Pragmatic and Observational Research

Dovepress
Taylor & Francis Group

Open Access Full Text Article

REVIEW

Better Understanding Rehabilitation of Motor Symptoms: Insights from the Use of Wearables

Yunus Celik, Conor Wall, Jason Moore, Alan Godfrey

Department of Computer and Information Sciences, Northumbria University, Newcastle upon Tyne, NE1 8ST, UK

Correspondence: Alan Godfrey, Department of Computer and Information Sciences, Northumbria University, Newcastle upon Tyne, NE1 8ST, UK, Email alan.godfey@northumbria.ac.uk

Abstract: Movement disorders present a substantial challenge by adversely affecting daily routines and overall well-being through a diverse spectrum of motor symptoms. Traditionally, motor symptoms have been evaluated through manual observational methods and patient-reported outcomes. While those approaches are valuable, they are limited by their subjectivity. In contrast, wearable technologies (wearables) provide objective assessments while actively supporting rehabilitation through continuous tracking, real-time feedback, and personalized physical therapy-based interventions. The aim of this literature review is to examine current research on the use of wearables in the rehabilitation of motor symptoms, focusing on their features, applications, and impact on improving motor function. By exploring research protocols, metrics, and study findings, this review aims to provide a comprehensive overview of how wearables are being used to support and optimize rehabilitation outcomes. To achieve that aim, a systematic search of the literature was conducted. Findings reveal that gait disturbance and postural balance are the primary motor symptoms extensively studied with tremor and freezing of gait (FoG) also receiving attention. Wearable sensing ranges from bespoke inertial and/or electromyography to commercial units such as personal devices (ie, smartwatch). Interactive (virtual reality, VR and augmented reality, AR) and immersive technologies (headphones), along with wearable robotic systems (exoskeletons), have proven to be effective in improving motor skills. Auditory cueing (via smartwatches or headphones), aids gait training with rhythmic feedback, while visual cues (via VR and AR glasses) enhance balance exercises through real-time feedback. The development of treatment protocols that incorporate personalized cues via wearables could enhance adherence and engagement to potentially lead to long-term improvements. However, evidence on the sustained effectiveness of wearable-based interventions remains limited.

Keywords: wearable technology, rehabilitation, movement disorders, motor symptoms

Introduction

Movement disorders (eg, Parkinson's disease, PD) pose significant challenges for millions of people worldwide, negatively impacting daily routines and overall well-being through a complex array of motor symptoms.[1–3] For example, gait disturbances such as shuffling make routine efforts to walk very challenging during habitual activities of daily living.[4,5] Equally, balance issues introduce a constant risk of falls even in familiar environments, diminishing a person's confidence in mobility and fostering a dependency on assistive devices or the aid of others.[6,7]

Typically, motor symptoms have been assessed via pen and paper approaches such the Unified Parkinson's Disease Rating Scale (UPDRS),[8] Expanded disability status scale (EDSS)[9] or the Berg Balance Scale.[10] Those methods, while valuable, come with subjective limitations. Additionally, use of those pen and paper approaches provide only a snapshot in time and do not capture the dynamic changes in symptoms that can occur over an extended period.[8] The limitations of traditional assessment scales highlight the critical need for objective, quantitative data.

Routine use of standalone (uni-modal) wearable technologies such as bespoke inertial measurement units (IMUs ie, accelerometers,[11,12] or gyroscopes[13,14]), force sensors,[15,16] pressure sensors[17,18] and electromyography (EMG)[19,20] could effectively address current assessment limitations by providing objective, continuous, real-time monitoring of motor symptoms. However, the integration/fusion of multiple sensing modalities (multi-modal) could provide holistic data on motor symptoms.[21,22]

Received: 23 May 2024
Accepted: 24 February 2025
Published: 19 March 2025

Wearables have shown utility in the early detection[23–26] of motor symptoms and in tracking symptoms[27–29] over time. Furthermore, wearables could deliver personalized rehabilitation programs via virtual reality (VR),[30,31] augmented reality (AR),[32,33] headphones,[34,35] or wearable exoskeletons[36,37] tailored to the specific needs of each individual. Personalization could be made optimal by using artificial intelligence (AI) to analyze large volumes of data to identify patterns, predict outcomes, and/or adapt/tweak interventions. For example, VR and AI based rehabilitation systems have been used to adapt task difficulty and feedback based on real-time motion data, ensuring a therapy remains challenging yet achievable.[38] That personalized approach is important to ensure rehabilitation programs are not only effective but also efficient, reducing the time required to achieve meaningful recovery milestones.

To date, numerous reviews have examined wearables for monitoring motor symptoms.[39–50] Yet, relatively few studies have investigated the application of wearables in the rehabilitation of motor symptoms.[51–54] those that have are often limited in scope, focusing exclusively on specific sensor types, such as inertial sensors alone, or on a particular neurological condition, such as PD.[52] Equally, reviews have been constrained to specific intervention modalities eg, telerehabilitation,[51] rhythmic or dance-based interventions,[55–57] VR and AR,[58,59] or robotic and exoskeleton-assisted therapies.[36,60,61] This highlights a gap in the literature regarding the broader potential of wearables in diverse rehabilitation contexts and across a wider range of neurological conditions.

The aim of this review is to provide a comprehensive overview of how current research leverages wearables in the rehabilitation of motor symptoms. We aim to highlight the existing gaps in wearables, interventions, and neurological conditions observed in the literature. This review takes a broad perspective, setting itself apart from earlier studies by covering various wearables across different cohorts and multiple training and rehabilitation programs. The structure of the review is as follows: it begins with a background of common motor symptoms associated with neurological conditions, as a basis for later sections. Next, a systematic search is presented using terms derived from previous reviews and results are presented, highlighting trends and statistics in the literature and an assessment of how various wearables are applied in rehabilitation studies. The review concludes with a discussion on the diverse applications of wearables in rehabilitation, their effectiveness, and the role of personalization, while addressing current limitations and offering insights into potential advancements and future improvements in the field.

Background: Motor Symptoms

Movement disorders encompass a wide spectrum of neurological conditions characterized by abnormal or impaired movement patterns, each posing distinctive challenges and complexities in their diagnosis and management. This section provides a brief introduction to gait disturbances, freezing of gait (FoG), tremors, and balance, outlining their key characteristics and fundamental descriptions.

Gait Disturbances

Gait disturbances refer to abnormalities in walking that can result from a wide range of conditions affecting the nervous system, musculoskeletal system, or both.[62–64] In the context of neurological conditions, gait disturbances often reflect underlying damage to or dysfunction in the areas of the brain, spinal cord, or peripheral nerves that are involved in movement control.[62,65–67] Shuffling gait is a type of gait disturbance characterized by short, dragging steps, often associated with reduced foot clearance and difficulty initiating movement.[68] This gait pattern is most readily associated with PD.[64,69]

Hemiplegic gait is a distinctive pattern of walking often observed in individuals who have experienced significant muscle weakness or paralysis on one side of their body, commonly due to stroke.[70,71] Hemiplegic gait is characterized by a circumduction movement, where the affected leg is swung outward and forward in a semicircle to compensate for the reduced control and strength.[72] Previous studies show a decrease in walking speed and an increase in the energy required for walking with hemiplegic gait, alongside an altered gait asymmetry due to the imbalance between the affected and unaffected sides.[73–75] The range of motion in the hip, knee, and ankle joints on the affected side is typically restricted, with a notable decrease in the ability to achieve full joint extension during the walking cycle.[73,76] These biomechanical changes are further compounded by modifications in the arm swing on the affected side, which can affect overall balance and gait stability.[77]

Ataxic gait is characterized by a lack of voluntary coordination of muscle movements, resulting in a wide-based, unsteady, and irregular gait.[78] Individuals exhibiting an ataxic gait often demonstrate a marked variation in stride length and an inability to maintain a straight trajectory, with a tendency to veer unpredictably.[79] This gait irregularity is further compounded by an impaired sense of balance and spatial positioning, which significantly increases the effort required to walk and the risk of falls.[80] Conditions such as cerebellar ataxia (CA), multiple sclerosis (MS) have been closely associated with this gait pattern.[81,82]

Freezing of Gait (FoG)

Freezing and festination of gait are often recognized as characteristic features associated with akinesia. FoG is a neurological phenomenon characterized by sudden and temporary episodes of immobility during walking. It can be described as a sudden and involuntary inability to initiate or continue walking and it typically lasts for a few seconds to minutes.[83] High-frequency oscillations and festinating steps, observed in the pre-FoG and during FoG phases, have been established as pivotal markers of this phenomenon.[84] FoG is closely associated PD and is extensively studied,[85] but also occurs frequently in other conditions like progressive supranuclear palsy (PSP).[86]

Tremor

Tremor is defined as a phenomenon characterized by oscillating and rhythmic involuntary movements occurring in relation to a fixed point, axis, or plane.[87] Tremors are classified into five distinct categories (rest, postural, kinetic, isometric, and action[88–92]) which are based on when the tremor occurs during voluntary muscle activation, maintenance of a stable posture, or active movement.[93]

Natural resonant frequency is an important concept to understand tremor. Symptomatic resting tremors usually have a frequency between 4 and 5 hertz (Hz) whereas postural tremors with dominant peaks around 6 Hz.[94] Tremor can present as either an isolated symptom of a disease, as seen in essential tremor (ET), or as a component of various neurological disorders, including PD,[95,96] stroke,[97,98] traumatic brain injury (TBI),[99] multiple sclerosis (MS).[100]

Balance

Poor postural balance/control is characterized by difficulties in controlling body alignment and stability during various activities eg, standing, walking, or sitting.[101] When individuals experience poor postural balance, they may sway, stumble, or fall more frequently than those with normal balance control. Poor postural balance can be commonly seen in various neurological conditions such as PD due to a loss of dopamine-producing neurons in the brain, which affects motor control, MS as it affects the central nervous system and stroke which results in damage to areas of the brain responsible for balance and coordination.[101–104] Postural instability is typically diagnosed subjectively through a clinical evaluation that involves physical examination, relevant laboratory tests, imaging, and an assessment of the patient's gait pattern.[105] However, there are also more objective methods available, such as the measurement of trunk velocity changes in response to physical perturbations, which can serve as potential indicators of gait stability[106] and more.[23,50]

Methods

Search Strategy and Study Selection Process

To identify relevant articles, a search was executed across two major scientific databases: PubMed and ScienceDirect. This review targeted journal articles written in English that explored the application of wearables in rehabilitation of movement disorders. The search strategy used a structured, stratified approach with specific search terms, Table 1. Specifically, wearables were categorized based on the types of data they generate:

- **Group 1**: Inertial-based devices such as bespoke inertial measurement units (IMUs: accelerometers, gyroscopes) and commercial devices like smartwatches and smartphones as well as research grade technologies such as Actigraph™, Kinesia™ and Parkinson's KinetiGraph (PKG™).
- **Group 2**: Pressure and force measurement devices: Pressure sensors, insoles and foot switches.
- **Group 3**: Electromyography (EMG).
- **Group 4**: Interactive and immersive technologies: VR, AR, headphones and gaming consoles.
- **Group 5**: Wearable assistive robotic systems: Robots, exoskeletons and vibrotactile devices.
- **Group 6**: Multimodal sensing.

Table 1 Search Terms

Wearable Technology		**Approach**		**Motor Symptom**
Group 1: Inertial Sensors: Wearable(s) [Title] OR Wearable Technology [Title] OR Wearable Devices [Title] OR Wearable Sensors [Title] OR sensor(s) [Title] OR Inertial Measurement Unit [Title] OR IMU(s) [Title] OR Accelerometer [Title] OR Acceleration [Title] OR Gyroscope [Title] OR Angular Velocity [Title] Personal Wearable Monitoring Devices Smartwatch [Title] OR Wrist Worn [Title] OR Finger Worn [Title] OR Smartphone [Title] OR Mobile Phone [Title] OR Actigraph [Title] OR Kinesia [Title] OR KinetiGrapgh [Title] Group 2: Pressure and Force Measurement Devices Force Sensors [Title] OR Insole [Title] OR Pressure Sensors [Title] Group 3: Electromyography (EMG) Electromyography [Title] Group 4: Interactive and Immersive Technologies Smart Glass [Title] OR Eye Tracker [Title] OR Virtual Reality [Title] OR Augmented Reality [Title] OR Headphone [Title] OR Wearable Camera [Title] OR Gaming Consoles [Title] Group 5: Wearable Assistive Robotic Systems: Robot [Title] OR Exoskeleton [Title] OR Vibrotactile [Title]	**AND**	Rehabilitation [Title] Treatment [Title] Intervention [Title] Therapy [Title] Training [Title]	**AND**	Shuffling Gait [Title] Hemiplegic Gait [Title] Ataxic Gait [Title] Freezing of Gait [Title] Tremor [Title] Postural Balance [Title] Balance [Title]

The review encompassed articles published from 01 January 2000 until 01 March 2024. Following the search, the process of article selection was guided by the PRISMA guidelines[107] (Figure 1) and involved: (1) YC and AG independently screened titles from the merged database results after duplicates were removed to identify relevant articles; (2) they then examined the titles and abstracts of these articles, resorting to full-text reviews when necessary to determine if the studies met the review criteria; and (3) YC, CW, JM and AG reviewed full texts to decide on their inclusion (Table 2). Additionally, the reference lists of all studies included in the review were thoroughly examined to identify any additional relevant publications that could be added. Throughout the selection process, decisions to include or exclude studies were collaboratively made by all authors.

Data Extraction

Data were synthesised into a table format by one author (YC) and another (AG) confirmed data entry. For each article, data were extracted on several key aspects, including the participants involved, the wearable used, the study protocol, any reference or additional measures employed, the outcome measures assessed, and the findings.

Search Results

The database search identified 341 articles, and an additional 17 articles were included through a citation search. Following the removal of duplicate records, reviews, books and book chapters, a total of 247 articles assessed for eligibility based on predetermined inclusion and exclusion criteria. Overall, 116 articles met the inclusion criteria (see Supplementary Material, search results). The full flow diagram of the screening process including the number of studies identified and excluded is shown in Figure 1.

Gait disturbance (52 articles) and postural balance (55 articles) are the most frequently studied, followed by FoG (8 articles) and tremor (5 articles). Some articles examined multiple motor symptoms within a single study. A total of 20 articles utilized inertial sensors to capture movement. Additionally, 3 articles focused on the application of pressure and force measurement devices to assess physical interactions and loads. EMG was employed in 8 articles. Furthermore, interactive and immersive technologies (VR, AR and headphones) were explored in 57 articles. Lastly, 32 articles reported on the use of wearable assistive robotic systems, Figure 2.

For the rehabilitation of motor symptoms, wearables were effectively used both as therapeutic tools within rehabilitation programs and as monitoring devices to assess progress. Table 3 presents a categorization of research articles based on wearables, motor symptoms, and neurological cohorts.

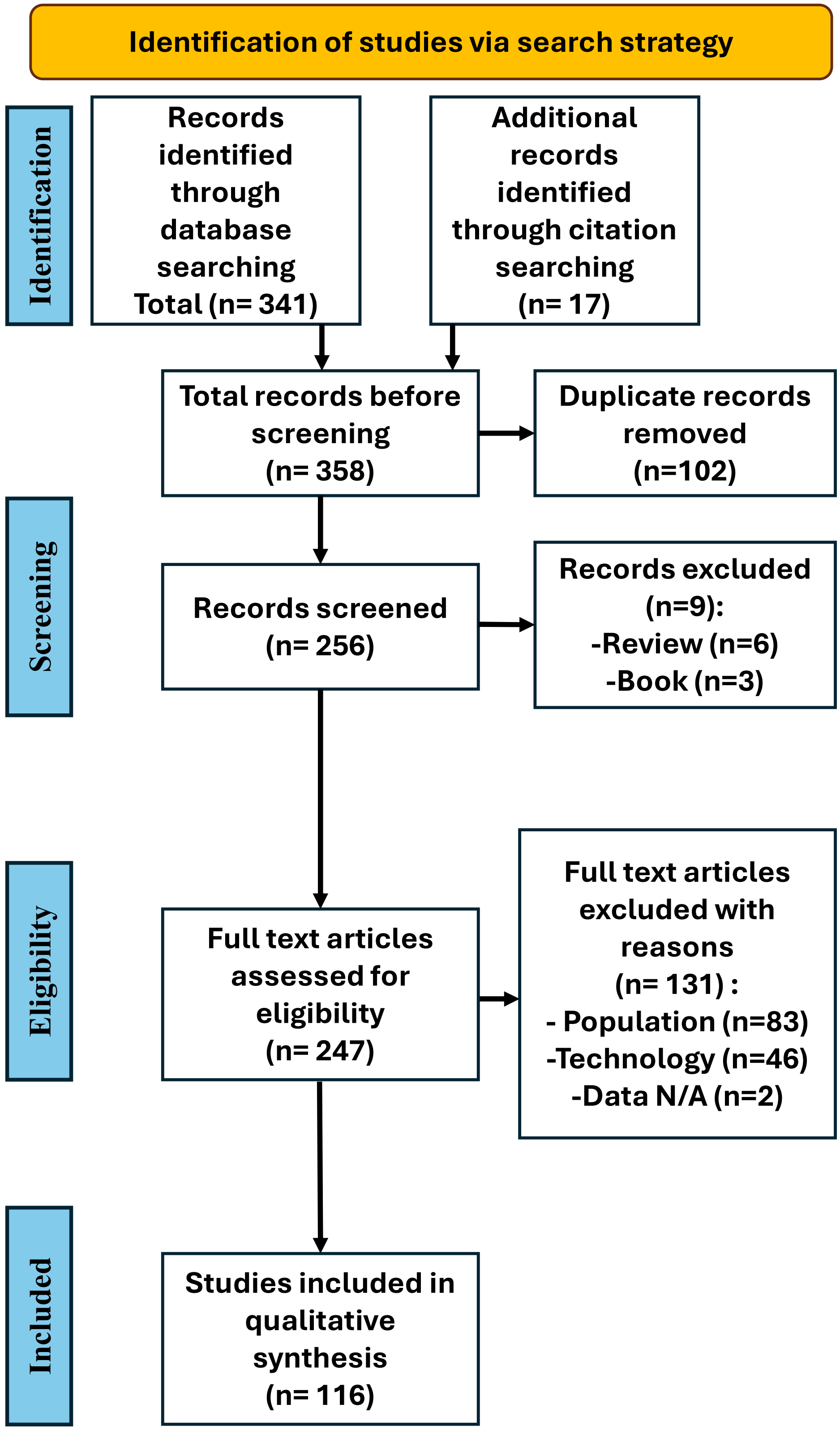

Figure 1 The article selection process flow diagram.

Stroke survivors (SS, 44 articles) and people with PD (38 articles) were the most extensively researched groups within the neurological population followed by MS with 13 articles, cerebral palsy (CP) with 12 articles, TBI with 5 articles, ET with 3 articles, and spinal cord injury (SCI) and PSP, each represented by one article. Rehabilitation of gait

Table 2 Eligibility Criteria

Inclusion criteria
The articles investigate treatment of at least one neurological condition or motor symptom: Neurological conditions: Stroke or Stroke Survivor (SS), Parkinson's Disease (PD), Traumatic Brain Injury (TBI), Multiple Sclerosis (MS), Essential Tremor (ET), Cerebral Palsy (CP), Spinal Cord Injury (SCI), Supranuclear Palsy (SP). Motor symptoms: shuffling gait, hemiplegic gait, ataxic gait, freezing of gait, tremor, postural balance and tremor
The articles contain one (uni) or multiple (multi) wearable technologies: IMU(s), accelerometer, gyroscope, smartwatch, smartphone, Actigraph, Kinesia, KinetiGrapgh, smart glass, eye tracker, virtual reality glass, augmented reality glass, headphone, wearable camera, gaming console, exoskeleton, vibrotactile, force sensors, smart insole, pressure sensors, electromyography
Included at least one clearly defined outcome measure relating to one of the motor symptoms: Gait speed, cadence, stride length, stride time, step time, stance time, swing time, walking distance, foot plantar pressure, joint kinematics, tremor score, turning velocity, postural stability parameters such as sway, Range of Motion (RoM) Timed Up and Go test (TUG), Six-Minute Walk Test (6MWT).
Included clear definition of observation, intervention, and protocol
Included at least one clinical test: Hoehn and Yahr scale (H&Y), Unified Parkinson's Disease Rating Scale (UPDRS), Montreal Cognitive Assessment (MoCA), Inertial Measurement Unit (IMU), Parkinson's Disease (PD), Healthy Subjects (HS), Range of Motion (RoM), Dynamic Gait Index (DGI), Berg Balance Scale (BBS), Activities-specific Balance Confidence scale (ABC), Multiple Sclerosis Walking Scale (MSWS), Expanded Disability Status Scale (EDSS), Modified Ashworth Scale (MAS), Gross Motor Function Classification System (GMFCS), American Spinal Injury Association Impairment Scale (ASIA)
Exclusion criteria
Article type: Book chapters, review papers, case studies
Studies that focus solely on monitoring or observation without implementing a rehabilitation protocol
Studies investigating movement disorders using non-wearable systems such as motion capture, instrumented walkways
Studies focusing on activity recognition only
Studies without information regarding protocol, wearable technology, or cohort
Studies with only healthy participants: eg, older adults, younger adults
Study concerns non-human animal subjects
Studies that use online datasets

disturbances has been investigated in SS with 18 articles, PD with 16 articles, MS with 6 articles, CP with 4 articles, TBI with 1 article, and SCI with 1 article. FoG has been exclusively studied in people with PD, with 8 articles. Balance recovery has been examined in SS (25 articles), PD (12 articles), CP (8 articles), MS (7 articles), TBI (4 articles), and PSP (1 article). In tremor treatment, ET is the most studied cohort, with 3 articles, followed by PD with 2 articles and SS with 1 article. Overall, PD and SS are the most frequently studied cohorts across various motor symptoms, particularly gait disturbance and balance recovery.

Wearables in Rehabilitation of Motor Symptoms

Table 4 presents all studies, providing details on intervention type, study protocol, number of subjects, clinical tests, type and quantity of wearables, placement of wearables, features targeted, and study findings.

Group 1

Gait Disturbances and FoG

Inertial sensors can play a role in gait rehabilitation by providing real-time feedback on spatial and temporal gait parameters, enabling patients to alter movements and improve functional performance in real-life and home-based settings.[118] For instance, the Gamepad system used IMUs to support the delivery of immediate auditory and visual

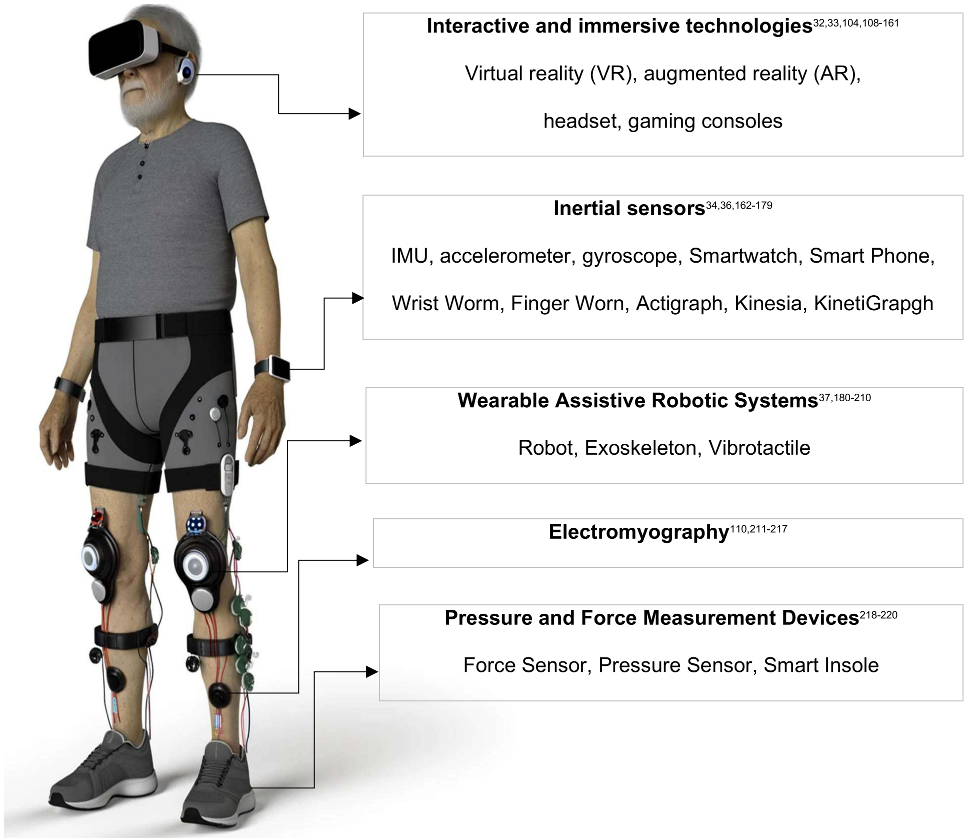

Figure 2 Wearable types used in reference rehabilitation articles.

cues, facilitating task-oriented training that mimicked daily activities in people with PD.[109] That approach enhanced motor learning and facilitated fine-tuning of the system during exercises. Similarly, CuPiD integrated IMUs with a smartphone application to provide real-time feedback on gait parameters such as cadence and stride length, with

Table 3 Categorization of Research Articles That Focus on Different Motor Symptoms Associated with Specific Neurological Disorders and Wearable Technology

Group 1: Inertial sensors	**Gait Disturbances**	PD,[34,36,108–110] SS,[111] MS[112–114]
	Tremor	ET,[115–117] PD,[115,118] SS[119]
	Balance	PD,[120–123] SS[124,125]
Group 2: Pressure and force measurement devices	**Gait Disturbances**	PD[126,127]
	FoG	PD[128]
Group 3: Electromyography	**Gait Disturbances**	CP,[129,130] SS,[131–133] MS[134,135]
	Balance	SS[136]
Group 4: Interactive and immersive technologies	**Gait Disturbances**	CP,[129,137,138] MS,[139,140] PD,[32,141–146] SS,[147–151] TBI[152]
	FoG	PD[153–156]
	Balance	CP,[137,157–162] MS,[104,163–165] PD,[33,165–168] SP,[169] SS,[170–185] TBI[186–189]
Group 5: Wearable assistive robotic systems	**Gait Disturbances**	CP,[190] PD,[191,192] SCI,[193] SS,[194–205] MS[206]
	FoG	PD[207–209]
	Balance	CP,[210] MS,[211–213] PD,[214,215] SS[37,216–220]

https://doi.org/10.2147/POR.S396198

Table 4 All Included Studies (Inc. randomized Controlled Trials And Clinical Trials) That Used Wearable During Rehabilitation of Movement Disorders

Ref	Intervention	Protocol	Subject	Age M.	Clinical Tests	Wearable Type (n) and Location	Features Targeted
[221]	Physiotherapy and Treadmill Training	Session:10 sessions Duration: 25 min Period: 2 weeks	105 PD Randomized Controlled Trial	No	H&Y UPDRS MoCA	IMU (1–2) Foot	Spatial and Temporal
Gait speed exhibited significant improvements of 4.2% with treadmill intervention and 8.3% with physiotherapy intervention. Both treatments also demonstrated enhancements in dual task walking abilities.							
[222]	Balance exercise	Session:30 sessions Duration: 60 min Period: 10 weeks	10 PD Randomized Controlled Trial	No	H&Y UPDRS	IMU (1) Lower Back	Spatial and Temporal
The results confirmed the feasibility of utilizing wearable sensors to gather training activity data, and the sampled data accurately represented the progressive nature of this intervention.							
[223]	Gait Retraining	Session:24 Duration: 45–60 min Period: 8 weeks	29 PD EXP1:15 CT:14 Randomized Controlled Trial	No	H&Y MoCA UPDRS	IMU (6) Lower Limb	Spatial and Temporal gait parameters. Bradykinesia, Rigidity, Tremor and Postural Instability Scores
Both groups demonstrated improvements in their typical gait speed. Furthermore, the experimental group showed enhancements in cadence and stride length. Both interventions effectively increased gait speed to a level that allows independent community mobility.							
[224]	Ballet Dancing	Session: N/A Duration: 90 min Period: 5–12 months	19 PD 13 hS Non-Randomized Controlled Trial	No	H&Y UPDRS	IMU (2) Hip and Sternum	RoM in hip and sternum.
The current study did not show that a weekly ballet lesson significantly improved the trunk coordination and range of motion of PD patients during walking.							
[225]	Gait Training	Session: 10–16 Duration: 60 min Period:2–4 weeks	34 PD EXP1:17 EXP2:17 Randomized Controlled Trial	No	H&Y UPDRS	Smart Watch Wrist	Spatial and Temporal Parameters
Both intervention training approaches led to equal improvements in measures of motor performance; however, high-intensity training proved to be more effective in achieving patient-perceived benefits							
[127]	Gait Training	Session: 12 Duration: 25 min Period: 4 weeks	7 PD Clinical Trial	No	H&Y UPDRS MoCA and more	Wearable Insoles Feet	Spatial and Temporal Parameters
Gait speed and gait variability showed significant improvement during dual tasking. Additionally, enhancements were observed in dual tasking conditions that were not specifically targeted during training, and these improvements were retained even one month after the training period.							
[226]	Balance and Gait Training	Session: 12 Duration: 90 min Period: 6–8 weeks	12 Stroke 12 PD EXP1:12 EXP2:12	No	DGI, BBS	IMU (7) Pressure sensors Hips, knees, ankles, and feet	Gait and Balance Parameters
Dynamic visual kinematic feedback from wireless pressure and motion sensors yielded comparable positive effects to those of verbal therapist feedback.							
[227]	Sardinian Folk Dance	Session: 24 Duration: 90 min Period: 12 weeks	20 PD EXP1:10 EXP2:10 A Randomized Controlled Pilot Trial	No	H&Y UPDRS	IMU (3) Ankle and Lower Back	Spatial and Temporal Parameters
Engaging in Sardinian folk dance, known as "Ballu Sardu", is a pleasurable activity that has demonstrated its effectiveness compared to standard care alone in bringing about positive alterations in various motor and non-motor symptoms associated with PD.							
[110]	Music Based Gait Training	Session: 20 Duration: 30 min Period: 4 weeks	45 PD	No	H&Y UPDRS	Wearable Headphone and IMU (5) Feet, Shank and Sternum	Spatial Parameters and Asymmetry Index.

(*Continued*)

Table 4 (Continued).

Ref	Intervention	Protocol	Subject	Age M.	Clinical Tests	Wearable Type (n) and Location	Features Targeted
There was no increase in pain, fatigue, or falls observed, and there was a decrease in the fear of falling, accompanied by an improvement in the quality of life. Furthermore, following the program, patients demonstrated enhanced gait parameters in the six-minute walk test, even without musical stimulation							
[35]	Music Based Gait Training	Session: 1	30 PD 32 hS	No	H&Y UPDRS	IMU (6) Lower Back, Sternum Wrists Feet	Kinematic Arm Movement and Sternum parameters, Spatial Temporal Parameters
Musification significantly increased arm swing range of motion in patients, with a greater improvement on the more affected side (+529.5% from baseline). It also enhanced arm swing symmetry, sternum rotation, and stride length. With musical feedback, patients with PD achieved arm swing movements comparable to or exceeding those of healthy individuals.							
[126]	Music Based Gait Training	Session: 1	30 PD 18 hS	No	H&Y UPDRS	Force Sensors (4) and IMU (7) Feet, Shanks, Thighs, and Pelvis	Spatial and Temporal Parameters
In addition to improvements in spatial-temporal parameters, a novel global index showed significant enhancement when subjected to rhythmic auditory stimulation at a frequency of 110% in both ON and OFF medication conditions. Interestingly, in the most severe patients, the same positive outcome was observed, even with rhythmic auditory stimulation at 100%.							
[228]	Music Based Gait Training	Session: 3 Duration: 3 min Period: 4 days	32 PD	No	H&Y	Wearable Headphone, Pressure Sensors (2) Head and Feet	Mean and the Coefficient of Variation of Stride Intervals
Findings indicate that interactive rhythmic cues played a significant role in helping patients' gait fluctuations gradually return to healthy levels. This suggests that mutual entrainment can be an effective facilitator for gait relearning.							
[113]	Music Based Gait Training	Session: 1 Duration: 12 min	27 MS 28 hS	No	MSWS	Wearable Headphone, IMU (2) and IMU (3) Ankle and Sternum	Spatial Parameters
Linking walking with music has the potential to introduce innovative approaches for motor task-oriented training in individuals with multiple sclerosis (MS).							
[229]	Music Based Gait Training	Session: 1	16 Stroke	No	Brunnstrom Stage of Motor Recovery score	IMU (6) Head, Torso, Arms, and Forearms	Kinematic Upper Limb Parameters
The study found that when melodic auditory cues were used, the root mean square error in angle measurements was significantly reduced, and the duration of movement execution during the holding phase was significantly shorter compared to other types of cueing. These results highlight the crucial role of melodic auditory cueing in enhancing movement precision, reducing variability, and improving endurance.							
[230]	Rhythmic Visual And Auditory Cueing Training	Session: 1 Duration: 2.5 hours	12 PD	No	H&Y UPDRS	IMU (7) Pelvis, Upper Legs, Lower Legs Feet	Spatial Parameters
The study results indicate that gait parameters consistently showed greater improvement when auditory cues were used compared to when visual cues were employed.							
[231]	Cueing And Feedback Training	Duration: 30 min Period: 6 weeks	28 PD EXP1:15 EXP2:13	No	H&Y UPDRS MoCA and more	Wearable Headphone and IMU (2) Head and Feet	Number of Gait Deviations
The freezers exhibited the most stable gait when subjected to continuous cueing, although the majority of them preferred intelligent feedback. On the other hand, non-freezers did not demonstrate significant differences between the conditions, but their gait appeared to be more stable when they received intelligent input, particularly when compared to the freezers.							
[34]	Music Based Gait Rehabilitation	Session: 20 Duration: 30 min Period: 4 weeks	23 PD	No	H&Y UPDRS MoCA	Wearable Headphone and Smart Watch Wrist	Spatial Parameters, Variability, and Symmetry
Sessions improved gait speed, stride length, cadence, and reduced gait variability. Daily moderate-intensity walking and step count increased on intervention days. After four weeks, quality of life, disease severity, walking endurance, and functional mobility significantly improved.							
[232]	Music Based Gait Rehabilitation	Session: 24 Duration: 17 min Period: 4 weeks	30 MS	No	EDSS	N/A	Spatial parameters

(*Continued*)

Table 4 (Continued).

Ref	Intervention	Protocol	Subject	Age M.	Clinical Tests	Wearable Type (n) and Location	Features Targeted
The interventions led to measurable improvements in physical capabilities such as increased walking speed and walking distance.							
[109]	Biofeedback Training -Visual -Auditory	Session: 20 Duration: 45 min	42 PD Randomized Controlled Trial	No	H&Y UPDRS	IMU (6) Upper Trunk, Lower Trunk, And Lower Limbs	10-M Walk Test- Balance Test Cop ML And AP Sway.
The group that received biofeedback training demonstrated superior balance performance compared to the group that underwent physiotherapy without biofeedback							
[233]	Telerehabilitation	Period: 16 weeks	50 PD Randomized Controlled Trial	No	H&Y UPDRS	Wrist Worn Wearable (1) Wrist	Overall Physical Activity
Physical activity and non-motor symptoms showed greater improvement in the intervention group, which received a 16-week intervention with information feedback, as opposed to the control group, which received only one-time education.							
[234]	Telerehabilitation	Period: 8 weeks Sessions: daily	20 PD	No	UPDRS	Smartphone App	Mini-BESTest
Improvements in PD severity, mobility and cognition were found at the end of training and maintained at follow-up.							
[108]	Smartphone-Delivered Automated Feedback Training	Period: 6 weeks	40 PD Clinical Trial	N/A	H&Y MoCA UPDRS	IMU (2) and Smartphone (1) Feet	Spatial and Temporal Gait Parameters
Utilizing automated feedback training delivered through smartphones and wearables is both feasible and well-received, proving to be an effective approach in promoting gait training. Participants demonstrated significant improvements in primary outcomes, including spatial and temporal gait parameters.							
[235]	Virtual Reality Treadmill Training	Session: 15 Duration: 30 min Period: 3 weeks	21 Stroke EXP1:11 EXP2:10 Randomized Controlled Trial	No	ABC	VR set Head	TUG Duration
Balance and balance self-efficacy were notably higher in the experimental group, signifying a significant improvement. Additionally, in both groups, there was a substantial increase in both balance and balance self-efficacy after three weeks when compared to the baseline values.							
[236]	Augmented Reality Training	Session: 1	48 PD	No	H&Y UPDRS	AR Headset With IMU Head	Spatial Parameters and Turn Parameters
The use of the AR platform should be explored as a potential method to address the dual-task declines associated with PD.							
[32]	Augmented Reality-Based Dance Training	Period: 3 weeks	7 PD Clinical Trial	No	H&Y UPDRS MoCA	Wearable AR Google Glass Head	Mini-BESTest, TUG
Upon comparing baseline and post-test results, no significant improvements were noted in the other motor outcome measures. Nevertheless, the dancing intervention demonstrated noteworthy medium to large effect sizes in Mini-BESTest (overall and dynamic gait sub scores), one-leg stance, and dual-task assessments							
[237]	Exergames and Telerehabilitation	Session: 12–36 Duration: 40 min Period: 4 weeks	6 Stroke Randomized Controlled Trial	No	BBS	Smartphone (1) And IMU (2) Lower Back and Thigh	Mini-Best Test and Balance Scores.
The findings reveal a significant improvement in balance for the telerehabilitation group through the use of Exergames and Telerehabilitation.							
[238]	Telerehabilitation and Virtual Reality-Video Games	Session: 20–40 Duration: 20–40 min Period: 10 weeks	50 MS Randomized Controlled Trial	No	EDSS	Xbox 360® and Kinect Console N/A	Sensory Organization Test
The results indicated that a telerehabilitation program utilizing VR video games led to improvements in overall balance for participants in both groups.							
[183]	VR Based Telerehabilitation	Session: 15 Duration: 20 min Period: 3 weeks	6 Stroke Clinical Trial	No	BBS	VR (1) Head	BBS, TUG

(*Continued*)

Table 4 (Continued).

Ref	Intervention	Protocol	Subject	Age M.	Clinical Tests	Wearable Type (n) and Location	Features Targeted
Among patients who underwent VR-supported balance training, the Berg Balance Scale (BBS) exhibited improvement by 15%, the Timed Up and Go (TUG) test showed a 29% enhancement, the 10-meter walk test demonstrated a 26% improvement, and the stance time on the affected and unaffected extremities increased by 200% and 67%, respectively.							
[172]	VR Based Telerehabilitation	Session: 20 Duration: 45 min	30 Stroke Randomized Controlled Trial	Yes	BBS	VR (1) Head	Rating Scales for Gait and Balance.
VR-based telerehabilitation interventions can facilitate the restoration of locomotor skills related to balance, mirroring the effectiveness observed in traditional in-clinic interventions.							
[145]	Visual And Auditory Feedback	Session: 14 Duration: 60 min Period: 2 weeks	13 PD Clinical Trial	No	UPDRS	VR (1) Head	Spatial Gait Parameters
Following the use of wearable VR goggles for 2 weeks, participants exhibited faster walking speeds and increased stride lengths.							
[239]	Gait Training Wearable Exoskeleton	Session: 1 Duration: 30 min	20 Stroke Clinical Trial	No	BBS	Wearable Hip-Assist Robot (1), Functional Near-Infrared Spectroscopy (fNIRS) Hip and Brain	Alterations In Sensorimotor Cortex (SMC), Premotor Cortices (PMC)
The wearable hip-assist robot increased sensorimotor cortex activation and balanced its activity, aiding gait restoration and reducing cortical involvement in stroke gait. It achieved this through rhythmic hip flexion and extension, enabling more efficient and coordinated gait patterns.							
[240]	Gait Training Wearable Exoskeleton	Session: 6 Period: 8 weeks	7 CP Clinical Trial	No	GMFCS, MAS	Wearable Exoskeleton (1), EMG Knee And Leg	Kinematic, Spatial and Temporal Parameters
Most participants displayed postural improvements comparable to outcomes reported in invasive orthopaedic surgery. Additionally, crouch improvements were observed throughout our multiweek exploratory trial.							
[192]	Gait Training Wearable Exoskeleton	Session: 10 Duration: 30 min Period: 3 months	12 PD Randomized Controlled Trial	Yes	H&Y UPDRS	Wearable Exoskeleton (1) Hip	Kinematic, Spatial and Temporal Parameters
Our findings showed that gait training with the wearable exoskeleton led to improved exercise endurance in participants with PD.							
[199]	Gait Training Wearable Exoskeleton	Session: 18 Duration: 45 min Period:6–8 weeks	50 Stroke Randomized Controlled Trial	No	N/A	Wearable Exoskeleton (1) Hip	Spatial and Temporal Parameters-
The wearable exoskeleton Stride Management Assist device has the potential to serve as a valuable therapeutic tool for enhancing spatiotemporal parameters and promoting improved functional mobility in stroke survivors.							
[190]	Gait Training Wearable Exoskeleton	Duration: 20 min Period: 4 weeks	6 CP	N/A	GMFCS	Wearable Lower Limb Ankle Exoskeleton (1) Waist, and Ankle	Strength, Speed, Walking Efficiency, TUG, 6MWT
Participants exhibited heightened average plantar flexor strength, an increased preferred walking speed on the treadmill, improved metabolic cost of transport, and enhanced performance on the Timed Up and Go test and the six-minute walk test.							
[202]	Gait Training Wearable Exoskeleton	Session: 18 Duration: 45 min Period: 6–8 weeks	50 Stroke Randomized Controlled Trial	No	BBS	Wearable Honda Stride Management Assist (SMA) Exoskeleton Hip And Thigh	Balance and Spatial Gait Parameters, 10–6 Meter Walk Tests
Following the treatment, the exoskeleton group exhibited enhanced walking speed as the primary outcome. In comparison to the functional group, individuals utilizing the exoskeleton demonstrated superior improvements in walking endurance and took more steps during therapy sessions. Notably, participants recovering from stroke displayed pronounced enhancements in balance while utilizing the exoskeleton.							
[203]	Gait Training Wearable Exoskeleton	Session: 12 Duration: 45 min Period:4 weeks	26 Stroke Randomized Controlled Trial	Yes	FAC, MAS, MoCA	Wearable Exoskeleton Hip And Thigh	Spatiotemporal Gait Parameters, Gait Symmetry Ratio

(*Continued*)

Table 4 (Continued).

Ref	Intervention	Protocol	Subject	Age M.	Clinical Tests	Wearable Type (n) and Location	Features Targeted
The group that underwent gait training with the exoskeleton demonstrated significantly greater improvement in spatiotemporal gait parameters and muscle efforts compared to the control group							
[200]	Gait Training Wearable Exoskeleton	Session: 12 Duration: 20 min Period:4 weeks	24 Stroke Randomized Controlled Trial	No	FAC	Wearable Hybrid Assistive Limb Hip and Lower Limb	Walking Speed, Stride, Cadence, 6MWT, TUG.
The group that received gait training with a lower limb exoskeleton experienced a substantial improvement in the Functional Ambulation Category after the interventions. Nevertheless, secondary outcome measures, including walking speed, stride, cadence, 6-minute walking distance, and the Timed Up-and-Go test, did not exhibit significant differences between the two groups.							
[201]	Gait Training Wearable Exoskeleton	Session: 20 Duration: 30 min	47 Stroke EXP1:14 EXP2:16 CT:17 Randomized Controlled Trial	No	BBS, FAC	Wearable Exoskeleton Ankle Robot Ankle-Foot	Walking Speed, Number of Stairs (Step), Walking Distance
After the 20-session interventions, all participants showed statistically significant and clinically meaningful within-group functional improvement in all outcome measures.							
[36]	Gait Training Wearable Exoskeleton	Session: 12 Duration: 5–8 min	8 PD Clinical Trial	No	UPDRS H&Y	Wearable Exoskeleton, IMU (8+2) Lower Back, Lower Limb	Spatial and Temporal Gait Parameters
Following the training, patients observed an increase in hip range of motion, gait speed, and stride length, along with a reduction in stride duration. Notably, these improvements were sustained even one month after the completion of the training.							
[114]	Gait Training Wearable Exoskeleton	Period:2 weeks	29 MS EXP1:15 EXP2:14 Randomized Controlled Trial	No	MAS	Wearable Exoskeleton and Actigraph GT3X Lower Back, Lower Limb	TUG, 6 MWT
Wearable exoskeleton seems to provide an exercise-related advantage for individuals with Multiple Sclerosis (MS), enhancing their unassisted gait endurance and ability to climb stairs.							
[193]	Gait Training Wearable Exoskeleton	Session: 16 Duration: 60 min Period: 8 weeks	2 SCI Clinical Trial	No	ASIA	Wearable Powered Exoskeleton Lower Back, Lower Limb	Spatial parameters during TUG, 6 MWT and 10 MWT
When utilizing the powered exoskeleton, participants achieved faster and longer walks, with no reported incidents of injury or falls, in contrast to when using a knee–ankle–foot orthosis.							

Abbreviations: Age M, age matched; H&Y, Hoehn and Yahr scale; UPDRS, Unified Parkinson's Disease Rating Scale; MoCA, Montreal Cognitive Assessment; IMU, Inertial Measurement Unit; PD, Parkinson's Disease; HS, Healthy Subjects; RoM, Range of Motion; DGI, Dynamic Gait Index; BBS, Berg Balance Scale; ABC, Activities-specific Balance Confidence scale; MSWS, Multiple Sclerosis Walking Scale; EDSS, Expanded Disability Status Scale; MAS, Modified Ashworth Scale; GMFCS, Gross Motor Function Classification System; ASIA, American Spinal Injury Association Impairment Scale; 6MWT, Six-Minute Walk Test; TUG, Timed Up and Go test; FAC, Functional Ambulatory Category.

a particular focus on home-based rehabilitation for PD.[108] Despite their potential, the effectiveness of inertial sensors can vary across conditions and applications. For example, one study used these sensors to assess gait changes in a MS cohort over 18 months. While parameters like stride velocity distinguished mildly and moderately disabled participants from healthy controls, no gait decline was observed over time. This highlight the sensors' ability to detect impairments but raised questions about sensitivity in tracking disease progression.[112] Wearables have also been explored to address FoG through external sensory cues. A closed-loop system with inertial sensors detected the stance phase of gait and delivered phase-dependent vibrations to the wrist. That provided real-time proprioceptive feedback to enhance sensory integration and motor coordination.[241]

Tremor

Inertial sensors can provide real-time feedback on tremor characteristics, such as amplitude and frequency. One study showed that IMUs could accurately assess kinetic tremor severity during wrist movements by measuring angular displacement and velocity to enable clinicians customize a rehabilitation protocol.[116] Similarly, IMUs have been used to monitor tremor dynamics during tasks like wrist flexion and extension under varying loading conditions. That approach distinguished central tremor components from mechanical reflex contributions, providing deeper insights into tremor mechanisms to help guide the development of more targeted therapeutic interventions.[117] Additionally, IMUs have proven useful in injection-based therapies. For instance, these sensors guided botulinum toxin type A (BoNT-A) injections in PD and ET patients. Specifically, IMUs improved treatment precision by identifying target muscles and assessing tremor severity through amplitude and frequency analysis.[115]

Balance

Application of inertial sensors can be important to improve balance, as they can provide real-time feedback on postural stability and sway dynamics.[180,197,242] Inertial sensors measure parameters such as centre of pressure (CoP) trajectory and sway velocity, enabling patients to make immediate postural adjustments during exercises.[121] For example, the RIABLO system combined IMUs with biofeedback, enabling users to visually monitor their balance performance and receive auditory cues for task-specific training that mimicked daily activities.[124] Similarly for SS, a home-based program combined a balance disc with a smartphone inclinometer app to deliver real-time feedback during seated balance exercises. Over four weeks, SS demonstrated significant improvements in postural control and daily living activities compared to conventional therapy.[111]

Group 2

Gait Disturbances and FoG

Foot pressure sensors and insoles provide a portable and discrete approach for objective data related to pressure distribution and some temporal gait parameters.[15] Rhythmic auditory stimulation (RAS) combined with foot pressure sensing has been used to analyze gait phases (eg, loading response, flat-foot, pre-swing, swing) by detecting events like heel strike and toe-off. RAS at 110% of preferred cadence significantly improved gait phase distribution, reducing double support time and increasing single support time to enhance gait stability in PD.[243–245] However, its long-term effects remain unclear.[126]

A pilot study on gait training used footswitch-equipped insoles to measure stride time variability and gait speed during single and dual-task conditions (eg, verbal fluency, arithmetic tasks). Over 12 sessions in four weeks, participants improved gait speed and stride time variability, with gains transferring to untrained dual-tasks, suggesting cognitive-motor benefits but the small sample size limited the generalizability of the results.[127] Another study used silicone insoles with thickened pads to apply controlled plantar pressure, improving sensory feedback through pressure sensors. That method enhanced spatio-temporal gait parameters and reduced FoG episodes in PD.[128]

Group 3

Gait Disturbances and Balance

EMG is widely used to assess muscle activation patterns and neuromuscular coordination during functional tasks.[133,246] Integrating EMG with other sensing modalities like IMUs enables real-time monitoring and feedback by simultaneously capturing muscle activity and movement patterns, enabling precise evaluation of interventions such as robotic exoskeleton training[133] and treadmill-based rehabilitation.[246] In CP, EMG alone has been essential for assessing the impact of selective percutaneous myofascial lengthening. It has been used to show improvements in gait function and strength in key lower-limb muscles.[130] Similarly, EMG-triggered functional electrical stimulation and biofeedback systems showed an improvement of voluntary muscle activation and gait symmetry, particularly in SS.[132] EMG has also been used to evaluate neuromuscular adaptations during progressive resistance training. It reliably measured dynamic and isokinetic knee muscle strength and assessed its impact on gait performance in SS.[131] In balance rehabilitation, task-oriented EMG biofeedback has proven effective in enhancing muscle strength and motor relearning. For example, targeting the tibialis anterior has improved anterior-posterior balance by promoting real-time feedback and motor learning principles in SS.[247]

Group 4

Gait Disturbances

Interactive and immersive technologies provide dynamic and customizable environments for patient engagement, precise tracking for assessment, and innovative therapeutic exercises.[31,144] A study used a closed-loop AR device with accelerometer-driven cues to improve walking speed, stride length, and cadence through adaptive visual feedback. Post-training, 70% of participants maintained at least a 20% improvement in speed or stride length.[145] Another study used Google Glass with an AR dance app to deliver cues for improving mobility in people with PD. Standard assessments showed enhanced mobility under cognitive load following the intervention.[32] A similar study used a portable auditory cueing device integrated with smart glasses, a smartphone app, and gait analysis to improve walking in people with PD. Listenmee® auditory cues increased walking speed by 38.1%, cadence by 28.1%, and stride length by 44.5%.[146]

FoG

VR has been used for dual motor-cognitive training in those with FOG by creating immersive environments that require users to perform cognitive and motor tasks simultaneously. That approach aims to mimic real-world complexities, improving dual-task performance and enhancing functional outcomes.[156] AR platforms, such as Google Glass™, have been investigated in pilot studies to deliver real-time, context-aware visual cues, showing preliminary success in reducing the incidence of FoG.[154] Additionally, a combination of VR and physical practice using video self-modelling has proven feasible and acceptable for rehabilitation to helps patients visualize and replicate optimal gait patterns to improve walking.[153]

Although it is evident that immersive technology supports rehabilitation, its effectiveness can vary among individuals where comparative research shows that treadmill training with VR affects patients with and without FoG differently.[155] Regardless, virtual environments offer a powerful tool for replicating FoG triggers, enabling controlled studies and targeted interventions while providing valuable insights into motor initiation and inhibition, thereby deepening the understanding of FoG mechanisms.[248,249] For instance, complex tasks like turning, a common FoG trigger, can be addressed using AR visual cues to improve gait control.[250] Similarly, VR-based interventions for overground walking demonstrate that virtual improvements can translate effectively to real-world ambulation, enhancing therapeutic outcomes.[31] AR-enhanced smart glasses further integrate augmented visual cues into daily life, helping to reduce FoG episodes in real-world settings.[251] Innovations like the "Crossing Virtual Doors" VR paradigm simulate specific gait challenges, advancing research on spatial navigation difficulties associated with FoG.[252] Additionally, wearable AR applications utilizing holographic cues have shown promise in improving walking and reducing FoG episodes, offering a practical and portable solution for patients.[253]

Balance

VR-based balance exercises provide immersive environments that can help improve balance outcomes.[187] Dual-task VR training has shown significant benefits for postural balance in chronic SS by integrating cognitive challenges with motor recovery.[147] Telerehabilitation programs using VR video games enhance balance in people with MS, showcasing remote, technology-driven care.[163] For adolescents with CP, tailored VR programs offer interactive solutions to improve functional balance and mobility.[137] Portable VR balance devices are also advancing mild traumatic brain injury (mTBI) care by enabling assessment, continuous monitoring, and therapy.[254] Combining VR with auditory biofeedback has shown improvements in balance-related sensory impairments for mTBI patients.[186] Additionally, autonomous VR systems have demonstrated safety, usability, and compliance which highlight the potential for patient-centred, home-based balance training in SS.[148] Nevertheless, it is reported that challenges remain in translating virtual balance improvements to real-world postural control, particularly for chronic SS.[170]

Group 5

Gait Disturbances

Wearable assistive technologies are favoured for their seamless integration into daily life, real-time feedback, and continuous monitoring of real-world activities.[200,239] For individuals with SCI, powered lower-limb exoskeletons enable assisted walking, promote gait retraining, and improve overall functional independence.[193] Similarly, in SS, the Hybrid Assistive Limb® (HAL), combined with neuro-controlled robotics, demonstrated significant improvements in gait parameters after structured training programs[200] Another exoskeleton, the stride management assist system (SMA®), refined spatiotemporal gait characteristics in SS by delivering precise, real-time gait adjustments.[199] Beyond SS, wearable adaptive resistance training improved ankle strength and walking efficiency in individuals with CP by providing adjustable, personalized resistance.[190] Randomized trials further highlighted the superior adaptability and precision of robotic systems like SMA® compared to traditional gait training.[202]

FoG

Assistive robotic systems, such as robot-assisted treadmill training, show promise in managing FoG symptoms in people with PD. For instance, a pilot study demonstrated that repetitive robot-assisted treadmill training reduced the occurrence.[209] Moreover, the sustained benefits of such technology have been observed in a study focusing on the long-term effects of robot-assisted treadmill walking. Over extended use, this modality has demonstrated a capacity to reduce the severity and frequency of FoG in people with PD.[207] Expanding the scope of intervention, an overground robot-assisted gait trainer has been evaluated for its efficacy in treating drug-resistant FoG in PD. This innovative system allows for more naturalistic walking scenarios, which can be particularly beneficial for patients who experience FoG in real-world environments.[208]

Balance

The domain of balance rehabilitation has been greatly enriched by the introduction of assistive robotic systems, which have proven to be an asset across a spectrum of neurodegenerative conditions. In a previous work, tongue electro-tactile biofeedback used the tongue's sensitivity to deliver real-time posture correction signals to advance balance rehabilitation therapy.[210] The use of vibro-tactile biofeedback for trunk sway is another novel approach that has shown characteristics of improvement in balance control among people with MS. By delivering sensory cues about body sway, this method helps patients adjust their posture to enhancing stability and reduce the risk of falls.[211]

High-intensity robot-assisted gait training was evaluated for its impact on dynamic balance and aerobic capacity in SS, and benefits for both mobility and cardiovascular health were reported.[216] Evidence from robot-assisted axial rotations provides insights into the early balance impairments in PD, suggesting that robotic systems can detect and potentially remediate balance issues before they become clinically apparent.[255] A study on hemiparetic SS compared robotic balance training (BEAR) with intensive balance training and conventional rehabilitation. The BEAR group, utilizing robotic technology, demonstrated significant improvements in balance assessed by Mini-BESTest scores.[217]

Group 6

Gait Disturbances

Feedback mechanisms (positive and corrective feedback, interactive rhythmic cues) are pivotal in providing real-time insights and adjustments to gait patterns, contributing to notable improvements stability and overall mobility.[35,169,213,256] A significant amount of research supports the effectiveness of these methods. Examples include a study that combined IMU and Google Glass to deliver visual and auditory cues for gait assistance, using flashing lights, optic flow, and metronome sounds. Results showed a clinical preference for auditory over visual cues.[230] Another study investigated the impact of walking to music and metronomes on MS, using IMUs and headphones to explore auditory-motor coupling. With IMUs on the ankles measuring cadence and step time, findings highlighted the effectiveness of music in enhancing gait characteristics.[113] A study combined IMUs and video-based wearable glasses to enhance fall risk assessment, with IMUs capturing gait data and glasses providing environmental context. Integrating both technologies offered a more comprehensive evaluation.[257]

Previous research has explored use of exoskeletons and wearables to enhance gait retraining and monitor improvements. In people with PD, overground gait training with a wearable Active Pelvis Orthosis (APO) exoskeleton and IMUs were evaluated. The APO adjusted gait in real time, while IMUs tracked dynamics. Training improved hip motion, gait speed, and stride, with effects lasting one month, though gait variability normalized only immediately post-training.[36] In a different study on the Keeogo™ exoskeleton for MS patients, researchers used a powered exoskeleton, IMUs, and an Actigraph™ to assess its effects. While gait performance slightly declined when wearing the device, unassisted performance significantly improved after two weeks of home use.[114] Additionally, the "WalkMate" system, incorporating pressure sensors and headphones, was used to deliver interactive rhythmic cues for gait retraining in people with PD. Those cues gradually but effectively reduced gait fluctuations.[228]

Balance

A telerehabilitation study used smartphone-based IMUs and exergames for balance training in early subacute SS. IMUs tracked movements, and exergames provided feedback, leading to improved balance and functional independence compared to conventional treatment.[237] Elsewhere, researchers used foot-mounted IMUs and headphones to study auditory input effects on gait stability in people with PD, with and without FoG. Those with FoG showed the most stable gait with continuous cueing, while non-FoG individuals showed no significant differences across conditions.[231] Alternatively, a vibrotactile biofeedback device with used with a Nintendo Wii Balance Board for balance training in chronic SS. The device provided vibration cues to improve postural control, while the Wii Board tracked CoP patterns, resulting in reduced postural variability and improved clinical balance performance.[220]

Discussion

The search findings reveal that wearables are playing a growing role in motor rehabilitation, with gait disturbances and balance recovery being the most studied areas. Interactive technologies, (VR and AR), were the most frequently used, particularly for gait and balance recovery. Wearable assistive robotic systems were the most favoured technology for tremor treatment. PD and SS were the most studied cohorts, while conditions like MS and TBI received less attention. All key findings from the literature search are presented in Box 1.

Effectiveness

Studies such as those focusing on balance exercises,[222] and gait training[127,225] highlight the effectiveness of wearables in delivering targeted and data-driven rehabilitation. Those approaches have demonstrated clear benefits in improving the quality of life for individuals with movement disorders.[34,110] For instance, notable improvements in gait parameters[221] and enhanced motor performance in high-intensity gait training[225] compared to other methods reveal the potential of personalized, real-time monitored interventions to address specific deficits in PD. However, this is not always effective. A previous work that utilised Gamepad system led to significant improvements in balance but showed no progress in gait outcomes.[109] This contrast suggests that while physical training can lead to progress, some complex and highly coordinated movements may not improve. Furthermore, the persistence of any longitudinal improvements is not well documented.[36,217] This indicates that future studies should need for follow-up assessments to confirm long-term outcomes.

Music and Rhythm Therapy

The diversity in intervention designs and wearable applications underscores the complexity of effectively deploying these technologies across neurological conditions. However, many PD-based studies demonstrate how wearables can enable precise and targeted rehabilitation. For instance, interventions such as music-based gait training[35,110,126,228] and cueing/feedback training[231] leverage wearables to manage and enhance motor performance in that cohort. Those technologies

Box 1 Key findings

Inertial sensors, pressure sensing, and EMG are widely used in rehabilitation studies as they offer a cost-effective way to monitor and enhance rehabilitation.
VR, AR and robotic systems are effective for gait and balance recovery, while robotic systems are also preferred for tremor treatment.
AR and exergames improve dual-tasking, gait, and balance, though further research is needed to optimize their use.
Auditory feedback most useful in gait retraining whereas visual feedback found most useful in balance.
Personalisation of audio-visual cues via AI enhance engagement, adherence, and lasting improvements while catering to diverse preferences.
Wearable-based interventions show promise for short-term health and mobility improvements, but evidence for sustained long-term benefits is still limited.
Complex motor skills like turning may be harder to improve through practice or rehabilitation compared to other tasks like walking or balance.

facilitate real-time tracking of gait parameters, such as speed, stride length, and variability, while enabling rhythmic auditory feedback, which has been shown to improve motor symmetry, coordination, and arm swing range of motion.[35] Wearables play a key role in delivering rhythmic auditory cues, such as music or metronomes, with music-based cues often preferred for their engaging nature, which promotes adherence to therapy.[232] That approach does extends beyond PD, as demonstrated in SS[113] and people with MS,[113] where music-based gait training reduced movement execution duration, improved movement precision, and supported task-oriented motor training.

Additionally, the use of time-stretching technology in wearables enables personalized auditory cueing by adjusting music tempo to match individual motor capabilities without altering pitch.[110] Studies comparing rhythmic auditory and visual cueing[230] further reinforce the effectiveness of auditory cues, as they tend to produce greater improvements. These advancements highlight the versatility of wearables in integrating real-time feedback and personalized interventions to address motor impairments across a range of neurological disorders.

Virtual and Remote Rehabilitation

Studies focusing on rehabilitation using VR-AR collectively highlight the nuanced effectiveness of such technologies in enhancing motor function, balance, and overall physical activity, albeit with varying degrees of success and application specificity.[155] Biofeedback training[109] and VR-based interventions[172,183,235] have shown significant improvements in balance and motor function, emphasizing the potential of real-time feedback and immersive environments to augment traditional rehabilitation. Particularly, VR-based telerehabilitation for SS[172] mirrored the efficacy of in-clinic interventions. The application of AR and exergames presents an innovative approach to address dual-task declines associated with PD while enhancing balance, albeit with mixed outcomes regarding the significance of improvements in motor outcome measures.[32,236,237] This suggests a potential area for further exploration, particularly in understanding the contexts in which AR and exergames yield the most benefit. Interestingly, the efficacy of interventions often correlated with the specificity of the technology to the rehabilitation goal, as seen in the smartphone-delivered automated feedback training[108] which was both feasible and effective for promoting gait training in PD.

Conversely, telerehabilitation (remote) interventions,[233,237,238] have expanded the accessibility of rehabilitation services. These technologies contribute to accessibility by reducing the need for in-person visits, enabling people to receive therapy from the comfort of their homes, which is particularly beneficial to those in remote or underserved areas. Moreover, they offer a cost-effective alternative to traditional rehabilitation by minimizing travel expenses, reducing clinic overheads, and enabling scalable delivery of personalized care, ultimately making rehabilitation more inclusive and sustainable for a broader population.[258]

Exoskeletons for Rehabilitation

Exoskeletons have shown varied efficacy in neurological rehabilitation, with improvements reported in gait parameters, balance, and mobility across conditions like stroke, CP, PD, MS, and SCI.[199–203,239] However, while studies in stroke highlight enhanced brain activation and functional mobility, the reliance on exoskeletons for restoring gait function raises questions about the sustainability of these gains without continued use. For CP, the results suggest non-invasive alternatives to invasive procedures, yet the long-term impact on motor function remains underexplored. In PD, improvements in range of motion and stride length are promising,[36,192] but evidence of durable outcomes beyond short-term interventions is limited. Despite advancements in unassisted mobility for SCI and MS,[114,193] the high cost, accessibility, and adaptability of exoskeletons pose significant barriers to widespread adoption. These challenges highlight the need for a thorough evaluation of their long-term effectiveness and practicality in everyday settings.

Increasing Adherence: Personalisation

The concept of personalizing content within wearables, especially through VR environments and music selections, offers a promising avenue to enhance user engagement and adherence, particularly.[259] This strategy not only leverages the intrinsic motivation and emotional engagement elicited by personalized experiences[227] but also extends to extrinsic factors, where intervention methods are tailored to fit the unique physiological conditions of the individual.[260,261] For example, personalization in gait retraining may include the use of biofeedback techniques, which adjust critical aspects of the patient's walking pattern, such as cadence or gait speed and provide real-time data that allows patients to make immediate adjustments.[262]

Music-based interventions that cater to individual musical preferences have been shown to improve gait and mobility in people with PD.[35] Furthermore, personalized VR environments that reflect users' interests or past experiences can potentially increase adherence to rehabilitation protocols by creating a more immersive and enjoyable therapeutic experiences. While direct evidence is limited, the principle of personalization increasing adherence is supported by broader research in digital health interventions.[263] Nevertheless, personalization poses challenges, such as variability in preferences and the need for extensive content libraries, increasing cost and complexity. Additionally, users with cognitive impairments or limited tech skills may find personalized options overwhelming.

The limitations of personalization could be addressed through AI by utilizing data from sensors, user feedback, and performance metrics to develop adaptive and tailored rehabilitation plans, ensuring effectiveness and usability.[263] AI-driven VR and AR systems can modify therapeutic tasks to align with an individual's pace and capabilities. One approach involves dynamically adjusting task difficulty and providing real-time feedback through a smartphone-based VR app so that therapists can customize cognitive and social rehabilitation programs to match the specific need of each patient.[264] Similarly, AI-driven VR systems can use advanced motion-tracking technology to monitor a user's three-dimensional movement, allowing them to evaluate the quality of exercises and support adherence to personalized rehabilitation programs.[265] Additionally, wearable data, combined with AI, can classify body movements with high accuracy and this could enable therapists to track progress and adjust interventions in real-time.[266]

Limitations of Current Literature

Protocols vary significantly across studies, with intervention durations ranging from a single session[35,239] to programs spanning several months.[227] This variability makes direct comparisons challenging and may affect the sustainability of the intervention's benefits. Short-term interventions might not capture long-term outcomes, whereas longer interventions may better reflect sustained effects but are more challenging to standardize and control. In terms of methodological robustness, most studies adopted a randomized controlled trial format. However, some limitations are present, such as the relatively small sample sizes in certain studies[240] (eg, with 7 CP patients) and the absence of long-term follow-up data. That underscores the need for larger-scale studies and extended monitoring to fully comprehend the long-term implications of wearables in rehabilitation. Moreover, the majority of studies did not consider age matching during recruitment, which could introduce bias, especially when interventions target conditions prevalent in older populations.[267] Finally, repeated exposure to interventions, especially those involving physical activity or cognitive engagement (eg, AR-VR), could lead to adaptation or learning effects that confound true treatment effects.

Conclusion

Wearables are revolutionizing motor rehabilitation by aiding precise, data-driven, and personalized interventions for individuals with movement disorders. These technologies have shown significant effectiveness in improving motor function, particularly gait, balance, and coordination, across neurological populations. Wearables enable tailored rehabilitation programs that address individual needs by integrating real-time biofeedback, rhythm-based therapies, and biomechanical systems. Their versatility spans both clinical and remote settings, with telerehabilitation expanding access to care for underserved populations and reducing barriers such as travel and clinic availability. Additionally, features like personalized auditory and visual cues, as well as adaptive AI-driven systems, further enhance engagement and adherence to wearable-based therapy. However, challenges remain in achieving sustained long-term outcomes, refining personalization to meet diverse user needs, and addressing issues of cost, accessibility, and usability. Despite some limitations, the growing body of evidence highlights the transformative potential of wearables to improve motor function, promote independence, and enhance the quality of life for individuals with movement disorders.

Funding

CW and JM are co-funded by a grant from the National Institute of Health Research (NIHR) Applied Research Collaboration (ARC) Northeast and North Cumbria (NENC) in the UK. CW and JM are also co-funded by the Faculty of Environment and Engineering at Northumbria University.

Disclosure

The author(s) report no conflicts of interest in this work.

References

1. Kompoliti K, Verhagen L. *Encyclopedia of Movement Disorders*. Vol. 1. Academic Press; 2010.
2. Shipton EA. Movement disorders and neuromodulation. *Neurol Res Int*. 2012;2012:1–8. doi:10.1155/2012/309431
3. Battista L, Romaniello A. A wearable tool for continuous monitoring of movement disorders: clinical assessment and comparison with tremor scores. *Neurol Sci*. 2021;1–8.
4. Pistacchi M, Gioulis M, Sanson F, et al. Gait analysis and clinical correlations in early Parkinson's disease. *Funct Neurol*. 2017;32(1):28. doi:10.11138/FNeur/2017.32.1.028
5. Mirelman A, Bonato P, Camicioli R, et al. Gait impairments in Parkinson's disease. *Lancet Neurol*. 2019;18:697–708. doi:10.1016/S1474-4422(19)30044-4
6. James SL, Lucchesi LR, Bisignano C, et al. The global burden of falls: global, regional and national estimates of morbidity and mortality from the Global Burden of Disease Study 2017. *Inj Prev*. 2020;26(Supp 1):i3–i11. doi:10.1136/injuryprev-2019-043286
7. Nouredanesh M, Godfrey A, Howcroft J, Lemaire ED, Tung J. Fall risk assessment in the wild: a critical examination of wearable sensors use in free-living conditions. *Gait Posture*. 2020 doi:10.1016/j.gaitpost.2020.04.010
8. Celik Y, Stuart S, Woo WL, Godfrey A. Gait analysis in neurological populations: progression in the use of wearables. *Med Eng Phys*. 2020 doi:10.1016/j.medengphy.2020.11.005
9. Kurtzke JF. Rating neurologic impairment in multiple sclerosis: an expanded disability status scale (EDSS). *Neurology*. 1983;33(11):1444. doi:10.1212/WNL.33.11.1444
10. Bogle Thorbahn LD, Newton RA. Use of the Berg Balance Test to predict falls in elderly persons. *Phys Therapy*. 1996;76(6):576–583. doi:10.1093/ptj/76.6.576
11. Ali SM, Arjunan SP, Peters J, et al. Wearable accelerometer and gyroscope sensors for estimating the severity of essential tremor. *IEEE Journal of Translational Engineering in Health and Medicine*. 2023.
12. San-Segundo R, Zhang A, Cebulla A, et al. Parkinson's disease tremor detection in the wild using wearable accelerometers. *Sensors*. 2020;20(20):5817. doi:10.3390/s20205817
13. Summa S, Tosi J, Taffoni F, et al. Assessing bradykinesia in Parkinson's disease using gyroscope signals. *IEEE Int Conf Rehabil Robot*. 2017;2017:1556–1561. doi:10.1109/ICORR.2017.8009469
14. Gallego JA, Rocon E, Roa JO, Moreno JC, Pons JL. Real-time estimation of pathological tremor parameters from gyroscope data. *Sensors*. 2010;10(3):2129–2149. doi:10.3390/s100302129
15. Zhao S. Flexible sensor matrix film-based wearable plantar pressure force measurement and analysis system. *PLoS One*. 2020;15.
16. Deligianni F, Wong C, Lo B, Yang G-Z. A fusion framework to estimate plantar ground force distributions and ankle dynamics. *Information Fusion*. 2018;41:255–263. doi:10.1016/j.inffus.2017.09.008
17. Aqueveque P, Germany E, Osorio R, Pastene F. Gait segmentation method using a Plantar pressure measurement system with custom-made capacitive sensors. *Sensors*. 2020;20(3):656. doi:10.3390/s20030656
18. Shu L, Hua T, Wang Y, Li Q, Feng DD, Tao X. In-shoe plantar pressure measurement and analysis system based on fabric pressure sensing array. *IEEE Transactions Inf Technol Biomed*. 2010;14(3):767–775. doi:10.1109/TITB.2009.2038904
19. Abd Ghani H, Alghwiri AA, Hisham H, Manaf H. Lower limb muscle fatigue alters spatiotemporal gait parameters and turning difficulty characteristics in Parkinson's Disease. *Ann Rehabil Med*. 2023;47(4):282. doi:10.5535/arm.23067
20. Yokote A, Hayashi Y, Yanamoto S, Fujioka S, Higa K, Tsuboi Y. Leg muscle strength correlates with gait performance in advanced Parkinson disease. *Int Med*. 2022;61(5):633–638. doi:10.2169/internalmedicine.7646-21
21. Zhao A, Li J, Dong J, et al. Multimodal gait recognition for neurodegenerative diseases. *IEEE Trans Cybernetics*. 2021;52(9):9439–9453. doi:10.1109/TCYB.2021.3056104
22. Nweke HF, Teh YW, Mujtaba G, Al-Garadi MA. Data fusion and multiple classifier systems for human activity detection and health monitoring: review and open research directions. *Inf Fusion*. 2019;46:147–170. doi:10.1016/j.inffus.2018.06.002
23. Castelli Gattinara Di Zubiena F, Menna G, Mileti I, et al. Machine learning and wearable sensors for the early detection of balance disorders in Parkinson's Disease. *Sensors*. 2022;22(24):9903. doi:10.3390/s22249903
24. Greene BR, Rutledge S, McGurgan I, et al. Assessment and classification of early-stage multiple sclerosis with inertial sensors: comparison against clinical measures of disease state. *IEEE J Biomed Health Inform*. 2015;19(4):1356–1361. doi:10.1109/JBHI.2015.2435057
25. Lin S, Gao C, Li H, et al. Wearable sensor-based gait analysis to discriminate early Parkinson's disease from essential tremor. *J Neurol*. 2023;270(4):2283–2301. doi:10.1007/s00415-023-11577-6
26. Pardoel S, Shalin G, Nantel J, Lemaire ED, Kofman J. Early detection of freezing of gait during walking using inertial measurement unit and plantar pressure distribution data. *Sensors*. 2021;21(6):2246. doi:10.3390/s21062246
27. Abate F, Russo M, Ricciardi C, et al. Wearable sensors for assessing disease severity and progression in Progressive Supranuclear Palsy. *Parkinsonism Related Disord*. 2023;109:105345. doi:10.1016/j.parkreldis.2023.105345
28. Filli L, Sutter T, Easthope CS, et al. Profiling walking dysfunction in multiple sclerosis: characterisation, classification and progression over time. *Sci Rep*. 2018;8(1):1–13. doi:10.1038/s41598-018-22676-0

29. Mancini M, Horak FB. Potential of APDM mobility lab for the monitoring of the progression of Parkinson's disease. *Expert Rev Med Devices*. 2016;13(5):455–462. doi:10.1586/17434440.2016.1153421
30. Akinci M, Burak M, Kasal FZ, Özaslan EA, Huri M, Kurtaran ZA. The effects of combined virtual reality exercises and robot assisted gait training on cognitive functions, daily living activities, and quality of life in high functioning individuals with subacute stroke. *Perceptual Motor Skills*. 2024;00315125241235420.
31. Yamagami M, Imsdahl S, Lindgren K, et al. Effects of virtual reality environments on overground walking in people with Parkinson disease and freezing of gait. *Disabil Rehabil*. 2023;18(3):266–273. doi:10.1080/17483107.2020.1842920
32. Tunur T, DeBlois A, Yates-Horton E, Rickford K, Columna LA. Augmented reality-based dance intervention for individuals with Parkinson's disease: a pilot study. *Disability Health J*. 2020;13(2):100848. doi:10.1016/j.dhjo.2019.100848
33. Yen C-Y, Lin K-H, Hu M-H, Wu R-M, Lu T-W, Lin C-H. 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 Therapy*. 2011;91(6):862–874. doi:10.2522/ptj.20100050
34. Zajac JA, Porciuncula F, Cavanaugh JT, et al.Feasibility and proof-of-concept of delivering an autonomous music-based digital walking intervention to persons with Parkinson's disease in a naturalistic setting. *J Parkinsons Dis*. 2023;(Preprint):1–13. doi:10.3233/JPD-229011
35. Mainka S, Schroll A, Warmerdam E, Gandor F, Maetzler W, Ebersbach G. The power of musification: sensor-based music feedback improves arm swing in Parkinson's disease. *Mov Disord Clin Pract*. 2021;8(8):1240–1247. doi:10.1002/mdc3.13352
36. Otlet V, Vandamme C, Warlop T, Crevecoeur F, Ronsse R. Effects of overground gait training assisted by a wearable exoskeleton in patients with Parkinson's disease. *J Neuroeng Rehabil*. 2023;20(1):156. doi:10.1186/s12984-023-01280-y
37. Sarkisian SV, Gunnell AJ, Foreman KB, Lenzi T. Knee exoskeleton reduces muscle effort and improves balance during sit-to-stand transitions after stroke: a case study. *IEEE*. 2022:1–6.
38. Koenig A, Novak D, Omlin X, et al. Real-time closed-loop control of cognitive load in neurological patients during robot-assisted gait training. *IEEE Trans Neural Syst Rehabil Eng*. 2011;19(4):453–464. doi:10.1109/TNSRE.2011.2160460
39. Jalloul N. Wearable sensors for the monitoring of movement disorders. *Biomedical Journal*. 2018;41(4):249–253. doi:10.1016/j.bj.2018.06.003
40. Vanmechelen I, Haberfehlner H, De Vleeschhauwer J, et al. Assessment of movement disorders using wearable sensors during upper limb tasks: a scoping review. *Front Rob AI*. 2023;9:1068413. doi:10.3389/frobt.2022.1068413
41. Maetzler W, Domingos J, Srulijes K, Ferreira JJ, Bloem BR. Quantitative wearable sensors for objective assessment of Parkinson's disease. *Mov Disord*. 2013;28(12):1628–1637. doi:10.1002/mds.25628
42. Adams JL, Lizarraga KJ, Waddell EM, et al. Digital technology in movement disorders: updates, applications, and challenges. *Curr Neurol Neurosci Rep*. 2021;21:1–11. doi:10.1007/s11910-021-01101-6
43. Lu R, Xu Y, Li X, et al. Evaluation of wearable sensor devices in Parkinson's disease: a review of current status and future prospects. *Parkinson's Dis*. 2020;2020(1):4693019. doi:10.1155/2020/4693019
44. Chen S, Lach J, Lo B, Yang G-Z. Toward pervasive gait analysis with wearable sensors: a systematic review. *IEEE J Biomed Health Inform*. 2016;20(6):1521–1537. doi:10.1109/JBHI.2016.2608720
45. Jarchi D, Pope J, Lee TK, Tamjidi L, Mirzaei A, Sanei S. A review on accelerometry-based gait analysis and emerging clinical applications. *IEEE Rev Biomed Eng*. 2018;11:177–194. doi:10.1109/RBME.2018.2807182
46. Chinmilli P, Redkar S, Zhang W, Sugar T. A review on wearable inertial tracking based human gait analysis and control strategies of lower-limb exoskeletons. *Int Robot Autom J*. 2017;3(7):00080.
47. Rast FM, Labruyère R. Systematic review on the application of wearable inertial sensors to quantify everyday life motor activity in people with mobility impairments. *J Neuroeng Rehabil*. 2020;17(1):1–19. doi:10.1186/s12984-020-00779-y
48. Giggins OM, Clay I, Walsh L. Physical activity monitoring in patients with neurological disorders: a review of novel body-worn devices. *Digital Biomarkers*. 2017;1(1):14–42. doi:10.1159/000477384
49. Block VA, Pitsch E, Tahir P, Cree BA, Allen DD, Gelfand JM. Remote physical activity monitoring in neurological disease: a systematic review. *PLoS One*. 2016;11(4):e0154335.
50. Hubble RP, Naughton GA, Silburn PA, Cole MH. Wearable sensor use for assessing standing balance and walking stability in people with Parkinson's disease: a systematic review. *PLoS One*. 2015;10(4):e0123705. doi:10.1371/journal.pone.0123705
51. Porciuncula F, Roto AV, Kumar D, et al. Wearable movement sensors for rehabilitation: a focused review of technological and clinical advances. *Pm&r*. 2018;10(9):S220–S232. doi:10.1016/j.pmrj.2018.06.013
52. Patel S, Park H, Bonato P, Chan L, Rodgers M. A review of wearable sensors and systems with application in rehabilitation. *J Neuroeng Rehabil*. 2012;9:1–17. doi:10.1186/1743-0003-9-21
53. Shokri S, Ward S, Anton P-AM, Siffredi P, Papetti G. Recent advances in wearable sensors with application in rehabilitation motion analysis. *arXiv preprint arXiv:200906062*. 2020.
54. Wang Q, Markopoulos P, Yu B, Chen W, Timmermans A. Interactive wearable systems for upper body rehabilitation: a systematic review. *J Neuroeng Rehabil*. 2017;14:1–21. doi:10.1186/s12984-017-0229-y
55. Dos Santos Delabary M, Komeroski IG, Monteiro EP, Costa RR, Haas AN. Effects of dance practice on functional mobility, motor symptoms and quality of life in people with Parkinson's disease: a systematic review with meta-analysis. *Aging Clin Exp Res*. 2018;30:727–735. doi:10.1007/s40520-017-0836-2
56. Ghai S, Ghai I, Schmitz G, Effenberg AO. Effect of rhythmic auditory cueing on parkinsonian gait: a systematic review and meta-analysis. *Sci Rep*. 2018;8(1):506. doi:10.1038/s41598-017-16232-5
57. Scataglini S, Van Dyck Z, Declercq V, Van cleemput G, Struyf N, Truijen S. Effect of music based therapy rhythmic auditory stimulation (RAS) using wearable device in rehabilitation of neurological patients: a systematic review. *Sensors*. 2023;23(13):5933. doi:10.3390/s23135933
58. Truijen S, Abdullahi A, Bijsterbosch D, et al. Effect of home-based virtual reality training and telerehabilitation on balance in individuals with Parkinson disease, multiple sclerosis, and stroke: a systematic review and meta-analysis. *Neurol Sci*. 2022;43(5):2995–3006. doi:10.1007/s10072-021-05855-2
59. Kearney E, Shellikeri S, Martino R, Yunusova Y. Augmented visual feedback-aided interventions for motor rehabilitation in Parkinson's disease: a systematic review. *Disability Rehabil*. 2019;41(9):995–1011. doi:10.1080/09638288.2017.1419292

60. Rodríguez-Fernández A, Lobo-Prat J, Font-Llagunes JM. Systematic review on wearable lower-limb exoskeletons for gait training in neuromuscular impairments. *J Neuroeng Rehabil*. 2021;18(1):22. doi:10.1186/s12984-021-00815-5
61. Kim C, Kim H-J. Effect of robot-assisted wearable exoskeleton on gait speed of post-stroke patients: a systematic review and meta-analysis of a randomized controlled trials. *Phys Ther Rehabil Sci*. 2022;11(4):471–477. doi:10.14474/ptrs.2022.11.4.471
62. Ataullah A, De Jesus O Gait disturbances. 2020.
63. Balaban B, Tok F. Gait disturbances in patients with stroke. *PM&R*. 2014;6(7):635–642. doi:10.1016/j.pmrj.2013.12.017
64. Snijders AH, Van De Warrenburg BP, Giladi N, Bloem BR. Neurological gait disorders in elderly people: clinical approach and classification. *Lancet Neurol*. 2007;6(1):63–74. doi:10.1016/S1474-4422(06)70678-0
65. Whittle MW. *Gait Analysis: An Introduction*. Butterworth-Heinemann; 2014.
66. Williams G, Morris ME, Schache A, McCrory PR. Incidence of gait abnormalities after traumatic brain injury. *Arch Phys Med Rehabil*. 2009;90 (4):587–593. doi:10.1016/j.apmr.2008.10.013
67. Pirker W, Katzenschlager R. Gait disorders in adults and the elderly. *Wiener Klinische Wochenschrift*. 2017;129(3):81–95. doi:10.1007/s00508-016-1096-4
68. Schlachetzki JC, Barth J, Marxreiter F, et al. Wearable sensors objectively measure gait parameters in Parkinson's disease. *PLoS One*. 2017;12 (10):e0183989. doi:10.1371/journal.pone.0183989
69. Hulleck AA, Menoth Mohan D, Abdallah N, El Rich M, Khalaf K. Present and future of gait assessment in clinical practice: towards the application of novel trends and technologies. *Front Med Technol*. 2022;4:901331. doi:10.3389/fmedt.2022.901331
70. Van Criekinge T, Saeys W, Hallemans A, et al. Trunk biomechanics during hemiplegic gait after stroke: a systematic review. *Gait Posture*. 2017;54:133–143. doi:10.1016/j.gaitpost.2017.03.004
71. Galli M, Cimolin V, Rigoldi C, Tenore N, Albertini G. Gait patterns in hemiplegic children with cerebral palsy: comparison of right and left hemiplegia. *Res Dev Disabilities*. 2010;31(6):1340–1345. doi:10.1016/j.ridd.2010.07.007
72. Li S, Francisco GE, Zhou P. Post-stroke hemiplegic gait: new perspective and insights. *Front Physiol*. 2018;9:389766. doi:10.3389/fphys.2018.01021
73. Celik Y, Stuart S, Woo WL, Sejdic E, Godfrey A. Multi-modal gait: a wearable, algorithm and data fusion approach for clinical and free-living assessment. *Information Fusion*. 2022;78:57–70. doi:10.1016/j.inffus.2021.09.016
74. Lefeber N, Degelaen M, Truyers C, Safin I, Beckwée D. Validity and reproducibility of inertial physilog sensors for spatiotemporal gait analysis in patients with stroke. *IEEE Trans Neural Syst Rehabil Eng*. 2019;27(9):1865–1874. doi:10.1109/TNSRE.2019.2930751
75. Chang H-C, Hsu Y-L, Yang S-C, Lin J-C, Wu Z-H. A wearable inertial measurement system with complementary filter for gait analysis of patients with stroke or Parkinson's disease. *IEEE Access*. 2016;4:8442–8453. doi:10.1109/ACCESS.2016.2633304
76. Boudarham J, Roche N, Pradon D, Bonnyaud C, Bensmail D, Zory R. Variations in kinematics during clinical gait analysis in stroke patients. *PLoS One*. 2013;8(6):e66421. doi:10.1371/journal.pone.0066421
77. Kim J-S, Kwon O-H. The effect of arm swing on gait in post-stroke hemiparesis. *J Korean Soc Phys Med*. 2012;7(1):95–101. doi:10.13066/kspm.2012.7.1.095
78. Marquer A, Barbieri G, Pérennou D. The assessment and treatment of postural disorders in cerebellar ataxia: a systematic review. *Ann Phys Rehabil Med*. 2014;57(2):67–78. doi:10.1016/j.rehab.2014.01.002
79. Stolze H, Klebe S, Petersen G, et al. Typical features of cerebellar ataxic gait. *J Neurol Neurosurg*. 2002;73(3):310–312. doi:10.1136/jnnp.73.3.310
80. Schniepp R, Wuehr M, Schlick C, et al. Increased gait variability is associated with the history of falls in patients with cerebellar ataxia. *J Neurol*. 2014;261:213–223. doi:10.1007/s00415-013-7189-3
81. Buckley E, Mazzà C, McNeill A. A systematic review of the gait characteristics associated with Cerebellar Ataxia. *Gait Posture*. 2018;60:154–163. doi:10.1016/j.gaitpost.2017.11.024
82. Erdeo F, Salci Y, Ali UU, Armutlu K. Examination of the effects of coordination and balance problems on gait in ataxic multiple sclerosis patients. *Neurosci J*. 2019;24(4):269–277. doi:10.17712/nsj.2019.4.20190038
83. Nutt JG, Bloem BR, Giladi N, Hallett M, Horak FB, Nieuwboer A. Freezing of gait: moving forward on a mysterious clinical phenomenon. *Lancet Neurol*. 2011;10(8):734–744. doi:10.1016/S1474-4422(11)70143-0
84. Moore ST, MacDougall HG, Ondo WG. Ambulatory monitoring of freezing of gait in Parkinson's disease. *J Neurosci Methods*. 2008;167 (2):340–348. doi:10.1016/j.jneumeth.2007.08.023
85. Nieuwboer A, Giladi N. Characterizing freezing of gait in Parkinson's disease: models of an episodic phenomenon. *Mov Disord*. 2013;28 (11):1509–1519. doi:10.1002/mds.25683
86. Factor SA. The clinical spectrum of freezing of gait in atypical parkinsonism. *Mov Disord*. 2008;23(S2):S431–S438. doi:10.1002/mds.21849
87. Singer HS, Mink JW, Gilbert DL, Jankovic J. *Movement Disorders in Childhood*. Academic press; 2015.
88. Samaee S, Kobravi HR. Predicting the occurrence of wrist tremor based on electromyography using a hidden Markov model and entropy based learning algorithm. *Biomed Signal Process Control*. 2020;57:101739. doi:10.1016/j.bspc.2019.101739
89. Rudzińska M, Krawczyk M, Wójcik-Pędziwiatr M, Szczudlik A, Tomaszewski T. Tremor in neurodegenerative ataxias, Huntington disease and tic disorder. *Neurologia i Neurochirurgia Polska*. 2013;47(3):232–240. doi:10.5114/ninp.2013.35585
90. Rigas G, Tzallas AT, Tsipouras MG, et al. Assessment of tremor activity in the Parkinson's disease using a set of wearable sensors. *IEEE Transactions Inf Technol Biomed*. 2012;16(3):478–487. doi:10.1109/TITB.2011.2182616
91. Liu S, Yuan H, Liu J, Lin H, Yang C, Cai X. Comprehensive analysis of resting tremor based on acceleration signals of patients with Parkinson's disease. *Technol Health Care*. 2022;30(4):895–907. doi:10.3233/THC-213205
92. Lenka A, Jankovic J. Tremor syndromes: an updated review. *Front Neurol*. 2021;12:684835. doi:10.3389/fneur.2021.684835
93. Elble R. *Accelerometry. Encyclopedia of Movement Disorders*. CA, USA: Academic Press; 2010.
94. Harrison MJ. *Contemporary Neurology.* Butterworth-Heinemann; 2013.
95. Jeon H, Lee W, Park H, et al. Automatic classification of tremor severity in Parkinson's disease using a wearable device. *Sensors*. 2017;17 (9):2067. doi:10.3390/s17092067
96. López-Blanco R, Velasco MA, Méndez-Guerrero A, et al. Smartwatch for the analysis of rest tremor in patients with Parkinson's disease. *J Neurol Sci*. 2019;401:37–42. doi:10.1016/j.jns.2019.04.011

97. Kalaiarasi A, Kumar LA. Sensor based portable tremor suppression device for stroke patients. *Acupunct Electro-Therap Res*. 2018;43(1):29–37. doi:10.3727/036012918X15202760634923
98. Mahadevan N, Demanuele C, Zhang H, et al. Development of digital biomarkers for resting tremor and bradykinesia using a wrist-worn wearable device. *Npj Digital Med*. 2020;3(1):5. doi:10.1038/s41746-019-0217-7
99. Campbell AH, Barta K, Sawtelle M, Walters A. Progressive muscle relaxation, meditation, and mental practice-based interventions for the treatment of tremor after traumatic brain injury. *Physiother Theory Pract*. 2023;1–17.
100. Motl RW, Sandroff BM, Sosnoff JJ. Commercially available accelerometry as an ecologically valid measure of ambulation in individuals with multiple sclerosis. *Expert Rev Neurotherapeutics*. 2012;12(9):1079–1088. doi:10.1586/ern.12.74
101. Viswanathan A, Sudarsky L. Balance and gait problems in the elderly. *Handbook Clin Neurol*. 2012;103:623–634.
102. Müller J, Ebersbach G, Wissel J, Brenneis C, Badry L, Poewe W. Disturbances of dynamic balance in phasic cervical dystonia. *J Neurol Neurosurg*. 1999;67(6):807–810. doi:10.1136/jnnp.67.6.807
103. Salzman B. Gait and balance disorders in older adults. *Am Family Phys*. 2010;82(1):61–68.
104. Eftekharsadat B, Babaei-Ghazani A, Mohammadzadeh M, Talebi M, Eslamian F, Azari E. Effect of virtual reality-based balance training in multiple sclerosis. *Neurological Res*. 2015;37(6):539–544. doi:10.1179/1743132815Y.0000000013
105. Appeadu MK, Gupta V. Postural Instability. 2020.
106. Fallahtafti F, Bruijn S, Mohammadzadeh Gonabadi A, et al. Trunk velocity changes in response to physical perturbations are potential indicators of gait stability. *Sensors*. 2023;23(5):2833. doi:10.3390/s23052833
107. Page MJ, McKenzie JE, Bossuyt PM, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ*. 2021;372.
108. Ginis P, Nieuwboer A, Dorfman M, et al. Feasibility and effects of home-based smartphone-delivered automated feedback training for gait in people with Parkinson's disease: a pilot randomized controlled trial. *Parkinsonism Related Disord*. 2016;22:28–34. doi:10.1016/j.parkreldis.2015.11.004
109. Carpinella I, Cattaneo D, Bonora G, et al. Wearable sensor-based biofeedback training for balance and gait in Parkinson disease: a pilot randomized controlled trial. *Arch Phys Med Rehabil*. 2017;98(4):622–630.e3. doi:10.1016/j.apmr.2016.11.003
110. Cochen De Cock V, Dotov D, Damm L, et al. BeatWalk: personalized music-based gait rehabilitation in Parkinson's disease. *Frontiers in Psychology*. 2021;12:1153. doi:10.3389/fpsyg.2021.655121
111. Aphiphaksakul P, Siriphorn A. Home-based exercise using balance disc and smartphone inclinometer application improves balance and activity of daily living in individuals with stroke: a randomized controlled trial. *PLoS One*. 2022;17(11):e0277870. doi:10.1371/journal.pone.0277870
112. Spain RI, Mancini M, Horak FB, Bourdette D. Body-worn sensors capture variability, but not decline, of gait and balance measures in multiple sclerosis over 18 months. *Gait Posture*. 2014;39(3):958–964. doi:10.1016/j.gaitpost.2013.12.010
113. Moumdjian L, Moens B, Maes P-J, et al. Continuous 12 min walking to music, metronomes and in silence: auditory-motor coupling and its effects on perceived fatigue, motivation and gait in persons with multiple sclerosis. *Mult Scler Relat Disord*. 2019;35:92–99. doi:10.1016/j.msard.2019.07.014
114. McGibbon CA, Sexton A, Jayaraman A, et al. Evaluation of the Keeogo exoskeleton for assisting ambulatory activities in people with multiple sclerosis: an open-label, randomized, cross-over trial. *J Neuroeng Rehabil*. 2018;15:1–14. doi:10.1186/s12984-018-0468-6
115. Samotus O, Lee J, Jog M. Long-term tremor therapy for Parkinson and essential tremor with sensor-guided botulinum toxin type A injections. *PLoS One*. 2017;12(6):e0178670. doi:10.1371/journal.pone.0178670
116. Héroux M, Pari G, Norman K. The effect of inertial loading on wrist kinetic tremor and rhythmic muscle activity in individuals with essential tremor. *Clin Neurophysiol*. 2011;122(9):1794–1801. doi:10.1016/j.clinph.2010.10.050
117. Héroux M, Pari G, Norman K. The effect of inertial loading on wrist postural tremor in essential tremor. *Clin Neurophysiol*. 2009;120(5):1020–1029. doi:10.1016/j.clinph.2009.03.012
118. Isaacson SH, Boroojerdi B, Waln O, et al. Effect of using a wearable device on clinical decision-making and motor symptoms in patients with Parkinson's disease starting transdermal rotigotine patch: a pilot study. *Parkinsonism Related Disord*. 2019;64:132–137. doi:10.1016/j.parkreldis.2019.01.025
119. Edwards CL, Sudhakar S, Scales MT, Applegate KL, Webster W, Dunn RH. Electromyographic (EMG) biofeedback in the comprehensive treatment of central pain and ataxic tremor following thalamic stroke. *Appl Psychophysiol Biofeedback*. 2000;25:229–240. doi:10.1023/A:1026406921765
120. Silva-Batista C, Wilhelm JL, Scanlan KT, et al. Balance telerehabilitation and wearable technology for people with Parkinson's disease (TelePD trial). *BMC Neurol*. 2023;23(1):368. doi:10.1186/s12883-023-03403-3
121. Rocchi L, Palmerini L, Weiss A, Herman T, Hausdorff JM. Balance testing with inertial sensors in patients with Parkinson's disease: assessment of motor subtypes. *IEEE Trans Neural Syst Rehabil Eng*. 2013;22(5):1064–1071. doi:10.1109/TNSRE.2013.2292496
122. An J, Kim J, Lai EC, Lee B-C. Effects of a smartphone-based wearable telerehabilitation system for in-home dynamic weight-shifting balance exercises by individuals with Parkinson's disease. *IEEE*. 2020:5678–5681.
123. Lee B-C, An J, Kim J, Lai EC. Performing dynamic weight-shifting balance exercises with a smartphone-based wearable Telerehabilitation system for home use by individuals with Parkinson's disease: a proof-of-concept study. *IEEE Trans Neural Syst Rehabil Eng*. 2022;31:456–463. doi:10.1109/TNSRE.2022.3226368
124. Lupo A, Giovanni Morone M, Cinnera AM, et al. Effects on balance skills and patient compliance of biofeedback training with inertial measurement units and exergaming in subacute stroke: a pilot randomized controlled trial. *Funct Neurol*. 2018;33(3):131–136.
125. Badke MB, Sherman J, Boyne P, Page S, Dunning K. Tongue-based biofeedback for balance in stroke: results of an 8-week pilot study. *Arch Phys Med Rehabil*. 2011;92(9):1364–1370. doi:10.1016/j.apmr.2011.03.030
126. Erra C, Mileti I, Germanotta M, et al. Immediate effects of rhythmic auditory stimulation on gait kinematics in Parkinson's disease ON/OFF medication. *Clin Neurophysiol*. 2019;130(10):1789–1797. doi:10.1016/j.clinph.2019.07.013
127. Yogev-Seligmann G, Giladi N, Brozgol M, Hausdorff JM. A training program to improve gait while dual tasking in patients with Parkinson's disease: a pilot study. *Arch Phys Med Rehabil*. 2012;93(1):176–181. doi:10.1016/j.apmr.2011.06.005
128. Phuenpathom W, Panyakaew P, Vateekul P, Surangsrirat D, Hiransuthikul A, Bhidayasiri R. Vibratory and plantar pressure stimulation: steps to improve freezing of gait in Parkinson's disease. *Parkinsonism Related Disord*. 2022;105:43–51. doi:10.1016/j.parkreldis.2022.10.024

129. Cho C, Hwang W, Hwang S, Chung Y. Treadmill training with virtual reality improves gait, balance, and muscle strength in children with cerebral palsy. *Tohoku J Exp Med*. 2016;238(3):213–218. doi:10.1620/tjem.238.213
130. Skoutelis VC, Kanellopoulos A, Vrettos S, Gkrimas G, Kontogeorgakos V. Improving gait and lower-limb muscle strength in children with cerebral palsy following selective percutaneous myofascial lengthening and functional physiotherapy. *NeuroRehabilitation*. 2019;43(4):361–368.
131. Flansbjer U-B, Miller M, Downham D, Lexell J. Progressive resistance training after stroke: effects on muscle strength, muscle tone, gait performance and perceived participation. *J Rehabil Med*. 2008;40(1):42–48. doi:10.2340/16501977-0129
132. Lee K. EMG-triggered pedaling training on muscle activation, gait, and motor function for stroke patients. *Brain Sci*. 2022;12(1):76. doi:10.3390/brainsci12010076
133. Androwis GJ, Pilkar R, Ramanujam A, Nolan KJ. Electromyography assessment during gait in a robotic exoskeleton for acute stroke. *Front Neurol*. 2018;9:630. doi:10.3389/fneur.2018.00630
134. Camerota F, Celletti C, Di Sipio E, et al. Focal muscle vibration, an effective rehabilitative approach in severe gait impairment due to multiple sclerosis. *J Neurol Sci*. 2017;372:33–39. doi:10.1016/j.jns.2016.11.025
135. Jonsdottir J, Lencioni T, Gervasoni E, et al. Improved gait of persons with multiple sclerosis after rehabilitation: effects on lower limb muscle synergies, push-off, and toe-clearance. *Front Neurol*. 2020;11:520441. doi:10.3389/fneur.2020.00668
136. Tsaih P-L, Chiu M-J, Luh -J-J, Yang Y-R, Lin -J-J, Hu M-H. Practice variability combined with task-oriented electromyographic biofeedback enhances strength and balance in people with chronic stroke. *Behav Neurol*. 2018;2018:1–9. doi:10.1155/2018/7080218
137. Brien M, Sveistrup H. An intensive virtual reality program improves functional balance and mobility of adolescents with cerebral palsy. *Pediatr Phys Ther*. 2011;23(3):258–266. doi:10.1097/PEP.0b013e318227ca0f
138. Pavão SL, Arnoni JLB, Oliveira AKCD, Rocha NACF. Impact of a virtual reality-based intervention on motor performance and balance of a child with cerebral palsy: a case study. *Rev Paulista Pediatria*. 2014;32:389–394. doi:10.1016/j.rpped.2014.04.005
139. Ozkul C, Guclu-Gunduz A, Yazici G, Guzel NA, Irkec C. Effect of immersive virtual reality on balance, mobility, and fatigue in patients with multiple sclerosis: a single-blinded randomized controlled trial. *Eur J Int Med*. 2020;35:101092. doi:10.1016/j.eujim.2020.101092
140. Fulk GD. Locomotor training and virtual reality-based balance training for an individual with multiple sclerosis: a case report. *J Neurol Phys Ther*. 2005;29(1):34–42. doi:10.1097/01.NPT.0000282260.59078.e4
141. Imbimbo I, Coraci D, Santilli C, et al. Parkinson's disease and virtual reality rehabilitation: cognitive reserve influences the walking and balance outcome. *Neurol Sci*. 2021;1–7.
142. Gulcan K, Guclu-Gunduz A, Yasar E, Ar U, Sucullu karadag Y, Saygili F. The effects of augmented and virtual reality gait training on balance and gait in patients with Parkinson's disease. *Acta Neurologica Belgica*. 2023;123(5):1917–1925. doi:10.1007/s13760-022-02147-0
143. Canning CG, Allen NE, Nackaerts E, Paul SS, Nieuwboer A, Gilat M. Virtual reality in research and rehabilitation of gait and balance in Parkinson disease. *Nat Rev Neurol*. 2020;16(8):409–425. doi:10.1038/s41582-020-0370-2
144. Feng H, Li C, Liu J, et al. Virtual reality rehabilitation versus conventional physical therapy for improving balance and gait in Parkinson's disease patients: a randomized controlled trial. *Med Sci Monit*. 2019;25:4186. doi:10.12659/MSM.916455
145. Espay AJ, Baram Y, Dwivedi AK, Shukla R. At-home training with closed-loop augmented-reality cueing device for. *J Rehabil Res Dev*. 2010;47(6–9):573–582. doi:10.1682/JRRD.2009.10.0165
146. Lopez WOC, Higuera CAE, Fonoff ET, de Oliveira Souza C, Albicker U, Martinez JAE. Listenmee® and Listenmee® smartphone application: synchronizing walking to rhythmic auditory cues to improve gait in Parkinson's disease. *Hum Mov Sci*. 2014;37:147–156. doi:10.1016/j.humov.2014.08.001
147. Fishbein P, Hutzler Y, Ratmansky M, Treger I, Dunsky A. A preliminary study of dual-task training using virtual reality: influence on walking and balance in chronic poststroke survivors. *J Stroke Cerebrovascular Dis*. 2019;28(11):104343. doi:10.1016/j.jstrokecerebrovasdis.2019.104343
148. Held JP, Ferrer B, Mainetti R, et al. Autonomous rehabilitation at stroke patients home for balance and gait: safety, usability and compliance of a virtual reality system. *Eur J Phys Rehabil Med*. 2017;54:545–553. doi:10.23736/S1973-9087.17.04802-X
149. Plummer P. Gait and balance training using virtual reality is more effective for improving gait and balance ability after stroke than conventional training without virtual reality [synopsis]. *J Physiother*. 2017;63(2):114. doi:10.1016/j.jphys.2017.02.009
150. Kim JH, Jang SH, Kim CS, Jung JH, You JH. Use of virtual reality to enhance balance and ambulation in chronic stroke: a double-blind, randomized controlled study. *Am J Phys Med Rehabil*. 2009;88(9):693–701. doi:10.1097/PHM.0b013e3181b33350
151. In T, Lee K, Song C. Virtual reality reflection therapy improves balance and gait in patients with chronic stroke: randomized controlled trials. *Med Sci Monit*. 2016;22:4046. doi:10.12659/MSM.898157
152. Kim KH, Kim DH. Improved balance, gait, and lower limb motor function in a 58-Year-old man with right hemiplegic traumatic brain injury following virtual reality-based real-time feedback physical therapy. *Am J Case Rep*. 2023;24:e938803–1. doi:10.12659/AJCR.938803
153. Goh L, Allen NE, Ahmadpour N, et al. A video self-modeling intervention using virtual reality plus physical practice for freezing of gait in Parkinson disease: feasibility and acceptability study. *JMIR Format Res*. 2021;5(11):e28315. doi:10.2196/28315
154. Lee A, Hellmers N, Vo M, et al. Can google glass™ technology improve freezing of gait in parkinsonism? A pilot study. *Disabil Rehabil*. 2023;18(3):327–332. doi:10.1080/17483107.2020.1849433
155. Bekkers EM, Mirelman A, Alcock L, et al. 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*. 2020;34(5):440–449. doi:10.1177/1545968320912756
156. Killane I, Fearon C, Newman L, et al. Dual motor-cognitive virtual reality training impacts dual-task performance in freezing of gait. *IEEE J Biomed Health Inform*. 2015;19(6):1855–1861. doi:10.1109/JBHI.2015.2479625
157. Park S-H, Son S-M, Choi J-Y. Effect of posture control training using virtual reality program on sitting balance and trunk stability in children with cerebral palsy. *NeuroRehabilitation*. 2021;48(3):247–254. doi:10.3233/NRE-201642
158. Lazzari RD, Politti F, Belina SF, et al. Effect of transcranial direct current stimulation combined with virtual reality training on balance in children with cerebral palsy: a randomized, controlled, double-blind, clinical trial. *J Motor Behavior*. 2017;49(3):329–336. doi:10.1080/00222895.2016.1204266

159. Jha KK, Karunanithi GB, Sahana A, Karthikbabu S. Randomised trial of virtual reality gaming and physiotherapy on balance, gross motor performance and daily functions among children with bilateral spastic cerebral palsy. *Somatosens Mot Res*. 2021;38(2):117–126. doi:10.1080/08990220.2021.1876016
160. Meyns P, Pans L, Plasmans K, Heyrman L, Desloovere K, Molenaers G. The effect of additional virtual reality training on balance in children with cerebral palsy after lower limb surgery: a feasibility study. *Games Health J*. 2017;6(1):39–48. doi:10.1089/g4h.2016.0069
161. Wu J, Loprinzi PD, Ren Z. The Rehabilitative effects of virtual reality games on balance performance among children with cerebral palsy: a meta-analysis of randomized controlled trials. *Int J Environ Res Public Health*. 2019;16(21):4161. doi:10.3390/ijerph16214161
162. Chang HJ, Jung YG, Park YS, et al. Virtual reality-incorporated horse riding simulator to improve motor function and balance in children with cerebral palsy: a pilot study. *Sensors*. 2021;21(19):6394. doi:10.3390/s21196394
163. Ortiz Gutierrez R, Galán Del Río F, Cano de la Cuerda R, Alguacil-Diego IM, Arroyo González R, Miangolarra Page JC. A telerehabilitation program by virtual reality-video games improves balance and postural control in multiple sclerosis patients. *NeuroRehabilitation*. 2013;33(4):545–554. doi:10.3233/NRE-130995
164. Molhemi F, Monjezi S, Mehravar M, et al. Effects of virtual reality vs conventional balance training on balance and falls in people with multiple sclerosis: a randomized controlled trial. *Arch Phys Med Rehabil*. 2021;102(2):290–299. doi:10.1016/j.apmr.2020.09.395
165. Kalron A, Fonkatz I, Frid L, Baransi H, Achiron A. The effect of balance training on postural control in people with multiple sclerosis using the CAREN virtual reality system: a pilot randomized controlled trial. *J Neuroeng Rehabil*. 2016;13:1–10. doi:10.1186/s12984-016-0124-y
166. Kashif M, Ahmad A, Bandpei MAM, Gilani SA, Hanif A, Iram H. 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*. 2022;22(1):381. doi:10.1186/s12877-022-03035-1
167. Yang W-C, Wang H-K, Wu R-M, Lo C-S, Lin K-H. Home-based virtual reality balance training and conventional balance training in Parkinson's disease: a randomized controlled trial. *JFormos Med Assoc*. 2016;115(9):734–743. doi:10.1016/j.jfma.2015.07.012
168. Liao -Y-Y, Yang Y-R, Cheng S-J, Wu Y-R, Fuh J-L, Wang R-Y. Virtual reality–based training to improve obstacle-crossing performance and dynamic balance in patients with Parkinson's disease. *Neurorehabil Neural Repair*. 2015;29(7):658–667. doi:10.1177/1545968314562111
169. Nicolai S, Mirelman A, Herman T, et al. Improvement of balance after audio-biofeedback. *Z Gerontol Geriatr*. 2010;43:224–228. doi:10.1007/s00391-010-0125-6
170. Miranda CS, Oliveira TDP, Gouvêa JXM, Perez DB, Marques AP, Piemonte MEP. Balance training in virtual reality promotes performance improvement but not transfer to postural control in people with chronic stroke. *Games Health J*. 2019;8(4):294–300. doi:10.1089/g4h.2018.0075
171. Sheehy L, Taillon-Hobson A, Sveistrup H, et al. Does the addition of virtual reality training to a standard program of inpatient rehabilitation improve sitting balance ability and function after stroke? Protocol for a single-blind randomized controlled trial. *BMC Neurol*. 2016;16:1–9. doi:10.1186/s12883-016-0563-x
172. Lloréns R, Noé E, Colomer C, Alcañiz M. Effectiveness, usability, and cost-benefit of a virtual reality–based telerehabilitation program for balance recovery after stroke: a randomized controlled trial. *Arch Phys Med Rehabil*. 2015;96(3):418–425.e2. doi:10.1016/j.apmr.2014.10.019
173. Kwon J-A, Shin Y-K, Kim D-J, Cho S-R. Effects of balance training using a virtual reality program in hemiplegic patients. *Int J Environ Res Public Health*. 2022;19(5):2805. doi:10.3390/ijerph19052805
174. Bonuzzi GMG, de Freitas TB, Palma GCDS, et al. Effects of the brain-damaged side after stroke on the learning of a balance task in a non-immersive virtual reality environment. *Physiother Theory Pract*. 2022;38(1):28–35. doi:10.1080/09593985.2020.1731893
175. Lee JI, Park J, Koo J, et al. Effects of the home-based exercise program with an augmented reality system on balance in patients with stroke: a randomized controlled trial. *Disability Rehabil*. 2023;45(10):1705–1712. doi:10.1080/09638288.2022.2074154
176. Sana V, Ghous M, Kashif M, Albalwi A, Muneer R, Zia M. Effects of vestibular rehabilitation therapy versus virtual reality on balance, dizziness, and gait in patients with subacute stroke: a randomized controlled trial. *Medicine*. 2023;102(24):e33203. doi:10.1097/MD.0000000000033203
177. Sultan N, Khushnood K, Qureshi S, et al. Effects of virtual reality training using Xbox Kinect on balance, postural control, and functional independence in subjects with stroke. *Games Health J*. 2023;12:440–444. doi:10.1089/g4h.2022.0193
178. Lee MM, Lee KJ, Song CH. Game-based virtual reality canoe paddling training to improve postural balance and upper extremity function: a preliminary randomized controlled study of 30 patients with subacute stroke. *Med Sci Monit*. 2018;24:2590. doi:10.12659/MSM.906451
179. Lloréns R, Gil-Gómez J-A, Alcañiz M, Colomer C, Noé E. Improvement in balance using a virtual reality-based stepping exercise: a randomized controlled trial involving individuals with chronic stroke. *Clin rehabilitat*. 2015;29(3):261–268. doi:10.1177/0269215514543333
180. Yang S, Hwang W-H, Tsai Y-C, Liu F-K, Hsieh L-F, Chern J-S. Improving balance skills in patients who had stroke through virtual reality treadmill training. *Am J Phys Med Rehabil*. 2011;90(12):969–978. doi:10.1097/PHM.0b013e3182389fae
181. Sheehy L, Taillon-Hobson A, Sveistrup H, Bilodeau M, Yang C, Finestone H. Sitting balance exercise performed using virtual reality training on a stroke rehabilitation inpatient service: a randomized controlled study. *Pm&r*. 2020;12(8):754–765. doi:10.1002/pmrj.12331
182. D'Antonio E, Tieri G, Patané F, Morone G, Iosa M. Stable or able? Effect of virtual reality stimulation on static balance of post-stroke patients and healthy subjects. *Hum Mov Sci*. 2020;70:102569. doi:10.1016/j.humov.2020.102569
183. Cikajlo I, Rudolf M, Goljar N, Burger H, Matjačić Z. Telerehabilitation using virtual reality task can improve balance in patients with stroke. *Disability Rehabil*. 2012;34(1):13–18. doi:10.3109/09638288.2011.583308
184. Lee H-C, Huang C-L, Ho S-H, Sung W-H. The effect of a virtual reality game intervention on balance for patients with stroke: a randomized controlled trial. *Games Health J*. 2017;6(5):303–311. doi:10.1089/g4h.2016.0109
185. Cho KH, Lee KJ, Song CH. Virtual-reality balance training with a video-game system improves dynamic balance in chronic stroke patients. *Tohoku J Exp Med*. 2012;228(1):69–74. doi:10.1620/tjem.228.69
186. Fino PC, Peterka RJ, Hullar TE, et al. Assessment and rehabilitation of central sensory impairments for balance in mTBI using auditory biofeedback: a randomized clinical trial. *BMC Neurol*. 2017;17:1–14. doi:10.1186/s12883-017-0812-7
187. Thornton M, Marshall S, McComas J, Finestone H, McCormick A, Sveistrup H. Benefits of activity and virtual reality based balance exercise programmes for adults with traumatic brain injury: perceptions of participants and their caregivers. *Brain Injury*. 2005;19(12):989–1000. doi:10.1080/02699050500109944

188. Llorens R, Colomer-Font C, Alcañiz M, Noé-Sebastián E. BioTrak virtual reality system: effectiveness and satisfaction analysis for balance rehabilitation in patients with brain injury. *Neurología*. 2013;28(5):268–275. doi:10.1016/j.nrl.2012.04.016
189. Cuthbert JP, Staniszewski K, Hays K, Gerber D, Natale A, O'dell D. Virtual reality-based therapy for the treatment of balance deficits in patients receiving inpatient rehabilitation for traumatic brain injury. *Brain Injury*. 2014;28(2):181–188. doi:10.3109/02699052.2013.860475
190. Conner BC, Remec NM, Orum EK, Frank EM, Lerner ZF. Wearable adaptive resistance training improves ankle strength, walking efficiency and mobility in cerebral palsy: a pilot clinical trial. *IEEE Open J Eng Med Biol*. 2020;1:282–289. doi:10.1109/OJEMB.2020.3035316
191. Picelli A, Melotti C, Origano F, et al. Robot-assisted gait training is not superior to balance training for improving postural instability in patients with mild to moderate Parkinson's disease: a single-blind randomized controlled trial. *Clin rehabilitat*. 2015;29(4):339–347. doi:10.1177/0269215514544041
192. Kawashima N, Hasegawa K, Iijima M, et al. Efficacy of wearable device gait training on Parkinson's disease: a randomized controlled open-label pilot study. *Internal Medicine*. 2022;61(17):2573–2580. doi:10.2169/internalmedicine.8949-21
193. Wu C-H, Mao H-F, Hu J-S, Wang T-Y, Tsai Y-J, Hsu W-L. The effects of gait training using powered lower limb exoskeleton robot on individuals with complete spinal cord injury. *J Neuroeng Rehabil*. 2018;15(1):1–10. doi:10.1186/s12984-018-0355-1
194. Bang D-H, Shin W-S. Effects of robot-assisted gait training on spatiotemporal gait parameters and balance in patients with chronic stroke: a randomized controlled pilot trial. *NeuroRehabilitation*. 2016;38(4):343–349. doi:10.3233/NRE-161325
195. Choi W. Effects of robot-assisted gait training with body weight support on gait and balance in stroke patients. *Int J Environ Res Public Health*. 2022;19(10):5814. doi:10.3390/ijerph19105814
196. Yoshimoto T, Shimizu I, Hiroi Y, Kawaki M, Sato D, Nagasawa M. Feasibility and efficacy of high-speed gait training with a voluntary driven exoskeleton robot for gait and balance dysfunction in patients with chronic stroke: nonrandomized pilot study with concurrent control. *Int J Rehabil Res*. 2015;38(4):338–343. doi:10.1097/MRR.0000000000000132
197. Kim HY, Shin J-H, Yang SP, Shin MA, Lee SH. Robot-assisted gait training for balance and lower extremity function in patients with infratentorial stroke: a single-blinded randomized controlled trial. *J Neuroeng Rehabil*. 2019;16(1):1–12. doi:10.1186/s12984-019-0553-5
198. Hwang D-Y, Lee H-J, Lee G-C, Lee S-M. Treadmill training with tilt sensor functional electrical stimulation for improving balance, gait, and muscle architecture of tibialis anterior of survivors with chronic stroke: a randomized controlled trial. *Technol Health Care*. 2015;23 (4):443–452. doi:10.3233/THC-150903
199. Buesing C, Fisch G, O'Donnell M, et al. Effects of a wearable exoskeleton stride management assist system (SMA®) on spatiotemporal gait characteristics in individuals after stroke: a randomized controlled trial. *J Neuroeng Rehabil*. 2015;12(1):1–14. doi:10.1186/s12984-015-0062-0
200. Watanabe H, Goto R, Tanaka N, Matsumura A, Yanagi H. Effects of gait training using the Hybrid Assistive Limb® in recovery-phase stroke patients: a 2-month follow-up, randomized, controlled study. *NeuroRehabilitation*. 2017;40(3):363–367. doi:10.3233/NRE-161424
201. Yeung L-F, Lau CC, Lai CW, Soo YO, Chan M-L, Tong RK. Effects of wearable ankle robotics for stair and over-ground training on sub-acute stroke: a randomized controlled trial. *J Neuroeng Rehabil*. 2021;18(1):1–10. doi:10.1186/s12984-021-00814-6
202. Jayaraman A, O'brien MK, Madhavan S, et al. Stride management assist exoskeleton vs functional gait training in stroke: a randomized trial. *Neurology*. 2019;92(3):e263–e273. doi:10.1212/WNL.0000000000006782
203. Lee H-J, Lee S-H, Seo K, et al. Training for walking efficiency with a wearable Hip-assist robot in patients with stroke: a pilot randomized controlled trial. *Stroke*. 2019;50(12):3545–3552. doi:10.1161/STROKEAHA.119.025950
204. Akıncı M, Burak M, Yaşar E, Kılıç RT. The effects of Robot-assisted gait training and virtual reality on balance and gait in stroke survivors: a randomized controlled trial. *Gait Posture*. 2023;103:215–222. doi:10.1016/j.gaitpost.2023.05.013
205. Park J, Chung Y. The effects of robot-assisted gait training using virtual reality and auditory stimulation on balance and gait abilities in persons with stroke. *NeuroRehabilitation*. 2018;43(2):227–235. doi:10.3233/NRE-172415
206. Drużbicki M, Guzik A, Przysada G, et al. Effects of robotic exoskeleton-aided gait training in the strength, body balance, and walking speed in individuals with multiple sclerosis: a single-group preliminary study. *Arch Phys Med Rehabil*. 2021;102(2):175–184. doi:10.1016/j.apmr.2020.10.122
207. Barbe MT, Cepuran F, Amarell M, Schoenau E, Timmermann L. Long-term effect of robot-assisted treadmill walking reduces freezing of gait in Parkinson's disease patients: a pilot study. *J Neurol*. 2013;260:296–298. doi:10.1007/s00415-012-6703-3
208. Pilleri M, Weis L, Zabeo L, et al. Overground robot assisted gait trainer for the treatment of drug-resistant freezing of gait in Parkinson disease. *J Neurol Sci*. 2015;355(1–2):75–78. doi:10.1016/j.jns.2015.05.023
209. Lo AC, Chang VC, Gianfrancesco MA, Friedman JH, Patterson TS, Benedicto DF. Reduction of freezing of gait in Parkinson's disease by repetitive robot-assisted treadmill training: a pilot study. *J Neuroeng Rehabil*. 2010;7:1–8. doi:10.1186/1743-0003-7-51
210. Čakrt O, Vyhnálek M, Slabý K, et al. Balance rehabilitation therapy by tongue electrotactile biofeedback in patients with degenerative cerebellar disease. *NeuroRehabilitation*. 2012;31(4):429–434. doi:10.3233/NRE-2012-00813
211. Allum J, Rust H, Lutz N, et al. Characteristics of improvements in balance control using vibro-tactile biofeedback of trunk sway for multiple sclerosis patients. *J Neurol Sci*. 2021;425:117432. doi:10.1016/j.jns.2021.117432
212. Sakel M, Saunders K, Hodgson P, et al. Feasibility and safety of a powered exoskeleton for balance training for people living with multiple sclerosis: a single-group preliminary study (Rapper III). *J Rehabil Med*. 2022;54.
213. Van Der Logt R, Findling O, Rust H, Yaldizli O, Allum J. The effect of vibrotactile biofeedback of trunk sway on balance control in multiple sclerosis. *Mult Scler Relat Disord*. 2016;8:58–63. doi:10.1016/j.msard.2016.05.003
214. Marchesi G, Casadio M, Ballardini G, et al. Robot-based assessment of sitting and standing balance: preliminary results in Parkinson's disease. *IEEE*. 2019;570–576.
215. Lee B-C, Fung A, Thrasher TA. The effects of coding schemes on vibrotactile biofeedback for dynamic balance training in Parkinson's disease and healthy elderly individuals. *IEEE Trans Neural Syst Rehabil Eng*. 2017;26(1):153–160. doi:10.1109/TNSRE.2017.2762239
216. Bae Y-H, Lee SM, Ko M. Comparison of the effects on dynamic balance and aerobic capacity between objective and subjective methods of high-intensity robot-assisted gait training in chronic stroke patients: a randomized controlled trial. *Topic Stroke Rehabilitation*. 2017;24 (4):309–313. doi:10.1080/10749357.2016.1275304
217. Inoue S, Otaka Y, Kumagai M, Sugasawa M, Mori N, Kondo K. Effects of Balance Exercise Assist Robot training for patients with hemiparetic stroke: a randomized controlled trial. *J Neuroeng Rehabil*. 2022;19(1):1–15. doi:10.1186/s12984-022-00989-6

218. Kim D-H, In T-S, Jung K-S. Effects of robot-assisted trunk control training on trunk control ability and balance in patients with stroke: a randomized controlled trial. *Technol Health Care*. 2022;30(2):413–422. doi:10.3233/THC-202720
219. Matjačić Z, Zadravec M, Olenšek A. Feasibility of robot-based perturbed-balance training during treadmill walking in a high-functioning chronic stroke subject: a case-control study. *J Neuroeng Rehabil*. 2018;15(1):1–15. doi:10.1186/s12984-018-0373-z
220. Yasuda K, Saichi K, Kaibuki N, Harashima H, Iwata H. Haptic-based perception-empathy biofeedback system for balance rehabilitation in patients with chronic stroke: concepts and initial feasibility study. *Gait Posture*. 2018;62:484–489. doi:10.1016/j.gaitpost.2018.04.013
221. Gaßner H, Trutt E, Seifferth S, et al. Treadmill training and physiotherapy similarly improve dual task gait performance: a randomized-controlled trial in Parkinson's disease. *J Neural Transm*. 2022;129(9):1189–1200. doi:10.1007/s00702-022-02514-4
222. Conradsson D, Nero H, Löfgren N, Hagströmer M, Franzén E. Monitoring training activity during gait-related balance exercise in individuals with Parkinson's disease: a proof-of-concept-study. *BMC Neurol*. 2017;17:1–8. doi:10.1186/s12883-017-0804-7
223. Grobbelaar R, Venter R, Welman KE. Backward compared to forward over ground gait retraining have additional benefits for gait in individuals with mild to moderate Parkinson's disease: a randomized controlled trial. *Gait Posture*. 2017;58:294–299. doi:10.1016/j.gaitpost.2017.08.019
224. McGill A, Houston S, Lee RY. Effects of a ballet intervention on trunk coordination and range of motion during gait in people with Parkinson's. *Cogent Med*. 2019;6(1):1583085. doi:10.1080/2331205X.2019.1583085
225. Ebersbach G, Grust U, Ebersbach A, Wegner B, Gandor F, Kühn AA. Amplitude-oriented exercise in Parkinson's disease: a randomized study comparing LSVT-BIG and a short training protocol. *J Neural Transm*. 2015;122:253–256. doi:10.1007/s00702-014-1245-8
226. Byl N, Zhang W, Coo S, Tomizuka M. Clinical impact of gait training enhanced with visual kinematic biofeedback: patients with Parkinson's disease and patients stable post stroke. *Neuropsychologia*. 2015;79:332–343. doi:10.1016/j.neuropsychologia.2015.04.020
227. Solla P, Cugusi L, Bertoli M, et al. Sardinian folk dance for individuals with Parkinson's disease: a randomized controlled pilot trial. *J Altern Complementary Med*. 2019;25(3):305–316. doi:10.1089/acm.2018.0413
228. Uchitomi H, Ota L, Ogawa K-I, Orimo S, Miyake Y. Interactive rhythmic cue facilitates gait relearning in patients with Parkinson's disease. *PLoS One*. 2013;8(9):e72176. doi:10.1371/journal.pone.0072176
229. Kang S, Shin J-H, Kim IY, Lee J, Lee J-Y, Jeong E. Patterns of enhancement in paretic shoulder kinematics after stroke with musical cueing. *Sci Rep*. 2020;10(1):18109. doi:10.1038/s41598-020-75143-0
230. Zhao Y, Nonnekes J, Storcken EJ, et al. Feasibility of external rhythmic cueing with the Google Glass for improving gait in people with Parkinson's disease. *J Neurol*. 2016;263:1156–1165. doi:10.1007/s00415-016-8115-2
231. Ginis P, Heremans E, Ferrari A, Bekkers EM, Canning CG, Nieuwboer A. External input for gait in people with Parkinson's disease with and without freezing of gait: one size does not fit all. *J Neurol*. 2017;264(7):1488–1496. doi:10.1007/s00415-017-8552-6
232. Seebacher B, Kuisma R, Glynn A, Berger T. Rhythmic cued motor imagery and walking in people with multiple sclerosis: a randomised controlled feasibility study. *Pilot Feasibility Stud*. 2015;1:1–13. doi:10.1186/s40814-015-0021-3
233. So HY, Kim SR, Kim S, et al. Effect of home-based self-management intervention for community-dwelling patients with early Parkinson's Disease: a feasibility study. *J Commun Health Nurs*. 2023;40(2):133–146. doi:10.1080/07370016.2022.2133566
234. Putzolu M, Manzini V, Gambaro M, et al. Home-based exercise training by using a smartphone app in patients with Parkinson's disease: a feasibility study. *Front Neurol*. 2023;14:1205386. doi:10.3389/fneur.2023.1205386
235. Jung J, Yu J, Kang H. Effects of virtual reality treadmill training on balance and balance self-efficacy in stroke patients with a history of falling. *J Phys Ther Sci*. 2012;24(11):1133–1136. doi:10.1589/jpts.24.1133
236. Gupta R, Kumari S, Senapati A, Ambasta RK, Kumar P. New era of artificial intelligence and machine learning-based detection, diagnosis, and therapeutics in Parkinson's disease. *Ageing Res Rev*. 2023;90:102013. doi:10.1016/j.arr.2023.102013
237. Burgos PI, Lara O, Lavado A, et al. Exergames and telerehabilitation on smartphones to improve balance in stroke patients. *Brain Sci*. 2020;10(11):773. doi:10.3390/brainsci10110773
238. Ortiz-Gutiérrez R, Cano-de-la-Cuerda R, Galán-del-Río F, Alguacil-Diego IM, Palacios-Ceña D, Miangolarra-Page JC. A telerehabilitation program improves postural control in multiple sclerosis patients: a Spanish preliminary study. *Int J Environ Res Public Health*. 2013;10(11):5697–5710. doi:10.3390/ijerph10115697
239. Lee S-H, Lee H-J, Shim Y, et al. Wearable Hip-assist robot modulates cortical activation during gait in stroke patients: a functional near-infrared spectroscopy study. *J Neuroeng Rehabil*. 2020;17:1–8. doi:10.1186/s12984-020-00777-0
240. Lerner ZF, Damiano DL, Bulea TC. A lower-extremity exoskeleton improves knee extension in children with crouch gait from cerebral palsy. *Sci, trans med*. 2017;9(404):eaam9145. doi:10.1126/scitranslmed.aam9145
241. Mancini M, Smulders K, Harker G, Stuart S, Nutt JG. Assessment of the ability of open-and closed-loop cueing to improve turning and freezing in people with Parkinson's disease. *Sci Rep*. 2018;8(1):12773. doi:10.1038/s41598-018-31156-4
242. Mancini M, Curtze C, Stuart S, et al. The impact of freezing of gait on balance perception and mobility in community-living with Parkinson's disease. *IEEE*. 2018;3040–3043.
243. Mak MK, Pang MY, Mok V. Gait difficulty, postural instability, and muscle weakness are associated with fear of falling in people with Parkinson's disease. *Parkinson's Dis*. 2012;2012. doi:10.1155/2012/901721
244. Marcante A, Di Marco R, Gentile G, et al. Foot pressure wearable sensors for freezing of gait detection in Parkinson's disease. *Sensors*. 2020;21(1):128. doi:10.3390/s21010128
245. Morris R, Hickey A, Del Din S, Godfrey A, Lord S, Rochester L. A model of free-living gait: a factor analysis in Parkinson's disease. *Gait Posture*. 2017;52:68–71. doi:10.1016/j.gaitpost.2016.11.024
246. Jonsdottir J, Lencioni T, Gervasoni E, et al. Improved gait of persons with multiple sclerosis after rehabilitation: effects on lower limb muscle synergies, push-off, and toe-clearance. *Front Neurol*. 2020;11:668.
247. Tsaih P-L, Chiu M-J, Luh -J-J, Yang Y-R, Lin -J-J, Hu M-H. Practice variability combined with task-oriented electromyographic biofeedback enhances strength and balance in people with chronic stroke. *Behav Neurol*. 2018;2018(1):7080218.
248. Shine J, Matar E, Bolitho S, et al. Modeling freezing of gait in Parkinson's disease with a virtual reality paradigm. *Gait Posture*. 2013;38(1):104–108. doi:10.1016/j.gaitpost.2012.10.026
249. Georgiades MJ, Gilat M, Martens KAE, et al. Investigating motor initiation and inhibition deficits in patients with Parkinson's disease and freezing of gait using a virtual reality paradigm. *Neuroscience*. 2016;337:153–162. doi:10.1016/j.neuroscience.2016.09.019

250. Janssen S, de Ruyter van Steveninck J, Salim HS, et al. The effects of augmented reality visual cues on turning in place in Parkinson's disease patients with freezing of gait. *Front Neurol*. 2020;11:185. doi:10.3389/fneur.2020.00185
251. Janssen S, Bolte B, Nonnekes J, et al. Usability of three-dimensional augmented visual cues delivered by smart glasses on (freezing of) gait in Parkinson's disease. *Front Neurol*. 2017;8:279. doi:10.3389/fneur.2017.00279
252. Gomez-Jordana LI, Stafford J, Peper CLE, Craig CM. Crossing virtual doors: a new method to study gait impairments and freezing of gait in Parkinson's disease. *Parkinson's Dis*. 2018;2018. doi:10.1155/2018/2957427
253. Geerse DJ, Coolen B, van Hilten JJ, Roerdink M. Holocue: a Wearable Holographic Cueing Application for Alleviating Freezing of Gait in Parkinson's Disease. *Front Neurol*. 2022;12:628388. doi:10.3389/fneur.2021.628388
254. Wright WG, McDevitt J, Tierney R, Haran FJ, Appiah-Kubi KO, Dumont A. Assessing subacute mild traumatic brain injury with a portable virtual reality balance device. *Disability Rehabil*. 2017;39(15):1564–1572. doi:10.1080/09638288.2016.1226432
255. Zampogna A, Mileti I, Martelli F, et al. Early balance impairment in Parkinson's Disease: evidence from Robot-assisted axial rotations. *Clin Neurophysiol*. 2021;132(10):2422–2430. doi:10.1016/j.clinph.2021.06.023
256. Mirelman A, Herman T, Nicolai S, et al. Audio-biofeedback training for posture and balance in patients with Parkinson's disease. *J Neuroeng Rehabil*. 2011;8:1–7. doi:10.1186/1743-0003-8-35
257. Moore J, Stuart S, McMeekin P, et al. Enhancing free-living fall risk assessment: contextualizing mobility based IMU data. *Sensors*. 2023;23(2):891. doi:10.3390/s23020891
258. Molina AI, Arroyo Y, Lacave C, Redondo MA, Bravo C, Ortega M. Eye tracking-based evaluation of accessible and usable interactive systems: tool set of guidelines and methodological issues. *Univ Access Inf Soc*. 2024;1–24.
259. Wall C, McMeekin P, Walker R, Hetherington V, Graham L, Godfrey A. Sonification for Personalised Gait Intervention. *Sensors*. 2023;24(1):65. doi:10.3390/s24010065
260. Bella SD, Dotov D, Bardy B, de Cock VC. Individualization of music-based rhythmic auditory cueing in Parkinson's disease. *Ann NY Acad Sci*. 2018;1423(1):308–317. doi:10.1111/nyas.13859
261. Wall C, McMeekin P, Walker R, Godfrey A. Gait retraining to reduce falls: an experimental study toward scalable and personalised use in the home. *Lancet*. 2023;402:S92 doi:10.1016/S0140-6736(23)02088-3
262. Wall C, Young F, Moore J, McMeekin P, Walker R, Godfrey A. A proposed pervasive smartphone application for personalised gait rehabilitation. *IEEE*. 2023:1–4 doi:10.1109/BSN58485.2023.10331603
263. Senadheera I, Hettiarachchi P, Haslam B, et al. AI applications in adult stroke recovery and rehabilitation: a scoping review using AI. *Sensors*. 2024;24(20):6585. doi:10.3390/s24206585
264. Maggio MG, Luca A, Cicero CE, et al. Effectiveness of telerehabilitation plus virtual reality (Tele-RV) in cognitive e social functioning: a randomized clinical study on Parkinson's disease. *Parkinsonism Related Disord*. 2024;119:105970. doi:10.1016/j.parkreldis.2023.105970
265. Maskeliūnas R, Damaševičius R, Blažauskas T, Canbulut C, Adomavičienė A, Griškevičius J. BiomacVR: a virtual reality-based system for precise human posture and motion analysis in rehabilitation exercises using depth sensors. *Electronics*. 2023;12(2):339. doi:10.3390/electronics12020339
266. Chae SH, Kim Y, Lee K-S, Park H-S. Development and clinical evaluation of a web-based upper limb home rehabilitation system using a smartwatch and machine learning model for chronic stroke survivors: prospective comparative study. *JMIR mHealth and uHealth*. 2020;8(7):e17216. doi:10.2196/17216
267. Potvin A, Tourtellotte WW, Pew RW, Albers JW, Henderson WG, Snyder D. The importance of age effects on performance in the assessment of clinical trials. *J Chronic Dis*. 1973;26(11):699–717. doi:10.1016/0021-9681(73)90067-2