Cueing Technologies in Parkinson's Disease: A Systematic Review

Original
Cueing Technologies in Parkinson's Disease: A Systematic Review / Iervasi, M; Maple-Grodem, J; Borzi', L; Alves, Gw; Eftestol, T; Demrozi, F. - In: IEEE ACCESS. - ISSN 2169-3536. - ELETTRONICO. - 13:(2025), pp. 216408-216427. [10.1109/ACCESS.2025.3647133]

Publisher:
IEEE-INST ELECTRICAL ELECTRONICS ENGINEERS

Published
DOI:10.1109/ACCESS.2025.3647133

IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received 7 November 2025, accepted 7 December 2025, date of publication 22 December 2025,
date of current version 30 December 2025.

Digital Object Identifier 10.1109/ACCESS.2025.3647133

TOPICAL REVIEW

Cueing Technologies in Parkinson's Disease: A Systematic Review

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ABSTRACT Parkinson's disease (PD) is a progressive neurodegenerative disorder characterized by motor and non-motor symptoms that significantly impact daily life. Wearable cueing technologies have emerged as promising interventions to alleviate these symptoms by providing external sensory stimuli to enhance movement, cognition, and overall function. However, the landscape of wearable cueing methodologies in PD clinical applications remains fragmented. In this systematic review, we analyze the effectiveness of wearable cueing technologies designed for people with PD (PwPD), focusing on their impact on motor and non-motor symptoms. Following PRISMA guidelines, we conducted a comprehensive literature search, identifying 1,640 studies, of which 39 met the inclusion criteria. These studies explored various cueing modalities, including auditory, visual, haptic, and multimodal approaches, tested in clinical settings. Our findings indicate that wearable cueing technologies show significant potential in mitigating motor symptoms, such as freezing of gait, bradykinesia, and postural instability. Although our review framework considered both motor and non-motor symptoms, none of the included studies explicitly addressed non-motor impairments (e.g., cognitive, affective, or sleep-related symptoms), highlighting an unmet research need in this area and confirming the current technological focus on motor rehabilitation. However, the effectiveness of these interventions varies depending on the cueing modality, patient-specific factors, and study design. Despite promising results, the heterogeneity in study protocols, sample sizes, and outcome measures poses challenges in establishing standardized conclusions. This review underscores the growing role of wearable cueing technologies in PD management and highlights the need for high-quality, standardized clinical trials to refine device design, optimize cueing parameters, and integrate these solutions into personalized treatment strategies. Our findings provide a foundation for future research and the development of evidence-based wearable interventions to enhance the quality of life for PwPD.

INDEX TERMS Parkinson's disease, wearable technology, cueing, stimulation, motor symptoms, non-motor symptoms, systematic review, PRISMA.

I. INTRODUCTION

Parkinson's Disease (PD) is a neurodegenerative disease affecting the central nervous system, which results in the development of both motor (bradykinesia, tremor, general gait disturbance, etc.) and non-motor (neuropsychiatric symptoms, cognitive impairment, etc.) symptoms. Tremor is among the most frequent motor symptoms, affecting more than 75% of patients [1]. Freezing of Gait (FoG) manifests through the patient's inability to initiate gait or continue walking, especially while turning. On the other hand, non-motor symptoms are correlated to motor symptoms. Among them, neuropsychiatric symptoms such as depression, anxiety, and apathy occur in the majority of patients with PD (PwPD),

The associate editor coordinating the review of this manuscript and approving it for publication was Lorenzo Mucchi.

and they are associated with degraded quality of life (QoL) of patients and their close relatives [2].

According to the World Health Organization, over 8.5 million people were living with PD in 2019, a number that has doubled during the last 25 years, along with the associated healthcare costs [3].

Currently, no available therapies can reverse neurodegeneration in PD. The most common pharmacological treatment for motor symptoms is levodopa, often combined with enzyme inhibitors such as carbidopa, MAO-B inhibitors, or COMT inhibitors. Over time, long-term complications such as levodopa-induced dyskinesia, which is characterized by involuntary and erratic movements, can develop due to fluctuating dopamine levels. Another common approach for the treatment of motor symptoms is Deep Brain Stimulation (DBS), which involves surgical implantation of electrodes in the subthalamic nucleus (STN) or globus pallidus interna (GPi) to modulate abnormal brain activity, and it is best suited for patients with motor fluctuations and dyskinesias whose symptoms are refractory to traditional medication. However, DBS requires careful patient selection, as cognitive impairment or psychiatric disorders are contraindications, along with the risk of bleeding or infection given the invasive nature of the operation [4].

In addition to pharmacological and surgical approaches, non-pharmacological interventions such as cueing have been explored to support movement in PwPD [5]. Cueing involves the use of external stimuli that help regulate movement, counteracting gait impairments commonly associated with PD. From a pathophysiological perspective, cueing is thought to compensate for impaired internal movement generation by recruiting modality-specific alternative neural pathways. Rhythmic auditory cues, for example, appear to engage cerebello-thalamo-cortical circuits that support temporal prediction, thereby bypassing striatal timing deficits [6]. Visual cues, such as lines or optic flow, may rely more on parietal–premotor networks that guide externally triggered actions [7]. Sensory cues can recruit somatosensory pathways, aiding movement initiation and scaling, reducing reliance on impaired basal ganglia loops [8]. Framing cueing in this way suggests that different modalities do not simply provide general "help" but rather tap into distinct compensatory circuits to support movement. By providing either temporal structure (e.g., auditory rhythm or vibrotactile pacing) or spatial structure (e.g., visual reference cues) through these routes, cueing can reduce motor blocks such as freezing of gait and improve gait regularity [9].

Figure 1 provides an overview of the four main cueing technologies/methods for symptom mitigation in PD.

FIGURE 1. **Wearable Cueing Technologies for PD from left to right: auditory cueing, which uses rhythmic sounds such as metronomes or verbal cues to regulate gait timing; tactile cueing, providing haptic feedback through vibration to assist movement initiation; electrical cueing, which delivers proprioceptive electrical impulses to trigger or correct motor responses in real-time; and visual cueing, employing visual prompts like floor lines or laser guides to enhance step length and coordination.**

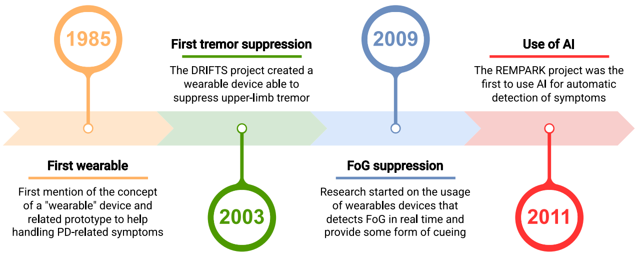

FIGURE 2. **Major milestones in wearable devices for PD cueing.**

A. CUEING TECHNOLOGIES IN PARKINSON'S DISEASE: HISTORICAL PERSPECTIVE

The application of external cueing to mitigate motor symptoms in PD has a long history, with early clinical investigations demonstrating its therapeutic potential. Figure 2 shows the major milestones achieved with cueing being applied using wearable technologies. As early as 1985, Rubow and Swift [10] pioneered the use of wearable biofeedback devices to support speech therapy in PwPD. Their microcomputer-based system provided real-time auditory feedback, enabling users to monitor and correct their speech during everyday communication. While not "wearable" in the contemporary sense (such as smart glasses or wristbands), this work was among the first to demonstrate the potential of body-worn technology to improve PD-related symptoms.

By 2003, wearable cueing systems had evolved further, as demonstrated in the DRIFTS (Dynamically Responsive Intervention for Tremor Suppression) project [11]. This initiative developed a proof-of-concept device that integrated real-time monitoring and mechanical dampening to selectively suppress upper-limb tremor frequencies, while allowing voluntary movements to continue unimpeded. This project highlighted the potential of combining sensing and actuation for targeted symptom management.

In 2009, Bächlin et al. [12] presented one of the first real-time detection systems for FoG that used wearables to detect and provide cueing in the form of audio. Their work was an important step forward in the use of wearable devices for PD rehabilitation where real-time detection of FoG events triggered cueing mechanisms. This shifted passive gait aid to a proactive approach, a change from generalized cueing to on-demand context-aware auditory feedback.

In 2011, the European Union-funded REMPARK project (Personal Health Device for the Remote and Autonomous Management of Parkinson's Disease) [13] advanced the state of wearable PD technologies by introducing a belt-worn inertial sensor for real-time detection of motor states such as ON, OFF, and dyskinesia. This system utilized machine learning algorithms to enhance detection accuracy and integrated auditory cueing to support gait when disturbances or FoG episodes were detected. With centralized data collection and remote access for clinicians, the REMPARK system enabled personalized treatment adjustments based on real-time data. Clinical trials involving 41 patients demonstrated 97% sensitivity in detecting OFF states and 88% specificity for ON states, validating the system's effectiveness.

B. CUEING TECHNOLOGIES IN PARKINSON'S DISEASE: CURRENT STATUS

In recent years, advances in wearable technology and miniaturized electronics have enabled the development of increasingly sophisticated cueing systems for PD. Modern devices now leverage wireless communication and form part of larger Wireless Sensor Networks (WSNs), allowing for seamless data transmission between multiple body-worn units and smartphones. These connected ecosystems facilitate real-time data analysis, often incorporating artificial intelligence (AI) to deliver adaptive and context-aware cueing interventions.

Today's wearable WSNs offer numerous benefits, including continuous monitoring, enhanced personalization of cueing strategies, and remote rehabilitation. They contribute to a more proactive and data-driven management of PD, especially in real-world settings beyond clinical environments.

Several recent investigations have explored the use of wearable cueing for specific motor symptoms such as FoG, gait abnormalities, and balance issues [14], [15]. For instance, studies have evaluated systems delivering somatosensory feedback through vibrotactile actuators [16], as well as auditory [17] and visual cueing [18] devices tailored for mobile use. Some systems operate continuously [19], while others employ on-demand [20] or context-aware triggering mechanisms based on detected gait disturbances [21]. The landscape of wearable cueing technology has also expanded to include targeted solutions for other motor symptoms, often overlooked, such as speech impairments [22].

This review presents a systematic classification and technical analysis of wearable cueing technologies designed for PwPD. By focusing on sensing modalities, stimulation strategies, and system architectures, it aims to provide a comprehensive overview of current capabilities and inspire future innovation in this rapidly evolving field.

To provide a comprehensive overview of the current state of wearable cueing technologies for PD, this paper is organized as follows: Section II outlines the systematic research methodology, including the search strategy, inclusion and exclusion criteria, and data extraction procedures, following PRISMA guidelines. Section III presents the results of the systematic review, offering a detailed classification of the identified technologies based on sensing modalities, stimulation types, and system configurations. Section IV discusses the main findings, technological challenges, and emerging trends in the field, with an emphasis on the potential for future integration of AI and multimodal systems. Finally, Section V provides concluding remarks and outlines future perspectives for the development and deployment of wearable cueing technologies aimed at improving the quality of life for individuals with Parkinson's disease.

```
("hearables" OR "earables" OR "wearable" OR "sensor" OR
↪  "smart-watch" OR "smart watch" OR "smart-glasses" OR
↪  "smart glasses" OR "monitoring" OR "WBAN" OR "WSN" OR
↪  "BSN" OR "Wireless")
AND ("Parkinson" OR "PD" OR "Parkinsons" OR "PwPD" OR
↪  "Parkinson's")
AND ("motor symptoms" OR "tremor" OR "bradykinesia" OR
↪  "rigidity" OR "postural instability" OR "FoG" OR
↪  "freezing of gait" or "non-motor symptoms" OR "non
↪  motor symptoms" OR "speech-related symptoms" OR
↪  "speech")
AND ("stimulation" OR "cueing" OR "vibration" OR "audio"
↪  OR "visual" OR "tactile")
```

Listing 1. Boolean search query.

II. METHODS

A. RESEARCH QUESTIONS, ELIGIBILITY CRITERIA, AND SEARCH STRATEGY

We conducted a systematic literature search to investigate the use of wearable technologies designed to provide cueing support for PwPD. This review explicitly targets studies that introduced wearable systems capable of delivering any form of cueing to mitigate PD-related symptoms, whether motor or non-motor. Studies focusing solely on symptom detection without any cueing intervention were excluded.

The databases consulted for this review were IEEE Xplore, PubMed, Scopus, and Web of Science. The primary research question for this review was:

> *What are the current trends in wearable cueing technologies for Parkinson's disease (PD) symptoms management?*

To address this overarching question, we formulated the following sub-questions:

- What cueing technologies currently exist for the management of PD?
- How can these technologies be categorized based on the type of stimulation and the targeted symptoms?
- What are the main limitations and knowledge gaps in the existing literature on wearable cueing interventions?

On such aim, the search query in Listing 1 was constructed to capture relevant studies involving wearable cueing technologies for PD.

Table 1 summarizes the number of articles retrieved from each source by October 24th, 2024.

B. GENERAL OVERVIEW OF THE SCREENING PROCESS

The PRISMA framework guidelines were followed. Figure 3 illustrates the overall screening process following a three-stage workflow. To manage the process, we utilized the

TABLE 1. Results for source database.

IEEE Xplore	PubMed	Scopus	Web of Science	Total
185	255	795	405	1640

TABLE 2. Inclusion/Exclusion criteria for article selection.

Inclusion Criteria	Exclusion Criteria
• Studies published in English	• Papers not in English
• Studies involving wearable cueing technologies for PD management	• Review papers and non-primary studies
• Full-text articles available	• Papers presenting wearable technology not able to provide cueing
• Studies that tested the wearable cueing on at least a PD patient	• Papers about non-wearable cueing technologies (e.g., DBS)
	• Pure abstracts or posters without full text

Rayyan software tool (https://rayyan.ai/). After importing search results, duplicate entries were removed automatically. Two reviewers (MI and FD) independently screened the titles and abstracts of the remaining studies based on predefined inclusion and exclusion criteria (Table 2).

In cases of uncertainty, feedback was sought from a clinical neurologist (JMG), who provided clinical insights to support decision-making.

Further, discrepancies between reviewers were discussed, and consensus was reached before proceeding to the full-text evaluation phase. Relevant information from the selected articles was extracted and analyzed systematically.

In detail, the initial search returned a total of 1,640 studies. After the removal of duplicates, 1,004 unique studies remained. Of these, 110 met the inclusion criteria applied during title and abstract screening, and 39 were deemed suitable following full-text evaluation.

Finally, we acknowledge that a formal risk-of-bias (RoB) assessment was not conducted in this review. This decision is consistent with the primary technological focus of this review, which systematically evaluates device architectures and stimulation designs rather than clinical efficacy outcomes, for which traditional RoB instruments are intended.

To support the reader in assessing study quality, we included a detailed account of each study's reported limitations in Table 6. While this does not replace a formal RoB evaluation, it offers practical insights into the methodological robustness and generalizability of the reviewed technologies.

C. OVERVIEW OF EXISTING SURVEYS

To ensure the novelty and relevance of this work, we examined the most significant recent reviews focusing on wearable cueing technologies for PD. Out of the 1,640 records initially retrieved, 131 were review articles, six of which investigated cueing devices for PD, but usually focusing on a single symptom like FoG. A comparative summary of these surveys and the present work is provided in Table 3, with a focus on the cueing modalities and symptom categories. A checkmark (✓) denotes coverage, while a cross (✗) indicates no coverage.

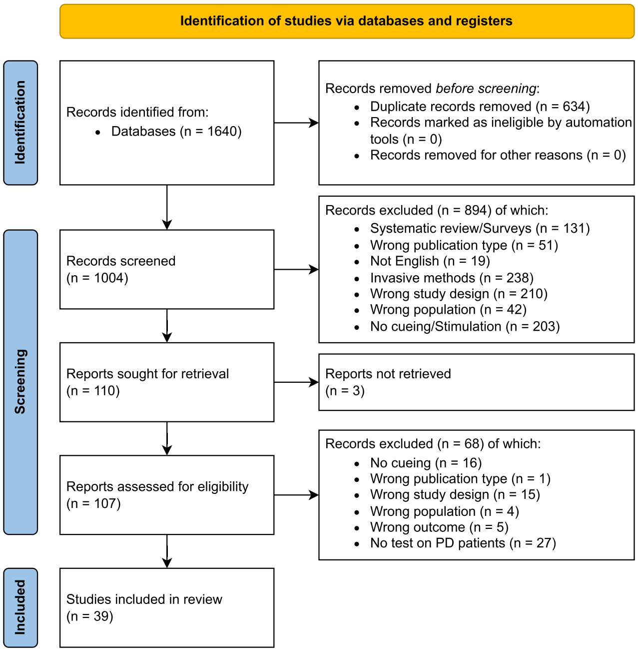

FIGURE 3. PRISMA flow diagram of the screening and selection process.

In 2019, Sweeney et al. [24] conducted a review of wearable auditory, visual, and somatosensory cueing systems aimed explicitly at reducing FoG in PD. A total of 18 studies were included, presenting various cueing modalities and strategies, such as continuous and on-demand stimulation. This review contributed valuable insights into the design and application of sensory cueing for gait freezing but focused exclusively on FoG-related interventions.

In 2021, Gonçalves et al. [25] provided a technical overview of vibrotactile cueing devices designed to address gait impairments, balance deficits, and fall risk in PD. The authors reviewed 11 studies, evaluating each system based on its actuation components, sensory input mechanisms, and control architecture. The review concentrated specifically on haptic feedback technologies, highlighting design trade-offs and clinical applicability.

More recently, in 2024, Zhang et al. [28] published a systematic review and meta-analysis of randomized controlled trials assessing the impact of wearable cueing devices on motor function and gait in PD. Seven randomized controlled trials were included, and the analysis showed a statistically significant improvement in walking speed. However, no significant changes were observed in broader motor metrics, such as the UPDRS-III, FoG Questionnaire scores, or other spatiotemporal gait parameters.

While previous reviews have significantly contributed to the field by addressing specific cueing modalities or targeting a subset of motor symptoms in PD, they often lack comprehensive coverage across both symptom categories and stimulation types. As shown in Table 3, most surveys primarily focus on FoG and select motor impairments, with limited or no attention given to non-motor symptoms.

TABLE 3. Comparison with previous reviews.

Ref.	Motor Symptoms						Non-Motor	Cueing Approach			
(Start-End Years)	FoG	Tremor	Postural Inst.	Gait dist.	Dyskinesia	Bradykinesia	Symptoms	Tactile	Audio	Visual	Electrical
[23] (2007-2017)	✓	✗	✓	✓	✗	✗	✗	✗	✓	✓	✗
[24] (2009-2018)	✓	✗	✗	✗	✓	✓	✗	✓	✓	✓	✓
[25] (2010-2020)	✓	✗	✓	✓	✗	✓	✗	✓	✗	✗	✗
[26] (2018-2021)	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓	✗
[27] (2000-2021)	✓	✗	✗	✗	✗	✗	✗	✓	✓	✓	✗
[28] (–2022)	✓	✗	✗	✓	✗	✗	✗	✗	✓	✓	✗
Our (–2024)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Furthermore, cueing strategies are typically restricted to one or two modalities, most commonly auditory or visual cues, with minimal exploration of tactile or electrical stimulation.

In contrast, this review (Row 7-Table 3) offers a holistic analysis of wearable cueing systems by encompassing all four major cueing modalities: tactile, auditory, visual, and electrical and by addressing both motor and non-motor symptoms. As highlighted in the comparison, this is the only review that systematically evaluates cueing technologies across the full spectrum of Parkinsonian symptoms, including tremor, dyskinesia, festination, and speech impairments, and that classifies the technologies according to their stimulation approach, target symptom, and technological implementation.

III. REVIEW RESULTS

To guide the analysis of the 39 selected studies, we developed a five-dimensional taxonomy that serves as the central framework for classification. This taxonomy is presented in Figure 4, which categorizes the reviewed systems according to 1) stimulation modality, 2) cueing strategy, 3) body placement, 4) sensing approach, and 5) symptom category. The latter includes a detailed breakdown of motor symptoms (such as tremor, bradykinesia, and FoG) while highlighting that no devices were identified as targeting non-motor impairments. The top and bottom axes of the figure represent mutually exclusive categories, whereas the left and right axes allow for non-exclusive classification, reflecting the multimodal and multi-symptom characteristics of many wearable cueing systems.

This visual taxonomy is complemented by a comprehensive synthesis of the selected studies, organized along key dimensions extracted from Tables 4 and 5. These tables summarize the studies based on their targeted symptoms, testing environments, cueing target regions, cueing timing strategies, and cueing modalities, providing a structured foundation for the analysis presented in the following sections.

> ***How to use Tables 4 and 5:*** *This table is designed to offer a high-level overview of the included studies, based on the types of PD symptoms addressed, cueing/stimulation modalities used, body regions targeted, and the environments in which interventions were tested. It allows researchers to quickly locate works that match specific research needs or application scenarios.*
>
> *Example 1:* If you are interested in studies addressing **bradykinesia**, using **tactile** stimulation, applied **at home**, and delivered to the **arm**, you can use this table to filter studies that meet all these criteria, facilitating a fast and focused literature retrieval.
>
> *Example 2:* If you aim to develop a wearable system for **FoG** that delivers **audio cues** to the **head** in a **home** setting using an **hybrid-based** approach, this table enables quick identification of similar studies and benchmarking points.

Table 6 instead goes into more detail for each study, presenting objective, results, and main limitations reported in the articles.

A. TARGETED SYMPTOMS

All of the studies reviewed focused on motor symptoms of PD, reflecting the central role of movement impairments in both diagnosis and daily-life disability. Among these, gait-related symptoms were the most frequently targeted, especially FoG, with a few studies including shuffling and festination, followed by tremor, postural instability, and bradykinesia. Despite our inclusion criteria explicitly considering non-motor symptoms, no wearable cueing technologies were identified that targeted domains such as cognitive impairment, mood, anxiety, or sleep disturbances. The only partial exception was a study addressing hypophonia, which, while affecting communication, remains a motor symptom since it involves vocal musculature rather than non-motor pathways.

1) FoG

FoG was the most frequently addressed symptom, with 29 studies proposing cueing solutions for mitigating FoG episodes, as shown in [21], [30], [35], [57], and [58] (see Figure 4 for full coverage). An interesting topic is the gradual change of the approach to FoG detection and mitigation, that has evolved substantially over time. Early systems, such as the work by Bächlin et al. [58], relied on handcrafted features and threshold-based classification

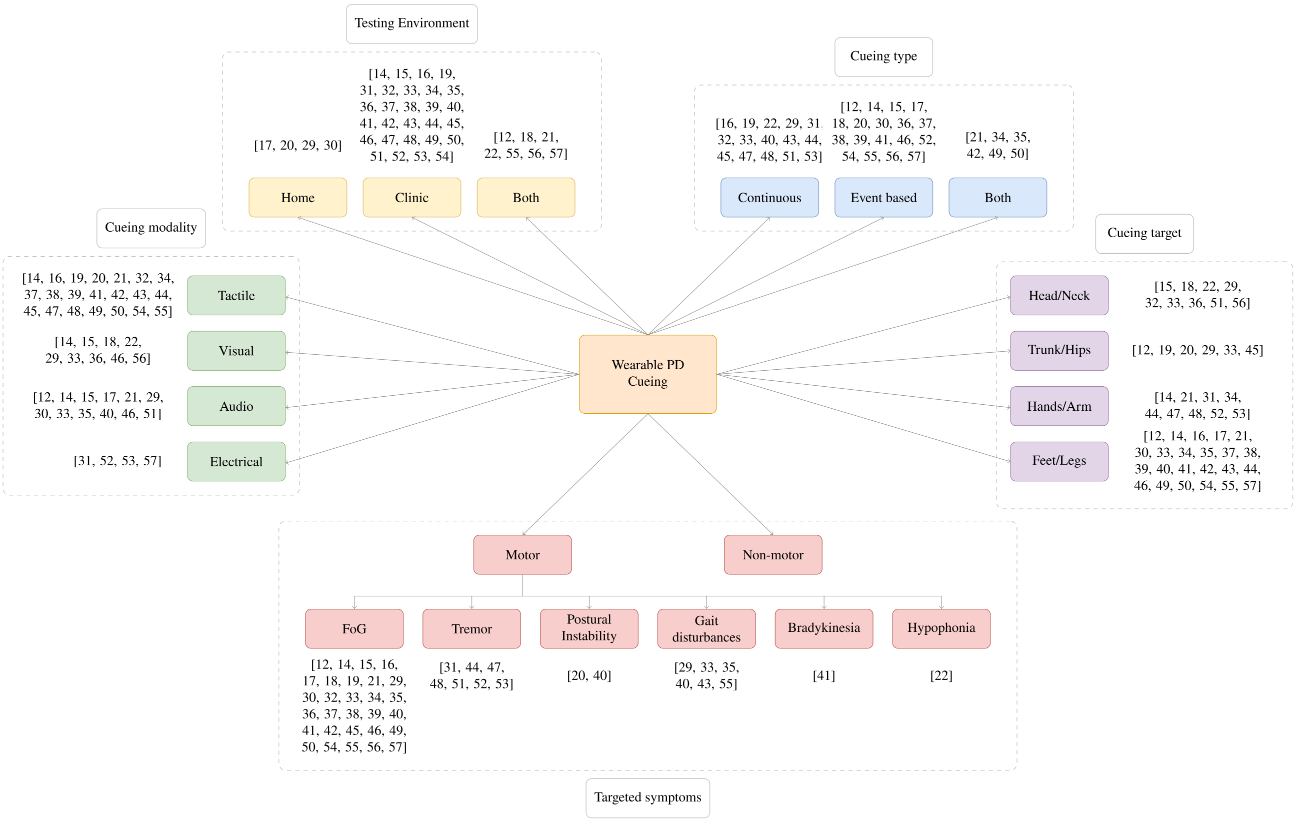

FIGURE 4. **Overview of the included studies categorized by stimulation modality, targeted symptom, cueing strategy, and body placement. This figure serves as a high-level taxonomy; for a more granular view of overlapping features and hybrid systems, please refer to Table 4.**

using inertial sensors for real-time FoG detection. These systems prioritized simplicity and computational feasibility, but were prone to false positives and limited generalizability across patient profiles. In contrast, recent studies like that of Dvorani et al. [57] have adopted machine learning models running on embedded edge devices, allowing for adaptive, personalized FoG detection with higher accuracy and real-time responsiveness.

2) TREMOR

Tremor was addressed in 7 studies such as [48] and [52] (see Figure 4 for full coverage), with notable advancements in wearable technologies. For instance, Schaik et al. [48] tested the "Emma Watch", a vibratory device designed to suppress action tremor through mechanical stimulation. Their pilot study indicated improved hand steadiness and reduced tremor amplitude, suggesting that non-invasive, real-time feedback can provide meaningful symptom relief in daily activities. Complementary to this, Habibollahi et al. [52] explored phase-locked peripheral electrical stimulation for tremor suppression, systematically analyzing timing and waveform characteristics, and highlighting the importance of synchronization in maximizing treatment efficacy.

3) POSTURAL INSTABILITY

Postural instability received limited attention, appearing in only 2 studies [20], [40]. van Wegen et al. [20] proposed a sensor-assisted posture detection system that provided real-time feedback to patients exhibiting a stooped posture. While not a cueing device in the strict rhythmic or event-based sense, the system actively encouraged upright posture correction through feedback, contributing to improved postural alignment. Similarly, Szydlowski et al. [40] evaluated auditory cueing in a rehabilitation context, reporting functional improvements in balance and posture. Although relatively underexplored, these studies suggest that wearable cueing or feedback mechanisms can offer benefit in fall prevention and mobility training for individuals with postural instability.

4) GAIT DISTURBANCES

Beyond episodic freezing, 5 studies addressed more general gait disturbances, such as reduced step length, irregular cadence, or instability. These interventions aimed to improve gait quality and regularity through rhythmic cueing. For instance, Winfree et al. [55] evaluated a rhythmic auditory stimulation system that provided metronome-like beats to enhance step timing and symmetry. Their results showed improved stride regularity and walking speed. Similarly, Brognara et al. [43] tested a wearable vibrotactile cueing system that delivered rhythmic pulses to the lower limbs, reporting increased cadence and reduced variability in gait patterns. These studies suggest that even in the absence of discrete freezing episodes, rhythmic cueing can support

TABLE 4. Classification of the included studies based on symptom type, test environment, cueing target, type, and approach.

Ref.	Symptom							Environment			Cueing target				Cueing type			Approach			
	FoG	Tremor	Postural Inst.	Gait dist.	Dyskinesia	Bradykinesia	Hypophonia	Home	Clinic	Hybrid	Head/Neck	Trunk/Hips	Arm/Hands	Legs/Feet	Continuous	Event based	Both	Tactile	Visual	Audio	Electrical
[12]	✓	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✓	✗	✓	✗	✓	✗	✗	✗	✓	✗
[29]	✓	✗	✗	✓	✗	✗	✗	✓	✗	✗	✓	✓	✗	✗	✓	✗	✗	✗	✓	✓	✗
[31]	✗	✓	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✓	✗	✓	✗	✗	✗	✗	✗	✓
[55]	✓	✗	✗	✓	✗	✗	✗	✗	✗	✓	✗	✗	✗	✓	✗	✓	✗	✓	✗	✗	✗
[21]	✓	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✓	✓	✗	✗	✓	✓	✗	✓	✗
[30]	✓	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✗	✓	✗	✓	✗	✗	✗	✓	✗
[32]	✓	✗	✗	✗	✗	✗	✗	✗	✓	✗	✓	✗	✗	✗	✓	✗	✗	✓	✗	✗	✗
[22]	✗	✗	✗	✗	✗	✗	✓	✗	✗	✓	✓	✗	✗	✗	✓	✗	✗	✗	✓	✗	✗
[33]	✓	✗	✗	✓	✗	✗	✗	✗	✓	✗	✓	✓	✗	✓	✓	✗	✗	✗	✓	✓	✗
[34]	✓	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✗
[35]	✓	✗	✗	✓	✗	✗	✗	✗	✓	✗	✗	✗	✗	✓	✗	✗	✓	✗	✗	✓	✗
[36]	✓	✗	✗	✗	✗	✗	✗	✗	✓	✗	✓	✗	✗	✗	✗	✓	✗	✗	✓	✗	✗
[14]	✓	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✓	✓	✗	✓	✗	✓	✓	✓	✗
[37]	✓	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✓	✗	✓	✗	✓	✗	✗	✗
[20]	✗	✗	✓	✗	✗	✗	✗	✓	✗	✗	✗	✓	✗	✗	✗	✓	✗	✓	✗	✗	✗
[19]	✓	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✓	✗	✗	✓	✗	✗	✓	✗	✗	✗
[38]	✓	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✓	✗	✓	✗	✓	✗	✗	✗
[39]	✓	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✓	✗	✓	✗	✓	✗	✗	✗
[40]	✓	✗	✓	✓	✗	✗	✗	✗	✓	✗	✗	✗	✗	✓	✓	✗	✗	✗	✗	✓	✗
[41]	✓	✗	✗	✗	✗	✓	✗	✗	✓	✗	✗	✗	✗	✓	✗	✓	✗	✓	✗	✗	✗
[42]	✓	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✓	✗	✗	✓	✓	✗	✗	✗
[43]	✗	✗	✗	✓	✗	✗	✗	✗	✓	✗	✗	✗	✗	✓	✓	✗	✗	✓	✗	✗	✗
[44]	✗	✓	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✓	✓	✓	✗	✗	✓	✗	✗	✗
[45]	✓	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✓	✗	✗	✓	✗	✗	✓	✗	✗	✗
[56]	✓	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✗	✗	✗	✗	✓	✗	✗	✓	✗	✗
[46]	✓	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✓	✗	✓	✗	✗	✓	✓	✗
[47]	✗	✓	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✓	✗	✓	✗	✗	✓	✗	✗	✗
[48]	✗	✓	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✓	✗	✓	✗	✗	✓	✗	✗	✗
[49]	✓	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✓	✗	✗	✓	✓	✗	✗	✗
[50]	✓	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✓	✗	✗	✓	✓	✗	✗	✗
[51]	✗	✓	✗	✗	✗	✗	✗	✗	✓	✗	✓	✗	✗	✗	✓	✗	✗	✗	✗	✓	✗
[15]	✓	✗	✗	✗	✗	✗	✗	✗	✓	✗	✓	✗	✗	✗	✗	✓	✗	✗	✓	✓	✗
[18]	✓	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✗	✗	✗	✗	✓	✗	✗	✓	✗	✗
[17]	✓	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✗	✓	✗	✓	✗	✗	✗	✓	✗
[52]	✗	✓	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✓	✗	✗	✓	✗	✗	✗	✗	✓
[57]	✓	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✓	✗	✓	✗	✗	✗	✗	✓
[53]	✗	✓	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✓	✗	✓	✗	✗	✗	✗	✗	✓
[16]	✓	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✓	✓	✗	✗	✓	✗	✗	✗
[54]	✓	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✓	✗	✓	✗	✓	✗	✗	✗

smoother and more stable gait in people with PD. Common gait disturbances such as shuffling gait and festination, which are characterized by small and rapid steps, were only marginally addressed in the reviewed studies, despite their prevalence and disabling impact. Zhao et al. [21] introduced a multi-cue unit that provided vibratory and visual feedback to regulate step length and cadence. Though primarily designed for FoG, the device showed secondary improvements in shuffling patterns by enhancing rhythmic step timing. Similarly, cueing systems that focused on real-time cadence feedback [30] helped reduce festination severity in clinical observations, though these outcomes were often not explicitly reported.

5) BRADYKINESIA AND DYSKINESIA

Although less frequently targeted, a few studies attempted to address upper limb bradykinesia through cueing strategies. Maneski et al. [31] employed functional electrical stimulation (FES) of forearm muscles to support voluntary motion in patients with upper limb slowness. Their approach enhanced motor output during fine tasks, suggesting that wearable electrical cueing could serve as a compensatory aid in bradykinetic movements. However, most such interventions remain exploratory and lack validation in daily-life contexts. We identified no studies exploring wearable cuing devices for the treatment of dyskinesia. It is medication-induced, most commonly related to levodopa, and involves excessive, involuntary movement. Unlike voluntary motor impairment, dyskinesia arises from abnormally increased motor drive within the basal ganglia. External cues can assist voluntary motor control by providing additional guidance or timing, but they cannot "override" the involuntary neural activity underlying dyskinesia.

6) HYPOPHONIA

One of the few works addressing speech-related impairments was by McNaney et al. [22], who developed "LApp", a Google Glass-based application offering real-time biofeedback for voice loudness in people with PD. By providing visual cues during speech, the system helped users self-regulate their vocal volume, a critical skill often diminished by hypophonia. While promising, such approaches remain rare, and voice-related cueing has not yet seen the same integration into wearable multi-symptom platforms as motor cueing has.

7) OTHER SYMPTOMS

Dyskinesia, often a side effect of dopaminergic therapy, was not directly targeted by cueing in any of the reviewed studies. Overall, the strong skew toward motor symptoms like FoG and tremor reflects a continued gap in addressing secondary and non-motor symptoms of PD through wearable interventions.

B. TESTING ENVIRONMENT

Regarding the testing environments, most studies were conducted in clinical settings (28 out of 39) as reported in [14], [33], and [43] (see Figure 4 for full coverage), while only 4 studies tested cueing devices in home-based environments [29], [30] (see Figure 4 for full coverage). A small group of 7 studies adopted a hybrid approach, combining lab and real-world environments to assess the generalizability of the cueing systems [18], [56]. This highlights the need for further validation in ecologically valid, daily life contexts.

1) CLINIC-BASED

Historically, earlier studies prioritized tightly controlled lab or clinical environments to test proof-of-concept systems, such as the initial augmented-reality cueing device evaluated by Espay et al. [29], which relied on structured trials to monitor cueing efficacy and patient responsiveness. These trials ensured safety and repeatability but limited external validity. More recent studies, such as Zoetewei et al. [17] and Geerse et al. [56], have emphasized home deployment and hybrid setups, incorporating wearable sensors and real-time feedback in uncontrolled environments. This shift not only increases systems' applicability in different scenarios, but also enables user-centric adaptation and actual help in everyday life activities. However, it also introduces challenges such as device adherence, sensor noise, and network dependency, factors that future work must address to bridge the gap between lab-based efficacy and real-world effectiveness. Within clinical settings, several standardized techniques were employed to ensure reliable symptom assessment and cueing evaluation. Gait analysis was typically performed using tools such as pressure-sensitive walkways, inertial measurement units (IMUs), or motion capture systems to track stride length, cadence, and variability. For studies targeting FoG, protocols like the Timed Up and Go (TUG), 360-degree turning tests, or obstacle navigation tasks were common, as they are known to provoke freezing episodes in controlled ways [30], [33]. The TUG test, one of the most widely used, involves having the patient stand up from a chair, walk three meters, turn, return, and sit down, offering a composite measure of gait initiation, balance, and turning ability, all of which are sensitive to freezing episodes. Similarly, 360-degree turning tests and narrow-passage walking tasks are employed to trigger FoG, particularly in confined or direction-changing scenarios. Some studies integrated dual-task paradigms, requiring patients to walk while solving cognitive tasks, to examine cueing effects under more realistic multitasking conditions [29]. In these cases, patients are often asked to perform a cognitive task (e.g., serial subtraction or word generation) while walking, simulating the multitasking demands of daily life. This setup is especially relevant for assessing the robustness of cueing under attentional load. For tremor, accelerometry and gyroscopic sensors were widely used to quantify amplitude and frequency in both resting and action phases [48], [52]. These methodological choices reflect an increasing effort to simulate the cognitive and biomechanical complexity of real-world scenarios, even within constrained environments.

2) HOME-BASED

Only 4 studies tested cueing systems in home or everyday settings [17], [29], which offer greater real-world relevance but pose significant technical challenges. Home-based setups enabled continuous monitoring and feedback without clinical supervision, allowing researchers to observe user interaction in unstructured, real-life contexts. For instance, Mazilu et al. [30] evaluated the GaitAssist system in unsupervised environments, while Zoetewei et al. [17] ran on-demand cueing trials directly in participants' homes. These studies highlighted practical factors like comfort, compliance, and long-term usage patterns that are often missed in short-term clinical assessments.

3) HYBRID

A small but growing group of 7 studies adopted a hybrid testing approach, combining lab evaluations with real-world trials to enhance both internal validity and ecological realism [18], [56]. For example, Geerse et al. [56] integrated holographic visual feedback and evaluated both gait performance and usability in mixed settings. Hybrid methods allow researchers to validate technical functionality in the lab, and then assess real-world usability, robustness, and user adaptation over time. However, they also introduce challenges like variability in sensor performance, environmental noise, and adherence issues that must be managed through careful protocol design.

C. CUEING TARGETS

Wearable devices were most commonly applied to the lower limbs, particularly the legs and feet, which were targeted in 23 studies as shown in [16], [41], and [42] (see Figure 4 for full coverage). This is consistent with the dominance of gait-related symptoms like FoG. Other target regions included the head/neck (e.g., for visual or auditory feedback via smart glasses or headsets like [29] and [36]), and the trunk/hips, often for sensor placement or vibration-based feedback [45]. A smaller number of studies focused on the arms, wrists, and hands, mostly for addressing tremor or upper limb bradykinesia like [31] and [48].

Over time, cueing targets have evolved from single-site placements to more integrated, multi-site systems. Early interventions largely focused on the feet or shins for rhythmic cueing to address FoG, prioritizing simplicity and step synchronization. Recent studies, however, have explored multimodal cueing across multiple body regions, such as combining auditory signals from head-mounted devices with tactile feedback on the ankles or waist such as [46] and [56]. Additionally, ergonomics and user acceptance have become increasingly influential: wrist-worn devices for tremor suppression, such as the Emma Watch [48], capitalize on social familiarity and comfort, while smart glasses offer hands-free interaction for visual cueing without restricting mobility.

1) HEAD/NECK

Espay et al. [29] demonstrated one of the earliest uses of a head-mounted augmented reality system, which provided continuous visual cues to aid gait in Parkinson's patients. Their system enabled patients to "step over" visual obstacles projected into their field of view, effectively mitigating FoG during indoor walking. The head-mounted design allowed for intuitive alignment with the user's visual field, improving spatial orientation and step initiation. More recently, Ahn et al. [36] developed Smart Gait-Aid Glasses incorporating visual markers and embedded sensors, showing improved usability and reduced cognitive load compared to handheld devices.

2) TRUNK/HIPS

Wilhelm et al. [45] explored trunk-based placement of a vibrotactile cueing device that provided hip-level stimuli to reduce FoG. Their study focused on design acceptance and indicated high user tolerability, particularly for older adults. By integrating the system near the body's center of mass, trunk cueing enabled bilateral stimulation aligned with natural gait cycles, offering promising results in improving rhythmic stepping. The central positioning also allowed the device to remain unobtrusive under clothing, enhancing wearability for daily use.

3) HANDS/ARM

Maneski et al. [31] implemented electrical stimulation for tremor suppression on the forearm muscles of Parkinson's patients, achieving significant reductions in tremor amplitude during controlled movements. This approach directly targeted the neuromuscular loop involved in tremor generation. More recently, Pacheco et al. [48] evaluated the Emma Watch, a wrist-worn vibratory cueing system that addressed action tremor. Their feasibility study showed improved task performance and strong user acceptance, validating the potential of wrist devices for discreet, daily-use tremor management.

4) FEET/LEGS

Koopman et al. [41] developed vibrating socks to support gait in Parkinson's disease, showing improved step regularity and rhythm. These socks delivered periodic tactile cues synchronized with the gait cycle. Similarly, Cen et al. [16] evaluated a vibrotactile foot device and reported significant reduction in FoG frequency and improved walking speed. The feet remain a highly effective cueing site due to their proximity to gait mechanics and responsiveness to rhythmic sensory input.

D. CUEING TYPE

The choice of cueing strategy often aligned with the symptom profile being targeted. Event-based cueing was particularly favored for episodic symptoms like FoG, where brief bursts of stimulation (triggered by gait anomalies or motion pauses) helped to re-initiate locomotion with minimal user fatigue. In contrast, continuous cueing proved more effective for persistent symptoms such as tremor or general gait instability, offering steady sensory input to stabilize motion patterns. Recent systems have advanced toward adaptive hybrid models that modulate cue type in response to detection reliability or user state.

1) EVENT-BASED

Cueing was most commonly delivered in an event-based manner (18 studies), where stimulation is triggered based on real-time symptom detection or pre-defined events as demonstrated in [30] and [38] (see Figure 4 for full coverage).

While continuous stimulation strategies do not require any signal processing step, event-driven approaches involve computer methods to trigger stimulation upon detection of a specific event or symptom. In this context, diverse data processing pipeline were proposed, with different complexity and applications. Cen et al. [16] proposed a wearable system that provides vibrotactile stimulation of the foot during the stance phase of walking. Cues are activated when pressure is registered under the foot (initial contact), and deactivated when no pressure is registered (final contact). In this case, the activation is based on a simple "switch" (on/off) approach. Maneski et al. [31] performed a zero-crossing analysis of the angular velocity signal recorded from the wrist to extract the dominant frequency. Tremor phase and frequency were extracted, and the system applied electrical stimulation to antagonist muscles out of phase with the agonist muscle's activity. In that case, tremor features are essential to provide an effective stimulation. Threshold-based methods represent simple processing algorithms that activate cues as soon as specific metrics exceed pre-defined thresholds. For example, Harrington et al. [34] used real-time gait phase estimation and freezing prediction from inertial data to trigger tactile stimulation during specific gait events. Cueing was activated when gait cycle parameters deviated from expected phase timings. Similarly, Habibollahi et al. [52] extracted tremor frequency and amplitude using wrist-worn sensors and activated electrical stimulation when these measures crossed predefined thresholds, demonstrating phase-locked cueing for effective tremor suppression. Khatavkar et al. [54] exploited infrared proximity sensors to calculate the foot-to-ground angle (FGA) and pressure sensitive insoles to compute the ground reaction force (GRF). Vibrotactile cues are activated only when both the FGA and GRF exceed specific thresholds. More advanced methods involve the use of machine learning models to automatically recognize specific symptoms and activate cues. Zoetewei et al. [17] extracted specific features (left-right cross-correlation, asymmetry, gait amplitude, freezing index) from acceleration and angular velocity signals and fed them to a Linear Discriminant Analysis (LDA) classifier. This resulted in a subject-independent (general) model that can predict FoG on new unseen subjects. Some studies exploited end-to-end deep learning models to provide fast and accurate cues. Dvorani et

TABLE 5. Taxonomy of the selected studies classified per different categories.

		Environment			Cueing Mode			Cueing Approach			
		Home	**Clinic**	**Hybrid**	**Continuous**	**Event Based**	**Both**	**Tactile**	**Visual**	**Audio**	**Electrical**
Target Motor Symptom	**FoG**	[17, 29, 30]	[14, 15, 16, 19, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 45, 46, 49, 50, 54]	[12, 18, 21, 55, 56, 57]	[16, 19, 29, 32, 33, 40, 45]	[12, 14, 15, 17, 18, 30, 36, 37, 38, 39, 41, 46, 54, 55, 56, 57]	[21, 34, 35, 42, 49, 50]	[14, 16, 19, 21, 32, 34, 37, 38, 39, 41, 42, 45, 49, 50, 54, 55]	[14, 15, 18, 29, 33, 36, 46, 56]	[12, 14, 15, 17, 21, 29, 30, 33, 35, 40, 46]	[57]
	Tremor		[31, 44, 47, 48, 51, 52, 53]		[31, 44, 47, 48, 51, 53]	[52]		[44, 47, 48]		[51]	[31, 52, 53]
	Postural Instability	[20]	[40]		[40]	[20]		[20]		[40]	
	Gait Disturbance	[29]	[33, 35, 40, 43]	[55]	[29, 33, 40, 43]	[55]	[35]	[43, 55]	[29, 33]	[29, 33, 35, 40]	
	Bradykinesia		[41]			[41]		[41]			
	Speech			[22]	[22]				[22]		
Environment	**Home**				[29]	[17, 20, 30]		[20]	[29]	[17, 29, 30]	
	Clinic				[16, 19, 31, 32, 33, 40, 43, 44, 45, 47, 48, 51, 53]	[14, 15, 36, 37, 38, 39, 41, 46, 52, 54]	[34, 35, 42, 49, 50]	[14, 16, 19, 32, 34, 37, 38, 39, 41, 42, 43, 44, 45, 47, 48, 49, 50, 54]	[14, 15, 33, 36, 46]	[14, 15, 33, 35, 40, 46, 51]	[31, 52, 53]
	Hybrid				[22]	[12, 18, 55, 56, 57]	[21]	[21, 55]	[18, 22, 56]	[12, 21]	[57]
Cueing Mode	**Continuous**							[16, 19, 32, 43, 44, 45, 47, 48]	[22, 29, 33]	[29, 33, 40, 51]	[31, 53]
	Event-based							[14, 20, 37, 38, 39, 41, 54, 55]	[14, 15, 18, 36, 46, 56]	[12, 14, 15, 17, 30, 46]	[52, 57]
	Both							[21, 34, 42, 49, 50]		[21, 35]	
Target	**Head**	[29]	[15, 33, 36, 51]	[18, 22, 56]	[22, 29, 33, 51]	[15, 18, 36, 56]			[15, 18, 22, 29, 33, 36, 56]	[15, 29, 33, 51]	
	Neck		[32]		[32]			[32]			
	Trunk	[20]	[19, 45]	[12]	[19, 45]	[12, 20]		[19, 20, 45]		[12]	
	Hip	[29]	[33]		[29, 33]				[29, 33]	[29, 33]	
	Arm			[21]			[21]	[21]		[21]	
	Hand		[14]			[14]		[14]	[14]	[14]	
	Elbow		[31]		[31]						[31]
	Wrist		[31, 34, 44, 47, 48, 52, 53]	[21]	[31, 44, 47, 48, 53]	[52]	[21, 34]	[21, 34, 44, 47, 48]		[21]	[31, 52, 53]
	Thigh			[12]		[12]				[12]	
	Legs		[14, 33, 38, 39, 49]	[21, 57]	[33]	[14, 38, 39, 57]	[21, 49]	[14, 21, 38, 39, 49]	[14, 33]	[14, 21, 33]	[57]
	Ankle	[30]	[37, 42, 44]	[12, 21]	[44]	[12, 30, 37]	[21, 42]	[21, 37, 42, 44]		[12, 21, 30]	
	Feet	[17]	[16, 33, 34, 35, 37, 40, 41, 43, 46, 50, 54]	[55, 57]	[16, 33, 40, 43]	[17, 37, 41, 46, 54, 55, 57]	[34, 35, 50]	[16, 34, 37, 41, 43, 50, 54, 55]	[33, 46]	[17, 33, 35, 40, 46]	[57]
Technology	**Hearables**	[29]	[51]	[12]	[29, 51]	[12]			[29]	[12, 29, 51]	
	Smartwatch		[48]		[48]			[48]			
	Smartglasses	[29]	[15, 33, 36]	[18, 22]	[22, 29, 33]	[15, 18, 36]			[15, 18, 22, 29, 33, 36]	[15, 29, 33]	
	Smartphone	[30]				[30]				[30]	
	Commercial wearables	[29]	[15, 32, 48]	[18, 56]	[29, 32, 48]	[15, 18, 56]		[32, 48]	[15, 29, 56]	[15, 29]	
	Research wearables	[17, 20, 30]	[14, 16, 19, 31, 34, 35, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 49, 50, 52, 53, 54]	[12, 21, 55, 57]	[16, 19, 31, 40, 43, 44, 45, 47, 53]	[12, 14, 17, 20, 30, 37, 38, 39, 41, 46, 52, 54, 55, 57]	[21, 34, 35, 42, 49, 50]	[14, 16, 19, 20, 21, 34, 37, 38, 39, 41, 42, 43, 44, 45, 47, 49, 50, 54, 55]	[14, 18, 46]	[12, 14, 17, 21, 30, 35, 40, 46]	[31, 52, 53, 57]

Commericial/Research wearables categories concern devices such as: anklets, wristbands, belts, socks or shoe-based devices, etc.

al. [57] developed a neural network-based system for real-time detection of gait phases and freezing episodes using raw inertial data. The model was implemented on a wearable edge device and triggered electrical cueing based on detected gait disturbances, thus avoiding reliance on hand-crafted features and extensive pre-processing. However, this case study includes only two participants and as such, the evidence remains insufficient.

2) CONTINUOUS

Continuous cueing was employed in 15 studies such as [29], especially for tremor suppression or rhythmic pacing. In contrast to event-based systems, continuous cueing proved more effective for persistent symptoms such as tremor or general gait instability, offering steady sensory input to stabilize motion patterns. These systems often rely on fixed-frequency stimulation (vibratory, auditory, or electrical) delivered

TABLE 6. Objective, results, and limitations of the included papers.

Ref.	Objective	Results	Limitations
[12]	Develop and evaluate a wearable system that detects FoG episodes in real-time and provides auditory cues to assist PD patients	Achieved 81.6% specificity in detecting FoG, most patients reported a benefit from the automatic cueing	Small sample size, short duration of the study, need for further real-world testing to validate the system's effectiveness
[29]	Evaluate effectiveness of a closed-loop visual-auditory cueing device in improving gait in PD patienets through at-home-training	Device significantly improved walking velocity and stride length both during use and after removal, FoG questionnaire also improved, overall gait improvement	Small sample size, lack of a control group, and variability in patient response to the device
[31]	Develop and test a system that uses electrical stimulation to suppress pathological tremor by activating antagonistic muscles out-of-phase with tremorogenic activation	Reduced tremor amplitude in 6 out of 7 patients by an average of 67 ± 13%	System's effectiveness varied among patients, and continuous assessment of tremor frequency and phase was challenging due to the interference of stimulation-generated muscle activity
[55]	Develop and test the PDShoe, a step-synchronized vibratory feedback device, and evaluate its effectiveness in improving gait in PD patients	Significant improvements in peak heel pressure timing, peak toe pressure timing, time on the heel sensor, and stance to swing ratio after one week of therapy	Small sample size and short duration of the study, limiting the generalizability of the results
[21]	Develop and evaluate the MuCU, a device that provides auditory and somatosensory cues to support gait in PD patients, and to assess its effectiveness in reducing FoG episodes	Four out of six patients experienced shorter FOG episodes and preferred situation-dependent cueing	Small sample size and short duration of the study, limiting the generalizability of the results
[30]	Develop and evaluate a wearable system for supporting and training PD patients with FoG in daily-life settings	Reduction in FoG duration, increased confidence in walking, high user satisfaction	Limited battery life of IMUs, need for simpler sensor attachment, preliminary study with a small sample size
[32]	Investigate the effects of vibratory stimulation of the neck muscles on step initiation performance in PD patients	Vibratory stimulation improved step initiation performance, reducing both first step latency time and anticipatory postural adjustments duration	Small sample size and the study was conducted in a laboratory setting, which may not fully represent real-life conditions
[22]	Develop and evaluate an application for Google Glass that helps PwPD monitor and manage their speech volume in real-time	Participants found the application beneficial for increasing speech volume and gaining confidence in social interactions	Small sample size, short trial period, and technical limitations of Google Glass
[33]	Evaluate the feasibility and effectiveness of using Google Glass for delivering rhythmic visual and auditory cues to improve gait in PwPD	Cueing led to a more stable gait pattern, particularly on complex walking courses, and metronome was more effective than visual cues and preferred by participants	Study was conducted in a laboratory setting, and the small sample size of participants who experienced FoG limits the generalizability of the findings
[34]	Develop and test a phase-dependent tactile biofeedback system to alleviate FoG in PD patients	Tactile biofeedback system significantly reduced FoG and was well-accepted by the participants	Study was a feasibility study with a small sample size, and comparisons between the metronome and biofeedback conditions were not made
[35]	Compare the effects of different types of external input on gait stability in PD patients with and without FoG and to explore the relationship with cognition and subjective preference	Continuous cueing provided the most stable gait for freezers, while non-freezers showed no significant differences between conditions, but cognitive ability influenced the effectiveness	Study had a relatively small sample size and relied on self-reported data for categorizing subgroups, further research with more sensitive cognitive assessments and a larger cohort is needed
[36]	Develop a smart gait-aid system using head-mounted sensors for real-time detection of FoG and provision of visual cues to assist PD patients	FOG detection accuracy of 92.86%, gait speed and stride length improved by $15.3 - 37.2\%$ and $18.7 - 31.7\%$	Limited processing and battery capacity of the smart glasses plus it requires pre-training for effective use
[14]	Design a cost-effective, individualized smart walking aid system capable of predicting FoG episodes and providing integrated visual, auditory, and vibratory cues to help overcome them	Freezing counts were significantly reduced, with no freezing observed when all three cues were applied, also step length and walking speed improved under the multi-cue condition	Small sample size and restricted indoor environment
[37]	Develop and evaluate a low-cost wearable system that uses vibratory stimulus to mitigate FoG in PD patients	The vibratory stimulus system significantly reduced the duration of FoG episodes by 50.94% and improved the overall time to complete the walking circuit by 34.25%	Study was conducted with a small sample size, and further testing with a larger cohort is needed to validate the findings
[20]	Test the efficacy, safety, practical utility, and user-friendliness of a posture correction and vibrotactile trunk angle feedback device (the UpRight) in the home setting for PD patients with a stooped posture	The UpRight device significantly reduced the trunk angle, indicating a less stooped posture, and was found to be safe, feasible, and beneficial for self-management	Small sample size, limited to moderately affected PD patients, further research with a larger cohort is needed to validate the findings and determine the long-term effects of the device
[19]	Identify the frequency threshold and minimum interval of vibrotactile perception for developing a wearable biofeedback system to help PD patients overcome FoG	Vibrotactile cues at 180Hz and intervals ≥ 250ms around the waist, especially at the navel and spine, were well perceived and accepted by PD patients	Small sample size and limited to laboratory settings
[38]	Design, develop, and implement a wireless system for detecting episodes of FoG and stimulating walking progression through vibratory feedback in PD patients	System demonstrated effectiveness in detecting FOG episodes and improving gait, with a specificity of 86.66% and a sensitivity of 60.61%	Study mentions the need for further testing and calibration of the device, as well as the potential for false positives when patients voluntarily stop or make spontaneous turns
[39]	Develop a low-cost, non-invasive system for real-time detection and intervention during FoG episodes in PD patients	Device showed sensitivity of 60.61%, specificity of 86.66%, and an effectiveness rate of 80% for resuming gait, reduced the average duration of FOG episodes by 27%	Limited sample size, need further testing and system improvements for better sensitivity and specificity
[40]	Evaluate the effectiveness of Electroskip auditory biofeedback technology in improving gait and balance in PwPD over a 6-week rehabilitation program	Timed Up and Go time improved from 53 seconds to 24 seconds with Electroskip after 6 weeks, FoG Questionnaire decresead from 14 to 6, high satisfaction	Single-subject case report limits generalizability, no home-based testing of device, need for randomized controlled trials
[41]	Develop a discrete, safe, and effective tactile cueing method to improve gait and reduce FoG in PD patients	Significant improvement in gait performance, as evidenced by faster completion of gait tests with tactile cueing	Limited to a single case study, further research is needed to generalize findings

TABLE 6. ***(Continued.)*** **Objective, results, and limitations of the included papers.**

Ref.	Objective	Results	Limitations
[42]	Evaluate the feasibility and effectiveness of wearable haptic anklets for improving gait and reducing FoG in PD	Walking velocity improved by an average of 4.5% and inter-stride variance reduced by 10%, FoG episode duration reduced by 19.5 − 49.9%	Small sample size and lack of long-term or real-world validation
[43]	Evaluate the effects of mechanical plantar stimulation on gait parameters in PD patients	Stride length improved significantly by 30.7% in PD patients, plus the differences between PD patients and controls were reduced	Small sample size and acute intervention effects only
[44]	Evaluate the safety, tolerability, and preliminary effectiveness of wearable vibrotactile devices for reducing resting tremor in PD patients	Moderate reduction in resting tremor severity during stimulation, high tolerability	Short trial duration, limiting insights into long-term use
[45]	Evaluate the acceptability of a study design using vibrotactile stimulation and gait analysis sensor insoles for assessing FoG in PD patients	All participants completed the tests successfully, SVSD showed promise in reducing FoG severity, but efficacy remains to be validated in larger studies	Small sample size, potential placebo effects, and limited FoG occurrence during testing, further studies with personalized settings and larger participant groups are required
[56]	Evaluate the immediate effect of patient-tailored holographic cues on alleviating FoG and understand the habituation effect of unfamiliar wearable devices	Holocue had no systematic immediate effect on group-wide FoG reduction, but individual benefits were noted, especially for participants with longer and more frequent FoG episodes	Limited field of view of the HoloLens, initial unfamiliarity effects, and lack of systematic group-wide benefits, further studies with improved technology and longer habituation times are recommended
[46]	Design and evaluate a wearable system that enhances mobility in PD patients by detecting and addressing FoG with timely sensory cues	IWS achieved 94% accuracy in FoG detection, a response time of 0.37s, and improved mobility, with 88% of participants reporting enhanced walking and 70% overcoming FoG	Limited sample size, individual variations in gait, and dependency on calibration for optimal performance
[47]	Evaluate the efficacy of a wearable vibration-based device for alleviating tremors in PD and identify response predictors	Substantial tremor reduction was observed in two participants, while one participant exhibited an entrainment-like effect, no significant effect was seen in others	Small sample size, limited response variability, and need for longer-term and home-based evaluations
[48]	Evaluate the feasibility of using the Emma Watch to attenuate action tremors and its impact on handwriting and fine motor tasks in people with PD	No significant differences in quantitative metrics across vibration conditions, but subjective improvements and visible changes in handwriting quality were reported by a subset of participants	Small sample size, short duration of device usage, and technical difficulties affecting data collection
[49]	Test whether rhythmic vibration cues triggered by FoG events can improve gait and reduce freezing in PD patients, and to develop real-time FoG detection algorithms	Responsive cueing significantly improved circuit completion time and step frequency, while reducing the number of FoG events	Small sample size, variable response to cueing across participants, and limited diversity in the cohort
[50]	Evaluate the effects of tactile cueing on FoG and compare its effectiveness to auditory cueing and uncued gait	No group-wide improvements were observed, but 71% of participants responded positively to at least one cueing condition	Limited sample size, variability in individual responses, and inapplicability for participants with sensory impairments
[51]	Assess the effects of binaural and conventional acoustic stimulation on motor symptoms, particularly tremor, in PD patients under ON and OFF medication conditions	BBS reduced resting tremor in the more affected limb during OFF medication, while CAS had broader motor benefits in the same condition, but neither method improved symptoms in ON medication conditions	Heterogeneity in patient cohort, small sample size, single-session study, and lack of standardized auditory and visual impairment testing
[15]	Test the feasibility and effectiveness of Google Glass for delivering personalized auditory and visual cues to improve gait and mitigate freezing in PD patients	"Walk With Me" improved straight walking and doorway navigation but worsened turning, "Unfreeze Me" showed inconsistent results with minimal benefits, user acceptance was positive	Small sample size, heterogeneity in participants' cognitive abilities and disease severity, and short-term single-session testing
[18]	Develop and evaluate an augmented reality system for providing visual cues that improve gait and reduce FoG episodes in PD patients	ARFoG effectively guided patients in dynamic environments and mitigated FoG triggers by maintaining focus on gait, usability issues with the device's size and weight were highlighted	Limited sample size, bulky hardware, and reduced field of vision through smart glasses
[17]	Evaluate the effectiveness of on-demand auditory cueing for reducing FoG in PD during daily life and FoG-provoking protocols	DeFOG reduced FoG episodes significantly during immediate use, especially when combined with dopaminergic medication, trembling FoG benefited more than akinetic FoG	Limited long-term impact without therapeutic reinforcement, technical challenges (false positives, battery issues), and variability among participants
[52]	Evaluate the effects of different FES parameters on wrist tremor suppression and identify optimal parameter combinations for individual variability	Tremor suppression was most effective at amplitudes near the motor threshold, results varied across participants due to differences in tremor intensity and response to stimulation	Small sample size, variability in individual tremor patterns, and lack of real-time adaptive control, muscle fatigue during prolonged stimulation may have affected results
[57]	Develop and test an autonomous wearable system for detecting and alleviating FoG episodes using machine learning and edge computing	The system achieved 94% accuracy in detecting gait phases and 84% accuracy in classifying FoG episodes, preliminary results indicate reduced FoG episodes and improved gait	Small sample size, reliance on one foot for detection and cueing, and inability to detect akinetic episodes without additional sensors
[53]	Design and evaluate a constant-current peripheral electrical stimulator for non-invasive tremor suppression in PD patients	RMIS achieved an 82.41% tremor suppression rate, and RNS achieved 75.92%, effects were sustained five minutes post-stimulation with minimal discomfort	Small sample size, lack of closed-loop feedback, limited channels, and absence of long-term testing
[16]	Assess the immediate effect of a vibrotactile foot device on reducing FoG and improving gait parameters in PD patients	Significant reductions in freezing episodes (33.1%) and time frozen (32.6%), with improvements in stride length and high patient satisfaction	Limited to immediate effects, small sample size, no real-world testing, and exclusion of individuals with sensory impairments
[54]	Design and evaluate a kinematic gait parameter-based vibrotactile cueing system to mitigate FoG in PD patients	Significant reductions in FoG episodes and improvements in gait parameters were observed, vibrotactile cueing system demonstrated comparable efficacy to medication in mitigating FoG	Small sample size, no real-world testing, limited device familiarization time, and variability in FoG response

throughout the movement to maintain rhythm or suppress symptoms. As continuous strategies do not rely on symptom detection, they are typically simpler to implement but may be less efficient in terms of energy consumption and user adaptation.

3) HYBRID

A smaller subset (7 studies) employed a hybrid strategy that alternated between continuous and event-based cues depending on patient status or detection confidence. Recent systems have advanced toward adaptive hybrid models that modulate cue type in response to detection reliability or user state. For example, Klaver et al. [50] introduced a tactile system that toggled between standby and active cueing modes depending on gait phase detection and user responsiveness. These developments highlight the growing sophistication of wearable systems in dynamically optimizing cueing for both efficacy and comfort.

E. CUEING MODALITIES

Wearable cueing systems for PD employ a variety of sensory modalities to improve motor performance. The most common are auditory cues (e.g., rhythmic tones or verbal instructions), visual cues (e.g., laser projections or augmented reality overlays), and tactile cues (e.g., vibrotactile pulses delivered to the skin).

In addition, several studies used electrical stimulation, either as low-level neuromodulation or FES, to modulate muscle activity or suppress tremor through phase-synchronized signals. Each modality has distinct advantages depending on the symptom being addressed and user preferences. Auditory and visual cues are often used to guide gait or overcome freezing episodes through rhythmic pacing or spatial prompts, while tactile and electrical cues are preferred for conditions like tremor, shuffling, or posture correction, where discrete or continuous physical feedback is beneficial. Some systems also combine multiple modalities to enhance robustness and personalization.

1) TACTILE

In terms of stimulation methods, tactile cueing was the most prevalent, implemented in 21 studies such as [41] and [48]. One of the most interesting studies was performed by Pacheco et al. [48], who investigated the use of the Emma Watch, a wrist-worn vibratory device developed by Microsoft, to address action tremor in PwPD. The device delivers high-frequency vibration through five linear resonant actuators on the wrist, intended to modulate sensory feedback and reduce tremor during fine motor tasks like handwriting and drawing. The study involved nine PwPD, who completed a set of stylus-based tasks under three conditions: no vibration, low-intensity vibration (sham), and high-intensity vibration. While no statistically significant improvements were found in most quantitative performance measures, a small subset of participants reported subjective improvements and demonstrated visual differences in handwriting quality, suggesting potential benefits for specific individuals.

2) AUDIO

Auditory cueing followed closely (12 studies), often realized through metronomes, tones, or verbal prompts as shown in [12], [17], and [35]. A notable study was presented by Bächlin et al. [12], who showed a context-aware wearable device intended to detect FoG episodes in real time and provided automated auditory cueing only during those episodes, shown in Figure 1 in [58]. The goal of the study was to reduce the limitations of continuous cueing and improve practicality in daily life, while also exploring patients' subjective experiences with the system. The proof-of-concept device used accelerometer data and threshold-based algorithms to detect FoG, and triggered a 1Hz metronome audio signal when detecting FoG. Most (5 out of 8) patients reported less FoG episodes.

3) VISUAL

Visual cues were applied in 9 studies like [15] and [29], often in the form of augmented reality overlays or LED-based signals, and generally it has been shown to be less effective than audio or tactile, though promising in some specific contexts, like the one showed by McNaney et al. [22] when they presented LApp, a wearable application developed for Google Glass to help PwPD to manage hypophonia. The app provides real-time visual cues using a simple "traffic light" or "thumbs up" display to prompt users when their voice volume drops below a personalized target threshold, shown in Figure 1 in [22]. Through a co-design approach with seven participants, followed by a three-day field trial with six of them, the study explored how in-situ visual feedback could support both conversation and self-practice. While participants reported increased confidence and awareness in their speech, the study also uncovered technical and usability challenges, such as difficulties navigating the interface and limited battery life.

4) ELECTRICAL

Electrical stimulation, though promising, was the least used modality, appearing in only 4 studies [31], [52], [53], most likely due to its invasiveness or patient discomfort concerns. Unlike tactile or auditory cues, which aim to externally prompt voluntary movement, electrical cueing typically interacts more directly with neuromuscular pathways or rhythmic motor circuits, making it suited for treating specific symptoms like pathological tremor. The 2024 study by Gong et al. [53] presents a wearable electrical stimulator specifically designed to suppress resting tremors in PD. The device consists of multiple sensors displaced in a finger, in the hand and in the forearm, connected to a lightweight FPGA, allowing precise adjustment of stimulation parameters, shown in Figure 4 in [53]. The researchers introduced two Co-contraction Avoidance Stimulation (CAS) strategies: one targeting muscles (Refined Motor Intervention Stimulation,

TABLE 7. Comparison of key technical parameters across wearable cueing studies.

Ref	Sensor	Cueing modality	Communication	Sample Rate	Range	Sensitivity (bit)	Latency	Battery capacity (mAh)	Battery life (hours)
[12]	Acc	Auditory	Bluetooth	64	-	-	0.5 s	500	6
[30]	IMU	Auditory	Bluetooth	32	-	-	0.5s	-	4
[17]	IMU	Auditory	Bluetooth	200	-	-	-	-	3
[42]	Force sensor	Vibration	Bluetooth	-	-	-	50 ms	-	4
[55]	Force sensor	Vibration	Xbee	20	98 N	10	-	1000	1
[34]	IMU	Vibration	Wired	128	±6g, ±1500°	-	-	-	18
[16]	IMU, Force sensor	Vibration	Bluetooth	128	-	-	-	-	-
[46]	Force sensor	Auditory, Visual	Bluetooth	-	-	-	0.37 s	-	12
[53]	IMU	Electrical	Wired	100	-	-	-	1500	-
[57]	IMU	Electrical	Bluetooth	200	±16g, ±2000°	12	7.5 ms	400	6
[48]	IMU	Vibration	Bluetooth	128	-	-	-	-	-
[38]	Acc	Vibration	Bluetooth	8	-	-	0.75 s	500	-
[39]	Acc	Vibration	Bluetooth	-	-	-	1s	500	4
[37]	IMU, Force sensor	Vibration	Bluetooth	44	-	-	-	-	-
[35]	IMU	Auditory	Bluetooth	100	-	-	-	-	-
[17]	IMU	Auditory	Bluetooth	-	-	-	-	-	3
[20]	Acc	Vibration	None	200	-	-	5 s	-	-
[36]	IMU	Visual	None	50	-	-	-	-	-
[52]	IMU	Electrical	USB	50	±2000°/s (gyro)	16	-	-	-

RMIS) and the other targeting sensory nerves (Radial Nerve Stimulation, RNS). In trials with four PwPD, both strategies significantly reduced tremor amplitude, with RMIS achieving an average suppression rate of 82.41% and RNS reaching 75.92%. These effects persisted even five minutes post-stimulation, and patients reported no discomfort or fatigue, highlighting the potential of low-intensity peripheral stimulation for daily, wearable tremor management.

F. SYSTEM SPECIFICATIONS

Some technical specifications of the sensor system are essential for real-world applicability. The battery life can represent one the main limitations for continuous, autonomous functioning in unsupervised, remote environments. However, information on battery capacity and/or autonomy was often omitted. Most studies performed brief laboratory experiments, with sessions lasting from 8 minutes [38] to 1.5 hours [48]. These do not allow for assessing the system autonomy in continuous working conditions. A few studies evaluated the system over 2 days [21], or 1 [20] to 4 weeks [17] of home monitoring. However, information on battery autonomy was mostly omitted, and it is not clear how frequently the devices should be recharged. When reported, battery life was mostly in the range from 3 to 6 hours [12], [17], [30], [42], [57], and up to 10 [31] and 18 hours [34] in a very few cases. Some studies reported the battery capacity, ranging from 300-500 mAh [12], [38] to 1000-1500 mAh [53], [55], [57].

Sensor technical specifications were rarely reported. Full-scale/range was set to ±6g [34] or ±16g [57]) for the accelerometer, between ±1500°/s and 2000°/s for the gyroscope [34], [52], [57], and 98 N for the forse sensor [55]. Sensitivity/resolution was reported in three studies, with a value in the range from 10-bit to 16-bit [52], [55], [57].

The sampling frequency was consistently reported in most studies. For inertial sensors, it ranged mainly from 32 to 64 Hz [12], [30], [36], [37] and 100 to 200 Hz [16], [17], [20], [34], [35], [48], [53], with lower values observed in a single work (8 Hz in [38]). Sampling rate was lower for force-resistive sensors and smart pressure insoles, ranging from 20 Hz [55] to 32 Hz [46] and 65 Hz [54].

Cueing frequency was heterogeneous among studies, with a 1 Hz sound produced by earphones described in [12], and vibration frequency produced by vibro-tactile motors from 160-200 [20] to 250-275 Hz [37], [42].

Computational complexity was not evaluated. However, a rough estimate of computational load can be obtained by analyzing the the data processing pipeline the cueing approach. For continuous cueing, real-time data processing is not needed, thus minimizing computational load. However, continuously providing auditory, visual, electrical or vibro-tactile feedback can represent a significant limitation for continuous operation, consuming a large portion of battery. Studies focusing on continuous stimulation did not provide any information on the system autonomy. For example, Gong et al. [53] employed a constant electrical stimulation on the patients' forearm to reduce tremor amplitude. The authors reported the battery capacity of the stimulator (1500 mAh) but not the power consumption or the system autonomy. Power consumption can be reduced by avoiding using continuous administration and activating cues only at specific time points. Rossi et al. [42] developed wearable anklets that provide vibro-tactile feedback at the ankles when pressing a button on the remote controller, resulting in a battery autonomy of 4 hours. This represents the less computational demanding method, based simply on a switch/button. Slightly demanding tasks include minimal data processing in real time. These can be represented by switches or force-resistive sensors under the foot for foot contact identification. In this case, cues are activated when the force/pressure is above a specific threshold. In this context, Winfree et al. [55] developed a system based on force sensors and vibro-tactile motors under the heel. Vibrations were delivered at the contact of the heel to the ground. The system included a 1000 mAh battery that lasted 70 minutes, on average. Increasingly demanding computational methods include the real-time acquisition of inertial signals, data transmission to a central procesisng unit via Bluetooth, and automatic activation of cues based on the recognition of specific events. Dvorani et al. [57] develop a wearable system based of an ankle-mounted inertial sensor sending data to a smartphone for real-time data processing, and gait-synchronous electrical stimulator on the lower leg. The system autonomy was found to be around 6 hours. Zoetewei et al. [17] evaluated a closed-lopp wearbale system composed of two IMUs on the shoes, asmartphone for real-time data processing, and earphones that provide auditory cues upon FoG detection. The battery life was around 3 hours. Similarly, Mazilu et al. [30] proposed a system based on two IMUs on the ankles for data acquisition, a smartphone on the pocket for data processing, and auditory cues activated upon FoG detection. The system could run continuously for 4 hours.

Latency, i.e., the delay from the onset of an event/symptom and the activation of cues, is an essential aspect to consider when timely (possibly real-time) triggers need to be delivered. This is especially true in FoG detection, where timely administration of cues can significantly reduce the incidence and duration of the phenomenon. A few studies evaluated this important technical aspect, obtaining promising results. Rossi et al. [42] reported a latency of 20 ms from the moment the remote button was pressed to the activation of vibrating anklets via Bluetooth. Dvorani et al. [57] found an evarage delay of 7.5 ms from events recorded by sensors and trigger received by the electrical stimulator via Bluetooth. In Mailu et el. [30], data processing (i.e., FFT computation, feature extraction, classification via C4.5 algorithm) required 6ms, and auditory cues were activated on average 0.5s after FoG onset. Yang et al. [46] reported an average latency of 0.37 s from FoG onset to auditory cue activation via Bluetooth. FoG recognition was based on foot contacts identification and gait temporal parameters calculation from smart pressure insole data. It is worth noting that latency information is particularly relevant for event-triggered cueing systems, where the timing between symptom detection and cue delivery critically affects system responsiveness. In contrast, latency is less critical in continuous cueing approaches, which provide ongoing feedback rather than discrete time-sensitive stimuli.

From the results above, it emerges that the computational complexity of data processing algorithms does not compromise real-time, closed-loop cueing strategies. Unfortunately, none of the studies evaluated the performance of end-to-end deep learning models. These can provide predictions by handling directly raw data, thus avoiding standard pre-processing techniques (e.g., filtering, feature extraction) [59]. In addition, implementation of the processing algorithms on the sensing device itself can reduce communication delays between sensors and wearable computers (e.g., due to Bluettoth or ZigBee data transfer), thus further reducing the latency [57], [60]. On the contrary, heavy data transformation methods (e.g., CWT), long temporal windows, and slow data transfer rate can significantly increase the delay between event onset and cue activation. Although these data provide an overview of current practices, the inconsistent reporting of technical specifications, and in particular battery autonomy, latency, and sensor characteristics, prevents a systematic comparison across studies. To partially address this, Table 7 summarizes the limited quantitative parameters available in the reviewed literature.

IV. DISCUSSION

This systematic review provides a comprehensive analysis of the technological landscape surrounding wearable cueing systems for PD. By reviewing 39 studies, we have identified major trends, categorized existing solutions, and highlighted current limitations in the field. Our investigation was guided by one overarching question—*What are the current trends in wearable cueing technologies for PD symptoms management?*—and three related sub-questions. Below, we elaborate on our findings in light of these questions.

The reviewed studies illustrate a rapidly evolving field, with a wide variety of wearable cueing systems being developed over the past two decades. These technologies have been proposed to manage core motor symptoms of PD, with FoG addressed in 29 of the included studies. Tactile and auditory cueing modalities emerged as the most commonly adopted strategies, featured in 21 and 12 of the studies, respectively. Visual cueing has also been explored extensively, particularly through head-mounted displays and augmented reality glasses, while electrical stimulation has gained renewed attention due to its potential for tremor suppression and postural control.

The devices ranged from simple metronomes and smartphone applications to highly integrated systems featuring inertial sensors, machine learning algorithms, and real-time actuation mechanisms. This shift towards smarter and more adaptive systems reflects a broader trend toward patient-specific, context-aware cueing strategies, moving from static stimulus delivery to intelligent, event-driven interventions.

Our classification of the reviewed works reveals a strong focus on motor symptoms, particularly FoG, tremor, and gait disturbances. As expected, no study addressed non-motor symptoms through cueing, despite their known impact on QoL in PD. Among motor targets, most devices focused on lower limbs, particularly the ankle and foot areas, likely due to their central role in gait mechanics. Tremor-related systems generally target the wrist or forearm.

Cueing modalities were categorized into four main types: tactile, auditory, visual, and electrical. Each of these has unique advantages and challenges. Tactile cueing tends to be discreet and well-tolerated, though desensitization could manifest in some prolonged use-cases. Auditory cues are effective but can interfere with environmental sounds. Visual cues, while promising in lab conditions, often face real-world usability issues such as limited field of view or hardware intrusiveness. Electrical stimulation shows promise for symptoms like tremor but demands complex control strategies and high patient-specific calibration. These modality-specific differences likely reflect the distinct compensatory neural pathways described in the Introduction, through which external cues support movement by supplementing impaired basal ganglia function.

Most systems were evaluated in controlled clinical settings, with only a minority tested in home or hybrid environments. This highlights a critical gap between laboratory validation and real-world usability. Systems used in the home (such as smartphone-based or wearable inertial platforms) offer promising avenues for long-term symptom management and rehabilitation. Yet, their efficacy remains under-explored due to short trial durations or limited participant diversity.

Use cases ranged from real-time gait correction during episodes of FoG, to long-term training interventions, to tremor suppression during fine motor tasks such as handwriting. Multi-modal systems, like those combining auditory and tactile feedback, were reported to be more effective than single-modality devices, especially for patients with varying symptom profiles.

A. TECHNOLOGICAL GAPS AND LIMITATIONS IN THE LITERATURE

Despite notable progress, the field faces several limitations. First, over 80% of the reviewed studies involved small sample sizes, in most cases under 20 participants, and short-term interventions, often limited to proof-of-concept validation, limiting the statistical significance and impact of the findings. Second, the personalization of cueing strategies is still underdeveloped, with fewer systems adopting real-time patient-specific preferences or symptom profiles. Third, usability and ergonomics remain significant barriers. Bulky hardware, battery limitations, and poor long-term adherence frequently compromise clinical translation. We also observed a critical lack of standardized reporting on technical characteristics such as sampling frequency, latency, and power consumption. Establishing uniform reporting guidelines for technological parameters would greatly enhance transparency, comparability, and the feasibility of meta-analyses in future studies. These limitations reflect the exploratory and prototype-oriented nature of the primary studies rather than the scope of this review, which intentionally includes feasibility works to provide a comprehensive overview of existing technological developments.

Another major limitation is the lack of attention to non-motor symptoms. Although our review framework included both motor and non-motor domains, the absence of studies targeting non-motor symptoms reflects a significant research gap. Non-motor symptoms represent a significant contributor to reduced quality of life in PD, yet none of the included wearable cueing systems attempted to address them. This observation underscores the early technological maturity of the field, which has so far prioritized motor rehabilitation, and identifies a clear direction for future development of wearable cueing systems addressing cognitive and affective domains.

Additionally, while machine learning has been increasingly adopted for event detection (e.g., FoG onset), its use for optimizing cueing strategies remains rare. It is worth noting that none of the reviewed studies implemented end-to-end deep learning models. Nevertheless, such approaches are becoming increasingly relevant for real-time applications, as lightweight DL architectures can potentially improve classification accuracy while reducing the need for pre-processing and handcrafted feature extraction typical of conventional machine learning pipelines. However, in studies employing continuous cueing or simple threshold-based detection, the use of deep learning methods might increase computational load without providing substantial performance advantages.

Ethical and privacy concerns related to long-term monitoring and remote data processing are also under-discussed in the reviewed literature.

Overall, wearable cueing systems represent promising approaches to improve PD-specific motor symptoms [28]. However, these technologies are currently at a preliminary stage of development and validation. From a technological perspective, this is evident from the lack of detailed technical information on system robustness, processing and actuation times, computational efficiency and autonomy. In particular, total reaction time is not commonly provided, despite the fact that it is essential for timely intervention. A complete calculation should take into account the length of the input segment and inter-segment interval (e.g., 4-second windows are analysed every 0.5 seconds), inference time (i.e. pre-processing and classification) and actuation time (i.e. the time frame from detection to actual triggering of cues) [17], [24]. Furthermore, inter-subject and intra-subject variability can significantly influence the reaction time (i.e. the interval between activation and actual cue effectiveness) [49]. The efficiency of the algorithms has not been widely reported, although it is essential to maximise the autonomy of the device, thus enabling long-term operation without recharging [61]. This aspect must be carefully considered along with the sizing of the internal battery, for which a compromise between size, weight, factor shape and autonomy must be carefully chosen. Finally, most studies involved a small cohort of subjects and short experimental laboratory sessions. The lack of heterogeneity in patients' characteristics and symptoms manifestations, along with brief evaluations during predefined structured tasks performed in controlled environments prevent an adequate assessment of the generalizability of the results to different subjects, conditions and environments [28]. Some studies included in their laboratory protocol some cognitive/motor dual-tasks [30] and/or free-living activities [12], to reproduce real-life challenges. A limited number of studies evaluated the wearable cueing system in home environments over long-term unsupervised monitoring [17], [20], [40]. These studies registered promising results, with improved postural control, reduced number and duration of FoG events, and improved gait parameters.

TABLE 8. Recommendations for future research in wearable cueing technologies for Parkinson's disease.

Research Area	Recommendations
Targeted Symptoms	Expand research beyond motor symptoms like FoG and tremor to address underexplored non-motor symptoms (e.g., speech, cognition, mood) using wearable cueing and/or coaching approaches.
Cueing Modalities	Encourage the development of multimodal systems combining tactile, auditory, visual, and electrical stimulation, allowing for tailored interventions based on patient preferences and needs.
Personalization	Design adaptive systems that personalize cueing parameters (e.g., frequency, intensity, timing) using real-time feedback, physiological signals, and patient behavior.
Context Awareness	Integrate context-awareness and intelligent sensing (e.g., activity recognition, environment classification) to trigger cueing only when necessary, improving effectiveness and user comfort.
Longitudinal Studies	Conduct long-term studies with larger and more diverse cohorts to assess sustained usability, efficacy, and user adherence in real-world settings.
Evaluation Settings	Shift from lab-based validation to in-the-wild evaluations, including home, community, and ambulatory settings, to improve generalizability and ecological validity.
Human-Centered Design	Engage PD patients and caregivers early in the design process to co-create solutions that align with user needs, preferences, and capabilities.
Hardware Design	Focus on comfort, discreteness, battery life, and ease of use to ensure long-term adoption. Explore integration with everyday objects (e.g., shoes, glasses, watches).
Reporting Standards	Adopt standardized reporting of study protocols, cueing parameters, outcome measures, and statistical analyses to enhance replicability and comparability across studies. Include usability and adherence-related metrics such as average daily wear time, recharge intervals, false-cue rates, and user-reported outcomes using validated instruments (e.g., SUS, QUEST, NASA-TLX).
Technical Documentation	Systematically report essential technical specifications including sampling frequency, full-scale range, sensor resolution, latency, and power consumption to enable cross-study benchmarking and meta-analyses. Establishing minimal technical reporting requirements would strengthen methodological transparency and reproducibility in future wearable-technology research.
Interdisciplinary Collaboration	Foster collaboration between engineers, neurologists, rehabilitation experts, and behavioral scientists to ensure clinical relevance and technological feasibility.

An additional limitation worth noting is the possibility of reporting or publication bias in the literature. Studies showing positive outcomes such as improvements in gait, reduction in tremor, or high user satisfaction, are more likely to be submitted and published, while negative or inconclusive results may remain unpublished. This bias could result in an over-representation of successful interventions and an underestimation of technical or clinical challenges. To mitigate this, future work should encourage the publication of neutral or negative findings and adopt pre-registered protocols and standardized reporting to improve transparency and reproducibility.

It is worth noting that most of the studies included in this review are engineering or feasibility-focused works involving hardware prototypes, sensor integration, and stimulation strategies, often lacking the methodological structure required for clinical risk-of-bias tools. While some studies reported clinical outcomes, these were typically secondary or exploratory in nature, and not powered as full clinical trials. Existing RoB assessment tools such as Cochrane RoB, ROBINS-I, or QUADAS-2 are designed for clinical effectiveness studies or AI-based prediction models. However, our review primarily targets hardware-driven systems, many of which rely on simple control logic or signal processing rather than advanced software or AI components. Applying these tools would therefore not only be inappropriate but could also unfairly penalize hardware-focused studies that were not designed with clinical RoB criteria in mind. We consider this a limitation of the current review, and we advocate for the development of dedicated RoB tools that are tailored to multidisciplinary studies evaluating hardware-based assistive technologies in clinical contexts.

B. TRADE-OFFS AND REAL-WORLD USABILITY

A key dimension that emerged from this review is the trade-off between continuous and event-based cueing strategies, and how these choices affect real-world usability. Continuous cueing, such as rhythmic auditory stimulation, minimizes detection latency and offers a straightforward user experience, but at the cost of higher actuator duty cycles and therefore reduced autonomy. Several studies did not report the endurance of devices under such conditions, yet reports of 3–6 hours of battery life suggest that continuous operation is often impractical for daily use outside the clinic [30], [42].

By contrast, event-based systems conserve energy by delivering stimulation only when a freezing episode or abnormal gait pattern is detected, but this requires more complex sensing pipelines and communication layers. Latency figures in these systems ranged from a few milliseconds in direct sensor-to-stimulator links [57] to several hundred milliseconds when smartphones mediated the cue delivery [46], which can be critical in determining whether a cue is timely enough to prevent freezing. False positives and missed detections remain a challenge, with consequences for trust and adherence in daily life [17]. Hybrid strategies, which combine a low-intensity continuous cue with context-dependent reinforcement, have been proposed as a compromise to mitigate both autonomy and robustness issues.

Beyond technical considerations, cueing strategies also differ in their cognitive and social impact. Continuous auditory or visual stimulation can enhance motor performance but may quickly become intrusive in daily life, particularly in public settings. By contrast, haptic cues are generally perceived as more discreet and socially acceptable [50], although they may provide less salient feedback in noisy or distracting environments. Event-based approaches reduce overall intrusiveness but can startle the user if cues are poorly timed or inconsistent in intensity.

Ultimately, usability depends on how well systems adapt to individual needs. Features such as adjustable cue intensity, the ability to pause or override stimulation, and seamless integration with the daily routines of putting on, taking off, and recharging the device strongly influence long-term adherence. To support translation from laboratory to home environments, studies should therefore report not only clinical outcomes but also adherence-related measures, including average wear time, recharge intervals, and false-cue rates. Standardized usability instruments (e.g., SUS, QUEST, NASA-TLX) would further enable cross-study comparison and provide clearer guidance for the design of patient-centered cueing technologies [35], [45].

C. EMERGING TRENDS, FUTURE DIRECTIONS, AND RECOMMENDATIONS FOR FUTURE RESEARCH

Several promising trends are emerging. First, there is growing interest in hybrid cueing systems (e.g., devices that combine two or more stimulation modalities). These systems aim to capitalize on the complementary strengths of different feedback channels, increasing cue salience and adaptability. Second, wearable systems are increasingly leveraging edge computing and AI for real-time symptom classification and adaptive cueing. Third, studies are gradually shifting from symptom-specific designs to modular platforms capable of addressing multiple PD impairments in a personalized way.

There is also a visible movement toward real-world validation, with some recent studies beginning to explore long-term usability, acceptability, and adherence in community-dwelling PwPD. This transition is essential to ensure scalability and impact in clinical practice.

Based on the analysis of the current landscape in wearable cueing technologies for PD, several research gaps and opportunities have emerged. To support this field's advancement and improve future systems' clinical and practical relevance, Table 8 summarizes a set of key recommendations. These guidelines are drawn from the trends observed in the reviewed studies and aim to inform researchers, designers, and clinicians working on next-generation cueing interventions for PD management.

V. CONCLUSION

This systematic review analyzed 39 clinical studies involving wearable cueing technologies for managing PD, with a particular focus on the types of stimulation used, targeted symptoms, real-world applicability, and system limitations. Our findings confirm that wearable cueing systems hold significant potential to support symptom management in PD, particularly for mitigating motor symptoms such as FoG, tremor, and gait disturbances.

Tactile and auditory cueing emerged as the most widely adopted modalities, while visual and electrical stimulation approaches are gaining momentum through advancements in augmented reality and functional electrical stimulation. Most devices target the lower limbs, with few systems designed for other motor impairments or non-motor symptoms. Furthermore, the majority of studies have been conducted in clinical settings, highlighting a lack of real-world testing and validation.

Despite growing interest and technological innovation, several challenges remain. These include the need for larger, more diverse cohorts, improved long-term usability, and better personalization of cueing strategies. Current systems often lack adaptability to individual user needs, and few studies address sustained use in everyday life. Additionally, non-motor symptoms, which significantly impact quality of life, remain largely unexplored in the context of wearable cueing.

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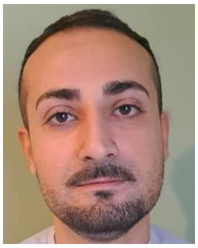

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