



The application of immersive technologies to alleviate lower-limb motor symptoms of Parkinson's disease: a scoping review and future research agenda

Zixin Tian¹ · Federico Colecchia¹ · Vanja Garaj¹

Received: 4 October 2024 / Accepted: 26 January 2026
© The Author(s) 2026

Abstract

The use of immersive technologies in conjunction with conventional rehabilitation methods holds potential for alleviating symptoms of Parkinson's disease. Recent research has highlighted the positive effects of multisensory stimuli within virtual immersive environments on maintaining motor function, as well as ways to mitigate the risks of and slow down undesired outcomes. However, existing reviews have primarily focused on the specific links between a single immersive technology and a particular set of symptoms. Such a restricted approach has led to a limited understanding of how different technology configurations and experiences can improve motor functions from a holistic perspective. To address this gap, this scoping review provides a comparative description and critical discussion of rehabilitation programmes and their outcomes across extended reality, including virtual reality, augmented reality and mixed reality, covering the full range of symptoms. The review emphasises the lower-limb motor functions and the benefits for individuals with Parkinson's disease engaging in tasks that simultaneously require motor and cognitive abilities. A set of design considerations and opportunities has been structured based on the review to guide future virtual immersive environments that enhance the overall rehabilitation experience by promoting social interaction while addressing issues of feasibility, safety and the effectiveness of physical exercise.

Keywords Parkinson's disease (PD) · Immersive technologies · Extended reality (XR) · Virtual reality (VR) · Augmented reality (AR) · Mixed reality (MR) · Rehabilitation · Physical therapy · Lower-limb motor functions

1 Introduction

Neurological diseases are one of the main sources of human disability worldwide and the disease with the fastest-growing prevalence is Parkinson's disease (PD) (Dorsey et al. 2018). Globally, PD has become the second most common neurodegenerative disease, affecting 2–3% of the global

population over the age of 65 (Poewe et al. 2017). Since the disease was first characterised by James Parkinson in 1817, the emphasis in clinical research has been on understanding and mitigating motor symptoms, including bradykinesia, muscle rigidity, resting tremor, postural instability and the disruption of gait (Goetz 2011; Balestrino and Schapira 2020). Research has shown that the loss of neurons in the substantia nigra section of the brain, associated with Lewy body pathology, correlates strongly with the severity of motor features of the disease, particularly bradykinesia (Greffard et al. 2006) and muscle rigidity (Vingerhoets et al. 1997). In addition to motor manifestations, PD is often associated with different neurological dysfunctions (Dickson 2018), including cognitive impairment, psychiatric symptoms, sleep disturbance, autonomic dysfunction, olfactory dysfunction, fatigue and pain (Khoo et al. 2013).

Most pharmacological interventions, especially those relying on levodopa, are effective in the management of PD.

✉ Federico Colecchia
Federico.Colecchia@brunel.ac.uk

Zixin Tian
Zixin.Tian@brunel.ac.uk

Vanja Garaj
Vanja.Garaj@brunel.ac.uk

¹ Brunel Design School, College of Engineering, Design and Physical Sciences, Brunel University of London, Kingston Lane, Uxbridge, Middlesex UB8 3PH, UK

Nonetheless, individuals with PD often still exhibit impairments, both motor and cognitive in nature (Lees et al. 2009; Sprenger and Poewe 2013). Such impairments include postural instability, freezing of gait (FoG) (Lees et al. 2009), speech disturbances, psychosis and emotional problems (Seppi et al. 2011). The impact of such symptoms extends throughout the disease cycle, from early to advanced stages (Goetz and Pal 2014), and negatively affect individuals' social activities and quality of life (Moore et al. 2007). Non-pharmacological treatment modalities should therefore be increasingly pursued to help manage both motor and non-motor manifestations of the disease (Bloem et al. 2015). Among such modalities, the most widely used is rehabilitation. The World Health Organisation (WHO) has defined rehabilitation as "a set of interventions designed to optimise functioning and reduce disability in individuals with health conditions, in interaction with their environment" (Mills et al. 2017). The application of rehabilitation to individuals with PD is regarded as adjunct to pharmacological treatment and surgery. Rehabilitation can help maximise motor and cognitive functions, thereby reducing and postponing the impact of disease complications such as panic attacks, anxiety, depression, dopamine dysregulation syndrome and impulse-control disorders (Van Der Kolk et al. 2019; Simonet et al. 2019).

Physical rehabilitation methods for individuals with PD relying on immersive technologies have been utilised for some time (Asadzadeh et al. 2021). 'Immersion' is typically achieved by combining different technologies in a way that allows individuals to receive real-time feedback (e.g., visual, auditory and tactile) reflecting their body movements within a virtual environment. This mechanism often enables natural user interactions resembling those that would occur in a physical environment (Tieri et al. 2018). The systems used for immersive rehabilitation include: (1) 2D interactive renderings of 3D virtual environments on a digital screen (usually providing a lower degree of immersion); (2) immersive virtual reality (VR) systems where interaction with the virtual environment is typically enabled via the use of handheld and wearable controller devices; (3) augmented reality (AR) where users can use a broader range of body movements (Tieri et al. 2018). The evaluation of the effectiveness of interventions developed using such systems has often relied on empiricist approaches with the emphasis on observed improvements in terms of behaviour and experience (Petzinger et al. 2013). More recent research has focused on generating evidence around the neurological basis of changes induced in individuals with PD (Droby et al. 2020; Maidan et al. 2018). This research has highlighted that rehabilitation methods based on immersive technologies can activate specific brain regions in individuals with

PD, thereby enhancing neural functional connectivity (Abbruzzese et al. 2016).

Published review articles in this field so far support the positive effects of the application of immersive technologies for the rehabilitation of individuals with PD with reference to: (1) rehabilitation using specific repetitive and task-oriented training that have been shown to be effective neurorehabilitation methods (Abbruzzese et al. 2016); (2) enriched immersive environments permitting individuals with PD to perform cognitive and motor activities simultaneously (Maidan et al. 2017); (3) immersive rehabilitation environments simulating real-world activities and providing enhanced ecological validity compared to conventional therapy (Camara Lopez et al. 2016; Lange et al. 2012); (4) activities that are unsafe to practice during training sessions in physical environments, which can instead be safely performed using immersive technologies (Pazzaglia et al. 2020) and (5) additional benefits for individuals with PD practicing over longer periods, as they often perceive immersive rehabilitation as more interesting and more enjoyable than conventional approaches (Pazzaglia et al. 2020).

However, most review studies to date focus on the specific rehabilitation effects of a single technology (VR or AR) in relation to a particular PD symptom or a limited combination of symptoms (Canning et al. 2020; Cikajlo and Peterlin Potisk 2019). The primary aim of this paper is therefore to address the need for a holistic review of research on the effects of immersive motor rehabilitation techniques in individuals with PD. To achieve this aim, the paper analyses the differences, advantages and disadvantages of the full range of immersive technologies (XR: VR, AR and MR) and relevant experiences for alleviating lower-limb motor symptoms of PD across the entire symptom spectrum. Additionally, the paper examines the differences between immersive technology-augmented rehabilitation methods and conventional approaches in terms of the benefits they present to individuals with PD.

There has been significant development in immersive PD rehabilitation methods and researchers have suggested that newly developed immersive PD rehabilitation methods should be specifically designed with the behavioural patterns and needs of individuals with PD in mind (Ehgoetz Martens et al. 2015b). Still, no review study so far has compared and analysed rehabilitation programmes and implementation plans. As a result, current immersive PD rehabilitation methods and programmes have not been the focus of user-centred design research addressing the issues of training task design as well as training duration and frequency.

To fill this gap, this review article has identified differences in the design and implementation of rehabilitation programmes across experimental studies, as well as advantages and disadvantages in terms of rehabilitation effects.

The article also provides a unified list and systematic discussion of the rehabilitation effects of different immersive technologies on the management of lower-limb PD symptoms. This perspective has enabled the identification of variations across lower-limb immersive PD rehabilitation approaches and highlighted relevant design opportunities. The insights generated by this review study hold potential to inform future user-centred design research focusing on innovative immersive PD rehabilitation programmes.

2 Immersive technologies

This review has highlighted a frequent misconception about the very nature of ‘VR’ applications, in that simpler video games in which virtual objects are rendered on a 2D screen are sometimes confused with proper VR applications. VR typically involves the use of handheld controllers and/or hand gestures, providing the user with a much higher degree of immersion and interactivity within the experience (Iosa et al. 2012; Tieri et al. 2018). However, with the increasingly mature and widespread application of 3D visual technology in video games, the boundaries between proper VR and methods of projecting 3D virtual objects onto 2D screens have gradually become blurred (Iosa et al. 2012). Systems relying on 2D displays for providing visual stimulation, sometimes referred to as ‘non-immersive VR’ (Mirelman 2016; Pelosin et al. 2020), typically include one or more cameras to detect user movements in real-time and create interactive computer-generated simulations. Such systems often allow users to “project themselves within computer-generated environments complete with real-time interactive features” (Pelosin et al. 2020). Relevant devices include Nintendo Wii (Kashif et al. 2022a; Lee 2018) and Kinect X-Box (Barbosa et al. 2018; Palacios-Navarro et al. 2015; Pelosin et al. 2020), which can project 3D virtual environments onto 2D displays.

Fully immersive VR systems typically include more advanced interfaces permitting participants to experience self-contained, computer-generated 3D virtual environments. Users can typically use their entire body to interact with the virtual world, performing actions such as exploring the virtual space and moving within it, as well as grasping and reshaping 3D virtual objects (Tieri et al. 2018; Wang et al. 2020). The users’ experience of real-time interaction with the virtual environment typically relies on multiple sensory channels, including auditory, visual, tactile and—in some cases—taste and smell (Tieri et al. 2018). In the context of these VR experiences, participants are completely immersed in the virtual environment and have no understanding of the physical environment they are in (Tieri et al. 2018).

As a distinct approach to VR, AR focuses on overlaying virtual objects onto the user’s view of the physical environment, which enables users to interact with both real and virtual objects simultaneously (Tieri et al. 2018; Wang et al. 2020). The advantage is that sensory cues originating from the virtual environment are experienced by users within familiar scenes, which makes the experiences, including the users’ reactions and feelings, more natural (Tieri et al. 2018; Wang et al. 2020). Both VR and AR require the use of displays. VR is typically accessed through Head-Mounted Displays (HMDs) (i.e., headsets) and AR through HMDs or screen-based analogues (e.g., smartphones and tablets). Both technologies often rely on additional handheld controls and wearable devices to enhance the user’s interaction with the environment (Tieri et al. 2018).

More advanced immersive systems typically combine specialised glasses with high-resolution rear projection screens, providing users with a constant projection surface (Tieri et al. 2018). Examples include immersive VR projection systems that consist of infrared motion-capture cameras combined with Powerwall screens. Powerwall screens are interactive visualisation tools featuring multiple interconnected display screens to support workflow integration and collaboration (ST Engineering ANTYCIP | Simulation & Virtual Reality Company n.d.; Oh et al. 2018). Another example is the Cave Automatic Virtual Environment (CAVE) (Cano Porrás et al. 2019; Cruz-Neira et al. 1993), a 360° room composed of multiple interconnected rear projection screens with an ultrasonic system for tracking the user’s perspective and for generating real-time images that are projected on the room’s walls, floor and ceiling.

The term ‘Mixed Reality’ (MR) is often used in relation to a range of immersive technologies with varying degrees of integration between virtual and physical environments (Milgram et al. 1995; Milgram and Kishino 1994; Speicher et al. 2019), although consensus on a precise definition of MR has not been reached (Speicher et al. 2019). Examples of views about MR from published research include the following: (1) MR is defined as a “reality-virtuality continuum” that connects the completely virtual world with the entirely physical world (Milgram et al. 1995; Milgram and Kishino 1994) and is sometimes seen as an incarnation of VR; (Speicher et al. 2019); (2) MR is understood as a combination of VR and AR using the same hardware and software equipment (Rokhsaritalemi et al. 2020; Speicher et al. 2019); (3) MR is treated as an enhanced version of AR enabling richer experiences with physical environments using dedicated hardware (Rokhsaritalemi et al. 2020; Speicher et al. 2019); (4) MR is seen by some as a synonym for AR (Speicher et al. 2019). Examples of MR implementation rely on Microsoft HoloLens 2 (Microsoft HoloLens | Mixed Reality Technology for Business n.d.), which has

been extended to a range of MR devices suitable for Windows systems, as well as MR toolkits and applications that support these devices (Speicher et al. 2019).

Extended reality (XR) is a general term referring to immersive technologies that enable combined physical and virtual experiences as well as human–machine interactions, generated by the combination of wearable devices and computer technologies (Colman et al. 2024; Lareyre et al. 2024; Ota et al. 2024). Recently, the term XR has been used as an umbrella term for all immersive technologies, including AR, VR, MR and everything in between (Jiang et al. 2024). XR, as an innovative technology, is considered the future of mobile computing. It has the potential to integrate smartphones, AR glasses and VR headsets into a single mobile device, thereby becoming a disruptive and ubiquitous technology like smartphones previously did (Qualcomm n.d.).

3 Method

3.1 Literature review

This review article follows the Scoping Review (ScR) framework outlined by Arksey and O'Malley (2005) and refined by Levac et al. (2010), Colquhoun et al. (2014) and Daudt et al. (2013). The review also adheres to the Preferred Reporting Items for Systematic Review (Moher et al. 2009), which focuses primarily on helping authors clearly report the reasons for the review, what they did (the 'interventions') and what they found (the effects of the 'interventions') (Page et al. 2021).

3.2 Scoping review

Compared to systematic reviews, which often address specific questions, scoping reviews are exploratory in nature and better suited for understanding the breadth of a concept or field of study. They are frequently used to generate more specific recommendations for future research (Peters 2020). This review has employed the first five steps in the overall process of the scoping review, namely: (1) identification of the research questions; (2) identification of relevant literature; (3) study selection; (4) charting the data and (5) collecting, summarising and reporting the results (Arksey and O'Malley 2005).

3.3 Literature search

Suitable databases of scholarly publications were identified. The databases used for this review study, including clinical medicine, neurology and psychology publications, are the following: MEDLINE (via PubMed),

the Cumulative Index to Nursing and Allied Health Literature (also known as CINAHL, PsycINFO or EBSCOhost), the Cochrane Central Register of Controlled Trials (also known as CENTRAL or Cochrane Library), Physiotherapy Evidence Database Score (PEDro), Web of Science or Web of Knowledge, IEEEExplore and Scopus. The literature search was designed to include journal articles, books and conference proceeding papers. Papers written in English and published between 01/01/2002 and 31/12/2024 were considered. The article title, keywords and abstract were searched using relevant keywords, as detailed below.

At the beginning of the study, the authors jointly defined the details of the search strategy based on findings from previous research on applications of immersive technologies to alleviate PD symptoms. The initial search keywords were defined according to their relevance to three key aspects of the study, namely: (1) the disease itself ("Parkinson's disease" OR "Parkinson disease" OR "PD" OR "parkinsons disease" OR "parkinsonism" OR "parkinsons"); (2) immersive technologies ("virtual reality" OR "VR" OR "immersive technologies") and (3) the evaluation of rehabilitation effectiveness ("rehabilitation" OR "therapy" OR "intervention" OR "physiotherapy" OR "physical therapy"). These groups of keywords were combined using AND operators in the search to ensure the relevance of the results to all three aspects.

The literature search returned several review studies on immersive technologies. Several recent systematic reviews and meta-analyses have discussed the application of VR to PD rehabilitation with reference to both motor and cognitive symptoms (Chuang et al. 2022; Lu et al. 2022; Sevchenko and Lindgren 2022). However, a knowledge gap needs to be addressed in relation to the use of different immersive technologies, including AR and MR, for PD rehabilitation and for alleviating PD symptoms. This review study was conducted to fill this gap, with an emphasis on lower-limb motor symptoms that negatively affect daily activities, such as those influencing walking speed, stride length, gait stability and balance, risk of falls, posture control, difficulty turning and freezing of gait. The coverage of immersive technologies for the purpose of this review was subsequently expanded to include AR and MR, considering the scope of the publications returned by the initial search. The query used for the database search is the following: ("Parkinson's disease" OR "Parkinson disease" OR "PD" OR "parkinsons disease" OR "parkinsonism" OR "parkinsons") AND ("virtual reality" OR "augmented reality" OR "mixed reality" OR "immersive technology") AND ("rehabilitation" OR "therapy" OR "intervention" OR "physiotherapy" OR "physical therapy").

3.4 Study selection

Article selection involved two steps. In the first step, inclusion and exclusion criteria were applied based on the occurrence of keywords in the title and abstract. In the second step, articles were required to document a PD-related lower-limb rehabilitation programme using immersive technologies, to present a clear implementation plan for the programme and to include a detailed discussion of the programme's effectiveness based on a qualitative and/or quantitative clinical evaluation trial. Articles not written in English were excluded, as were those exclusively presenting research plans without reporting results in relation to lower-limb motor improvement. In addition, the authors jointly decided to exclude all articles not immediately relevant to the research topic of this review, based on full-text analysis. Finally, the full text of all articles retained after this initial filtering stage was analysed.

3.5 Charting the data

An information extraction protocol was defined based on a full-text analysis of the articles (including research materials, methods and results). A pilot analysis was conducted on seven articles to assess the suitability of the protocol. Relevant information was collected, particularly with reference to hardware technologies and the design of different software solutions for rehabilitation within immersive environments, as well as information about the effects of varying rehabilitation programmes on individuals affected by PD. The information included: author(s) and year of publication; rehabilitation hardware equipment and software; experimental methods (including whether a control group was involved); rehabilitation protocol; number of subjects involved in the study; their age range; their gender ratio; subject disease severity, evaluated as discussed further in the text; inclusion and exclusion criteria for participant recruitment; rehabilitation outcomes in terms of balance, gait, risk of falling and perceived quality of life, among others. Where there was uncertainty about the information extracted from the articles, consensus was reached following discussions among the authors. Please refer to the Table S1, Appendix: Supplementary Material in the online resource for details about the extraction form.

3.6 Collating, summarising and reporting the results

Publications were categorised and a narrative for the review was developed based on the Preferred Reporting Items for Systematic Reviews and the scoping review framework (Thomas and Harden 2008). Intervention types, intervention

designs and rehabilitation outcomes were analysed and compared to identify opportunities for further development in relation to the application of immersive technologies for alleviating lower-limb PD symptoms.

4 Results

A total of 7 databases of scholarly publications were searched and 1493 articles that met the inclusion criteria were identified. 106 of these articles were relevant to the research topic of this review. An overview of the search strategy is presented in Fig. 1, which outlines all steps in the article selection process, including the search keywords used across different databases, additional inclusion and exclusion criteria and the number of articles retained at each stage of the selection.

4.1 Characteristics of the selected studies

90 international peer-reviewed journal articles, 15 conference proceedings papers and one book chapter were included, i.e., 106 publications in total. The geographic regions where the studies were conducted include Europe, Asia, North America, Latin America, Oceania and Africa (Mirelman et al. 2016). The number of published studies focusing on applications of immersive technologies to PD rehabilitation has increased in recent years, reflecting a higher degree of maturity of the technologies. In particular, the number of relevant studies from 2019 onwards ($n=62$) is significantly greater than the total number of studies published from 2002 to 2018 ($n=44$).

A summary of the key information extracted from the reviewed studies is provided in Table 1 and in Table S1, Appendix: Supplementary Material in the online resource. The appendix summarises all 106 studies, while Table 1 provides a "preview" by featuring only the first nine studies from the appendix. Both Table 1 and Appendix A list the studies in alphabetical order by study title. The summarised information primarily relates to the study characteristics such as the design of the rehabilitation programmes, the characteristics of the study participants and the outcomes of the studies in terms of benefits to individuals with PD.

4.2 Participant characteristics

Groups of 20–60 individuals with PD were typically involved in the studies reviewed, with sample size lower than 10 reported in 13 studies (Brandín De La Cruz et al. 2020; Bosch-Barceló et al. 2024; Cornejo Thumm et al. 2021; Di Biagio et al. 2014; Kashif et al. 2022c; Krieger et al. 2013; Lee et al. 2023; Loureiro et al. 2012; Palacios-Navarro et

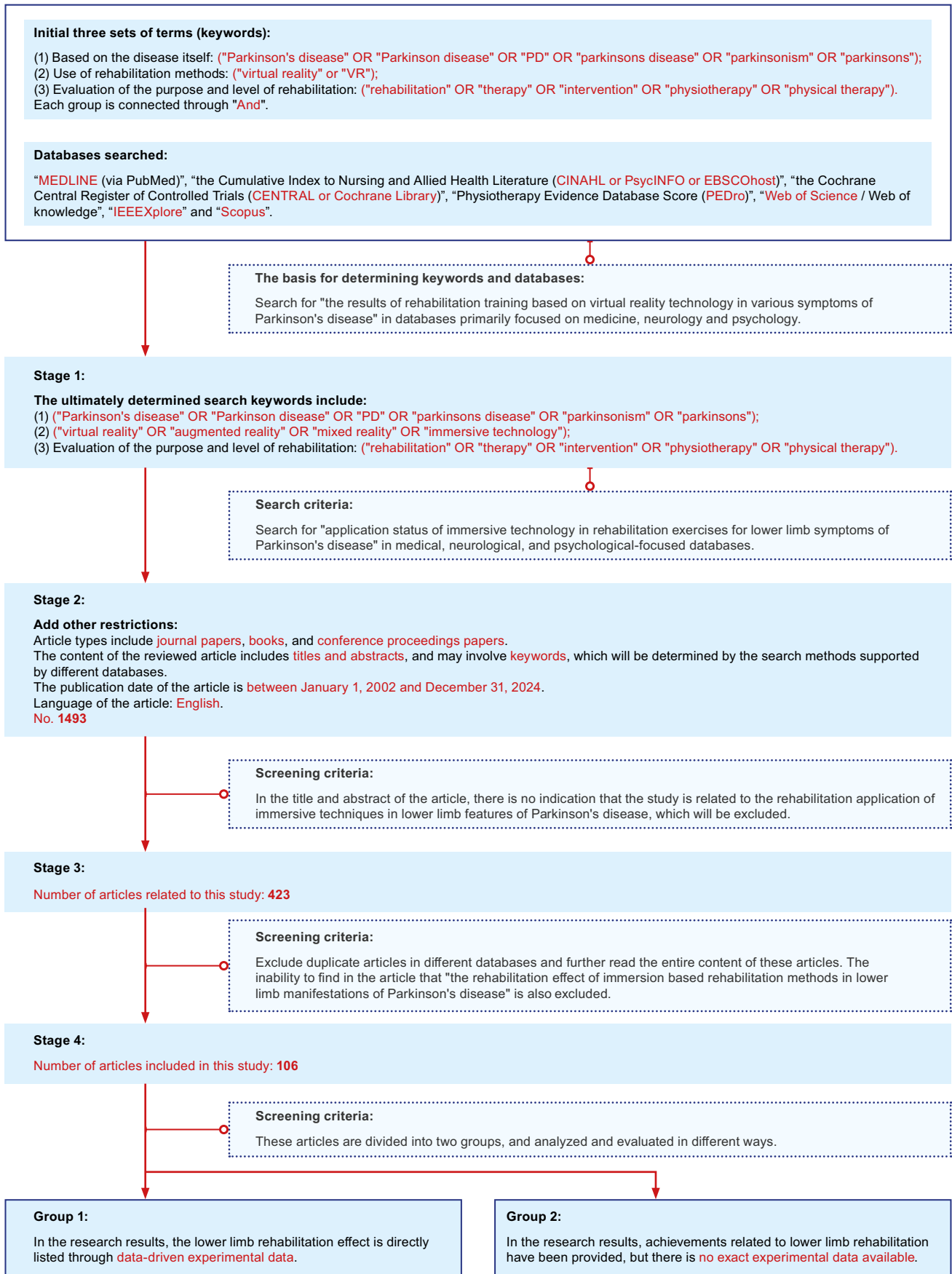


Fig. 1 Overview of the search strategy and selection criteria adopted for the inclusion of published articles into this review study

al. 2015; Pompeu et al. 2014; Sadek et al. 2024; Tunur et al. 2020; Wang et al. 2020) and sample size above 100 reported in 5 studies (Bekkers et al. 2020; Del Din et al. 2020; Mirelman et al. 2016; Van Der Kolk et al. 2019). The two studies with the largest sample size involved 130 participants each (Mirelman et al. 2016; Van Der Kolk et al. 2019). The participants' age ranged from 50 to 85 years (Kashif et al. 2022a; Mirelman et al. 2016). No gender bias was reported in relation to the recruitment and grouping of study subjects and established randomisation methods were applied (Ogundele et al. 2018; Pazzaglia et al. 2020).

The studies focused on the effects of physical therapy on lower-limb PD symptoms; participants were able to walk independently (Ehgoetz Martens et al. 2015b; Hajebrahimi et al. 2022; Pelosin et al. 2020) and did not suffer from severe cognitive impairment (Mini-Mental State Examination score ≥ 24) (Palacios-Navarro et al. 2015; Suarez et al. 2011). Participant exclusion criteria differed across studies, depending on the study setting and purpose. Exclusion criteria were typically based on the presence of orthopaedic, cardiovascular or neurological diseases affecting postural stability, severe movement disorders (Amprimo et al. 2022; Goh et al. 2021), visual impairments and a history of PD surgery (Kashif et al. 2022a). Some studies also excluded participants with recent experience of immersive physical therapy (Brachman et al. 2021; Kashif et al. 2022a; Palacios-Navarro et al. 2015).

Standard criteria for clinical diagnosis of PD disease severity are the Hoehn and Yahr (H+Y) scale (Gilbert and Khemani 2022) and the Unified Parkinson's disease rating scale (UPDRS) (Martínez-Martín et al. 1994; Movement Disorder Society Task Force on Rating Scales for Parkinson's disease 2003). These methods were typically used to screen for disease severity in individuals with PD who met the study inclusion criteria (Júlio et al. 2022; Kashif et al. 2022b; Nuic et al. 2018; Tunur et al. 2020). The H+Y scale primarily focuses on PD motor symptoms. The scale categorises the disease's development into five stages (Gilbert and Khemani 2022), as outlined in Table 2. Compared to the H+Y scale, the UPDRS also considers non-motor PD manifestations (Martínez-Martín et al. 1994; Movement Disorder Society Task Force on Rating Scales for Parkinson's Disease 2003). Most studies selected individuals with PD at early or medium stages of the disease (Campo-Prieto et al. 2021; Júlio et al. 2022; Kashif et al. 2022b), corresponding to stages 0–3 of the H+Y scale. At the time this review study was conducted, only five studies focused on the outcomes of immersive lower-limb rehabilitation involving individuals with advanced PD (scores greater than three on the H+Y scale) (Badarny et al. 2014; Feng et al. 2019; Hara

et al. 2024; Nuic et al. 2018; Pullia et al. 2023). Instead of relying on the X+Y and UPDRS scales for assessing disease severity, other studies have inferred disease severity from disease duration, namely the time elapsed from disease onset to diagnosis (Albiol-Pérez et al. 2017; Severiano et al. 2018; Zeigelboim et al. 2021). Given the significant degree of variability in the relationship between disease duration and symptom severity (Gilbert and Khemani 2022), the use of the X+Y and UPDRS scales should be preferred for estimating disease severity.

4.3 Immersive technologies and immersive rehabilitation programmes

The immersive technologies and hardware devices applied in the studies included in this review are presented in Table 3. The table includes information about devices and interventions used in co-interventions, as well as the interventions used as comparisons. Ninety-six studies applied VR technology. Specifically, fifteen studies used VR HMDs by various manufacturers (Krieger et al. 2013), including Oculus Rift DK2 (Gómez-Jordana et al. 2018); VR Box (Schuch et al. 2020); Oculus Go (Goh et al. 2021); Oculus/Meta Quest II (Rodríguez-Fuentes et al. 2024); Meta Quest III (Cancela-Carral et al. 2024); HTC Vive (Besharat et al. 2022; Janeh et al. 2019; Lheureux et al. 2020; Yamagami et al. 2023); HTC Vive Pro (Yun et al. 2023); Sensics zSight (Ehgoetz Martens et al. 2015a, b); Motigravity (Brandín De La Cruz et al. 2020) and MediVR KAGURA (Hara et al. 2024). Seven studies used VR devices and technologies based on the Computer Assisted Rehabilitation Environment (CAREN), such as CAREN Dome, CAREN Base, V-Gait and C-Mill (Calabrò et al. 2020; Cano Porras et al. 2019; Formica et al. 2023; Impellizzeri et al. 2022, 2024; Pullia et al. 2023; Wang et al. 2022). One study combined neurologic music therapy with CAREN (Impellizzeri et al. 2024).

Fifteen studies used other technologies and hardware devices for VR rehabilitation. Two of these studies used VR based on the Neuromotor Rehabilitation System NIRVANA (Imbimbo et al. 2021; Pazzaglia et al. 2020). One study used VR based on Lokomat (Fundarò et al. 2019). The remaining twelve studies did not specify the VR technology and hardware devices used (Bekkers et al. 2018; De Lima et al. 2021; Feng et al. 2019; Gemin et al. 2017; Huang et al. 2020; Lee 2019; Mirelman et al. 2011; Shih et al. 2011; Simcsik et al. 2021; Suarez et al. 2011; Van Der Kolk et al. 2019; van Wegen et al. 2015). Among these studies, three combined treadmill training (TT) (Bekkers et al. 2018; Brandín De La Cruz et al. 2020; Mirelman et al. 2011) and two combined transcranial direct current stimulation (tDCS) (De Lima et al. 2021; Simcsik et al. 2021).

The immersive virtual reality experiences in 59 trials were enabled by delivering visual stimuli through two-dimensional displays, commonly referred to as non-immersive VR or semi-immersive VR (Goffredo et al. 2023a, b; Maranesi et al. 2022). The hardware devices involved were mainly Nintendo Wii (Albiol-Pérez et al. 2017; Di Biagio et al. 2014; Fearon et al. 2017; Killane et al. 2015; Lee 2018; Loureiro et al. 2012; Mendes et al. 2012; Severiano et al. 2018; Zeigelboim et al. 2021), usually used with Nintendo Wii balance board (adopted in 26 studies), Microsoft X-Box Kinect (Amprimo et al. 2022; Nuic et al. 2018; Palacios-Navarro et al. 2015; Pompeu et al. 2014; Ribeiro Bacha et al. 2021; Souza et al. 2018) (used in 24 studies) and other unspecified 2D screen-based VR devices and technologies (Sadek et al. 2024; Su et al. 2014). Ten of these studies combined the immersive hardware devices with TT (Bekkers et al. 2020; Bosch-Barceló et al. 2024; Cornejo Thumm et al. 2021; Droby et al. 2020; Del Din et al. 2020; Lau et al. 2022; Maidan et al. 2018; Mirelman et al. 2016; Pelosin et al. 2020, 2022) and three combined Wii-based VR with motor imagery (Kashif et al. 2022a, b, c). One study used both Kinect-based VR and Wii-based VR for a comparison (Alves et al. 2018).

Thirteen studies focused on AR. The technologies and hardware devices used included HMD-based AR (Badarny et al. 2014; Krieger et al. 2013), such as Google Glass (Lee et al. 2023; Tunur et al. 2020), HTC Vive Pro in AR mode (Wang et al. 2020), Magic Leap 2 and Microsoft HoloLens 2 (Alberts et al. 2023; Hardeman et al. 2024; Janssen et al. 2020; Rosenfeldt et al. 2025), as well as other unspecified AR devices (Araújo et al. 2023; Bell Boucher et al. 2013; Pisano et al. 2024; Smaili et al. 2019). One study combined tDCS with AR training (Pisano et al. 2024). Another study combined AR intervention with HMD-based VR training (Krieger et al. 2013). In addition, two studies compared the rehabilitation effects of AR and Nintendo Wii-based VR (Araújo et al. 2023; Smaili et al. 2019).

From the perspective of immersive training programme design, among the ninety-two immersive rehabilitation outcome evaluation trials targeting PD lower-limb symptoms, twenty-one trials used customised or specialised immersive rehabilitation software solutions developed and designed specifically for PD lower-limb movement symptoms (Alberts et al. 2023; Badarny et al. 2014; Bekkers et al. 2020; Bosch-Barceló et al. 2024; Cornejo Thumm et al. 2021; Del Din et al. 2020; Droby et al. 2020; Goh et al. 2021; Isernia et al. 2020; Lau et al. 2022; Lee et al. 2023; Maidan et al. 2018; Mirelman et al. 2011, 2016; Pelosin et al. 2020, 2022; Rosenfeldt et al. 2025; Tunur et al. 2020; Van Der Kolk et al. 2019; Wang et al. 2020; Yun et al. 2023). The remaining studies mostly used other commonly used serious games on the market (Barbosa et al. 2018; Loureiro

et al. 2012; Ribeiro Bacha et al. 2021; Santos et al. 2019; Souza et al. 2018) and other immersive training applications designed for general physical therapy, including those suitable for improving a wider range of movement disorders, training and recovery of physical fitness or physical functions (Brandín De La Cruz et al. 2020; Calabrò et al. 2020; Cancela-Carral et al. 2024; Hardeman et al. 2024; Pisano et al. 2024; Wang et al. 2022), as well as more specific neurological disorders (Goffredo et al. 2023a, b; Imbimbo et al. 2021; Maranesi et al. 2022; Pazzaglia et al. 2020).

4.4 Rehabilitation outcome measures

Ninety-two studies demonstrated the specific rehabilitation outcomes of different immersive interventions on various PD lower-limb symptoms. Table 4 presents the detailed outcome measures used to evaluate the effectiveness of immersive PD lower-limb rehabilitation interventions across different studies. The most frequently used test indicators were balance (41 studies), gait (26 studies), gait speed (22 studies), quality of life (17 studies), falls (16 studies), gait performance under dual-task conditions (10 studies) and motor function (9 studies). The key symptoms that were least tested were resting tremors (Kashif et al. 2022b), rigidity (Kashif et al. 2022b), body bradykinesia (Kashif et al. 2022b) and turning (Rosenfeldt et al. 2025), all of which were only studied in one study. The other less frequently evaluated test indicators included postural control (7 studies), postural stability (6 studies), freezing of gait (5 studies) and muscle strength (3 studies). These studies are listed in Table 4.

The remaining fourteen studies have revealed key mechanisms as well as positive and negative responses by which immersive technology-based rehabilitation experiences and virtual environments may affect PD lower-limb rehabilitation and exercise training (Bell Boucher et al. 2013; Besharat et al. 2022; Ehgoetz Martens et al. 2015a, b; Gómez-Jordana et al. 2018; Imbimbo et al. 2021; Impellizzeri et al. 2022; Janeh et al. 2019; Janssen et al. 2020; Lheureux et al. 2020; Mendes et al. 2012; Su et al. 2014; Suarez et al. 2011; Yamagami et al. 2023). For example, in immersive VR experiences, the high-quality motion field of the virtual environment played a more significant role in the balance ability of individuals with PD than stable visual information (Suarez et al. 2011). Moreover, individuals with PD exhibited more cautious gait patterns when walking in virtual environments, characterised by significantly reduced speed and stride length, increased stride variability and longer steps (Ehgoetz Martens et al. 2015b).

Assessing and demonstrating the effectiveness of immersive-based interventions for the rehabilitation of lower-limb symptoms in PD through controlled trials with other

Table 1 Overview of the information extracted from the articles included in the review

Title of the article	References		Material and method			Subject Number	
	References	Equipment type	Software	Experiment type	Assessment time		Exercise protocol
A gamified virtual environment intervention for gait rehabilitation in Parkinson's disease: co-creation and feasibility study	Bosch-Barceló et al. (2024)	Virtual reality (VR), a customised gamified virtual reality environment for treadmill gait training	The intervention consists of a walking simulation in 3 different environments (countryside, city and park), which has a progressive increase in difficulty over time based on 5 different parameters: speed, visibility, path width, obstacles and distractors	A single-arm, pre-post feasibility study	After training	All participants participated in three different sessions. Participants started with a short 2-min warm-up on the treadmill with no VR at the beginning of every session. Sessions were scheduled once a week. Walking speed increased based on preferred ground walking speed as levels progressed	4 patients
A Kinect-based system for lower limb rehabilitation in Parkinson's disease patients: a pilot study	Palacios-Navarro et al. (2015)	Kinect-based VR	Lateral leg movements	A pilot study without a control group	Before and after training	The programme was performed with a 5-week training period (10 h of treatment, 4 sessions per week). Each training session consisted of 30 min and was organised into epochs, each one corresponding to 40 repetitions of the target. The time between epochs was at least 3 min	7 patients
A multimodal training modulates short afferent inhibition and improves complex walking in a cohort of faller older adults with an increased prevalence of Parkinson's disease	Pelosin et al. (2020)	Modified Microsoft Kinect-based VR and treadmill training (TT) combination	Participants in the TT+VR group walked on a treadmill while interacting with a virtual environment that included real-life challenges	Controlled experiment (TT plus non-immersive VR (TT+VR) or TT alone)	1 week before training, 1 week after training, and 6 months after training (FU)	Participants received training for 6 weeks, three times a week, with each session lasting about 45 min	24 patients: TT (n = 14); TT+VR (n = 10)
A randomised clinical trial to evaluate a digital therapeutic to enhance gait function in individuals with Parkinson's disease	Alberts et al. (2023)	Augmented reality (AR), Microsoft HoloLens 2	The dual-task augmented reality treatment protocol (a therapeutic protocol that mirrors traditional dual-task training interventions)	A single-blind randomised controlled trial (dual-task augmented reality treatment or traditional dual-task training)	Baseline, end of treatment and 8 weeks after treatment completion	Both groups completed 16 45-min sessions over 8 weeks	47 patients: dual-task augmented reality treatment (n = 25); Traditional dual-task training (n = 22)
A randomised controlled trial of motor imagery combined with virtual reality techniques in patients with Parkinson's disease	Kashif et al. (2022b)	A combination of Wii box-based VR and motor imagery	A mixed exercise training of multiple types of dynamic balance games and static balance games	Controlled experiment (VR and motor imagery together with physical therapy or only physical therapy)	At the beginning (week 0) and at the end of the intervention (weeks 6 and 12) and 1 month after the intervention (week 16)	Patients received 12 weeks of assigned treatment (including 40 min of conventional physical therapy, 10–15 min of VR and 5–10 min of motor imagery), 3 days per week, on alternate days	44 patients: VR and motor imagery together with physical therapy group (n = 20); only physical therapy group (n = 21)

Table 1 (continued)

Title of the article	References	Material and method			Experiment type	Assessment time	Exercise protocol	Subject Number
		Equipment type	Software	Personalisation strategies				
A video self-modelling intervention using virtual reality plus physical practice for freezing of gait in Parkinson's disease: feasibility and acceptability study	Goh et al. (2021)	Oculus Go head-mounted display (HMD)-based VR	Personalisation strategies	A pilot study without a control group	1 week before training and 1 week after training	Participants were asked to watch videos using the HMD twice a day, 5 days a week, for 6 weeks. After each video viewing, participants practised their strategies for 10 min	10 participants were initially enrolled, but 1 participant dropped out after 3 weeks of intervention	
A virtual reality exercise program improves the balance function and quality of life of patients with Parkinson's disease	Lee (2018)	Wii-based VR	Wii balance-training	Controlled experiment	Before and after training	Patients participated in 40-min training sessions three times a week for 12 weeks	50 patients: the experimental group (n = 25); the control group (n = 25)	
Accuracy in virtual task for upper limbs associated with transcranial direct current electrical stimulation in people with Parkinson's disease	Simcsik et al. (2021)	A mixed therapeutic intervention through VR and transcranial direct current stimulation (tDCS)	A MoveHero game	Controlled experiment (tDCS treatment (Active and Sham) and VR combination)	Before and after training	The intervention was performed in a single day. The total duration of the tDCS stimulus was 18 min, with the patients playing MoveHero for 4 min with the upper limbs and 4 min with the lower limbs	55 patients: the active group (n = 26); the sham group (n = 29)	
Addition of a non-immersive virtual reality component to treadmill training to reduce fall risk in older adults (V-TIME): a randomised controlled trial	Mirelman et al. (2016)	Modified micro-soft Kinect-based VR and TT combination	Participants in the TT + VR group walked on a treadmill while interacting with a virtual environment that included real-life challenges	Controlled experiment (TT plus non-immersive VR (TT + VR) or TT alone)	1 week before training, 1 week after training and 6 months after training	Participants received training for 6 weeks, three times a week, with each session lasting about 45 min	130 patients: TT (n = 64); TT + VR (n = 66)	

Table 1 (continued)

Title of the article	References	Subject	Gender	Recruitment criteria	Disease severity	Medication cycle	Outcome
A gamified virtual environment intervention for gait rehabilitation in Parkinson's disease: co-creation and feasibility study	Bosch-Barceló et al. (2024)	Mean age (years) 61 ± 9	1 female, 3 males	Inclusion criteria were: (1) age between 45 and 80; (2) Stage II–III in the Hoehn and Yahr scale (H&Y); (3) ability to walk for 10 or more minutes unassisted; (4) MiniMental State Examination (MMSE) score over 24 points. Exclusion criteria included significant cognitive decline based on the MMSE (<23), severe auditory or visual deficits, other neurological or psychiatric conditions, any cardiovascular complications that contraindicate physical activity and a clinical history of any brain surgery or use of a deep-brain stimulation device	2 at Hoehn and Yahr (H&Y) stage 2, 2 at H&Y stage 3	ON	This customised gamified virtual reality environment was a feasible option for training gait under dual-task conditions for PD. Participants demonstrated a clear preference for naturalistic environments and gamification elements were perceived as positive. Difficulty settings worked as intended, but in some cases, they lowered the enjoyment of the experience

Table 1 (continued)

Title of the article	References	Subject	Gender	Recruitment criteria	Disease severity	Medication cycle	Outcome
A Kinect-based system for lower limb rehabilitation in Parkinson's disease patients: a pilot study	Palacios-Navarro et al. (2015)	Mean age (years) 66.8 ± 3.5	4 males, 3 females	Subjects have intact cognition, with no uncontrolled chronic diseases and have no prior experience in balance or gait training. They also had no experience in testing virtual environments focused on Virtual Motor Rehabilitation	/	ON	Significant improvements: completion time and the 10-Meter Walk Test (10MWT) score
A multimodal training modulates short afferent inhibition and improves complex walking in a cohort of faller older adults with an increased prevalence of Parkinson's disease	Pelosi et al. (2020)	TT (71.9) and TT + VR (73.2)	Gender distribution ($\chi^2 = 0.209, p = 0.64$)	Subjects had a history of two or more falls within 6 months prior to the experiment, but were able to walk independently for 5 min, were in stable physical condition and were conscious within 1 month before the experiment, without a history of psychiatric illness or neurological disease	Hoehn and Yahr (H&Y) stages II–III	ON	Significant improvements: obstacle crossing performance, the number of falls, step length and step length variability. Crossing step length remained significantly increased at follow-up (FU) after 6 months

Table 1 (continued)

Title of the article	References	Subject	Gender	Recruitment criteria	Disease severity	Medication cycle	Outcome
A randomised clinical trial to evaluate a digital therapeutic to enhance gait function in individuals with Parkinson's disease	Alberts et al. (2023)	Mean age (years) Dual-task augmented reality treatment (70.0±6.4) and Traditional dual-task training (68.1±5.9)	Dual-task augmented reality treatment: 3 females, 22 males; Traditional dual-task training: 8 females, 14 males	Inclusion criteria were as follows: confirmed diagnosis of idiopathic PD, Hoehn and Yahr I to III, ability to ambulate at least 10 min without the use of an assistive device and self-reported gait or balance deficits. Exclusion criteria included: surgical procedures for PD including deep brain stimulation or focused ultrasound, a diagnosis of dementia or neurocognitive deficit by a physician or physician extender that would impair the ability to provide consent, a musculoskeletal or cardiopulmonary condition that would restrict walking activity, other neurological disorder(s) such as stroke or multiple sclerosis and 3 or more errors on the Short Portable Mental Status Questionnaire	33 at stage 2, 14 at stage 3	ON	Significant improvement in single- and dual-task gait kinematics, including gait speed, cadence and step length, but no change in the clinical MDS-UPDRS III

Table 1 (continued)

Title of the article	References	Subject	Gender	Recruitment criteria	Disease severity	Medication cycle	Outcome
A randomised controlled trial of motor imagery combined with virtual reality techniques in patients with Parkinson's disease	Kashif et al. (2022b)	Mean age (years) VR and motor imagery together with physical therapy group: 10 (63.86 ± 4.57) and only the physical therapy group (62.32 ± 4.61)	VR and motor imagery together with physical therapy group: 9 females, 13 males; only physical therapy group: 10 females, 12 males	Participants had no history of virtual game therapy or fear of virtual games within the past 3 months, were cognitively intact and were without any other neurological or orthopaedic diseases, visual abnormalities, cardiovascular problems, severe movement disorders or a history of Parkinson's disease (PD) surgery	The mean H&Y stage in the VR and motor imagery together with physical therapy group was (2.11 ± 0.74) and in the only physical therapy group was (2.25 ± 0.67)	ON	Improvements: resting tremors, rigidity, body bradykinesia, posture, postural stability, gait, rapid alternating movements and the ability to arise from a chair.No improvements: speech, facial expression, action or postural tremor, finger taps, hand movements or leg agility
A video self-modelling intervention using virtual reality plus physical practice for freezing of gait in Parkinson's disease: feasibility and acceptability study	Goh et al. (2021)	70.6 ± 7.7	9 males, 1 female	Participants had freezing of gait (FoG) and were cognitively intact. They did not have any medical conditions that would interfere with study safety and implementation, such as unstable cardiovascular disease and neurological conditions other than PD and they did not have severe head tremors or motion sickness that limited the ability to use virtual reality headsets	Moderate to severe disease severity with a mean Movement Disorder Society (MDS)—Unified Parkinson's disease Rating Scale III (UPDRS-III)—motor score of 37.3 (SD 13.3)	ON	Improvements: the ability to control FoG (even after stopping medication), self-confidence and anxiety

Table 1 (continued)

Title of the article	References	Subject			Disease severity	Medication cycle	Outcome
		Mean age (years)	Gender	Recruitment criteria			
A virtual reality exercise program improves the balance function and quality of life of patients with Parkinson's disease	Lee (2018)	/	/	/	/	Improvements: imbalance, depression, anxiety and activities of daily living (ADL), as assessed by the verbal analogue scale (VAS), activities specific balancing confidence scale (ABC), Parkinson's disease quality of life (PDQ-39) scale and fall index assessment	

Table 1 (continued)

Title of the article	References	Subject Mean age (years)	Gender	Recruitment criteria	Disease severity	Medication cycle	Outcome
Accuracy in virtual task for upper limbs associated with transcranial direct current electrical stimulation in people with Parkinson's disease	Simsik et al. (2021)	The active group (62.2±11) and the sham group (66.3±7.2)	/	Patients who used wheelchairs and auxiliary walking devices, used Deep Brain Stimulation (DBS) and were unable to complete the procedures were excluded	H&Y stages I–III	/	TDCS may not affect the effectiveness of VR training, possibly because individuals did not have time to adapt to the proposed task, as the regimen was applied for only one day
Addition of a non-immersive virtual reality component to treadmill training to reduce fall risk in older adults (V-TIME): a randomised controlled trial	Mirelman et al. (2016)	TT (71.0±6.1) and TT+VR (71.0±6.3)	TT group: 40 females, 24 males; TT+VR group: 27 females, 39 males	Subjects had a history of two or more falls within 6 months prior to the experiment, but were able to walk independently for 5 min, were in stable physical condition and were conscious within 1 month before the experiment, without a history of psychiatric illness or neurological disease. In addition, individuals with mild cognitive impairment were also included	H&Y stages II–III	ON	Improvements: the incident rate, gait speed under usual and obstacle negotiation walking conditions, gait variability, falls, gait and balance, even at the 6-month FU

VR, virtual reality; TT, treadmill training; H&Y, Hoehn and Yahr; FU, follow-up; PD, Parkinson's disease; AR, augmented reality; FoG, freezing of gait; EG, Exergaming; ET, Exercise Therapy; VRG, Virtual reality gaming; AGBT, Activity-based gait and balance training

Table 2 The stages and overview of the Hoehn and Yahr Scale and the Modified Hoehn and Yahr Scale

Stage	Hoehn and Yahr Scale	Modified Hoehn and Yahr Scale
1	Unilateral involvement only, usually with minimal or no functional disability	Unilateral involvement only
1.5	–	Unilateral and axial involvement
2	Bilateral or midline involvement without impairment of balance	Bilateral involvement without impairment of balance
2.5	–	Mild bilateral disease with recovery on pull test
3	Bilateral disease: mild to moderate disability with impaired postural reflexes; physically independent	Mild to moderate bilateral disease; some postural instability; physically independent
4	Severe disability; still able to walk or stand unassisted	Severely disabling disease; still able to walk or stand unassisted
5	Confinement to bed or a wheelchair unless aided	Wheelchair bound or bedridden unless aided

interventions is an appropriate research approach. This approach has been arranged in fifty-nine studies, including fifty-six studies focusing on VR, five studies focusing on AR (Alberts et al. 2023; Araújo et al. 2023; Pisano et al. 2024; Rosenfeldt et al. 2025; Smaili et al. 2019) and two studies involving both AR and VR (Araújo et al. 2023; Smaili et al. 2019). These studies are included in Table 3. The most frequently used intervention for comparison was conventional / traditional rehabilitation (Goffredo et al. 2023a, b; Lau et al. 2022; Maranesi et al. 2022; Pazzaglia et al. 2020; Pulia et al. 2023), such as conventional gait training (Fundarò et al. 2019), traditional balance training (Brachman et al. 2021; Yen et al. 2011), conventional activity-based gait and balance training (Ogundele et al. 2018, 2019), traditional dual-task training (Alberts et al. 2023; Rosenfeldt et al. 2025) and traditional sitting balance training (Shih et al. 2011). The second most frequently used intervention for comparison was TT (Bekkers et al. 2018, 2020; De Melo et al. 2018; Del Din et al. 2020; Droby et al. 2020; Liao et al. 2015a, b; Maidan et al. 2018; Melo et al. 2018; Mirelman et al. 2016; Pelosin et al. 2020).

More specialised comparative studies have focused on the differences in rehabilitation effects of VR rehabilitation combined with TT relative to different training durations (Pelosin et al. 2022), VR interventions with varying needs of training (Barbosa et al. 2018), VR interventions based on different technologies and hardware devices (Alves et al. 2018), AR interventions versus VR interventions (Araújo et al. 2023; Smaili et al. 2019) and whether VR and AR combined with tDCS (De Lima et al. 2021; Pisano et al. 2024; Simcsik et al. 2021).

In addition, thirty-seven studies have conducted follow-up studies to clarify the potential positive and sustained effects of immersive technology-mediated interventions on PD lower-limb symptoms, including thirty-three studies using VR experiences (Alves et al. 2018; Bekkers et al. 2018, 2020; Calabrò et al. 2020; De Melo et al. 2018; Del Din et al. 2020; Di Biagio et al. 2014; Gandolfi et al. 2017; Gemin et al. 2017; Huang et al. 2020; Isernia et al. 2020; Kashif et al. 2022a, b, c, 2024; Liao et al. 2015a, b; Melo et al. 2018; Mendes et al. 2012; Mirelman et al. 2011, 2016; Nuic et al. 2018; Pelosin et al. 2020, 2022; Piemonte et al. 2017; Pompéu et al. 2016; Ribeiro Bacha et al. 2021; Shih et al. 2011; Souza et al. 2018; van Wegen et al. 2015; Wang et al. 2022; Yang et al. 2016; Yen et al. 2011) and four studies using AR interventions (Alberts et al. 2023; Badarny et al. 2014; Pisano et al. 2024; Rosenfeldt et al. 2025). The shortest follow-up period in one AR PD intervention study has been recorded as one week (Badarny et al. 2014). The longest follow-up study period was six months, among multiple follow-up studies (Bekkers et al. 2018, 2020; Del Din et al. 2020; Mirelman et al. 2016; Pelosin et al. 2020, 2022).

4.5 Thematic analysis of the findings

This scoping review focuses on two core themes. The first theme is the outcomes of immersive rehabilitation in relation to lower-limb PD symptoms, which are key manifestations of the disease affecting the daily living standards of individuals with PD. The second theme is the differences in the effectiveness of various immersive rehabilitation software solutions used in conjunction with different hardware equipment. The outcomes of lower-limb rehabilitation for individuals with PD are discussed in the following sections, including those relating to gait, balance, risk of falls and freezing of gait. The safety and feasibility of interventions based on different technologies are elaborated upon, as are the participants' experiences and perceptions of the technology. Finally, the use of various types of hardware equipment and software solutions for implementing rehabilitation strategies is discussed, along with remarks on the benefits achieved and key factors to consider when designing interventions for individuals with PD.

4.6 Overall outcomes of lower-limb rehabilitation

Several studies have shown that immersive rehabilitation has the ability to achieve significant rehabilitation outcomes in the overall lower-limb symptoms of PD, mainly manifested as follows: resting tremors in one study (Kashif et al. 2022b); rigidity in one study (Kashif et al. 2022b); body bradykinesia in one study (Kashif et al. 2022b); gait in 26 studies (Hajebrahimi et al. 2022; Hardeman et al. 2024;

Table 3 Immersive technologies and hardware devices applied in the selected studies, including other interventions or devices combined with them, as well as interventions or devices compared to them

Types of hardware devices	Combined devices or interventions	Compared devices or interventions	Software designed specifically for PD (Yes or No)	Number of studies	References
Virtual reality	–	–	NO	96	–
Virtual reality based on head-mounted displays	–	Psychoeducation	NO	1	Schuch et al. (2020)
		–	NO	9	Besharat et al. (2022), Cancela-Carral et al. (2024), Ehgoetz Martens et al. (2015a, b), Gómez-Jordana et al. (2018), Hara et al. (2024), Janich et al. (2019), Lheureux et al. (2020), Yamagami et al. (2023)
	Treadmill Training	–	YES	2	Goh et al. (2021), Yun et al. (2023)
	High-Intensity Forced Cycling	High-Intensity Forced Cycling	NO	1	Brandin De La Cruz et al. (2020)
	Augmented Reality by Sony PlayStation 2	–	NO	1	Rodríguez-Fuentes et al. (2024)
Virtual reality based on computer assisted rehabilitation environment (including CAREN Dome, the CAREN Base, the V-Gait and the C-Mill)	–	–	NO	5	Cano Porras et al. (2019), Calabrò et al. (2020), Formica et al. (2023), Impellizzeri et al. (2022), Wang et al. (2022)
Virtual reality by neuromotor rehabilitation system NIRVANA	Neurologic Music Therapy	Conventional Physiotherapy	NO	1	Pullia et al. (2023)
	–	Virtual Reality based on CAREN	NO	1	Impellizzeri et al. (2024)
Virtual reality by lokomat	–	Conventional Rehabilitation	NO	1	Imbimbo et al. (2021)
	–	Conventional Gait Training	NO	1	Pazzaglia et al. (2020)
	–	–	NO	1	Fundarò et al. (2019)

Table 3 (continued)

Types of hardware devices	Combined devices or interventions	Compared devices or interventions	Software designed specifically for PD (Yes or No)	Number of studies	References
Virtual reality not specifically mentioned	Transcranial Direct Current Stimulation	Sham Transcranial Direct Current Stimulation Treatment	NO	2	De Lima et al. (2021) Simcsik et al. (2021)
	Treadmill Training	–	YES	1	Mirelman et al. (2011)
	–	Treadmill Training	NO	1	Bekkers et al. (2018)
	Cycle on a Stationary Home-trainer	Non-Aerobic Intervention (stretching, flexibility and relaxation exercises)	YES	1	Van Der Kolk et al. (2019)
	–	–	NO	1	Suarez et al. (2011)
	–	Drug-Only; Drug-Combined Audio-Visual Training; Drug-Combined Repetitive Transcranial Magnetic Stimulation	NO	1	Huang et al. (2020)
	–	Conventional Physical Therapy (Exercises)	NO	4	Feng et al. (2019), Gemin et al. (2017), Lee (2019), van Wegen et al. (2015)
	–	Conventional Sitting Balance Training	NO	1	Shih et al. (2011)
	–	–	NO	9	Albio-Pérez et al. (2017), Di Biagio et al. (2014), Fearon et al. (2017), Killane et al. (2015), Lee (2018), Loureiro et al. (2012), Mendes et al. (2012), Severiano et al. (2018), Zeigelboim et al. (2021))
	–	Conventional Exercise Therapy	NO	5	Hajebrahimi et al. (2022), Kashif et al. (2024), Lee (2016a, b), Santos et al. (2019)
Virtual reality based on the Nintendo Wii	Motor Imagery with Routine Physical Therapy	Motor Imagery with Routine Physical Therapy	NO	1	Kashif et al. (2024)
	Conventional Balance Training	Conventional Balance Training	NO	2	Anwar et al. (2021), Lee Geun-Ho (2015)
	In-clinic Sensory Integration Balance Training	In-clinic Sensory Integration Balance Training	NO	1	Gandolfi et al. (2017)
	Treadmill Training	Treadmill Training	NO	2	Liao et al. (2015a, b)
	Fall-prevention Education	Fall-prevention Education	NO	2	Liao et al. (2015a, b)
	Neurodevelopmental Therapy Combined with Functional Electrical Stimulation	Neurodevelopmental Therapy Combined with Functional Electrical Stimulation	NO	1	Lee et al. (2015)
	Virtual Reality Combined with Manual and Verbal Guidance from a Physical Therapist	Virtual Reality Combined with Manual and Verbal Guidance from a Physical Therapist	NO	1	Piemonte et al. (2017)
	Neurofunctional Physiotherapy	Neurofunctional Physiotherapy	NO	2	Araújo et al. (2023), Smaili et al. (2019)
	Augmented Reality	Augmented Reality	NO	2	Araújo et al. (2023), Smaili et al. (2019)
	–	–	NO	2	Kashif et al. (2022b, c)
Motor Imagery	Physical Therapy	NO	1	Kashif et al. (2022a)	

Table 3 (continued)

Types of hardware devices	Combined devices or interventions	Compared devices or interventions	Software designed specifically for PD (Yes or No)	Number of studies	References
Virtual reality based on the kinect supporting X-Box or Microsoft	–	–	NO	6	Amprimo et al. (2022), Nuic et al. (2018), Palacios-Navarro et al. (2015), Pompeu et al. (2014), Ribeiro Bacha et al. (2021), Souza et al. (2018) Brachman et al. (2021)
	Conventional Balance Training	Conventional Activity-based Gait and Balance Training	NO	1	Ogundele et al. (2018, 2019)
	Conventional Balance Training	Intervention based on the European Physiotherapy Guideline	NO	1	Pompéu et al. (2016)
	Bicycle Exercise	Treadmill Training	NO	2	De Melo et al. (2018, Melo et al. (2018)
	Usual Care Condition	Virtual Reality Interventions for Different Training Needs	YES	1	Ferraz et al. (2018)
	Virtual Reality based on the Nintendo Wii	Treadmill Training alone	NO	1	Isemia et al. (2020)
	Different training durations	Different training durations	NO	1	Barbosa et al. (2018)
	Conventional Balance Training Trained by a Physical Therapist	Conventional Rehabilitation Programme	YES	1	Alves et al. (2018)
	Conventional Rehabilitation Programme	Virtual Reality based on the Nintendo Wii	YES	6	Bekkers et al. (2020), Del Din et al. (2020), Drobny et al. (2020), Maidan et al. (2018), Mirelman et al. (2016), Pelosin et al. (2020)
Other virtual reality based on 2D Screens	–	–	YES	1	Pelosin et al. (2022)
	–	–	YES	1	Comejo Thumm et al. (2021)
	Conventional Balance Training	Conventional Rehabilitation Programme	NO	2	Sadek et al. (2024), Su et al. (2014)
	Conventional Rehabilitation Programme	Virtual Reality based on the Nintendo Wii	NO	1	Yen et al. (2011)
	Virtual Reality based on the Nintendo Wii	Traditional Dual-task Training	NO	1	Yang et al. (2016)
	–	–	NO	3	Goffredo et al. (2023a, b), Maranesi et al. (2022)
	–	–	YES	1	Lau et al. (2022)
	–	–	YES	1	Bosch-Barceló et al. (2024)
	–	–	NO	2	Araújo et al. (2023), Smaili et al. (2019)
	–	–	YES	4	Badamy et al. (2014), Lee et al. (2023), Tunur et al. (2020), Wang et al. (2020)
	–	–	NO	3	Bell Boucher et al. (2013), Hardeman et al. (2024), Janssen et al. (2020)
	–	–	YES	2	Alberts et al. (2023), Rosenfeldt et al. (2025)
Virtual Reality based on Head-Mounted Displays	–	–	NO	1	Krieger et al. (2013)
Transcranial Direct Current Stimulation	Sham Transcranial Direct Current Stimulation Treatment	Sham Transcranial Direct Current Stimulation Treatment	NO	1	Pisano et al. (2024)

Table 4 Overview of outcome measures used by the selected studies to assess the rehabilitation effectiveness of Parkinson's disease (i.e., lower-limb symptoms of Parkinson's disease), including positive outcomes and unimproved symptoms

Result evaluation measures	Number of studies	Authors and year
<i>Actively responding</i>		
Resting tremors	1	Kashif et al. (2022b)
Rigidity	1	Kashif et al. (2022b)
Body bradykinesia	1	Kashif et al. (2022b)
Gait	26	Anwar et al. (2021), Bekkers et al. (2018), Calabrò et al. (2020), Feng et al. (2019), Goffredo et al. (2023a, b), Hajebrahimi et al. (2022), Hardeman et al. (2024), Huang et al. (2020), Kashif et al. (2022b), Krieger et al. (2013), Lau et al. (2022), Lee et al. (2023), Melo et al. (2018), Mirelman et al. (2016), Ogundele et al. (2019), Piemonte et al. (2017), Pompeu et al. (2014), Pullia et al. (2023), Rodríguez-Fuentes et al. (2024), Sadek et al. (2024), Santos et al. (2019), Wang et al. (2020, 2022), Yang et al. (2016), Yun et al. (2023)
Gait performance under single- and dual-tasks	6	Alves et al. (2018), Alberts et al. (2023), Barbosa et al. (2018), Cano Porras et al. (2019), Fearon et al. (2017), Killane et al. (2015)
Gait performance under dual tasks	10	Alves et al. (2018), Alberts et al. (2023), Barbosa et al. (2018), Bosch-Barceló et al. (2024), Cano Porras et al. (2019), Fearon et al. (2017), Killane et al. (2015), Lee et al. (2023), Mirelman et al. (2011), Pelosin et al. (2022)
Gait speed (velocity)	22	Alberts et al. (2023), Badarny et al. (2014), Brandín De La Cruz et al. (2020), Calabrò et al. (2020), Cano Porras et al. (2019), Cornejo Thumm et al. (2021), De Melo et al. (2018), Di Biagio et al. (2014), Droby et al. (2020), Formica et al. (2023), Gandolfi et al. (2017), Lau et al. (2022), Liao et al. (2015b), Maidan et al. (2018), Mirelman et al. (2011), Mirelman et al. (2016), Nuic et al. (2018), Ogundele et al. (2018), Palacios-Navarro et al. (2015), Pelosin et al. (2022), Sadek et al. (2024), Schuch et al. (2020)
Gait speed variability	1	Pelosin et al. (2022)
Gait variability	2	Mirelman et al. (2016), Pelosin et al. (2020)
Gait distance	1	Brandín De La Cruz et al. (2020)
Step length	4	Alberts et al. (2023), Nuic et al. (2018), Ogundele et al. (2018), Pelosin et al. (2020)
Stride length	7	Badarny et al. (2014), Droby et al. (2020), Liao et al. (2015b), Maidan et al. (2018), Mirelman et al. (2011), Ogundele et al. (2018), Pelosin et al. (2022)
Stride time	1	Mirelman et al. (2011)
Cadence	3	Alberts et al. (2023), Droby et al. (2020), Ogundele et al. (2018)
Walking capacity	1	Ferraz et al. (2018)
Walking adaptability	1	Hardeman et al. (2024)
Walking distance	2	De Melo et al. (2018), Lau et al. (2022)
Walking endurance (duration of walking time)	1	Cornejo Thumm et al. (2021)
Obstacle negotiation (avoidance)	5	Mirelman et al. (2011, 2016), Pelosin et al. (2020, 2022), Wang et al. (2022)
Obstacle crossing velocity and crossing stride length	1	Liao et al. (2015a)
Rapid alternating movements	1	Kashif et al. (2022b)
Stand-up time and sit-down time	1	Melo et al. (2018)
Ability to stand up and sit	1	Ferraz et al. (2018)
Arising from a chair	1	Kashif et al. (2022b)
Gait ability to adapt to complex walking tasks	1	Pazzaglia et al. (2020)
Balance	41	Anwar et al. (2021), Bekkers et al. (2018), Calabrò et al. (2020), Cancela-Carral et al. (2024), Di Biagio et al. (2014), Droby et al. (2020), Feng et al. (2019), Formica et al. (2023), Goffredo et al. (2023a, b), Hajebrahimi et al. (2022), Isernia et al. (2020), Kashif et al. (2022a, c, 2024), Krieger et al. (2013), Lee (2015, 2016a, b, 2018, 2019), Lee Geun-Ho (2015), Loureiro et al. (2012), Maranesi et al. (2022), Mirelman et al. (2016), Nuic et al. (2018), Ogundele et al. (2018, 2019), Pazzaglia et al. (2020), Piemonte et al. (2017), Pompeu et al. (2014), Pullia et al. (2023), Rodríguez-Fuentes et al. (2024), Santos et al. (2019), Severiano et al. (2018), Shih et al. (2011), van Wegen et al. (2015), Wang et al. (2020), Yang et al. (2016), Yun et al. (2023), Zeigelboim et al. (2021)

Table 4 (continued)

Result evaluation measures	Number of studies	Authors and year
Dynamic balance	7	Brachman et al. (2021), Calabrò et al. (2020), Goffredo et al. (2023a, b), Hardeman et al. (2024), Liao et al. (2015a), Cano Porras et al. (2019)
Balance confidence	5	Cornejo Thumm et al. (2021), Kashif et al. (2022a, c, (2024), Lee Geun-Ho (2015)
Posture	1	Kashif et al. (2022b)
Postural stability	6	Bekkers et al. (2020), Brachman et al. (2021), Calabrò et al. (2020), Kashif et al. (2022b), Pisano et al. (2024), Rosenfeldt et al. (2025)
Postural control	7	Albiol-Pérez et al. (2017), Araújo et al. (2023), Gandolfi et al. (2017), Pompéu et al. (2016), Ribeiro Bacha et al. (2021), Smaili et al. (2019), Yen et al. (2011)
Stability	1	Tunur et al. (2020)
Turning	1	Rosenfeldt et al. (2025)
Falls	16	Bekkers et al. (2018, 2020), Cano Porras et al. (2019), Del Din et al. (2020), Gandolfi et al. (2017), Hardeman et al. (2024), Maidan et al. (2018), Maranesi et al. (2022), Mirelman et al. (2016), Nuic et al. (2018), Pelosin et al. (2020, 2022), Pullia et al. (2023), Rodríguez-Fuentes et al. (2024), Severiano et al. (2018), Tunur et al. (2020)
Fear of falling	3	Formica et al. (2023), Krieger et al. (2013), Pelosin et al. (2022)
Freezing of gait	5	Fearon et al. (2017), Goh et al. (2021), Killane et al. (2015), Lee et al. (2023), Nuic et al. (2018)
Motor function (UPDRS-III)	9	Fundarò et al. (2019), Hajebrahimi et al. (2022), Hara et al. (2024), Kashif et al. (2022a, c, 2024), Pullia et al. (2023), Sadek et al. (2024), Van Der Kolk et al. (2019)
Functional mobility	7	Cano Porras et al. (2019), Cancela-Carral et al. (2024), Gemin et al. (2017), Isernia et al. (2020), Rosenfeldt et al. (2025), Santos et al. (2019), Tunur et al. (2020)
(Functional) independence	3	Fundarò et al. (2019), Hara et al. (2024), Zeigelboim et al. (2021)
Executive functions	7	Araújo et al. (2023), Bekkers et al. (2020), Formica et al. (2023), Impellizzeri et al. (2024), Maidan et al. (2018), Pelosin et al. (2022), Yun et al. (2023)
Lower-limb (muscle) strength	3	Cancela-Carral et al. (2024), Hardeman et al. (2024), Liao et al. (2015b)
Trunk function	1	Shih et al. (2011)
Feeling handicapped	1	Krieger et al. (2013)
Accuracy and precision of movement	1	De Lima et al. (2021)
Subjective stability perception	1	Di Biagio et al. (2014)
Activities of daily living	7	Calabrò et al. (2020), Kashif et al. (2022a, c, 2024), Lee (2018), Lee et al. (2015), Souza et al. (2018)
Quality of life	17	Brandín De La Cruz et al. (2020), Cancela-Carral et al. (2024), Gandolfi et al. (2017), Gemin et al. (2017), Hajebrahimi et al. (2022), Isernia et al. (2020), Krieger et al. (2013), Lee (2019), Lee Geun-Ho (2015), Ogundele et al. (2018, 2019), Pazzaglia et al. (2020), Pompeu et al. (2014, (2016), Santos et al. (2019; Severiano et al. (2018), Yang et al. (2016)
Self-confidence	5	Cano Porras et al. (2019), Gandolfi et al. (2017), Goh et al. (2021), Severiano et al. (2018), Zeigelboim et al. (2021)
Cardiopulmonary aptitude	1	Pompeu et al. (2014)
Anxiety	3	Alves et al. (2018), Goh et al. (2021), Lee (2018)
Fatigue	1	Sadek et al. (2024)
Depressive symptoms	3	Formica et al. (2023), Lee (2019), Lee et al. (2015)
Aerobic capacity	1	Cancela-Carral et al. (2024)
Sensory integration ability	1	Liao et al. (2015b)
No responding		
Motor function (UPDRS-III)	1	Alberts et al. (2023)
Gait speed	1	Maranesi et al. (2022)
Balance confidence	1	Tunur et al. (2020)
Postural stability	1	Yen et al. (2011)
Freezing of gait	2	Bekkers et al. (2018, 2020)
Action or postural tremor	1	Kashif et al. (2022b)

Table 4 (continued)

Result evaluation measures	Number of studies	Authors and year
Leg agility	1	Kashif et al. (2022b)
Quality of life	2	Souza et al. (2018), Tunur et al. (2020)
Depressive symptoms	1	Tunur et al. (2020)

Huang et al. 2020); gait performance under dual-tasks in 10 studies (Alves et al. 2018; Alberts et al. 2023; Barbosa et al. 2018); balance in 41 studies (Anwar et al. 2021; Bekkers et al. 2018; Calabrò et al. 2020; Cancela-Carral et al. 2024); postural stability in 6 studies (Brachman et al. 2021; Calabrò et al. 2020); postural control in 7 studies (Araújo et al. 2023; Gandolfi et al. 2017); turning in one study (Rosenfeldt et al. 2025); risk of falls in 16 studies (Cano Porrás et al. 2019; Del Din et al. 2020); fear of falling in 3 studies (Formica et al. 2023; Krieger et al. 2013; Pelosin et al. 2022); freezing of gait in 5 studies (Killane et al. 2015; Lee et al. 2023; Nuic et al. 2018); motor function in 9 studies (Fundarò et al. 2019; Hajebrahimi et al. 2022; Hara et al. 2024); functional mobility in 7 studies (Rosenfeldt et al. 2025; Santos et al. 2019); lower-limb muscle strength in 3 studies (Cancela-Carral et al. 2024; Hardeman et al. 2024; Liao et al. 2015b); executive functions in 7 studies (Bekkers et al. 2020; Formica et al. 2023); activities of daily living (ADL) in 7 studies (Kashif et al. 2024; Lee 2018) and quality of life in 17 studies (Pompéu et al. 2016; Santos et al. 2019).

Current research has shown that both VR and AR can bring about improvement in the rehabilitation outcomes for PD lower-limb symptoms. However, it is worth noting that, to date, only eleven trial-based studies were conducted using AR technology in lower-limb rehabilitation for people with PD. Further improved PD symptoms and their relationship with the interventions of immersive technologies are detailed in Table 5.

Improved balance ability and gait performance are often among the most notable effects associated with the use of immersive technologies for lower-limb PD rehabilitation (Wang et al. 2020). For example, after receiving CAREN training (Home—motekmedical.com n.d.), individuals with PD walked faster, with improved stability (under both single-task and dual-task conditions) and with longer steps, and their functional mobility under cognitive load was significantly enhanced (Calabrò et al. 2020; Cano Porrás et al. 2019). Similarly, a significant improvement was observed in terms of single-leg standing score (Tunur et al. 2020), stride length (the distance between successive initial contact points of the same foot during walking), cadence (number of steps per unit time) (Ogundele et al. 2018) and the asymmetry of arm swing during walking (Amprimo et al. 2022). In addition, the improvement of balance ability also

included dynamic balance (Brachman et al. 2021; Calabrò et al. 2020) and balance confidence (Cornejo Thumm et al. 2021).

Moreover, immersive rehabilitation has been shown to improve postural control (Bacha et al. 2021; Brachman et al. 2021) in terms of the following: ‘limits of stability’ (Bacha et al. 2021; Brachman et al. 2021), defined as “*the outmost range in any direction a person can lean from the vertical, without changing the original base of support (i.e., stepping, reaching for support or falling)*” (Ragnarsdóttir 1996: page 368); average ‘centre of pressure’ velocity (Brachman et al. 2021), defined as “*the point of location of the vertical ground reaction force vector*” (Jamshidi et al. 2010: page 33) and balance ability (Bacha et al. 2021).

Freezing of gait (FoG) is defined as “*a brief, episodic absence or marked reduction of forward progression of the feet despite the intention to walk*” (Rahimpour et al. 2021: page 829). FoG and reduced postural control are important motor manifestations of the disease in its later stages, for which improvement has rarely been reported following conventional rehabilitation. Immersive rehabilitation can alleviate FoG, including when pharmacological treatment is discontinued (Goh et al. 2021). The use of immersive VR HMDs and of physical therapy based on personally tailored movement strategies is a feasible and acceptable method of addressing FoG in individuals with PD (Goh et al. 2021). It is worth noting that there is a degree of variability in the benefits observed for individuals with PD across studies using immersive technologies, which may reflect differences in the rehabilitation methods employed. For example, one experiment (Bekkers et al. 2020) showed that, although TT combined with VR reduced the frequency of falls compared to TT alone, no improvement was observed in FoG.

Rehabilitation methods using immersive technologies are often more effective than conventional rehabilitation in improving lower-limb motor function (Pazzaglia et al. 2020). Compared to physical therapy alone, the inclusion of immersive virtual elements in the rehabilitation experience can significantly reduce resting tremor, rigidity and body bradykinesia and improve posture and posture stability (i.e., static balance) (Kashif et al. 2022c). The addition of virtual immersive elements to treadmill training (TT) has been associated with a significant reduction in the number of falls, with improvement in obstacle negotiation performance,

Table 5 (continued)

Rehabilitation outcomes		Types of immersive technologies (and the references to studies)				
Improved symptoms		Virtual reality (VR)				
Main symptoms	Specific manifestations	HMD-based VR	CAREN-based VR	Nintendo Wii-based VR	Kinect-based VR	2D Screen-based VR
Balance	Obstacle crossing velocity and crossing stride length	Cancela-Carral et al. (2024), Krieger et al. (2013), Rodriguez-Fuentes et al. (2024), Yun et al. (2023)	Calabrò et al. (2020), Formica et al. (2023), Pullia et al. (2023)	Anwar et al. (2021), Di Biagio et al. (2014), Hajebrahimi et al. (2022), Kashif et al. (2022a, c, 2024), Lee (2016a, b, 2018), Lee et al. (2015), Lee Geun-Ho (2015), Loureiro et al. (2012), Piemonte et al. (2017), Santos et al. (2019), Severiano et al. (2018), Zeigelboim et al. (2021)	Droby et al. (2020), Isermia et al. (2020), Mirelman et al. (2016), Nuic et al. (2018), Ogundele et al. (2018, 2019), Pompeu et al. (2014)	Goffredo et al. (2023a, b), Maranesi et al. (2022), Yang et al. (2016)
	Gait ability to adapt to complex walking tasks			Liao et al. (2015a)		
	Rapid alternating movements			Kashif et al. (2022b)		
Accuracy and precision of movement						
	Balance					
Posture	Dynamic balance		Calabrò et al. (2020), Cano Porras et al. (2019)	Liao et al. (2015a)	Brachman et al. (2021)	Goffredo et al. (2023a, b)
	Balance confidence			Kashif et al. (2022a, c, 2024), Lee Geun-Ho (2015)	Cornejo Thumm et al. (2021)	
Falls	Postural control			Albiol-Pérez et al. (2017), Gandolfi et al. (2017)	Pompéu et al. (2016), Ribeiro Bacha et al. (2021)	Yen et al. (2011)
	Postural stability		Calabrò et al. (2020)	Kashif et al. (2022b)	Bekkers et al. (2020), Brachman et al. (2021)	
Freezing of gait	Stability			Di Biagio et al. (2014)		
	Subjective stability perception					
Freezing of gait	Risk of falls	Rodriguez-Fuentes et al. (2024)	Cano Porras et al. (2019), Pullia et al. (2023)	Gandolfi et al. (2017), Severiano et al. (2018)	Bekkers et al. (2020), Del Din et al. (2020), Maidan et al. (2018), Mirelman et al. (2016), Nuic et al. (2018), Pelosin et al. (2020, 2022)	Maranesi et al. (2022)
	Fear of falling	Krieger et al. (2013)	Formica et al. (2023)		Pelosin et al. (2022)	
Motor function (UPDRS-III)	Freezing of gait	Goh et al. (2021)		Fearon et al. (2017), Killane et al. (2015)	Nuic et al. (2018)	
	Motor function (UPDRS-III)	Hara et al. (2024)	Pullia et al. (2023)	Hajebrahimi et al. (2022), Kashif et al. (2022a, c, 2024)		Sadek et al. (2024)
Functional mobility	Functional mobility	Cancela-Carral et al. (2024)	Cano Porras et al. (2019)	Santos et al. (2019)	Isermia et al. (2020)	

Table 5 (continued)

Rehabilitation outcomes		Types of immersive technologies (and the references to studies)				
Improved symptoms		Virtual reality (VR)				
Main symptoms	Specific manifestations	HMD-based VR	CAREN-based VR	Nintendo Wii-based VR	Kinect-based VR	2D Screen-based VR
Muscle strength	(Functional) independence	Hara et al. (2024)		Zeigelboim et al. (2021)		
Turning	–	Cancela-Carral et al. (2024)		Liao et al. (2015b)		
Self-confidence	–	Goh et al. (2021)	Cano Porras et al. (2019)	Gandolfi et al. (2017), Severiano et al. (2018), Zeigelboim et al. (2021)		
Executive functions	–	Yun et al. (2023)	Formica et al. (2023), Impellizzeri et al. (2024)			Bekkers et al. (2020), Maidan et al. (2018), Pelosin et al. (2022)
Activities of daily living	–		Calabrò et al. (2020)	Kashif et al. (2022a, 2022c, 2024), Lee (2018), Lee et al. (2015)	Souza et al. (2018)	
Quality of life	–	Brandin De La Cruz et al. (2020), Cancela-Carral et al. (2024), Krieger et al. (2013)		Gandolfi et al. (2017), Hejebrahimi et al. (2022), Lee Geun-Ho (2015), Santos et al. (2019); Severiano et al. (2018)	Isernia et al. (2020), Ogundele et al. (2019), Pompeu et al. (2014), Pompéu et al. (2016)	Yang et al. (2016)
Depressive symptoms	–		Formica et al. (2023)	Lee et al. (2015)		
Anxiety	–	Goh et al. (2021)		Lee (2018)	Alves et al. (2018)	Sadek et al. (2024)
Fatigue	–					
Other body functions	Stand-up time and sit-down time				Melo et al. (2018)	
	Ability to stand up and sit				Ferraz et al. (2018)	
	Arising from a chair					
	Trunk function					
	Feeling handicapped	Krieger et al. (2013)				
	Sensory integration ability			Liao et al. (2015b)		
	Aerobic capacity	Cancela-Carral et al. (2024)				
	Cardiopulmonary aptitude				Pompeu et al. (2014)	
Rehabilitation outcomes		Types of immersive technologies (and the references to studies)				
Improved symptoms		Virtual reality (VR)				
Main symptoms	Specific manifestations	VR by other technologies			Augmented reality (AR)	
					HMD-based AR	
					AR by other technologies	
Resting tremors	–					
		Total number of studies				
		1				

Table 5 (continued)

Rehabilitation outcomes		Types of immersive technologies (and the references to studies)			Total number of studies
Improved symptoms	Virtual reality (VR)	Augmented reality (AR)			
Main symptoms	Specific manifestations	VR by other technologies	HMD-based AR	AR by other technologies	
Rigidity	–				1
Body bradykinesia	–				1
Walking	Gait	Bekkers et al. (2018), Feng et al. (2019), Huang et al. (2020)	Hardeman et al. (2024), Lee et al. (2023), Wang et al. (2020)	Krieger et al. (2013)	26
	Gait performance under single- and dual-tasks		Alberts et al. (2023)		6
	Gait performance under dual tasks	Mirelman et al. (2011)	Alberts et al. (2023), Lee et al. (2023)		10
	Gait speed (velocity)	Mirelman et al. (2011)	Alberts et al. (2023), Badamy et al. (2014)		22
	Gait speed variability				1
	Gait variability				2
	Gait distance				1
	Step length		Alberts et al. (2023)		4
	Stride length	Mirelman et al. (2011)	Badamy et al. (2014)		7
	Stride time	Mirelman et al. (2011)			1
	Cadence		Alberts et al. (2023)		3
	Walking capacity				1
	Walking adaptability		Hardeman et al. (2024)		1
	Walking distance				2
	Walking endurance				1
	Obstacle negotiation (avoidance)	Mirelman et al. (2011)			5
	Obstacle crossing velocity and crossing stride length				1
	Gait ability to adapt to complex walking tasks	Pazzaglia et al. (2020)			1
	Rapid alternating movements				1
	Accuracy and precision of movement	De Lima et al. (2021)			1
Balance	Balance	Bekkers et al. (2018), Feng et al. (2019), Lee (2019), Pazzaglia et al. (2020), Shih et al. (2011), van Wegen et al. (2015)	Wang et al. (2020)	Krieger et al. (2013)	41
	Dynamic balance		Hardeman et al. (2024)		7
	Balance confidence			Araújo et al. (2023), Smaili et al. (2019)	5
Posture	Postural control	Araújo et al. (2023), Smaili et al. (2019)		Pisano et al. (2024)	7
	Postural stability		Rosenfeldt et al. (2025)		6
	Stability		Tunur et al. (2020)		1
	Subjective stability perception				1

Table 5 (continued)

Rehabilitation outcomes		Types of immersive technologies (and the references to studies)			Total number of studies
Improved symptoms	Virtual reality (VR)	Augmented reality (AR)			
Main symptoms	Specific manifestations	VR by other technologies	HMD-based AR	AR by other technologies	
Falls	Risk of falls	Bekkers et al. (2018)	Hardeman et al. (2024), Tunur et al. (2020)		16
Freezing of gait	Fear of falling			Krieger et al. (2013)	3
Motor function (UPDRS-III)	Freezing of gait		Lee et al. (2023)		5
	Motor function (UPDRS-III)	Fundarò et al. (2019), Van Der Kolk et al. (2019)			9
	Functional mobility	Gemin et al. (2017)	Rosenfeldt et al. (2025); Tunur et al. (2020)		7
Muscle strength	(Functional) independence	Fundarò et al. (2019)			3
Turning	–		Hardeman et al. (2024)		3
Self-confidence	–		Rosenfeldt et al. (2025)		1
Executive functions	–			Araújo et al. (2023)	5
Activities of daily living	–	Araújo et al. (2023)			7
Quality of life	–				17
Depressive symptoms	–	Lee (2019), Pazzaglia et al. (2020), Gemin et al. (2017)		Krieger et al. (2013)	3
Anxiety	–	Lee (2019)			3
Fatigue	–				1
Other body functions	Stand-up time and sit-down time				1
	Ability to stand up and sit				1
	Arising from a chair				1
	Trunk function	Shih et al. (2011)			1
	Feeling handicapped			Krieger et al. (2013)	1
	Sensory integration ability				1
	Aerobic capacity				1
	Cardiopulmonary aptitude				1

VR, virtual reality; AR, augmented reality; CAREN, Computer Assisted Rehabilitation Environment; HMD, Head-Mounted Displays

increased step length (the distance the foot can be moved forward during the step) (Pelosin et al. 2020), increased gait speed (the time required to walk a specified distance) and reduced gait variability (Mirelman et al. 2016). Such improvements are often retained following rehabilitation, from 16 weeks (Kashif et al. 2022b) to 6 months (Mirelman et al. 2016; Pelosin et al. 2020). More detailed information about the benefits of including immersive technologies in lower-limb rehabilitation methods is provided in Table S1, Appendix: Supplementary Material in the online resources.

4.7 Dual-task motor and cognitive training

The combination of traditional rehabilitation approaches with the use of immersive technologies can enable individuals with PD to enhance their motor performance during dual-task training, i.e., training that requires the simultaneous execution of two distinct tasks. Such training typically enables individuals with PD to exercise their cognitive abilities while performing motor training tasks (Pelosin et al. 2022), which often rely on standard training methods that involve obstacle avoidance and games played within a maze (Killane et al. 2015). Training methods that focus simultaneously on motor and cognitive function are typically designed to combine motor training tasks with varying degrees of cognitive load, such as gradually increasing or decreasing the frequency of obstacle appearance in obstacle avoidance training. This approach is designed to facilitate the adaptation of training sessions to an individual's disease severity and needs, particularly when the person is at more advanced stages of the disease. (Amprimo et al. 2022). A notable improvement was observed in individuals with FoG in terms of increased dual-task performance and a reduced frequency of FoG episodes following interventions delivered within immersive virtual environments (Killane et al. 2015). Other studies have shown that immersive dual-task training can result in significant, long-term positive effects on the motor performance of individuals with PD, with changes persisting for up to 6 months after rehabilitation (Mirelman et al. 2016; Pelosin et al. 2022). The benefits of dual-task training for individuals with PD can be understood in consideration of the disease's pathophysiology, as most physical PD manifestations are associated with interactions between cognitive deficits and motor impairments (Mirelman et al. 2016).

The clinical potential of immersive rehabilitation methods relying on dual tasks, as opposed to single-task methods, has been recognised (Mirelman et al. 2013). Immersive dual tasks require individuals with PD to exercise cognitive functions, such as action execution (including attention, response selection and action planning) while processing multisensory stimuli from the environment, including

visual, auditory and haptic cues. (Krieger et al. 2013; Mirelman et al. 2016). Studies have suggested that strengthening multimodal sensory stimulation within realistic immersive environments can lead to improved task execution performance, enhanced self-reported well-being and further alleviation of PD symptoms, including those affecting cognitive functions (Krieger et al. 2013). Individuals with PD who report a stronger sense of body and presence in the virtual environment often achieve better rehabilitation results (Krieger et al. 2013). Moreover, with reference to dual-task training, the need for higher degrees of concentration, planning ability and executive function can help individuals with PD negotiate obstacles more effectively in complex environments. This multitasking often results in improved motor performance over longer periods, as evidenced by better gait adjustment for obstacle avoidance during walking and by enhanced motor control during falls (Mirelman et al. 2016). It is essential to recognise that excessive cognitive load, which occurs when individuals with PD execute tasks within immersive environments, such as those associated with the presence of virtual inanimate objects not directly related to the task, may negatively impact the motivation to engage in training (Amprimo et al. 2022). For this reason, cognitive load needs to be carefully considered when designing PD interventions relying on immersive digital environments.

It is assumed that individuals with PD often face more challenges than mainstream users when engaging with complex immersive systems (Kashif et al. 2022a, 2022c). Nevertheless, there is also a growing recognition of the safety of immersive virtual environments for most individuals with PD when it comes to dual-task training (Dantas et al. 2018; Killane et al. 2015; Maggio et al. 2018; Pelosin et al. 2022). Recent studies have highlighted that the additional cognitive demands associated with dual-task training are unlikely to be linked to adverse events or safety issues for most individuals with PD (Tunur et al. 2020). However, in almost all studies reviewed, individuals with PD with cognitive impairment and at advanced stages of the disease were excluded from participant recruitment (Kashif et al. 2022c; Palacios-Navarro et al. 2015; Suarez et al. 2011). This exclusion has led to a gap in knowledge regarding the safety of virtual immersive rehabilitation methods for this subgroup of individuals with PD. In other studies focusing on cognitive functions, there was almost unanimous agreement that rehabilitation based on immersive technologies can promote cognitive abilities of individuals with PD in addition to motor function (Kashif et al. 2022c; Pelosin et al. 2022; Pezzi et al. 2022; Zhu et al. 2021). The engagement in immersive rehabilitation programmes of individuals with PD affected by cognitive impairment and at more advanced stages of the disease should therefore be encouraged. Further

research should provide additional evidence relating to this user group, emphasising dual-task training, while also making sure that the immersive experiences used are designed for safety and to meet the users' needs.

4.8 Immersive rehabilitation with other interventions

Research indicates that integrating immersive technologies with other rehabilitation methods is often beneficial for individuals with PD, leading to improved perceived well-being compared to physical therapy alone (Brandín De La Cruz et al. 2020; Kashif et al. 2022a, b, c). Successful interventions have been developed using VR systems in combination with TT (Bekkers et al. 2020; Brandín-De la Cruz et al. 2020; Droby et al. 2020; Mirelman et al. 2016; Pelosin et al. 2020), as well as delivering auditory cues within virtual immersive environments, including the use of music in relation to dance-based tasks (Lee et al. 2015, 2023; Tunur et al. 2020). Studies comparing the outcomes of individuals with PD following TT with and without the use of immersive technologies (with emphasis on VR) suggest that immersive rehabilitation benefits both motor and cognitive function (Mirelman et al. 2013).

In several studies, VR has been used in combination with motor imagery (MI) training (Kashif et al. 2022a, b, c). As a psychological simulation process, MI training involves the systematic use of imagination to rehearse movements covertly without executing them (Moran and O'Shea 2020). Embedding MI in physical therapy can enable VR rehabilitation programmes to deliver greater improvements for individuals with PD in all-around motor functions. Examples relate to the management of rigidity, resting tremor, gait disorders and bradykinesia, improving movement when rising from a chair, enhancing rapid alternating movements and posture stability (Kashif et al. 2022b), as well as increasing balance ability, balance confidence and performance in activities of daily living. Improvements have been observed to last for up to 16 weeks after rehabilitation (Kashif et al. 2022b). Moreover, balance and gait training in dual-task mode, combined with MI, can promote executive function in individuals with PD (Sarasso et al. 2021). The inclusion of MI in rehabilitation has also been reported to enhance participant motivation, attention, concentration and—ultimately—motor learning ability and task execution performance (Kashif et al. 2022b).

VR has been combined with tDCS into a hybrid treatment approach (Harris et al. 2018; Simcsik et al. 2021). The experiment documented in Simcsik et al. (2021) indicates that tDCS might not necessarily add value to VR training. However, this indication could be a result of the intervention having been delivered only for one day, which might

not have given the experiment participants enough time to familiarise themselves with the tasks. A recent study combining tDCS with C-Mill-based AR has demonstrated that this combination effectively improves posture stability in individuals with PD (Pisano et al. 2024). Finally, neuromotor rehabilitation interventions have been documented based on a combination of robot-assisted therapy and VR. Such interventions have been observed to improve the motor and cognitive function of individuals with PD, as well as their perceived well-being and quality of life (Zanatta et al. 2023). For example, equipment such as the Lokomat System (Hocoma n.d.), a robotic device consisting of a treadmill, body weight support and an exoskeleton, holds promise for supporting rehabilitation programmes delivered within immersive virtual environments (Fundarò et al. 2019).

4.9 Safety and feasibility

This section discusses the safety and feasibility, covering affordability and convenience, of using immersive technologies in PD rehabilitation.

4.9.1 Safety issues

Several technology-augmented PD rehabilitation methods rely on commercial entertainment equipment such as Xbox Kinect (Xbox Kinect n.d.) and Nintendo Wii (Nintendo Wii n.d.; Campo-Prieto et al. 2021; Severiano et al. 2018), which are typically characterised by good usability (Severiano et al. 2018). Research has generally highlighted the safety of such rehabilitation methods (Campo-Prieto et al. 2021; Júlio et al. 2022; Mirelman et al. 2016; Palacios-Navarro et al. 2015; Tunur et al. 2020; Van Wegen et al. 2015) and their suitability for elderly individuals with PD as well as for those with mild-to-moderate PD symptoms (Campo-Prieto et al. 2021; Muñoz et al. 2022). Adverse effects, such as anxiety, confusion and dizziness, have been reported occasionally (Campo-Prieto et al. 2021; Júlio et al. 2022; Mirelman et al. 2016; Palacios-Navarro et al. 2015; Tunur et al. 2020; Van Wegen et al. 2015). Furthermore, it has been observed that individuals with PD participating in interventions within virtual immersive environments experience almost no falls (Severiano et al. 2018; Tunur et al. 2020), balance and posture problems, FoG episodes (Impellizzeri et al. 2022; Severiano et al. 2018) and peripheral symptoms besides occasional gastrointestinal symptoms (Impellizzeri et al. 2022).

Some studies have highlighted that prolonged exposure to virtual immersive environments can lead to eye fatigue and cybersickness, particularly with VR (Mittelstaedt et al. 2019). Cybersickness typically manifests as dizziness, lightheadedness and/or nausea, often resulting from

a misalignment between visual stimuli and proprioceptive feedback (Tunur et al. 2020). However, cybersickness is relatively rare (Impellizzeri et al. 2022; Tunur et al. 2020) and the negative impact on rehabilitation benefits for individuals with PD is limited. Risks can be mitigated by controlling the duration of exposure to the immersive environments. This control often requires a balance to be struck, considering the need for interventions to provide individuals with PD with sufficient time to adapt to new environments (Impellizzeri et al. 2022). VR is more likely to have adverse effects on study subjects compared to other immersive modalities, if the intervention is not appropriately designed (Goh et al. 2021). For example, prolonged use of HMDs is not recommended, as individuals with PD might exhibit lower tolerance to the equipment due to movement impairments around their head and neck, combined with dizziness. The use of various immersive technologies, such as AR, can mitigate these risks.

Motor impairment in individuals with PD often has a limited impact on sensitivity to stimuli within virtual immersive environments and on the outcomes of interventions (Saredakis et al. 2020). For those individuals with PD who are more sensitive to enriched environments or who are concerned about the possibility of suffering from cybersickness during immersive rehabilitation, it is recommended that they start with training programmes and devices that are simpler to operate and use. Tasks requiring fewer skills and fewer elements within the virtual environment are recommended, as opposed to tasks executed in environments containing a larger number of more detailed virtual elements (Impellizzeri et al. 2022). Overall, cybersickness within VR environments is more likely to occur than with 360° video games and with immersive experiences that consist of pure scenery or enable simpler user interaction (Saredakis et al. 2020). Ease of use and personalised design have been identified as key features of immersive devices and environments on which the rehabilitation of individuals with PD should be based, to improve user comfort and experience and to reduce the incidence of cybersickness (Zhao et al. 2015).

4.9.2 Feasibility: affordability and convenience

With recent technology advancement, commercial entertainment equipment often used for immersive PD rehabilitation has become increasingly price-competitive (Severiano et al. 2018). The availability of low-cost devices that enable interactive experiences within virtual immersive environments, combined with the design of interventions based on immersive technologies, makes immersive PD rehabilitation more cost-effective than methods based on other technologies, including those that require real-time monitoring systems and robots to control specific body movements

(Palacios-Navarro et al. 2015). The additional cost of embedding VR equipment and systems in a typical TT intervention has been estimated at less than €4,000, making the equipment price-competitive for residents of middle- and high-income countries (Mirelman et al. 2016). The study documented in Cornejo Thumm et al. (2021) has suggested a lower additional cost of approximately US\$2,000. The equipment used included a treadmill, a depth camera (Microsoft Kinect) with a Microsoft High-Definition camera, a TV screen and a personal computer to run the VR software. The feasibility of active-balance immersive rehabilitation training for individuals with PD, utilising a Nintendo Wii Balance Board with a unit cost of less than US\$100, has also been documented, with additional advantages in terms of device ease of use and portability (Albiol-Pérez et al. 2017). Nonetheless, a more detailed cost-benefit analysis of the use of immersive technologies for PD rehabilitation will be required as these technologies continue to develop and additional detailed knowledge of the associated benefits to individuals with PD is acquired.

Some individuals with PD experience difficulties with balance and can be at risk of falling during traditional interventions, which is why the presence of a professional caregiver to guide and assist them is often recommended. This preference adds to the cost of the interventions and can limit the scalability of their deployment when a limited number of professionals is available. Some PD interventions relying on immersive technologies are suitable for delivery in domestic environments (Tunur et al. 2020). The domestic delivery is particularly convenient for clinical professionals to track the progress of individuals with PD over time without having physical access to them, considering the possibility for caregivers to monitor and control the intervention remotely (Amprimo et al. 2022). Although the presence of a professional caregiver is often recommended, relatives who have undergone basic training can, in some cases, provide appropriate guidance and help to the individuals with PD during the interventions (Mirelman et al. 2016; Palacios-Navarro et al. 2015). On the other hand, most interventions based on immersive technologies, especially those relying on AR (Tunur et al. 2020), are likely to require little to no external assistance, which reduces associated costs (Kashif et al. 2022a, b; Tunur et al. 2020).

4.10 User experience of immersive rehabilitation

This section focuses on the user experience (UX) of immersive rehabilitation in the context of PD, summarising its advantages and limitations.

4.10.1 Advantages

Participants' perceptions of devices and software used for rehabilitation, including acceptability and ease of use, play a crucial role in establishing the feasibility of technology-augmented interventions (Lee et al. 2023). Individuals with PD have generally provided positive feedback on their experience with technology-augmented rehabilitation (Brachman et al. 2021; Campo-Prieto et al. 2021; Muñoz et al. 2022), including interventions relying on AR (Lee et al. 2023; Tunur et al. 2020; Wang et al. 2020) and VR (Campo-Prieto et al. 2021; Cano Porrás et al. 2019; Muñoz et al. 2022). In studies on VR rehabilitation, participants with PD often found that experiencing VR environments within the context of their rehabilitation was interesting, enjoyable and motivating and that the interactive features of these environments were intuitive (Campo-Prieto et al. 2021; Cano Porrás et al. 2019). As for immersive rehabilitation that requires wearing an HMD, participants have reported that it typically takes only a few minutes for them to adapt to the equipment, although they may feel uncomfortable when wearing the HMD for the first time (Wang et al. 2020).

In a qualitative study using Google Glass as part of PD rehabilitation, almost all participants expressed their interest in purchasing a pair of smart glasses that supported rehabilitation programmes after training and highlighted their willingness to recommend the equipment to others (Lee et al. 2023). Another study suggested that participants using AR devices for dance practice reported additional positive feelings, including a self-perception of better coordination and reduced rigidity, as well as a sense of 'elegance' in movement (Tunur et al. 2020). Studies have generally shown a consensus among subjects participating in immersive rehabilitation that such interventions are more pleasant and enjoyable than conventional rehabilitation (Brachman et al. 2021; Wang et al. 2020).

4.10.2 Limitations

Participants are generally satisfied with the use of immersive technologies in rehabilitation interventions. Nevertheless, a degree of concern has been expressed at times, for example, regarding the level of comfort provided by the equipment (Muñoz et al. 2022). Moreover, subjects have sometimes reported anxiety regarding the use of new technologies (Lee et al. 2023) and difficulties completing tasks within immersive virtual environments (Cano Porrás et al. 2019), which can prevent them from completing the rehabilitation tasks as required (Lee et al. 2023). In two studies using Google Glass in the context of rehabilitation, a small number of subjects reported difficulties operating

the hardware due to limited ease of use of controls (Lee et al. 2023), insufficient volume of audio feedback, limited screen size (Lee et al. 2023; Tunur et al. 2020) and physical discomfort while wearing smart glasses (Tunur et al. 2020). Subjects also provided negative feedback about the interactive properties of the software, including unclear on-screen instructions that led to confusion and the fact that using devices in the presence of ambient noise would distract them from the rehabilitation (Lee et al. 2023). In another study using the HTC Vive Pro (HTC VIVE n.d.), a VR device, participants in a rehabilitation context reported complaints about the weight of the HMD (Wang et al. 2020). Some subjects reported a reduced sense of accomplishment after completing tasks in immersive environments compared to how they would have felt in a physical environment (Cano Porrás et al. 2019). This reduction may be because virtual scenarios and activities are set and take place within controlled environments and are therefore not equivalent to real-world environments and experiences (Cano Porrás et al. 2019; Júlio et al. 2022).

4.11 Effectiveness and user preferences across immersive rehabilitation programmes

This section analyses the effectiveness of immersive rehabilitation for PD, including the specification of user preferences for different available options.

4.11.1 Variability in the effectiveness of immersive rehabilitation across training programmes

PD rehabilitation plans developed using different equipment, software solutions and training protocols are likely to achieve different rehabilitation outcomes, for example, due to the impact of varying rehabilitation procedures on specific PD motor symptoms. Rehabilitation programmes focusing on gait can improve motor performance in conjunction with dual tasks. In contrast, those programmes focusing on balance have produced improved gait under both single- and dual-task conditions, with longer-lasting rehabilitation effects in controlled studies (Barbosa et al. 2018). Regarding different immersive technologies, improvements in motor performance and cognitive abilities have been reported with reference to the use of both VR and AR in the context of PD rehabilitation programmes. However, no consensus has been reached regarding significant differences between the two technologies in terms of benefits to individuals with PD (Araújo et al. 2023). With reference to VR, a comparative study of the Nintendo Wii and Xbox Kinect has shown that individuals with PD using the Nintendo Wii for rehabilitation can achieve better motor function performance than those using the Xbox Kinect.

Table 6 Differences in rehabilitation outcomes based on different types of immersive equipment and software in some of the selected studies

Experience	Details of Experience	Types of Immersive Technologies	Equipment	Training Objectives	Rehabilitation Outcomes	References
Lateral leg movements	The individual with PD was introduced to the video game and prompted to make leg lateral movements to reach and squash a series of moles that appear on the screen. While standing, the subjects were required to reach one of the two moles, which were presented in random order, either to the right or to the left of the subject (always aligned to the same horizontal line). The individual with PD saw themselves in the game	Virtual reality (VR)	Kinect-based VR	/	Significant improvements were noted in completion time and the 10-Meter Walk Test score	Palacios-Navarro et al. (2015)
Real-life challenges	The virtual environment consisted of obstacles, different pathways, narrow corridors and distractors, requiring modulation of step amplitude in two planes (i.e., height and width) to be coordinated with walking behaviour. The number, speed, orientation, size, frequency of appearance and shape of the obstacles were manipulated according to individual needs following a standardised protocol. Environmental features (e.g., visibility, settings and distractors) were adjusted to increase training complexity. During week 1, obstacles appeared infrequently (e.g., every 30 s, at a low level of difficulty and unilateral in direction and the environmental features were minimal (i.e., high visibility, daytime walking and minimal distractors). The frequency of appearance of the obstacles increased based on the subject's performance in weeks 2 and 3, the frequency of appearance of the obstacles increased, obstacles were appearing increasingly on the more challenged side of the user's body and their features (horizontal vs. vertical) was individualised. Environmental features appeared with some minimal distractors during weeks 2 and 3. In week 4, subjects were introduced to a new environment to allow for greater diversity in training and to maximise transfer to the real world. Throughout training had to maintain the ratio of 80:20 success/failure rates to enhance motor learning. If subjects were not successful, the difficulty level was adjusted to the previously achieved level and vice versa	VR	Modified Microsoft Kinect-based VR and treadmill training combination	The virtual environment imposed a cognitive load that requires attention, planning, dual-tasking, response selection and processing of rich auditory and visual stimuli, involving multiple perceptual processes—to enhance motor learning	Significant improvements were observed in obstacle crossing performance, reducing the number of falls, increasing step length and step length variability. The crossing step length remained significantly increased at follow-up (FU) after 6 months	Pelosi et al. (2020)

Table 6 (continued)

Experience	Details of Experience	Types of Immersive Technologies	Equipment	Training Objectives	Rehabilitation Outcomes	References
A mixed exercise training of multiple types of dynamic balance games and static balance games	In terms of motor functions, tennis, bowling and kicking were used, whereas soccer, table tilt, penguin slide and tilt city were used to enhance dynamic balance, while single-leg extension and torso twist were used to improve static balance. During each training session, there was a dynamic balancing game and a specific static balance game. Exercises were selected based on their difficulty level and the degree of difficulty was progressively raised in accordance with the results of the individual with PD. Individuals with PD began with the penguin slide and worked their way up through table tilt, tilt city and then soccer. Initially, each game was played for 2–3 min per session. With the progression of performance, 3–4 min of table tilt were added. Weight shifts and movement patterns improved as a result of playing this video game. For up to 2 min a day, the individuals with PD did single-leg extensions. Additional exercises were introduced in subsequent weeks, including soccer, torso twists and a tilt city. The subjects performed these activities for 1 to 5 min per session. Treatment sessions then progressed to motor function games, including bowling, tennis, kicking and boxing (from least challenging to most challenging), with most treatment sessions ending with boxing. Boxing was performed in the last three weeks of therapy because of the increased balance and coordination demands. Each session lasted for 10–15 min	VR	Wii box-based VR. The VR system consisted of a wall-mounted display, a Wii box, a Wii remote and a Wii Fit board on which the individual with PD stood while interacting with the VR system and playing the selected games	Motor functions, dynamic balance and static balance	Significant improvements: resting tremors, rigidity, body bradykinesia, posture, postural stability, gait, rapid alternating movements and arising from a chair, as well as balance ability, balance confidence and activities of daily living (ADL) performance, even in the FU after 16 weeks	Kashif et al. (2022a, b)
Personalisation strategies	Appropriate personalised strategies were developed through the clinical judgment of physical therapists during home visits and participants' self-assessment of their progress. Examples of strategy included stepping in time to the beats of an external rhythmic auditory cueing device, self-initiated movement strategies such as counting, shifting weight from side to side and/or simplifying complex tasks and progressing by increasing the complexity of tasks where appropriate	VR	A Mirage 3D camera (producing personalisation 180° strategy videos) and an Oculus Go VR head-mounted display	Freezing of gait (FoG)	Improvements include the ability to control FoG (even after stopping medication), increased self-confidence and reduced anxiety	Goh et al. (2021)

Table 6 (continued)

Experience	Details of Experience	Types of Immersive Technologies	Equipment	Training Objectives	Rehabilitation Outcomes	References
Wii balance-training	/	VR	Companion device for Wii	/	Improvements: imbalance, depression, anxiety and ADL	Lee (2018)
Two programmes from the “Moving through Glass” app: “Walk with Me” and “Unfreeze Me.”	Subjects were taught to switch between the two immersive experiences using voice-activation phrases by trained research coordinators. Participants were asked to participate in the experience and attempt to replicate the exact movements they viewed on the small screen of the Google Glass device while wearing it. “Walk with Me” displays a video in which a person walks outside on a promenade to rhythmic music, providing simultaneous visual cues of footsteps that can be followed, as well as auditory cues to the wearer. The rhythm serves as a metronome, setting the walking pace. The subject can choose from four different speeds, based on their personal level of function. The four tempos to cue walking speed are “Gentle,” “Medium,” “Medium Fast,” and “Fast”. “Unfreeze Me” consists of three different modules featuring various musical songs and marching-in-place dances designed to provide cues that allow the subject to become “unfrozen” by following the marching movements to the beat of a song of their choice	Augmented reality	Google Glass	/	Improvements: gait, dual-task performance and FoG. For the “Walk with Me” experience, improvements were observed in all walking tasks, except for turning, including a 25-foot straight walk and a dual task of walking straight while navigating through a doorway. In contrast, for the “Unfreeze Me” experience, all walking tasks deteriorated, except for the dual task of walking straight	Lee et al. (2023)

VR, virtual reality; FU, follow-up; ADL, activities of daily living; FoG, freezing of gait.

This improvement has been interpreted as a consequence of Xbox Kinect being more difficult to use for individuals with PD due to the increased complexity of the user interface associated with richer graphical detail (Alves et al. 2018).

Studies using different immersive rehabilitation software solutions have highlighted that rehabilitation plans for individuals with FoG should prioritise cognitive training over gait-specific training (Lee et al. 2023). For example, the immersive experience ‘Walk with Me’, developed by the Mark Morris Dance Group, a dance training centre that develops targeted community programmes for individuals with PD, aims to address both cognitive and motor manifestations of PD, whereby rhythmic auditory cues are used to increase cognitive load during the execution of walking tasks. A detailed description is shown in Table 6. After receiving rehabilitation with the software solution, individuals with FoG showed improved gait performance, as measured by both single and dual tasks and a reduced incidence of FoG, except for tasks requiring them to turn (Lee et al. 2023).

Compared to immersive rehabilitation programmes designed for other diseases, such as stroke (Bekkers et al. 2020), those specifically designed for PD appear to lead to more significant improvements in motor function, particularly in FoG, which is often not achievable using conventional rehabilitation methods (Griffin et al. 2011). Immersive digital experiences, such as ‘Walk with Me,’ contain features that can divert attention from the task, as well as others that can strengthen visuospatial function and help individuals with PD suppress stimuli and behavioural responses that are not relevant to the task. These features have been observed to enhance dual-task performance and decrease the frequency of FoG episodes in individuals with PD (Lee et al. 2023).

Results achieved through rehabilitation programmes, as documented in selected studies, are provided in Table 6. The table includes information about the immersive technologies and devices used, the design of the programmes, the training goals and the rehabilitation outcomes. Results corresponding to all studies considered for this review are reported in Table S2, Appendix: Supplementary Material in the online resource.

4.11.2 User preferences

Participants in rehabilitation programmes relying on the use of immersive technologies have expressed different preferences regarding the choice of devices and software solutions, depending on their individual experiences and emotional reactions to the virtual environments. This variability is illustrated by a recent study involving multiple immersive rehabilitation programmes and different

devices (Cano Porras et al. 2019). The VR rehabilitation programmes used in this study were all generated using CAREN. CAREN (motekmedical.com n.d.) is a biomechanics lab that combines a high-performance split-belt treadmill, a 6-degree-of-freedom motion base and AR and VR technologies to provide individuals with PD with flexible balance and gait training programmes. CAREN Base and CAREN Dome, compared to 2D immersive systems such as V-Gait (Home—motekmedical.com n.d.) and C-Mill (Home—motekmedical.com n.d.), attracted more positive feedback from individuals with PD due to higher levels of perceived immersion, for example, thanks to the Dome’s 360-degree, room-size, shaped screen. The feedback by individuals with PD about virtual environments and the nature of the tasks to be executed within them varied across software solutions. Environments that replicate physical settings and focus on actions to be performed within them (such as avoiding obstacles when walking on a road and riding a boat) are often preferred. This choice is likely to reflect personal predispositions and preferences of individuals with PD. It is worth investigating in depth as part of future research, considering the fast-paced evolution of the relevant technologies. An overview of training objectives and outcomes corresponding to different rehabilitation programmes is provided in Table S2, Appendix: Supplementary Material in the online resource.

5 Discussion

The discussion section presents the overall advantages and disadvantages of using immersive technologies in PD rehabilitation and relevant future research, suggests the directions for the design of future immersive PD rehabilitation programmes and analyses the strengths and limitations of this review.

5.1 Advantages and limitations of immersive rehabilitation for PD and future research

Compared to 2D rehabilitation based on serious games and other conventional physical therapy methods, 3D immersive rehabilitation often yields more significant improvements in performance, as measured by game-specific parameters such as performance and engagement scores, as well as kinematic parameters, particularly motor performance (Pazzaglia et al. 2020). This finding suggests a considerable potential for 3D immersive rehabilitation methods to alleviate PD lower-limb motor symptoms, including reduction of resting tremors, rigidity, body bradykinesia, rapid alternating movements (Kashif et al. 2022b), risk of falls (Cano Porras et al. 2019; Mirelman et al. 2016), fear of falls

(Krieger et al. 2013) and gait disorders (Cano Porras et al. 2019; Feng et al. 2019; Mirelman et al. 2016); improved static balance, i.e., postural stability (Brachman et al. 2021), dynamic balance (Brachman et al. 2021; Cano Porras et al. 2019; Lee 2018; Mirelman et al. 2016), balance confidence (Kashif et al. 2022a) and postural control and reduced FoG severity (Goh et al. 2021). More generally, 3D immersive rehabilitation has been proposed for improving performance on activities of daily life for individuals with PD (Kashif et al. 2022c; Lee 2018), considering the benefits for individuals with PD observed regarding the execution of dual tasks in 3D immersive environments (Killane et al. 2015; Mirelman et al. 2016; Pelosin et al. 2022).

Neurological research has confirmed that interventions based on immersive technologies can have a positive impact on functional connectivity in various brain regions of individuals with PD, consistent with the observed benefits on motor function and cognitive performance (Droby et al. 2020). Different immersive technologies and software solutions can affect different brain regions. For example, TT combined with VR rehabilitation has been shown to result in more efficient activation of subjects' frontal-striatal circuits than TT alone (Maidan et al. 2017). Frontal-striatal circuits are neural pathways connecting the striatum and frontal lobe regions that modulate motor, behavioural and cognitive functions of the brain and receive inputs from dopaminergic cell populations regulating information processing (Morris et al. 2016). Another study has compared the EEG power spectra of individuals with PD undergoing VR and AR rehabilitation. The results suggest that the use of AR as opposed to VR can lead to different EEG power spectra in individuals with PD: lower activity in the alpha frequency band (8–12 Hz) has been observed with AR in the right frontal and right temporal regions and higher activity in the beta frequency band (13–30 Hz) has been reported with AR in the right frontal and right temporal regions (Seyedebrahimi et al. 2019). Activity in the alpha frequency band is typically associated with a relaxed state of wakefulness, characterised by decreased visual fixation, stimulation and attention. Activity in the beta frequency band is usually associated with sensorimotor behaviour and therefore typically decreases with sleepiness and increases with alertness (Xavier et al. 2020). It is anticipated that additional research will help clarify the clinical significance of the observed differences in EEG activity patterns associated with the use of VR and AR in PD rehabilitation.

Immersive technologies for rehabilitation have been increasingly accepted by individuals with PD and clinicians in recent years, thanks to the associated benefits of increased security, increased efficiency in the implementation of rehabilitation interventions, ease of use in relation to data collection and analysis, affordability, flexibility at

the deployment stage and the ability to simulate realistic environments. According to typical manufacturer recommendations and observations from the studies included in this review, a surface area of 5 m² is often sufficient for most individuals with PD to complete immersive rehabilitation interventions (Campo-Prieto et al. 2021; Wang et al. 2020). However, tasks within immersive environments are not entirely equivalent to activities in physical settings (Júlio et al. 2022).

The use of immersive technologies is not recommended for all individuals with PD. For example, it has been suggested that the technologies should be avoided by those individuals with PD who wear glasses or are prone to visual fatigue (Cikajlo and Peterlin Potisk 2019). These considerations are important because, in the context of immersive rehabilitation, individuals with PD may face greater psychological and physical pressure than healthy individuals when it comes to coping with complex environments and executing tasks in the presence of time constraints and the prolonged use can cause a significant visual strain (Cikajlo and Peterlin Potisk 2019). However, many of the HMDs that have been released to the market over the past few years now come with the design features that accommodate the needs of users with hyperopia and myopia (e.g., ZEISS optical (lens) inserts for Apple Vision Pro (Zeiss n.d.) and “glasses spacer” and prescription lens inserts for Meta Quest devices (Meta n.d.a; Meta n.d.b) and it would therefore be essential to review the above recommendation on glasses-wearing individuals with PD empirically.

Individuals with PD can also suffer from tremor and movement disorders, which can make it more difficult for them to access and operate immersive hardware and software equipment. The interface control can be especially challenging for visually impaired individuals with PD (Goh et al. 2021). Such obstacles can reduce the enthusiasm of individuals with PD about participating in immersive rehabilitation, which, in turn, can reduce compliance and learning benefits in terms of improved motor function (Goh et al. 2021). The use of high visual contrast and easily identifiable colours in digital interfaces can help elderly individuals with PD distinguish between the virtual and physical environments in the context of AR-augmented PD rehabilitation. Similarly, reliance on high visual contrast and carefully selected colours in VR environments can make it easier for individuals with PD to distinguish between background features of the environment (for which user interaction is not supported) and interactive features, including those that provide real-time user instructions and prompts (Wang et al. 2020).

Individuals with PD often feel more comfortable using immersive equipment and rate experiences in virtual immersive environments as more enjoyable when they can avoid

using wearable devices, including HMDs, wearable sensors and markers used to monitor and evaluate task performance (Liao et al. 2023; Palacios-Navarro et al. 2015; Smith 2013). For this reason, recent research has focused on the development of ‘natural’ user interfaces that enable users to interact with digital systems without physical encumbrances, such as using voice, gestures and body movements (Liao et al. 2023; Nanjappan et al. 2017; Smith 2013). With such interfaces, often combined with motion-sensing input devices such as Kinect (Smith 2013) and Intel RealSense (Intel RealSense n.d.), individuals with PD can directly access real-time metrics reflecting their performance on the training tasks without reliance on wearable monitoring devices, which can enhance motivation and engagement (Palacios-Navarro et al. 2015). More advanced immersive systems that do not require users to wear any devices, such as systems including voice and gesture-based interfaces and equipment such as CAREN Base and CAREN Dome, may be more attractive to a broader range of individuals with PD. Advanced gesture and voice-based MR systems have also started becoming available. For example, the recently launched Apple Vision Pro (Apple n.d.) and Meta Quest 3 HMDs (Meta n.d.c) both include highly intuitive gesture and voice interfaces enabling the use of the HMD without physical controllers.

5.2 Design considerations relevant to future immersive rehabilitation programmes for PD

The future immersive rehabilitation for PD should consider the personalisation and structuring of rehabilitation programmes, the standardisation of immersive training and assessment protocols, the optimisation of somatosensory information flow and a more strategic use of multisensory cues and interactive elements.

5.2.1 Personalised and structured design

Individual PD symptom profiles and disease severity can significantly impact rehabilitation outcomes (Wang et al. 2020). Moreover, different PD rehabilitation programmes can lead to different outcomes in terms of alleviating different symptoms, due to the nature of the training tasks. For example, immersive tasks focusing on road obstacle avoidance during walking have been reported to improve the performance of individuals with PD in terms of obstacle negotiation and tasks associated with boat riding and surfing have been observed to facilitate weight shifting (Cano Porrás et al. 2019). Several studies have pointed out that effective rehabilitation strategies should rely on interventions carefully selected by clinicians (Harris et al. 2018). Customisation has been recommended to align each

intervention with the specifications of the immersive equipment, the nature of the virtual environments and personal symptomatic profiles and needs of individuals with PD (Brachman et al. 2021; Cano Porrás et al. 2019). For this reason, the design of immersive rehabilitation programmes should follow a structured approach to deliver personalised experiences (Wang et al. 2020). Different immersive environments and tasks should be considered when developing customised and personalised programmes, ideally based on the observation of daily activities of individuals with PD (Klinger et al. 2013). Immersive rehabilitation programmes should be designed for scalability – for example, by building on a set of basic software training modules combined with additional performance assessment tasks (Amprimo et al. 2022), in a way that stimulates a broader range of motor functions.

Recent research suggests that immersive rehabilitation programmes designed to deliver personalised and structured training experiences can be more attractive to individuals with PD and can improve rehabilitation outcomes (Cano Porrás et al. 2019; Kashif et al. 2022a; Wang et al. 2020). If carefully designed, immersive rehabilitation programmes can, in fact, deliver experiences customised individually in terms of both content and task difficulty (Wang et al. 2020). This flexibility can enable the selection of training interventions relative to disease severity, whereby task difficulty can be gradually increased based on performance and tasks can be refined as individuals with PD progress through their rehabilitation programme (Brachman et al. 2021; Cano Porrás et al. 2019; Kashif et al. 2022a). The inclusion of auxiliary activities can enhance the familiarity of individuals with PD with the execution of specific motor functions and improve their abilities (Palacios-Navarro et al. 2015). For example, the combination of specific dynamic and static balance training within immersive virtual environments has been observed to improve balance function and posture control (Kashif et al. 2022a, b, c). This observation further highlights the importance of developing diversified rehabilitation training programmes customised to fulfil individual requirements.

5.2.2 Standardised immersive training and assessment protocols

Recent research has highlighted a scarcity of standardised training protocols for immersive PD rehabilitation (Barbosa et al. 2018; Cano Porrás et al. 2019) and there are calls for more rigour, controls and standardisation in the XR-related healthcare research in general, for example, in Vlaker et al. (2024). This scarcity and the calls are likely due to a diversification of immersive rehabilitation

experiences and to the resulting availability of multiple options with varying degrees of complexity in terms of both virtual environments and training tasks. Additional research is therefore required to achieve a balance between the need to develop structured and personalised rehabilitation experiences that can meet the needs of a heterogeneous population of individuals with PD and the requirement for standardised evaluation. Regarding training duration and intervention frequency, studies have shown that a 10- to 20-min VR-based intervention does not significantly enhance motor performance and cognitive abilities (Schuch et al. 2020). Other studies have identified three 30-min sessions per week as the minimum requirement to achieve positive results in PD, with an optimal range of more demanding sessions ranging from 7 to 10 sessions per week (O'Neil et al. 2018). In terms of the training cycle, 6 weeks of intervention is enough to maximise the improvement in dual-task gait performance of individuals with PD and the benefits last for 6 months. In contrast, the 12-week intervention has a more prominent effect on falls and fear of falling than the 6-week intervention (Pelosin et al. 2022). However, some studies have suggested that there is no clear relationship between the improvement of the condition of individuals with PD and the specific number of sessions or treatment duration (Navarro-Lozano et al. 2022). Therefore, developing specific intervention models and training guidelines for immersive rehabilitation of PD remains a core issue. In the future, standardised training and evaluation protocols should be established—for example, by developing and designing more precise and scientific rehabilitation protocols after clarifying the impact of the exact training cycle, frequency, intensity and timing (Brachman et al. 2021). In addition, further usability and user experience surveys on devices and software should be conducted to maximise the engagement of individuals with PD and rehabilitation effectiveness (Zanatta et al. 2023; Zhao et al. 2015).

5.2.3 Somatosensory information flow

Individuals with PD often have impaired ability to process somatosensory cues. For example, it has been documented that their balance and posture control can be impaired when they are stimulated by continuous flows of visual information associated with changes in open-space environments (Suarez et al. 2011). Individuals with PD often exhibit sensory perception deficits that can lead to more severe judgment errors under faster visual flows (Ehgoetz Martens et al. 2015a; Goh et al. 2021). The executive functions of individuals with PD are often slowed down compared to those of mainstream individuals, in such a way that good executive accuracy can be maintained during

task implementation. Impaired functions include the following: planning; organisation; sequencing (the ability to arrange events in order, including processing serial order, feedforward control and detecting repetitive patterns); set-shifting (the ability to move across mental sets or different tasks, often used as a measure of cognitive flexibility); attentional control; inhibitory control; completing and monitoring task execution; multi-task processing; decision-making; judgement. This slowing down is consistent with a well-documented trade-off between speed and accuracy (Júlio et al. 2022). Moreover, both the degree of executive function impairment and the response times of individuals with PD to environmental stimuli are positively correlated with disease severity (Júlio et al. 2022). For this reason, virtual environments for immersive PD rehabilitation programmes should be designed to accommodate slower visual information flows, thereby allowing for longer reaction times. It is also recommended that more straightforward and intuitive display systems be relied upon, in a way that the immersive equipment can provide clear and easily identifiable visual information and cues to action. Moreover, the time between consecutive operations to be performed by individuals with PD within virtual environments should be programmable to accommodate the different needs of individuals with PD.

5.2.4 Strategic use of multisensory cues

The design of immersive virtual environments providing multisensory feedback to individuals with PD (for example, by relying on changing environmental cues) can have significant benefits for individuals with PD. Examples include improvements in motor skill learning ability (Cano Porrás et al. 2019), increased motivation to engage in training and learning (Lee et al. 2015), as well as enhanced motor coordination, spatial perception and proprioception (Severiano et al. 2018). Visual and auditory stimuli have been successfully combined within virtual immersive environments in the context of vestibular rehabilitation, the aim of which is “to modify the postural control system by means of specific and repetitive physical exercises in different conditions” (Severiano et al. 2018: p. 79). Such exercises are typically designed to improve muscle and joint proprioception, to increase movement coordination of the head, eyes and the rest of the body (Lee et al. 2015; Severiano et al. 2018) and to enhance gait performance (Lee et al. 2015) and balance ability (Van Wegen et al. 2015). These benefits can be attributed to external cues and multisensory feedback accelerating and strengthening the natural mechanisms of neuroplasticity by triggering neurophysiological reward mechanisms, including the dopaminergic reward system. This system responds to the cues and feedback by facilitating the release

of dopamine, which, in turn, results in the improved proprioception and other benefits as above (Campo-Prieto et al. 2021; Marsh et al. 2010; Severiano et al. 2018). Additionally, another study has specifically explored reward-based VR rehabilitation experiences, including the role of visual input and haptic feedback. This study has suggested that feedback and cues based on errors and rewards can provide insights into the rehabilitation of dopaminergic nervous system function (Nardi et al. 2023).

It has been observed that visual stimulation can increase cognitive load and distract individuals with PD during exercises carried out within virtual environments, thereby triggering FoG (Lee et al. 2023). Humanoid virtual characters, combined with the provision of multiple sensory cues from the virtual environment, have been successfully used to mitigate such risks (Lee et al. 2023). Examples relate to rehabilitation software that incorporates walking and dancing tasks, involving the presence of humanoid virtual characters combined with rhythmic auditory stimuli (Lee et al. 2023). Further research should lead to the identification of a broader range of design options for mitigating the risk of FoG in the context of immersive PD rehabilitation.

Similarly, further research is required to elucidate the implications of neurophysiological research findings on the design of personalised immersive PD rehabilitation experiences. One EEG study focusing on the effect of environmental cues on cerebral cortex activity in individuals with PD during tasks performed within virtual immersive environments has pointed to increased activity in the alpha frequency band in the temporal and frontal lobes, with activation detected in the beta frequency band in all cerebral lobes (Muñoz et al. 2022). This study elucidated the neurophysiological effects of different virtual environment cues on individuals with PD. Activity in the alpha frequency band is typically associated with decreased visual fixation, stimulation and attention. Activity in the beta frequency band is usually associated with sensorimotor behaviour (Xavier et al. 2020). Studying the neurophysiological performance of individuals with PD during task execution in immersive experiences containing different virtual cues can help define, summarise and select personalised immersive rehabilitation experience design styles, including categories of virtual environment cues. Such benefits can often be interpreted as a result of external cues and multisensory feedback.

5.2.5 Strategic use of interactive elements

Several studies have introduced innovative elements of interaction between individuals with PD and virtual immersive environments in the context of PD rehabilitation (Fearon et al. 2017; Júlio et al. 2022; Pelosin et al. 2020;

Wang et al. 2020). However, in such studies, interaction often occurs between participants and immersive systems—for example, via real-time interactive features of the virtual environments—and is not extended to social interaction. For this discussion, ‘social interaction’ is defined as any form of behavioural or otherwise conscious relationship between two or more individuals (Kringelbach and Rolls 2003). It has been noted that individuals with PD who engage in more frequent social interactions are often able to achieve higher social returns, for example, in terms of a self-reported strengthened sense of connectedness with others and society (Baumeister and Leary 1995). A link has been observed between increased activation of the dopaminergic system (Kawamichi et al. 2016; Straulino et al. 2016a) and enhanced self-reported intention to engage in social interaction, as well as a reduced occurrence of communication impairments (Straulino et al. 2016b). Notably increased dopaminergic activity has been reported in the striatum, which plays a vital role in reward mechanisms (O’Doherty 2004). Correspondingly, reducing the frequency of social behaviours can be associated with impaired secretion of dopamine (Liu et al. 2017) and of dopamine D1 receptors (Liu et al. 2017; Plavén-Sigray et al. 2014). For this reason, the definition of design directions for the development of future PD virtual immersive rehabilitation programmes should consider the inclusion of elements of social interaction among individuals with PD, drawing on the emerging technological platforms for Social VR (IXDF - Interaction Design Foundation 2023). Enabling multiple participants to immerse themselves in the same virtual scene at the same time can encourage social interaction within digital environments. Whereas the potential to elicit and facilitate social interaction among individuals is relevant to different types of immersive technologies, including VR, AR and MR, AR and MR have been identified as more promising, considering the possibility afforded for participants to interact both with virtual characters and with other individuals with PD in physical space (Tieri et al. 2018; Wang et al. 2020).

5.3 Strength and limitations

This review study has provided a comprehensive in-depth summary and discussion of recent research on rehabilitation methods relying on immersive technologies to alleviate lower-limb PD symptoms. Information has been presented regarding the hardware and software involved, experimental techniques, as well as results in terms of rehabilitation outcomes and self-reported experience. By including information about the perspectives of individuals with PD on immersive rehabilitation, including positive and negative feedback about experiences with immersive digital environments, this study has addressed a gap in previous review

studies regarding the quality of immersive rehabilitation programmes from a user perspective. Crucially, this review study has provided the first overview and comparison of PD rehabilitation programmes based on different immersive technologies with reference to the associated symptoms and outcomes. Attention has been paid to differences between rehabilitation programmes and to benefits to individuals with PD in terms of impact on different PD symptoms and on quality of life more broadly. The insights have highlighted design opportunities towards the development of future personalised virtual immersive experiences for individuals with PD.

A few limitations may affect the universality of statements regarding the effectiveness of immersive digital rehabilitation methods for alleviating lower-limb PD symptoms. Firstly, the scope of the review has been restricted to articles written in English, which might have led to the exclusion of beneficial results published in other languages. Secondly, almost all studies reviewed had exclusion criteria in place at the subject screening stage regarding individuals with PD with cognitive impairment and only five studies focused on the individuals at more advanced stages of the disease. Although there may be safety concerns in exposing such individuals with PD to virtual immersive rehabilitation, benefits have been reported in terms of improved cognitive abilities (Kashif et al. 2022a; Pelosin et al. 2022; Pezzi et al. 2022; Zhu et al. 2021). This improvement highlights a need for additional research involving individuals with PD with different symptomatic profiles, including those with more severe cognitive impairment. Finally, only thirteen out of 106 studies reviewed focused on AR and none focused on MR. Therefore, a similar review study should be conducted in the future, once additional evidence has been gathered regarding the use of AR and MR in the context of immersive PD rehabilitation. Expanding the knowledge base on the experiences of individuals with PD and the rehabilitation outcomes, thereby covering broader groups of individuals with PD as well as different immersive technologies, will be an essential step forward towards the design of future personalised virtual environments and experiences for PD rehabilitation.

6 Conclusion

Rehabilitation based on immersive technologies holds potential for alleviating lower-limb PD motor symptoms. The studies reviewed for this article have highlighted benefits in terms of reduced tremor, rigidity, bradykinesia, risk of falls, gait impairment and FoG, as well as improved static and dynamic balance and posture control. Moreover, immersive digital interventions relying on dual tasks have

been observed to promote motor performance and executive function in individuals with PD. The use of virtual immersive systems in combination with one or more different rehabilitation techniques holds potential to achieve better outcomes compared to a single task-based intervention. Neurological research has, so far, highlighted that the brain regions stimulated during virtual immersive rehabilitation are typically consistent with those affected in individuals with PD and that rehabilitation involving the use of immersive technologies often results in strengthened functional connectivity across brain regions. Studies focusing on user experience in relation to virtual immersive PD rehabilitation have generally reported positive user feedback with reference to ease of use, acceptability, safety, affordability of the technology, intuitive interactive virtual environments leading to enjoyable immersive experiences, as well as motivation and willingness to engage in the training programmes.

This review of PD research studies involving the use of different immersive devices and software has highlighted that rehabilitation effects often depend on individual disease progression and symptomatic profiles. For this reason, the design of structured and personalised rehabilitation programmes is recommended with a view to maximising individual benefits. The design of virtual immersive environments for PD rehabilitation should consider different factors, including individual reaction times to changes in the environments and the time required for operation feedback. Slower visual flows should be preferred, in line with the personal characteristics of individuals with PD, with a view to achieving better training fluency and higher satisfaction. The use of multisensory cues in the context of immersive PD rehabilitation often has a positive effect on individuals with PD in terms of rehabilitation outcomes and user experience. Similarly, the use of intuitive interactive features within virtual immersive environments can improve the efficacy of immersive PD rehabilitation and encourage individuals to engage with rehabilitation. A knowledge gap has been identified in relation to virtual environments that provide opportunities for social interaction during PD rehabilitation. Further design research is therefore needed for the development of structured personalised PD rehabilitation experiences. Emphasis should be placed on the use of multisensory cues within virtual environments designed for encouraging the execution of tasks in pairs or small groups, with a view to enabling the delivery of personalised immersive experiences.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10055-026-01331-4>.

Author contributions ZT and FC produced and revised the initial draft of this article. ZT and VG edited the article to the publication-ready stage. All authors commented and agreed on the progressive edits

throughout the writing process.

Funding The authors acknowledge that no institutional funding was provided for this research.

Data availability No primary data has been collected for this review study.

Declarations

Conflict of interest The authors declare no conflict of interest.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Abbruzzese G, Marchese R, Avanzino L, Pelosin E (2016) Rehabilitation for Parkinson's disease: current outlook and future challenges. *Parkinsonism Relat Disord* 22:S60–S64. <https://doi.org/10.1016/j.parkreldis.2015.09.005>
- Alberts JL, Kaya RD, Penko AL, Streicher M, Zimmerman EM, Davidson S, Walter BL, Rosenfeldt AB (2023) A randomized clinical trial to evaluate a digital therapeutic to enhance gait function in individuals with Parkinson's disease. *Neurorehabil Neural Repair* 37:603–616. <https://doi.org/10.1177/15459683231184190>
- Albiol-Pérez S, Gil-Gómez J-A, Muñoz-Tomás M-T, Gil-Gómez H, Vial-Escolano R, Lozano-Quilis J-A (2017) The effect of balance training on postural control in patients with Parkinson's disease using a virtual rehabilitation system. *Methods Inf Med* 56:138–144. <https://doi.org/10.3414/ME16-02-0004>
- Alves MLM, Mesquita BS, Morais WS, Leal JC, Satler CE, Dos Santos Mendes FA (2018) Nintendo Wii™ versus Xbox Kinect™ for assisting people with Parkinson's disease. *Percept Mot Skills*. <https://doi.org/10.1177/0031512518769204>
- Amprimo G, Masi G, Priano L, Azzaro C, Galli F, Pettiti G, Mauro A, Ferraris C (2022) Assessment tasks and virtual exergames for remote monitoring of Parkinson's disease: an integrated approach based on Azure Kinect. *Sensors* 22:8173. <https://doi.org/10.3390/s22218173>
- Anwar N, Akram S, Ilyas A, Khalid K, Munir M, Hayat MK (2021) Comparison of virtual reality and conventional balance training to improve balance and walking in Parkinson's disease patients. *In: Med. Forum*. pp 129–133
- Apple (n.d) Apple Vision Pro | Apple (United Kingdom). <https://www.apple.com/uk/apple-vision-pro/> Accessed 21 July 2024.
- Araújo HAGDO, Souza RJD, Da Silva TCO, Nascimento TS, Terra MB, Smaili SM (2023) Immediate effect of augmented reality, virtual reality, and neurofunctional physiotherapy on postural control and executive function of individuals with Parkinson's disease. *Games Health J* 12:211–219. <https://doi.org/10.1089/g4h.2021.0222>
- Arksey H, O'Malley L (2005) Scoping studies: towards a methodological framework. *Int J Soc Res Methodol* 8:19–32. <https://doi.org/10.1080/1364557032000119616>
- Asadzadeh A, Samad-Soltani T, Salahzadeh Z, Rezaei-Hachesu P (2021) Effectiveness of virtual reality-based exercise therapy in rehabilitation: a scoping review. *Inform Med Unlocked* 24:100562. <https://doi.org/10.1016/j.imu.2021.100562>
- Bacha JMR, Cunha MCC, Freitas TB, Nuvolini RA, Doná F, Silva KGda, Torriani-Pasin C, Ganança FdeF, Pompeu JE (2021) Effects of virtual rehabilitation on postural control of individuals with Parkinson disease. *Motricidade* 17:220–227. <https://doi.org/10.6063/motricidade.20207>
- Badarny S, Aharon-Peretz J, Susel Z, Habib G, Baram Y (2014) Virtual reality feedback cues for improvement of gait in patients with Parkinson's disease. *Tremor Other Hyperkinet Mov* 4:225. <https://doi.org/10.5334/tohm.192>
- Balestrino R, Schapira AHV (2020) Parkinson disease. *Eur J Neurol* 27:27–42. <https://doi.org/10.1111/ene.14108>
- Barbosa P, COSTA AD, Falconi A, d'Alencar M, Piemonte ME (2018) Can choice of games influence the therapeutic results obtained by training in virtual reality for gait improvement in people with Parkinson's disease?. *In: Movement Disorders*. Wiley, pp S106–S107.
- Baumeister RF, Leary MR (1995) The need to belong: desire for interpersonal attachments as a fundamental human motivation. *Psychol Bull* 117:497–529. <https://doi.org/10.1037/0033-2909.117.3.497>
- Bekkers E, Mirelman A, Del Din S, Avanzino L, Nieuwhof F, Hausdorff J, Nieuwboer A (2018) The effects of treadmill training augmented by virtual reality on postural control and freezing of gait in Parkinson's disease. *Mov Disord* 33:S155–S156
- Bekkers EMJ, Mirelman A, Alcock L, Rochester L, Nieuwhof F, Bloem BR, Pelosin E, Avanzino L, Cereatti A, Della Croce U, Hausdorff JM, Nieuwboer A (2020) Do patients with Parkinson's disease with freezing of gait respond differently than those without to treadmill training augmented by virtual reality? *Neurorehabil Neural Repair* 34:440–449. <https://doi.org/10.1177/1545968320912756>
- Bell Boucher D, Roberts-South A, Garcia AA, Katchabaw M, Jog MS (2013) Immersive augmented reality: investigating a new tool for Parkinson disease rehabilitation. *In: 2013 6th International IEEE/EMBS conference on neural engineering (NER)*. Presented at the 2013 6th International IEEE/EMBS conference on neural engineering (NER), IEEE, San Diego, CA, USA, pp 1570–1573. <http://doi.org/10.1109/NER.2013.6696247>
- Besharat A, Imsdahl SI, Yamagami M, Nhan N, Bellatin O, Burden SA, Cummer K, Pradhan SD, Kelly VE (2022) Virtual reality doorway and hallway environments alter gait kinematics in people with Parkinson disease and freezing. *Gait Posture* 92:442–448. <https://doi.org/10.1016/j.gaitpost.2021.12.013>
- Bloem BR, De Vries NM, Ebersbach G (2015) Nonpharmacological treatments for patients with Parkinson's disease. *Mov Disord* 30:1504–1520. <https://doi.org/10.1002/mds.26363>
- Bosch-Barceló P, Masbernat-Almenara M, Martínez-Navarro O, Tera-Miralles C, Pakarinen A, Fernández-Lago H (2024) A gamified virtual environment intervention for gait rehabilitation in Parkinson's disease: co-creation and feasibility study. *J Neuroeng Rehabil* 21:107. <https://doi.org/10.1186/s12984-024-01399-6>
- Brachman A, Marszałek W, Kamieniarz A, Michalska J, Pawłowski M, Juras G (2021) Biomechanical measures of balance after balance-based exergaming training dedicated for patients with Parkinson's disease. *Gait Posture* 87:170–176. <https://doi.org/10.1016/j.gaitpost.2021.04.036>
- Calabrò RS, Naro A, Cimino V, Buda A, Paladina G, Di Lorenzo G, Manuli A, Milardi D, Bramanti P, Bramanti A (2020) Improving motor performance in Parkinson's disease: a preliminary study on

- the promising use of the computer assisted virtual reality environment (CAREN). *Neurol Sci* 41:933–941. <https://doi.org/10.1007/s10072-019-04194-7>
- Camara Lopez M, Deliens G, Cleeremans A (2016) Ecological assessment of divided attention: what about the current tools and the relevancy of virtual reality. *Rev Neurol (Paris)* 172:270–280. <http://doi.org/10.1016/j.neurol.2016.01.399>
- Campo-Prieto P, Rodríguez-Fuentes G, Cancela-Carral JM (2021) Can immersive virtual reality videogames help Parkinson's disease patients? A case study. *Sensors* 21:4825. <https://doi.org/10.3390/s21144825>
- Cancela-Carral JM, Campo-Prieto P, Rodríguez-Fuentes G (2024) The IntegraPark study: an opportunity to facilitate high-intensity exercise with immersive virtual reality in Parkinson's disease patients. *JFMK* 9:156. <https://doi.org/10.3390/jfmk9030156>
- Canning CG, Allen NE, Nackaerts E, Paul SS, Nieuwboer A, Gilat M (2020) Virtual reality in research and rehabilitation of gait and balance in Parkinson disease. *Nat Rev Neurol* 16:409–425. <https://doi.org/10.1038/s41582-020-0370-2>
- Cano Porras D, Sharon H, Inzelberg R, Ziv-Ner Y, Zeilig G, Plotnik M (2019) Advanced virtual reality-based rehabilitation of balance and gait in clinical practice. *Ther Adv Chronic Dis*. <https://doi.org/10.1177/2040622319868379>
- Chuang C-S, Chen Y-W, Zeng B-Y, Hung C-M, Tu Y-K, Tai Y-C, Wu Y-C, Hsu C-W, Lei W-T, Wu S-L, Stubbs B, Carvalho AF, Su K-P, Chen T-Y, Tseng P-T, Wu M-K, Tsai C-H (2022) Effects of modern technology (exergame and virtual reality) assisted rehabilitation vs conventional rehabilitation in patients with Parkinson's disease: a network meta-analysis of randomised controlled trials. *Physiotherapy* 117:35–42. <https://doi.org/10.1016/j.physio.2022.07.001>
- Cikajlo I, Peterlin Potisk K (2019) Advantages of using 3D virtual reality-based training in persons with Parkinson's disease: a parallel study. *J Neuroeng Rehabil* 16:119. <https://doi.org/10.1186/s12984-019-0601-1>
- Colman M, Millar J, Patil B, Finnegan D, Russell A, Higson-Sweeney N, Aguiar MDS, Stanton Fraser D (2024) A systematic review and narrative synthesis of the use and effectiveness of extended reality technology in the assessment, treatment and study of obsessive compulsive disorder. *J Obsessive Compuls Relat Disord* 42:100893. <https://doi.org/10.1016/j.jocrd.2024.100893>
- Colquhoun HL, Levac D, O'Brien KK, Straus S, Tricco AC, Perrier L, Kastner M, Moher D (2014) Scoping reviews: time for clarity in definition, methods, and reporting. *J Clin Epidemiol* 67:1291–1294. <https://doi.org/10.1016/j.jclinepi.2014.03.013>
- Cornejo Thumm P, Giladi N, Hausdorff JM, Mirelman A (2021) Tele-rehabilitation with virtual reality: a case report on the simultaneous, remote training of two patients with Parkinson disease. *Am J Phys Med Rehabil* 100:435–438. <https://doi.org/10.1097/PHM.0000000000001745>
- Cruz-Neira C, Sandin DJ, DeFanti TA (1993) Surround-screen projection-based virtual reality: the design and implementation of the CAVE, in: Proceedings of the 20th Annual conference on computer graphics and interactive techniques. Presented at the SIGGRAPH93: 20th Annual conference and exhibition on computer graphics and interactive techniques, ACM, Anaheim CA, pp 135–142. <https://doi.org/10.1145/166117.166134>
- Dantas IV, Leal JC, Hilgert LS, Allegretti ALC, Dos Santos Mendes FA (2018) Training healthy persons and individuals with Parkinson's disease to use Xbox Kinect games: a preliminary study. *Int J Ther Rehabil* 25:280–290. <https://doi.org/10.12968/ijtr.2018.25.6.280>
- Daudt HM, Van Mossel C, Scott SJ (2013) Enhancing the scoping study methodology: a large, inter-professional team's experience with Arksey and O'Malley's framework. *BMC Med Res Methodol* 13:48. <https://doi.org/10.1186/1471-2288-13-48>
- De Lima JA, Simcsik AO, Rodrigues FD, Raimundo RD, Galhardoni R, Monteiro CBDM, Da Silva TD (2021) Virtual task associated with transcranial stimulation by continuing the current in people with Parkinson's disease. *Rev Pesq Fisio* 10:31–34. <https://doi.org/10.17267/2238-2704rpf.v10i5.3582>
- De Melo GEL, Kleiner AFR, Lopes JBP, Dumont AJL, Lazzari RD, Galli M, Oliveira CS (2018) Effect of virtual reality training on walking distance and physical fitness in individuals with Parkinson's disease. *NRE* 42:473–480. <https://doi.org/10.3233/NRE-172355>
- Del Din S, Galna B, Lord S, Nieuwboer A, Bekkers EMJ, Pelosin E, Avanzino L, Bloem BR, Olde Rikkert MGM, Nieuwhof F, Cereatti A, Della Croce U, Mirelman A, Hausdorff JM, Rochester L (2020) Falls risk in relation to activity exposure in high-risk older adults. *J Gerontol A Biol Sci Med Sci* 75:1198–1205. <https://doi.org/10.1093/gerona/glaa007>
- Di Biagio L, Ferretti M, Cingolani D, Buzzatti L, Capecci M, Ceravolo MG (2014) Virtual reality: a new rehabilitative approach in neurological disorders. In: Longhi S, Siciliano P, Germani M, Monteriù A (eds) *Ambient assisted living*. Springer, Cham
- Dickson DW (2018) Neuropathology of Parkinson disease. *Parkinsonism Relat Disord* 46:S30–S33. <https://doi.org/10.1016/j.parkrelid.2017.07.033>
- Dorsey ER, Sherer T, Okun MS, Bloem BR (2018) The emerging evidence of the Parkinson pandemic. *J Parkinsons Dis* 8:S3–S8. <http://doi.org/10.3233/JPD-181474>
- Droby A, Maidan I, Jacob Y, Giladi N, Hausdorff JM, Mirelman A (2020) Distinct effects of motor training on resting-state functional networks of the brain in Parkinson's disease. *Neurorehabil Neural Repair* 34:795–803. <https://doi.org/10.1177/1545968320940985>
- Ehgoetz Martens KA, Ellard CG, Almeida QJ (2015a) Anxiety-provoked gait changes are selectively dopa-responsive in Parkinson's disease. *Eur J Neurosci* 42:2028–2035. <https://doi.org/10.1111/ejn.12928>
- Ehgoetz Martens KA, Ellard CG, Almeida QJ (2015b) Does manipulating the speed of visual flow in virtual reality change distance estimation while walking in Parkinson's disease? *Exp Brain Res* 233:787–795. <https://doi.org/10.1007/s00221-014-4154-z>
- ST Engineering Antycip (n.d) ST Engineering ANTYCIP | Simulation and Virtual Reality Company. <https://steantycip.com/> Accessed 21 July 2024.
- Fearon C, Killane I, Newman L, Beck R, Munteanu T, Birsanu D, Butler J, Magennis B, Reilly R, Lynch T (2017) Combined motor and cognitive training improves motor and cognitive function in people with Parkinson's disease and freezing of gait, In: *Movement disorders*. Wiley 111 RIVER ST, HOBOKEN 07030-5774, NJ USA. <https://doi.org/10.1002/mds.27087>
- Feng H, Li C, Liu J, Wang L, Ma J, Li G, Gan L, Shang X, Wu Z (2019) Virtual reality rehabilitation versus conventional physical therapy for improving balance and gait in Parkinson's disease patients: a randomized controlled trial. *Med Sci Monit* 25:4186–4192. <https://doi.org/10.12659/MSM.916455>
- Ferraz DD, Trippo KV, Duarte GP, Neto MG, Bernardes Santos KO, Filho JO (2018) The effects of functional training, bicycle exercise, and exergaming on walking capacity of elderly patients with Parkinson disease: a pilot randomized controlled single-blinded trial. *Arch Phys Med Rehabil* 99:826–833. <https://doi.org/10.1016/j.apmr.2017.12.014>
- Formica C, Bonanno L, Latella D, Ferrera MC, Maresca G, Logiudice AL, Sorbera C, Brigandi A, Di Lorenzo G, Marino S (2023) The effect of computer assisted rehabilitation environment (CAREN) in cognitive impairment and coping strategies in Parkinson's disease: a preliminary study. *Sci Rep* 13:2214. <https://doi.org/10.1038/s41598-023-29299-0>

- Fundarò C, Maestri R, Ferriero G, Chimento P, Taveggia G, Casale R (2019) Self-selected speed gait training in Parkinson's disease: robot-assisted gait training with virtual reality versus gait training on the ground. *Eur J Phys Rehabil Med*. <https://doi.org/10.23736/S1973-9087.18.05368-6>
- Gandolfi M, Geroin C, Dimitrova E, Boldrini P, Waldner A, Bonadiman S, Picelli A, Regazzo S, Stirbu E, Primon D, Bosello C, Gravina AR, Peron L, Trevisan M, Garcia AC, Menel A, Bloccari L, Valè N, Saltuari L, Tinazzi M, Smania N (2017) Virtual reality telerehabilitation for postural instability in Parkinson's disease: a multicenter, single-blind, randomized, controlled trial. *BioMed Res Int* 2017:1–11. <https://doi.org/10.1155/2017/7962826>
- Gemin C, Da Silva L, Correa MR, Teive HG, Valderramas S (2017) Are the exergaming effective for improving functional exercise capacity, and quality of life in patients with Parkinson's disease?, In: *Movement disorders*. Wiley 111 RIVER ST, HOBOKEN 07030–5774, NJ USA. <https://doi.org/10.1002/mds.27087>
- Geun-Ho L (2015) Effects of virtual reality exercise program on balance and quality of life among patients with Parkinson's disease. *J Korean Acad Kinesiol* 17:49–61. <https://doi.org/10.15758/jkak.2015.17.1.49>
- Gilbert R, Khemani P (2022) Treatment of advanced Parkinson's disease. *J Geriatr Psychiatry Neurol* 35:12–23. <https://doi.org/10.1177/0891988720988904>
- Goetz CG (2011) The history of Parkinson's disease: early clinical descriptions and neurological therapies. *Cold Spring Harb Perspect Med* 1:a008862–a008862. <https://doi.org/10.1101/cshperspect.a008862>
- Goetz CG, Pal G (2014) Initial management of Parkinson's disease. *BMJ* 349:g6258–g6258. <https://doi.org/10.1136/bmj.g6258>
- Goffredo M, Baglio F, DE Icco R, Proietti S, Maggioni G, Turolla A, Pournajaf S, Jonsdottir J, Zeni F, Federico S, Cacciante L, Cioeta M, Tassorelli C, Franceschini M, Calabrò RS, RIN_TR_Group (2023a) Efficacy of non-immersive virtual reality-based telerehabilitation on postural stability in Parkinson's disease: a multicenter randomized controlled trial. *Eur J Phys Rehabil Med* 59:689–696. <https://doi.org/10.23736/S1973-9087.23.07954-6>
- Goffredo M, Pagliari C, Turolla A, Tassorelli C, Di Tella S, Federico S, Pournajaf S, Jonsdottir J, De Icco R, Pellicciari L, Calabrò RS, Baglio F, Franceschini M (2023b) Non-immersive virtual reality telerehabilitation system improves postural balance in people with chronic neurological diseases. *J Clin Med* 12:3178. <https://doi.org/10.3390/jcm12093178>
- Goh L, Allen NE, Ahmadpour N, Ehgoetz Martens KA, Song J, Clemson L, Lewis SJG, MacDougall HG, Canning CG (2021) A video self-modeling intervention using virtual reality plus physical practice for freezing of gait in Parkinson disease: feasibility and acceptability study. *JMIR Form Res* 5:e28315. <https://doi.org/10.2196/28315>
- Gómez-Jordana LI, Stafford J, Peper C (Lieke)E, Craig CM (2018) Crossing virtual doors: a new method to study gait impairments and freezing of gait in Parkinson's disease. *Parkinsons Dis* 2018:1–8. <https://doi.org/10.1155/2018/2957427>
- Greffard S, Verny M, Bonnet A-M, Beinis J-Y, Gallinari C, Meaume S, Piette F, Hauw J-J, Duyckaerts C (2006) Motor score of the Unified Parkinson Disease Rating Scale as a good predictor of lewy body-associated neuronal loss in the substantia nigra. *Arch Neurol* 63:584. <https://doi.org/10.1001/archneur.63.4.584>
- Griffin HJ, Greenlaw R, Limousin P, Bhatia K, Quinn NP, Jahanshahi M (2011) The effect of real and virtual visual cues on walking in Parkinson's disease. *J Neurol* 258:991–1000. <https://doi.org/10.1007/s00415-010-5866-z>
- Hajebrahimi F, Velioglu HA, Bayraktaroglu Z, Helvacı Yılmaz N, Hanoglu L (2022) Clinical evaluation and resting state fMRI analysis of virtual reality-based training in Parkinson's disease through a randomized controlled trial. *Sci Rep* 12:8024. <https://doi.org/10.1038/s41598-022-12061-3>
- Hara M, Murakawa Y, Wagatsuma T, Shinmoto K, Tamaki M (2024) Feasibility of somato-cognitive coordination therapy using virtual reality for patients with advanced severe Parkinson's disease. *J Parkinsons Dis* 14:895–898. <https://doi.org/10.3233/JPD-240011>
- Hardeman LES, Geerse DJ, Hoogendoorn EM, Nonnekes J, Roerdink M (2024) Remotely prescribed, monitored, and tailored home-based gait-and-balance exergaming using augmented reality glasses: a clinical feasibility study in people with Parkinson's disease. *Front Neurol*. <https://doi.org/10.3389/fneur.2024.1373740>
- Harris DM, Rantalainen T, Muthalib M, Johnson L, Duckham RL, Smith ST, Daly RM, Teo W-P (2018) Concurrent exergaming and transcranial direct current stimulation to improve balance in people with Parkinson's disease: study protocol for a randomised controlled trial. *Trials* 19:387. <https://doi.org/10.1186/s13063-018-2773-6>
- Hocoma, (n.d) Advanced technologies for movement rehabilitation - HOCOMA. <https://www.hocoma.com/> Accessed 21 July 2024.
- Huang X, Chen L, Cai G, Xin J, Yang Y, Ye Q (2020) Improvement for gait disorders in Parkinson's disease through novel comprehensive treatment (improve study): a prospective, open-label, randomized controlled clinical trial, In: *Movement disorders*. Wiley 111 RIVER ST, HOBOKEN 07030–5774, NJ USA, pp. S398–S399.
- Imbimbo I, Coraci D, Santilli C, Loreti C, Piccinini G, Ricciardi D, Castelli L, Fusco A, Bentivoglio AR, Padua L (2021) Parkinson's disease and virtual reality rehabilitation: cognitive reserve influences the walking and balance outcome. *Neurol Sci* 42:4615–4621. <https://doi.org/10.1007/s10072-021-05123-3>
- Impellizzeri F, Naro A, Basile G, Bramanti A, Gazia F, Galletti F, Militi D, Petralito F, Calabrò RS, Milardi D (2022) Does cybersickness affect virtual reality training using the Computer Assisted Rehabilitation Environment (CAREN)? Preliminary results from a case-control study in Parkinson's disease. *Physiother Theory Pract* 38:2603–2611. <https://doi.org/10.1080/09593985.2021.1964117>
- Impellizzeri F, Maggio MG, De Pasquale P, Bonanno M, Bonanno L, De Luca R, Paladina G, Alibrandi A, Milardi D, Thaut M, Hurt C, Quartarone A, Calabrò RS (2024) Coupling neurologic music therapy with immersive virtual reality to improve executive functions in individuals with Parkinson's disease: a quasi-randomized clinical trial. *Clin Parkinsonism Relat Disord* 11:100277. <https://doi.org/10.1016/j.prdoa.2024.100277>
- Iosa M, Morone G, Fusco A, Bragoni M, Coiro P, Multari M, Venturiero V, De Angelis D, Pratesi L, Paolucci S (2012) Seven capital devices for the future of stroke rehabilitation. *Stroke Res Treat* 2012:187965. <https://doi.org/10.1155/2012/187965>
- Isernia S, Di Tella S, Pagliari C, Jonsdottir J, Castiglioni C, Gindri P, Salza M, Gramigna C, Palumbo G, Molteni F, Baglio F (2020) Effects of an innovative telerehabilitation intervention for people with Parkinson's disease on quality of life, motor, and non-motor abilities. *Front Neurol* 11:846. <https://doi.org/10.3389/fneur.2020.00846>
- IxDF - Interaction Design Foundation (2023) What is Social VR?. IxDF - Interaction Design Foundation. <https://www.interaction-design.org/literature/topics/social-virtual-reality-vr>. Accessed 21 Jan 2026.
- Jamshidi N, Rostami M, Najarian S, Menhaj MB, Saadatnia M, Salami F (2010) Differences in center of pressure trajectory between normal and steppage gait. *J Res Med Sci* 15:33–40
- Janeh O, Fründt O, Schönwald B, Gultberti A, Buhmann C, Gerloff C, Steinicke F, Pötter-Nerger M (2019) Gait training in virtual reality: short-term effects of different virtual manipulation techniques

- in Parkinson's disease. *Cells* 8:419. <https://doi.org/10.3390/cells8050419>
- Janssen S, de van Ruyter SteveninckSalim JHS, Cockx HM, Bloem BR, Heida T, van Wezel RJA (2020) The effects of augmented reality visual cues on turning in place in Parkinson's disease patients with freezing of gait. *Front Neurol* 11:185. <https://doi.org/10.3389/fneur.2020.00185>
- Jiang J, Goepel G, Crolla K, Fryer LK (2024) Impact of extended reality on students' interest, self-efficacy and performance in architecture education: a mixed-methods research. *Adv Eng Inform* 62:102744. <https://doi.org/10.1016/j.aei.2024.102744>
- Júlio F, Ribeiro MJ, Morgadinho A, Sousa M, Van Asselen M, Simões MR, Castelo-Branco M, Januário C (2022) Cognition, function and awareness of disease impact in early Parkinson's and Huntington's disease. *Disabil Rehabil* 44:920–938. <https://doi.org/10.1080/09638288.2020.1783001>
- Kashif M, Ahmad A, Bandpei MAM, Gilani SA, Hanif A, Iram H (2022a) Combined effects of virtual reality techniques and motor imagery on balance, motor function and activities of daily living in patients with Parkinson's disease: a randomized controlled trial. *BMC Geriatr* 22:381. <https://doi.org/10.1186/s12877-022-03035-1>
- Kashif M, Ahmad A, Bandpei MAM, Syed HA, Raza A, Sana V (2022b) A randomized controlled trial of motor imagery combined with virtual reality techniques in patients with Parkinson's disease. *JPM* 12:450. <https://doi.org/10.3390/jpm12030450>
- Kashif M, Ahmad A, Mohseni Bandpei MA, Gillani SA (2022c) The combined effects of virtual reality with motor imagery techniques in patients with Parkinson's disease. *J Pak Med Assoc* 72:2549–2554. <https://doi.org/10.47391/JPMA.4856>
- Kashif M, Albalwi AA, Zulfiqar A, Bashir K, Alharbi AA, Zaidi S (2024) Effects of virtual reality versus motor imagery versus routine physical therapy in patients with parkinson's disease: a randomized controlled trial. *BMC Geriatr*. <https://doi.org/10.1186/s12877-024-04845-1>
- Kawamichi H, Sugawara SK, Hamano YH, Makita K, Kochiyama T, Sadato N (2016) Increased frequency of social interaction is associated with enjoyment enhancement and reward system activation. *Sci Rep* 6:24561. <https://doi.org/10.1038/srep24561>
- Khoo TK, Yarnall AJ, Duncan GW, Coleman S, O'Brien JT, Brooks DJ, Barker RA, Burn DJ (2013) The spectrum of nonmotor symptoms in early Parkinson disease. *Neurology* 80:276–281. <https://doi.org/10.1212/WNL.0b013e31827deb74>
- Killane I, Fearon C, Newman L, McDonnell C, Waechter SM, Sons K, Lynch T, Reilly RB (2015) Dual motor-cognitive virtual reality training impacts dual-task performance in freezing of gait. *IEEE J Biomed Health Inform* 19:1855–1861. <https://doi.org/10.1109/JBHI.2015.2479625>
- Klinger E, Joseph P-A, Le Guiet J-L, Fuchs P, Du Lac N, Servant F (2013) AGATHE: a tool for personalized rehabilitation of cognitive functions, in: ACM SIGGRAPH '13: Special interest group on computer graphics and interactive techniques conference, ACM, Anaheim California, pp. 1–1. <https://doi.org/10.1145/2503368.2503369>
- Krieger V, Lallart E, Jouvent R (2013) Bodily manifestations of affects: the example of gait and virtual reality, in: 2013 Humaine Association Conference on affective computing and intelligent interaction. Presented at the 2013 Humaine Association Conference on affective computing and intelligent interaction (ACII), IEEE, Geneva, Switzerland, pp. 179–184. <https://doi.org/10.1109/ACII.2013.36>
- Kringelbach ML, Rolls ET (2003) Neural correlates of rapid reversal learning in a simple model of human social interaction. *Neuroimage* 20:1371–1383. [https://doi.org/10.1016/S1053-8119\(03\)00393-8](https://doi.org/10.1016/S1053-8119(03)00393-8)
- la Brandín-De Cruz N, Secorro N, Calvo S, Benyoucef Y, Herrero P, Bellosta-López P (2020) Immersive virtual reality and antigravity treadmill training for gait rehabilitation in Parkinson's disease: a pilot and feasibility study. *Rev Neurol* 71:447–454. <https://doi.org/10.33588/rn.7112.2020352>
- Lange B, Koenig S, Chang C-Y, McConnell E, Suma E, Bolas M, Rizzo A (2012) Designing informed game-based rehabilitation tasks leveraging advances in virtual reality. *Disabil Rehabil* 34:1863–1870. <https://doi.org/10.3109/09638288.2012.670029>
- Lareyre F, Mialhe C, Nasr B, Poggi E, Di Lorenzo G, Rajhi K, Chaudhuri A, Raffort J (2024) Extended and augmented reality in vascular surgery: opportunities and challenges. *Semin Vasc Surg*. <https://doi.org/10.1053/j.semvascsurg.2024.07.003>
- Lau J, Regis C, Burke C, Kaleda M, McKenna R, Muratori LM (2022) Immersive technology for cognitive-motor training in Parkinson's disease. *Front Hum Neurosci* 16:863930. <https://doi.org/10.3389/fnhum.2022.863930>
- Lee G-H (2016a) Effects of virtual reality exercise program on balance in lower parkinsonism patients. *Parkinsonism Relat Disord* 22:e70. <https://doi.org/10.1016/j.parkreldis.2015.10.164>
- Lee N-Y, Lee D-K, Song H-S (2015) Effect of virtual reality dance exercise on the balance, activities of daily living, and depressive disorder status of Parkinson's disease patients. *J Phys Ther Sci* 27:145–147. <https://doi.org/10.1589/jpts.27.145>
- Lee A, Hellmers N, Vo M, Wang F, Popa P, Barkan S, Patel D, Campbell C, Henchcliffe C, Sarva H (2023) Can Google glass™ technology improve freezing of gait in parkinsonism? A pilot study. *Disabil Rehabil Assist Technol* 18:327–332. <https://doi.org/10.1080/17483107.2020.1849433>
- Lee G-H (2016) Virtual-reality balance training with Nintendo-Wii games improves dynamic balance in Parkinson's disease patients, In: *Movement disorders*. Wiley-Blackwell 111 RIVER ST, HOBOKEN 07030–5774, NJ, USA, pp S656–S656. <https://doi.org/10.1002/mds.26688>
- Lee G (2018) A virtual reality exercise program improves the balance function and quality of life of patients with Parkinson's disease, in: *Movement disorders*. Wiley 111 RIVER ST, HOBOKEN 07030–5774, NJ, USA, pp S114–S115.
- Lee G (2019) Effects of virtual reality exercise program using the Sony PlayStation 2 gaming platform on balance, emotion and quality of life in patients with Parkinson's disease, in: *Movement disorders*. Wiley 111 RIVER ST, HOBOKEN 07030–5774, NJ USA, pp. S56–S56.
- Lees AJ, Hardy J, Revesz T (2009) Parkinson's disease. *Lancet* 373:2055–2066. [https://doi.org/10.1016/S0140-6736\(09\)60492-X](https://doi.org/10.1016/S0140-6736(09)60492-X)
- Levac D, Colquhoun H, O'Brien KK (2010) Scoping studies: advancing the methodology. *Implement Sci* 5:69. <https://doi.org/10.1186/1748-5908-5-69>
- Lheureux A, Lebleu J, Frisque C, Sion C, Stoquart G, Warlop T, Detrembleur C, Lejeune T (2020) Immersive virtual reality to restore natural long-range autocorrelations in Parkinson's disease patients' gait during treadmill walking. *Front Physiol* 11:572063. <https://doi.org/10.3389/fphys.2020.572063>
- Liao Y-Y, Yang Y-R, Cheng S-J, Wu Y-R, Fuh J-L, Wang R-Y (2015a) Virtual reality-based training to improve obstacle-crossing performance and dynamic balance in patients with Parkinson's disease. *Neurorehabil Neural Repair* 29:658–667. <https://doi.org/10.1177/1545968314562111>
- Liao Y-Y, Yang Y-R, Wu Y-R, Wang R-Y (2015b) Virtual reality-based Wii Fit training in improving muscle strength, sensory integration ability, and walking abilities in patients with Parkinson's disease: a randomized control trial. *Int J Gerontol* 9:190–195. <https://doi.org/10.1016/j.ijge.2014.06.007>
- Liao L, Liang Y, Li H, Ye Y, Wu G (2023) A systematic review of global research on natural user interface for smart home system.

- Int J Ind Ergon 95:103445. <https://doi.org/10.1016/j.ergon.2023.103445>
- Liu Q, Shi J, Lin R, Wen T (2017) Dopamine and dopamine receptor D1 associated with decreased social interaction. *Behav Brain Res* 324:51–57. <https://doi.org/10.1016/j.bbr.2017.01.045>
- Loureiro APC, Ribas CG, Zott TGG, Chen R, Ribas F (2012) Feasibility of virtual therapy in rehabilitation of Parkinson's disease patients: pilot study. *Fisioter Mov* 25:659–666. <https://doi.org/10.1590/S0103-51502012000300021>
- Lu Y, Ge Y, Chen W, Xing W, Wei L, Zhang C, Yang Y (2022) The effectiveness of virtual reality for rehabilitation of Parkinson disease: an overview of systematic reviews with meta-analyses. *Syst Rev* 11:50. <https://doi.org/10.1186/s13643-022-01924-5>
- Maggio MG, De Cola MC, Latella D, Maresca G, Finocchiaro C, La Rosa G, Cimino V, Sorbera C, Bramanti P, De Luca R, Calabrò RS (2018) What about the role of virtual reality in Parkinson disease's cognitive rehabilitation? Preliminary findings from a randomized clinical trial. *J Geriatr Psychiatry Neurol* 31:312–318. <https://doi.org/10.1177/0891988718807973>
- Maidan I, Rosenberg-Katz K, Jacob Y, Giladi N, Hausdorff JM, Mirelman A (2017) Disparate effects of training on brain activation in Parkinson disease. *Neurology* 89:1804–1810. <https://doi.org/10.1212/WNL.0000000000004576>
- Maidan I, Nieuwhof F, Bernad-Elazari H, Bloem BR, Giladi N, Hausdorff JM, Claassen JAHR, Mirelman A (2018) Evidence for differential effects of 2 forms of exercise on prefrontal plasticity during walking in Parkinson's disease. *Neurorehabil Neural Repair* 32:200–208. <https://doi.org/10.1177/1545968318763750>
- Maranesi E, Casoni E, Baldoni R, Barboni I, Rinaldi N, Tramontana B, Amabili G, Benadduci M, Barbarossa F, Luzi R, Di Donna V, Scendoni P, Pelliccioni G, Lattanzio F, Riccardi GR, Bevilacqua R (2022) The effect of non-immersive virtual reality exergames versus traditional physiotherapy in Parkinson's disease older patients: preliminary results from a randomized-controlled trial. *IJERPH* 19:14818. <https://doi.org/10.3390/ijerph192214818>
- Marsh R, Hao X, Xu D, Wang Z, Duan Y, Liu J, Kangarlu A, Martinez D, Garcia F, Tau GZ, Yu S, Packard MG, Peterson BS (2010) A virtual reality-based fMRI study of reward-based spatial learning. *Neuropsychologia* 48:2912–2921. <https://doi.org/10.1016/j.neuropsychologia.2010.05.033>
- Martínez-Martín P, Gil-Nagel A, Gracia LM, Gómez JB, Martínez-Sarriés J, Bermejo F, The Cooperative Multicentric Group (1994) Unified Parkinson's disease rating scale characteristics and structure. *Mov Disord* 9:76–83. <https://doi.org/10.1002/mds.870090112>
- Melo G, Kleiner AFR, Lopes J, Zen GZD, Marson N, Santos T, Dumont A, Galli M, Oliveira C (2018) P100 - Effects of virtual reality training on mobility in individuals with Parkinson's disease. *Gait Posture* 65:394–395. <https://doi.org/10.1016/j.gaitpost.2018.06.071>
- Mendes FAdosS, Pompeu JE, Lobo AM, da Silva KG, Oliveira TdeP, Zomignani AP, Piemonte MEP (2012) Motor learning, retention and transfer after virtual-reality-based training in Parkinson's disease—effect of motor and cognitive demands of games: a longitudinal, controlled clinical study. *Physiotherapy* 98:217–223. <https://doi.org/10.1016/j.physio.2012.06.001>
- Meta, (n.d.b) Zenni VR prescription lenses for Meta Quest. <https://www.meta.com/help/quest/1050152622641152/> Accessed 20 Aug. 2025.
- Meta, (n.d.a) How to wear glasses when using Meta Quest. <https://www.meta.com/help/quest/3920738394639999/> Accessed 20 Aug. 2025.
- Meta, (n.d.c) Meta Quest 3: new mixed reality VR headset. <https://www.meta.com/gb/quest/quest-3/> Accessed 21 Jul. 2024.
- Microsoft HoloLens (n.d) Microsoft HoloLens | Mixed Reality Technology for business. <https://www.microsoft.com/en-gb/hololens/> Accessed 21 Jul. 2024.
- Milgram P, Kishino F (1994) A taxonomy of mixed reality visual displays. *IEICE Trans Inf Syst* 77:1321–1329
- Milgram P, Takemura H, Utsumi A, Kishino F (1995) Augmented reality: a class of displays on the reality-virtuality continuum. In: Das H (ed) Presented at the photonics for industrial applications. Boston
- Mills J-A, Marks E, Reynolds T, Cieza A (2017) Rehabilitation: essential along the continuum of care. In: Jamison DT, Gelband H, Horton S, Jha P, Laxminarayan R, Mock CN, Nugent R (eds) Disease control priorities: Improving health and reducing poverty. The international bank for reconstruction and development, Washington DC
- Mirelman A, Maidan I, Herman T, Deutsch JE, Giladi N, Hausdorff JM (2011) Virtual reality for gait training: can it induce motor learning to enhance complex walking and reduce fall risk in patients with Parkinson's disease? *J Gerontol A Biol Sci Med Sci* 66A:234–240. <https://doi.org/10.1093/gerona/glq201>
- Mirelman A, Rochester L, Reelick M, Nieuwhof F, Pelosin E, Abbruzzese G, Dockx K, Nieuwboer A, Hausdorff JM (2013) V-TIME: a treadmill training program augmented by virtual reality to decrease fall risk in older adults: study design of a randomized controlled trial. *BMC Neurol* 13:15. <https://doi.org/10.1186/1471-2377-13-15>
- Mirelman A, Rochester L, Maidan I, Del Din S, Alcock L, Nieuwhof F, Rikkert MO, Bloem BR, Pelosin E, Avanzino L, Abbruzzese G, Dockx K, Bekkers E, Giladi N, Nieuwboer A, Hausdorff JM (2016) Addition of a non-immersive virtual reality component to treadmill training to reduce fall risk in older adults (V-TIME): a randomised controlled trial. *Lancet* 388:1170–1182. [https://doi.org/10.1016/S0140-6736\(16\)31325-3](https://doi.org/10.1016/S0140-6736(16)31325-3)
- Mittelstaedt JM, Wacker J, Stelling D (2019) Vr aftereffect and the relation of cybersickness and cognitive performance. *Virtual Reality* 23:143–154. <https://doi.org/10.1007/s10055-018-0370-3>
- Moher D, Liberati A, Tetzlaff J, Altman DG, PRISMA Group (2009) Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *BMJ* 339:b2535–b2535. <https://doi.org/10.1136/bmj.b2535>
- Moore O, Peretz C, Giladi N (2007) Freezing of gait affects quality of life of peoples with Parkinson's disease beyond its relationships with mobility and gait. *Mov Disord* 22:2192–2195. <https://doi.org/10.1002/mds.21659>
- Moran A, O'Shea H (2020) Motor imagery practice and cognitive processes. *Front Psychol* 11:394. <https://doi.org/10.3389/fpsyg.2020.00394>
- Morris LS, Kundu P, Dowell N, Mechelmans DJ, Favre P, Irvine MA, Robbins TW, Daw N, Bullmore ET, Harrison NA, Voon V (2016) Fronto-striatal organization: defining functional and microstructural substrates of behavioural flexibility. *Cortex* 74:118–133. <https://doi.org/10.1016/j.cortex.2015.11.004>
- Motekmedical.com (n.d) Home - motekmedical.com. <https://www.motekmedical.com/> Accessed 21 Jul. 2024.
- Movement Disorder Society Task Force on Rating Scales for Parkinson's Disease (2003) The Unified Parkinson's Disease Rating Scale (UPDRS): status and recommendations. *Mov Disord* 18:738–750. <https://doi.org/10.1002/mds.10473>
- Muñoz D, Barria P, Cifuentes CA, Aguilar R, Baleta K, Azorin JM, Múnera M (2022) EEG evaluation in a neuropsychological intervention program based on virtual reality in adults with Parkinson's disease. *Biosensors* 12:751. <https://doi.org/10.3390/bios12090751>
- Nanjappan V, Liang H-N, Wang W, Man KL (2017) Chapter 1-big data: a classification of acquisition and generation methods, In: Hsu H-H, Chang C-Y, Hsu C-H (Eds), Big data analytics for

- sensor-network collected intelligence, intelligent data-centric systems. Academic Press, pp 3–20. <https://doi.org/10.1016/B978-0-12-809393-1.00001-5>
- Nardi F, Haar S, Faisal AA (2023) Bill-EVR: an embodied virtual reality framework for reward-and-error-based motor rehab-learning. In: 2023 International conference on rehabilitation robotics (ICORR). Presented at the 2023 International conference on rehabilitation robotics (ICORR), IEEE, Singapore, pp 1–6. <https://doi.org/10.1109/ICORR58425.2023.10304742>
- Navarro-Lozano F, Kiper P, Carmona-Pérez C, Rutkowski S, Pineropinto E, Luque-Moreno C (2022) Effects of non-immersive virtual reality and video games on walking speed in Parkinson disease: a systematic review and meta-analysis. *JCM* 11:6610. <https://doi.org/10.3390/jcm11226610>
- Nintendo Wii (n.d.) Nintendo of Europe AG. <https://www.nintendo.com/en-gb/Wii/Wii-94559.html> Accessed 21 July 2024.
- Nuic D, Vinti M, Karachi C, Foulon P, Van Hamme A, Welter M-L (2018) The feasibility and positive effects of a customised videogame rehabilitation programme for freezing of gait and falls in Parkinson's disease patients: a pilot study. *J Neuroeng Rehabil* 15:31. <https://doi.org/10.1186/s12984-018-0375-x>
- O'Doherty JP (2004) Reward representations and reward-related learning in the human brain: insights from neuroimaging. *Curr Opin Neurobiol* 14:769–776. <https://doi.org/10.1016/j.conb.2004.10.016>
- O'Neil O, Fernandez MM, Herzog J, Beorchia M, Gower V, Gramatica F, Starost K, Kiwull L (2018) Virtual reality for neurorehabilitation: insights from 3 European clinics. *PM&R* 10:S198–S206. <https://doi.org/10.1016/j.pmrj.2018.08.375>
- Ogundele A, Olaogun M, Komolafe M (2018) Comparison of virtual-reality-gaming and activity-based gait and balance training on gait, balance and quality of life in patients with Parkinson's disease. In: *Movement disorders*. Wiley 111 RIVER ST, HOBOKEN 07030–5774, NJ USA, pp S20–S20.
- Ogundele A, Olaogun MOB, Komolafe MA (2019). Effect of virtual reality gaming and conventional rehabilitation on physical function and quality of life in patients with Parkinson's disease, in: *Abstract Book of the 5th World Parkinson Congress*. p. 144. <http://doi.org/10.3233/JPD-199900>
- Oh K, Stanley CJ, Damiano DL, Kim J, Yoon J, Park H-S (2018) Biomechanical evaluation of virtual reality-based turning on a self-paced linear treadmill. *Gait Posture* 65:157–162. <https://doi.org/10.1016/j.gaitpost.2018.07.175>
- Ota Y, Aikawa G, Nishimura A, Kawashima T, Imanaka R, Sakuramoto H (2024) Effects of educational methods using extended reality on pre-registration nursing students' knowledge, skill, confidence, and satisfaction: a systematic review and meta-analysis. *Nurse Educ Today* 141:106313. <https://doi.org/10.1016/j.nedt.2024.106313>
- Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, Shamseer L, Tetzlaff JM, Akl EA, Brennan SE, Chou R, Glanville J, Grimshaw JM, Hróbjartsson A, Lalu MM, Li T, Loder EW, Mayo-Wilson E, McDonald S, McGuinness LA, Stewart LA, Thomas J, Tricco AC, Welch VA, Whiting P, Moher D (2021) The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ*. <https://doi.org/10.1136/bmj.n71>
- Palacios-Navarro G, García-Magariño I, Ramos-Lorente P (2015) A Kinect-based system for lower-limb rehabilitation in Parkinson's disease patients: a pilot study. *J Med Syst* 39:103. <https://doi.org/10.1007/s10916-015-0289-0>
- Pazzaglia C, Imbimbo I, Tranchita E, Minganti C, Ricciardi D, Lo Monaco R, Parisi A, Padua L (2020) Comparison of virtual reality rehabilitation and conventional rehabilitation in Parkinson's disease: a randomised controlled trial. *Physiotherapy* 106:36–42. <https://doi.org/10.1016/j.physio.2019.12.007>
- Pelosin E, Cerulli C, Ogliastrò C, Lagravinese G, Mori L, Bonassi G, Mirelman A, Hausdorff JM, Abbruzzese G, Marchese R, Avanzino L (2020) A multimodal training modulates short afferent inhibition and improves complex walking in a cohort of faller older adults with an increased prevalence of Parkinson's disease. *J Gerontol A Biol Sci Med Sci* 75:722–728. <https://doi.org/10.1093/gerona/glz072>
- Pelosin E, Ponte C, Putzolu M, Lagravinese G, Hausdorff JM, Nieuwboer A, Ginis P, Rochester L, Alcock L, Bloem BR, Nieuwhof F, Cereatti A, Della Croce U, Mirelman A, Avanzino L (2022) Motor-cognitive treadmill training with virtual reality in Parkinson's disease: the effect of training duration. *Front Aging Neurosci* 13:753381. <https://doi.org/10.3389/fnagi.2021.753381>
- Peters MDJ, Marnie C, Tricco AC, Pollock D, Munn Z, Alexander L, McInerney P, Godfrey CM, Khalil H (2020) Updated methodological guidance for the conduct of scoping reviews. *JBI Evid Synth* 18:2119–2126. <https://doi.org/10.11124/JBIES-20-00167>
- Petzinger GM, Fisher BE, McEwen S, Beeler JA, Walsh JP, Jakowec MW (2013) Exercise-enhanced neuroplasticity targeting motor and cognitive circuitry in Parkinson's disease. *Lancet Neurol* 12:716–726. [https://doi.org/10.1016/S1474-4422\(13\)70123-6](https://doi.org/10.1016/S1474-4422(13)70123-6)
- Pezzi L, Di Matteo A, Insabella R, Mastrogiacomo S, Baldari C, Machado Reiss V, Paolucci T (2022) How cognitive reserve should influence rehabilitation choices using virtual reality in Parkinson's disease. *Parkinsons Dis* 2022:7389658. <https://doi.org/10.1155/2022/7389658>
- Piemonte M, Falconi A, D'ALENCAR M, Okamoto E, others (2017) Manual and verbal guidance during the balance training based in virtual reality is essential for therapeutic results in people with Parkinson's disease: a randomized clinical trial, In: *Movement disorders*. Wiley.
- Pisano F, Mellace D, Fugatti A, Aiello EN, Diotti S, Curti B, Giust A, Marfoli A, Perin C, De Sandi A, Alimonti D, Priori A, Ferrucci R (2024) Cerebellar tDCS combined with augmented reality treadmill for freezing of gait in Parkinson's disease: a randomized controlled trial. *J Neuroeng Rehabil*. <https://doi.org/10.1186/s12984-024-01457-z>
- Plavén-Sigra P, Gustavsson P, Farde L, Borg J, Stenkrone P, Nyberg L, Bäckman L, Cervenka S (2014) Dopamine D1 receptor availability is related to social behavior: a positron emission tomography study. *Neuroimage* 102:590–595. <https://doi.org/10.1016/j.neuroimage.2014.08.018>
- Poewe W, Seppi K, Tanner CM, Halliday GM, Brundin P, Volkman J, Schrag A-E, Lang AE (2017) Parkinson disease. *Nat Rev Dis Primers* 3:17013. <https://doi.org/10.1038/nrdp.2017.13>
- Pompeu JE, Arduini LA, Botelho AR, Fonseca MBF, Pompeu SMAA, Torriani-Pasin C, Deutsch JE (2014) Feasibility, safety and outcomes of playing Kinect Adventures!™ for people with Parkinson's disease: a pilot study. *Physiotherapy* 100:162–168. <https://doi.org/10.1016/j.physio.2013.10.003>
- Pompéu JE, Silva K, Freitas T, Nuvolini R, Doná F, Torriani-Pasin C, Ganaça F, Ferraz H (2016) Effect of European physiotherapy guideline for Parkinson's disease and Microsoft Kinect adventures games training on postural control, cognition and quality of life: randomized clinical trial. *Mov Disord* 31:S184. <https://doi.org/10.1002/mds.26688>
- Pullia M, Ciatto L, Andronaco G, Donato C, Aliotta RE, Quartarone A, De Cola MC, Bonanno M, Calabrò RS, Cellini R (2023) Treadmill training plus semi-immersive virtual reality in Parkinson's disease: results from a pilot study. *Brain Sci* 13:1312. <https://doi.org/10.3390/brainsci13091312>
- Qualcomm (n.d) Extended reality. <https://www.qualcomm.com/research/extended-reality> accessed 21 Jul. 2024.
- Ragnarsdóttir M (1996) The concept of balance. *Physiotherapy* 82:368–375. [https://doi.org/10.1016/S0031-9406\(05\)66484-X](https://doi.org/10.1016/S0031-9406(05)66484-X)

- Rahimpour S, Gaztanaga W, Yadav AP, Chang SJ, Krucoff MO, Cajigas I, Turner DA, Wang DD (2021) Freezing of gait in Parkinson's disease: invasive and noninvasive neuromodulation. *Neuromodulation* 24:829–842. <https://doi.org/10.1111/ner.13347>
- Intel RealSense, (n.d) Intel® RealSense™ Computer Vision - Depth and Tracking cameras. <https://www.intelrealsense.com/> Accessed 21 Jul. 2024.
- Ribeiro Bacha JM, Da Cunha MCC, Freitas TBD, Nuvolini RA, Doná F, Guedes Da Silva K, Torriani-Pasin C, Ganança FDF, Pompeu JE (2021) Effects of virtual rehabilitation on postural control of individuals with Parkinson disease. *Motricidade* 17:3. <https://doi.org/10.6063/MOTRICIDADE.20207>
- Rodríguez-Fuentes G, Campo-Prieto P, Cancela-Carral JM (2024) Immersive virtual reality high-intensity aerobic training to slow Parkinson's disease: the revipark program. *Appl Sci* 14:4708. <https://doi.org/10.3390/app14114708>
- Rokhsaritalemi S, Sadeghi-Niaraki A, Choi S-M (2020) A review on mixed reality: current trends, challenges and prospects. *Appl Sci* 10:636. <https://doi.org/10.3390/app10020636>
- Rosenfeldt AB, Streicher MC, Kaya RD, Penko AL, Zimmerman EM, Liao JY, Walter BL, Alberts JL (2025) An augmented reality dual-task intervention improves postural stability in individuals with Parkinson's disease. *Gait Posture* 115:102–108. <https://doi.org/10.1016/j.gaitpost.2024.11.007>
- Sadek AT, Djerdjour L, Reyes RA, Adams GP, Logan CH, Smith MA, Biddle SG, Wiles TS, Urrea-Mendoza E, McConnell TM, Revilla FJ, Trilk JL (2024) The feasibility and efficacy of a virtual reality tandem cycling program for persons with Parkinson's disease and their care partners. *Neurol Ther* 13:1237–1257. <https://doi.org/10.1007/s40120-024-00636-3>
- Santos P, Machado T, Santos L, Ribeiro N, Melo A (2019) Efficacy of the Nintendo Wii combination with conventional exercises in the rehabilitation of individuals with Parkinson's disease: a randomized clinical trial. *NRE* 45:255–263. <https://doi.org/10.3233/NRE-192771>
- Sarasso E, Agosta F, Piramide N, Gardoni A, Canu E, Leocadi M, Castelnovo V, Basaia S, Tettamanti A, Volontè MA, Filippi M (2021) Action observation and motor imagery improve dual task in Parkinson's disease: a clinical/fMRI study. *Mov Disord* 36:2569–2582. <https://doi.org/10.1002/mds.28717>
- Saredakis D, Szpak A, Birkhead B, Keage HAD, Rizzo A, Loetscher T (2020) Factors associated with virtual reality sickness in head-mounted displays: a systematic review and meta-analysis. *Front Hum Neurosci* 14:96. <https://doi.org/10.3389/fnhum.2020.00096>
- Schuch CP, Balbinot G, Bonilla MN, Guedes Machado A, Oliveira AAD (2020) Feasibility of a short-term virtual reality balance intervention to improve mobility smoothness in Parkinson's disease. *Front Virtual Real* 1:7. <https://doi.org/10.3389/frvir.2020.0007>
- Seppi K, Weintraub D, Coelho M, Perez-Lloret S, Fox SH, Katzenschlager R, Hametner E-M, Poewe W, Rascol O, Goetz CG, Sampaio C (2011) The movement disorder society evidence-based medicine review update: treatments for the non-motor symptoms of Parkinson's disease. *Mov Disord* 26(3):S42–80. <https://doi.org/10.1002/mds.23884>
- Sevcenko K, Lindgren I (2022) The effects of virtual reality training in stroke and Parkinson's disease rehabilitation: a systematic review and a perspective on usability. *Eur Rev Aging Phys Act* 19:4. <https://doi.org/10.1186/s11556-022-00283-3>
- Severiano MIR, Zeigelboim BS, Teive HAG, Santos GJB, Fonseca VR (2018) Effect of virtual reality in Parkinson's disease: a prospective observational study. *Arq Neuro-Psiquiatr* 76:78–84. <https://doi.org/10.1590/0004-282x20170195>
- Seyedebrahimi A, Khosrowabadi R, Hondori HM (2019) Brain mechanism in the human-computer interaction modes leading to different motor performance, en: 2019 27th Iranian conference on electrical engineering (ICEE). Presented at the 2019 27th Iranian conference on electrical engineering (ICEE), IEEE, Yazd, Iran, pp 1802–1806. <https://doi.org/10.1109/IranianCEE.2019.8786750>
- Shih I, Hu M, Lu T, Wu R, Lin K (2011) Effects of virtual reality-augmented sitting balance training on pressure distribution and functional performance in patients with Parkinson's disease. *Physiotherapy* 97:eS693–eS694. <https://doi.org/10.1016/j.physio.2011.04.002>
- Simcsik AO, De Lima JA, Da Silva TD, De Mello Monteiro CB, Magalhães FH, Bethiol AL, Galhardoni R (2021) Accuracy in virtual task for upper limbs associated with transcranial direct current electrical stimulation in people with Parkinson's disease. *Rev Pesq Fisio* 10:8–11. <https://doi.org/10.17267/2238-2704rpf.v10i5.3568>
- Simonet C, Tolosa E, Camara A, Valldeoriola F (2019) Emergencies and critical issues in Parkinson's disease. *Pract Neurol Practneurol*. <https://doi.org/10.1136/practneurol-2018-002075>
- Smaili S, Araujo H, de Souza R, da Silva T, Nascimento T, Terra M (2019) Immediate effect of the virtual and augmented reality and neurofunctional physiotherapy on postural control and cognition in patients with Parkinson's disease: a randomized clinical trial, in: movement disorders. Wiley 111 River st, Hoboken 07030–5774, NJ USA, pp. S271–S274.
- Smith K (2013) Chapter 6—playing for health. In: Smith K (ed) *Digital Outcasts*. Morgan Kaufmann, Boston
- Souza MFDS, Bacha JMR, Silva KGD, Freitas TBD, Torriani-Pasin C, Pompeu JE (2018) Effects of virtual rehabilitation on cognition and quality of life of patients with Parkinson's disease. *Fisioter Mov*. <https://doi.org/10.1590/1980-5918.031.a012>
- Speicher M, Hall BD, Nebeling M (2019) What is mixed reality?, in: Proceedings of the 2019 CHI conference on human factors in computing systems. Presented at the CHI '19: CHI conference on human factors in computing systems, ACM, Glasgow Scotland UK, pp 1–15. <https://doi.org/10.1145/3290605.3300767>
- Sprenger F, Poewe W (2013) Management of motor and non-motor symptoms in Parkinson's disease. *CNS Drugs* 27:259–272. <https://doi.org/10.1007/s40263-013-0053-2>
- Straulino E, Scaravilli T, Bulgheroni M, D'Amico E, Castiello U (2016a) It's all in the type of the task: dopamine modulates kinematic patterns during competitive vs. cooperative interaction in Parkinson's disease. *Neuropsychologia* 93:106–115. <https://doi.org/10.1016/j.neuropsychologia.2016.10.008>
- Straulino E, Scaravilli T, Castiello U (2016b) Dopamine depletion affects communicative intentionality in Parkinson's disease patients: evidence from action kinematics. *Cortex* 77:84–94. <https://doi.org/10.1016/j.cortex.2016.01.016>
- Su K-J, Hwang W-J, Wu C, Fang J-J, Leong I-F, Ma H-I (2014) Increasing speed to improve arm movement and standing postural control in Parkinson's disease patients when catching virtual moving balls. *Gait Posture* 39:65–69. <https://doi.org/10.1016/j.gaitpost.2013.05.029>
- Suarez H, Geisinger D, Ferreira ED, Nogueira S, Arocena S, Roman CS, Suarez A (2011) Balance in Parkinson's disease patients changing the visual input. *Braz J Otorhinolaryngol (Impr)* 77:651–655. <https://doi.org/10.1590/S1808-86942011000500019>
- Thomas J, Harden A (2008) Methods for the thematic synthesis of qualitative research in systematic reviews. *BMC Med Res Methodol* 8:45. <https://doi.org/10.1186/1471-2288-8-45>
- Tieri G, Morone G, Paolucci S, Iosa M (2018) Virtual reality in cognitive and motor rehabilitation: facts, fiction and fallacies. *Expert Rev Med Devices* 15:107–117. <https://doi.org/10.1080/1743444.2018.1425613>
- Tunur T, DeBlois A, Yates-Horton E, Rickford K, Columba LA (2020) Augmented reality-based dance intervention for individuals with

- Parkinson's disease: a pilot study. *Disabil Health J* 13:100848. <https://doi.org/10.1016/j.dhjo.2019.100848>
- Van Der Kolk NM, De Vries NM, Kessels RPC, Joosten H, Zwinderman AH, Post B, Bloem BR (2019) Effectiveness of home-based and remotely supervised aerobic exercise in Parkinson's disease: a double-blind, randomised controlled trial. *Lancet Neurol* 18:998–1008. [https://doi.org/10.1016/S1474-4422\(19\)30285-6](https://doi.org/10.1016/S1474-4422(19)30285-6)
- Van Wegen E, Van Den Heuvel M, Beek P, Daffertshofer A, Berendse H, Kwakkel G (2015) Balance training with augmented visual feedback in Parkinson's disease: a randomized clinical trial. *Physiotherapy* 101:e1580–e1581. <https://doi.org/10.1016/j.physio.2015.03.1584>
- Vingerhoets FJG, Schulzer M, Calne DB, Snow BJ (1997) Which clinical sign of Parkinson's disease best reflects the nigrostriatal lesion? *Ann Neurol* 41:58–64. <https://doi.org/10.1002/ana.410410111>
- HTC VIVE (n.d) The professional-grade VR headset | VIVE Pro United Kingdom. <https://www.vive.com/uk/product/vive-pro/> Accessed 21 Jul. 2024.
- Vlake JH, Drop DLQ, Van Bommel J, Riva G, Wiederhold BK, Cipresso P, Rizzo AS, Rothbaum BO, Botella C, Hooft L, Bienvenu OJ, Jung C, Geerts B, Wils E-J, Gommers D, van Genderen ME, RATE-XR Expert Group (2024) Reporting guidelines for the early-phase clinical evaluation of applications using extended reality: RATE-XR qualitative study guideline. *J Med Internet Res* 26:e56790
- Wang Y, Gao L, Yan H, Jin Z, Fang J, Qi L, Zhen Q, Liu C, Wang P, Liu Y, Wang R, Liu Y, Su Y, Liu A, Fang B (2022) Efficacy of c-mill gait training for improving walking adaptability in early and middle stages of Parkinson's disease. *Gait Posture* 91:79–85. <https://doi.org/10.1016/j.gaitpost.2021.10.010>
- Wang Y-W, Chen C-H, Lin Y-C (2020) Balance rehabilitation system for Parkinson's disease patients based on augmented reality, in: 2020 IEEE Eurasia conference on IOT, communication and engineering (ECICE). Presented at the 2020 IEEE Eurasia conference on IOT, communication and engineering (ECICE), IEEE, Yunlin, Taiwan, pp. 191–194. <https://doi.org/10.1109/ECICE50847.2020.9302018>
- Xavier G, Su Ting A, Fauzan N (2020) Exploratory study of brain waves and corresponding brain regions of fatigue on-call doctors using quantitative electroencephalogram. *J Occup Health* 62:e12121. <https://doi.org/10.1002/1348-9585.12121>
- Xbox Kinect (n.d) All Xbox Consoles | Xbox. <https://www.xbox.com/en-GB/consoles/all-consoles> Accessed 21 Jul. 2024.
- Yamagami M, Imsdahl S, Lindgren K, Bellatin O, Nhan N, Burden SA, Pradhan S, Kelly VE (2023) Effects of virtual reality environments on overground walking in people with Parkinson disease and freezing of gait. *Disabil Rehabil Assist Technol* 18:266–273. <https://doi.org/10.1080/17483107.2020.1842920>
- Yang W-C, Wang H-K, Wu R-M, Lo C-S, Lin K-H (2016) Home-based virtual reality balance training and conventional balance training in Parkinson's disease: a randomized controlled trial. *J Formos Med Assoc* 115:734–743. <https://doi.org/10.1016/j.jfma.2015.07.012>
- Yen C-Y, Lin K-H, Hu M-H, Wu R-M, Lu T-W, Lin C-H (2011) Effects of virtual reality-augmented balance training on sensory organization and attentional demand for postural control in people with Parkinson disease: a randomized controlled trial. *Phys Ther* 91:862–874. <https://doi.org/10.2522/ptj.20100050>
- Yun SJ, Hyun SE, Oh B-M, Seo HG (2023) Fully immersive virtual reality exergames with dual-task components for patients with Parkinson's disease: a feasibility study. *J NeuroEng Rehabil*. <https://doi.org/10.1186/s12984-023-01215-7>
- Zanatta F, Steca P, Fundarò C, Giardini A, Felicetti G, Panigazzi M, Arbasi G, Grilli C, D'Addario M, Pierobon A (2023) Biopsychosocial effects and experience of use of robotic and virtual reality devices in neuromotor rehabilitation: a study protocol. *PLoS ONE* 18:e0282925. <https://doi.org/10.1371/journal.pone.0282925>
- Zeigelboim BS, José MR, Severiano MIR, Santos GJBD, Teive HAG, Liberalesso PBN, Marques JM, Rosa MRD, Santos RS, Malisky JS (2021) The use of exergames in the neurorehabilitation of people with Parkinson disease: the impact on daily life. *Int Arch Otorhinolaryngol* 25:e64–e70. <https://doi.org/10.1055/s-0040-1702973>
- Zeiss (n.d) Zeiss Optical Inserts for Apple Vision Pro. <https://www.zeiss.com/vision-care/us/zeiss-optical-inserts.html> Accessed 20 Aug. 2025.
- Zhao Y, Heida T, Van Wegen EEH, Bloem BR, Van Wezel RJA (2015) E-health support in people with Parkinson's disease with smart glasses: a survey of user requirements and expectations in the Netherlands. *J Parkinsons Dis* 5:369–378. <https://doi.org/10.3233/JPD-150568>
- Zhu S, Sui Y, Shen Y, Zhu Y, Ali N, Guo C, Wang T (2021) Effects of virtual reality intervention on cognition and motor function in older adults with mild cognitive impairment or dementia: a systematic review and meta-analysis. *Front Aging Neurosci* 13:586999. <https://doi.org/10.3389/fnagi.2021.586999>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.