time and number of collisions are good candidates, as they are already commonly used; further, number of collisions are also used in the WST to assess whether skills have been acquired. In terms of statistical approaches to analyse the data, most studies used some sort of statistical analysis test, most commonly the ANOVA test; all types of analysis used by the studies are outlined in Table 3. Quantitative data analysis, such as the ANOVA test, could be useful to compare the performance of a new wheelchair users before and after VR training to determine whether acquisition of skills was successful in a standardisation protocol. A standardisation in which different studies acquire the same kind of data and perform the same statistical tests, as those we suggested, would allow for an easier comparison between the effectiveness of the system of different studies, and thus it would be easier to identify the areas in which different systems are effective.

Furthermore, to successfully use VR, its limitations must be considered. A major limitation found by the different studies is cybersickness, a common side effect of VR due to the disorientation to the user's sense of motion [56]. This effect is mainly observed when using a HMD for VR, as John et al. [42] found when comparing to monitor screens, and they found that HMD provoke much more symptoms of it. The assessment of cybersickness and the implementation of mitigating approaches should be incorporated into future VR training systems. At the moment, cybersickness is mainly assessed using self-reported questionnaires for SoP and users. However, some studies have shown that these aspects can be measured using implicit performance metrics such as users' HR during training [34,35,46,47]. In fact, Salgado et al. [47] found a positive relationship between simulator sickness scores and HR measures, thus showing that the perceived level of cybersickness corresponds to an increased HR. This provides a promising starting point for future research, where the training of wheelchair skills in VR can incorporate the analysis of physiological measurements to better understand how the user is feeling in real time. Future research should also focus on how to best limit cybersickness, rather than simply assessing it. It would be useful to include regular breaks throughout the training to avoid prolonged exposure to a system that may cause cybersickness. Further, cybersickness has been shown to be reduced when participants have a fixed object to focus on as it limits their field-of-view [35]. These findings provide a promising start point for developing systems that provoke limited cybersickness. Future research could also investigate how VR can serve as a comprehensive rehabilitation tool by incorporating applications that address needs beyond acquiring wheelchair driving skills. For example, transitioning to a wheelchair involves not only physical adjustments but also psychological challenges, and VR has proven to be effective in supporting mental health [59] and for cognitive rehabilitation [60]. Thus, VR could play a role in supporting people who are transitioning to wheelchair use adjust to the new changes of their physical body by stimulating self-compassion and empathy [61], in addition to supporting their physical rehabilitation.

5. Conclusions

This review aimed to present the most current VR technology for training WUs, to understand how training in VR can be used to complement conventional training in real life. To answer this, attention was given to existing systems, their respective outcomes, and limitations. All the studies analysed in this review demonstrate that VR has significant potential for wheelchair skill training, ranging from activities of simple navigation to more complex tasks such as moving within restricted spaces and with moving obstacles. In addition, developing VR for powered wheelchairs is more cost effective than for manual wheelchairs as to control the VR environment all that is needed is a joystick, while manual wheelchairs require platforms equipped with sensors to control navigation. Furthermore, VR has the potential to be used in conjunction with various navigation simulators for powered WUs, ranging from a classic joystick to eye tracking or EEG signals, thus allowing a wider group of users to benefit from virtual training. It was also found that real-life training for manual WUs is more effective using the WSTP, while for powered Wus it remains unclear whether a specific program is more effective than another. Thus, VR could complement traditional training methods, in particular for the training of powered WUs. However, a standardised approach for VR training should be developed as current methods vary greatly between one another. This review also suggests ideas for future research: more focus should be put on limiting the side effects of VR (such as cybersickness), finding a quantitative approach to assess how the user is feeling throughout the training, and developing standardised assessments of the effectiveness of VR systems in translating skills to the real word.

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