Gait & Posture 122 (2025) 358–374

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Effectiveness of haptic cues on gait in people with Parkinson's disease – A systematic review and meta-analysis

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ARTICLE INFO

Keywords:
Parkinson's disease
Haptic cue
Vibrotactile
Walking
Systematic review
Meta-Analysis
Gait

ABSTRACT

Background: Haptic cueing to improve gait in people with Parkinson's Disease (PD) is an emerging treatment approach of interest. This systematic review [PROSPERO CRD42023483230] aimed to critically appraise the available literature on the effectiveness of haptic cues on gait in people with PD.
Methods: Articles published from inception to May 2025 were searched in EMBASE, MEDLINE, APA PsycINFO, and CINAHL. Both randomized and non-randomized clinical trials that investigated the effects of haptic cues on gait parameters (stride length, gait velocity, cadence) in people with PD were included. Two reviewers independently selected articles, extracted data, and assessed the risk of bias (ROB) using the Downs and Black tool.
Results: Twenty-nine studies, including 661 participants with PD, were included. Four studies were randomized controlled trials (RCTs) with strong methodological quality, while the others were pre-post interventional studies. Three RCTs reported outcomes suitable for pooled analysis.
Conclusions: Results indicate that haptic cueing improves gait (mainly velocity and stride length), with some improvements noted in additional spatiotemporal parameters and freezing of gait. Despite positive findings, evidence is limited and more robust RCTs are required to verify the efficacy of haptic cues, particularly for sustained effects on gait.

1. Introduction

Parkinson's disease is the second most common neurodegenerative disorder worldwide, with a global prevalence of six million between 1990 and 2016 [1]. This number is anticipated to double in the next generation due to population aging and increased life expectancy [1]. Parkinson's disease is characterised by the degeneration of dopaminergic neurons in the substantia nigra, leading to reduced dopamine in the striatum and the presence of Lewy bodies in the remaining cells, which is the pathological hallmark of PD [2]. The widespread neuropathological changes in the brainstem and cortical regions contribute to both motor and non-motor symptoms experienced in PD [3,4]. Among motor dysfunctions, gait impairments are particularly common and disabling [5], significantly contributing to decreased mobility and quality of life (QOL) [6]. These impairments can cause people to perceive themselves as a burden to their family or caregiver, potentially leading to feelings of isolation and negatively affecting their health-related QOL [7].

One possible cause of PD gait impairments is the lack of internal rhythmic cues needed to regulate walking, resulting in difficulty with movement execution, which can contribute to freezing and festination [8–10]. Therefore, providing external cues such as visual, auditory and somatosensory cues to assist with walking in PD has emerged as a promising management approach [11]. In PD management, cueing is defined as "using external temporal or spatial stimuli to facilitate movement initiation and continuation" [12]. Sensory cues stimulate voluntary control of movement by activating the attentional-executive motor control system and bypassing the defective, habitual sensorimotor pathway in the basal ganglia [13]. The mechanisms underlying the effects of cueing in PD have been thought to involve the activation of

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https://doi.org/10.1016/j.gaitpost.2025.08.069
Received 18 December 2024; Received in revised form 17 July 2025; Accepted 18 August 2025
Available online 19 August 2025

'external' brain networks, such as the cerebello-parieto-premotor loops [14,15], compensating for the underactive basal ganglia-supplementary motor area, which comprises the 'internal' networks [16]. According to Redgrave et al. [13] the neurophysiological mechanism of cueing in PD involves redirecting activity from more affected neural circuits (the direct and indirect pathways of the basal ganglia circuit) to those that are relatively unaffected. This shift transitions motor control from habitual patterns, primarily mediated by the posterior putamen, to goal-directed behaviour involving the anterior putamen [13].

Although auditory and visual cueing have been widely studied, they present practical challenges, such as requiring the use of earbuds or loudspeakers, which can interfere with environmental stimuli and negatively impact gait [17,18]. These devices can also disrupt situational awareness (e.g., distraction), potentially leading to unsafe situations [18,19]. Additionally, some people with PD are hesitant to use visible cueing devices, such as laser shoes (for visual cues) or earplugs (for rhythmic auditory cueing), due to concerns about associated stigma [20]. To address these limitations, somatosensory cueing through haptic stimulation has begun to attract attention, including already reaching clinical practice [17,20]. However, research in this area remains limited, and only a few systematic reviews have been conducted to evaluate the effects of haptic cues on gait and mobility in PD.

In 2021, Marazzi et al. [21] conducted a systematic review and meta-analysis on the effects of vibratory stimulation on balance and gait in PD, but their primary focus was on whole-body vibration, as there were only a limited number of studies on localized vibrations. Since localized vibrations or haptic cueing to improve gait in PD was an emerging approach at the time, Marazzi et al. [21] concluded there was insufficient evidence to compare its effectiveness to conventional treatment strategies [21]. Therefore, by focusing exclusively on haptic cues, this systematic review aimed to identify potential research gaps and critically evaluate the available evidence on the effectiveness of haptic cues on gait and functional mobility in PD.

2. Methods

This review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines [22]. The protocol was registered in the International Prospective Register of Systematic Reviews (PROSPERO) on 26th November 2023 (CRD42023483230).

2.1. Literature search and search strategy

A search strategy was developed with a librarian specialist (CH). The search strategy is provided in supplementary material 1. Searches were conducted by the principal reviewer (SMD) on the Embase (on Embase.com), MEDLINE (via EBSCOhost), APA PsycINFO (via EBSCOhost), and CINAHL (via EBSCOhost) databases on December 14, 2023, with no date limitations. The search was updated on May 6, 2025. Search terms focused on "Parkinson's Disease", "Cueing", and "Gait". Reference lists of all included articles were also hand-searched.

2.2. Eligibility

Eligible studies included experimental studies (both randomized and non-randomized) that assessed the effectiveness of at least one session of haptic cueing on gait-related outcomes in people with idiopathic PD. Only peer-reviewed articles published in English with full text available were included in this review. Conference proceedings, protocol studies, and case studies were excluded. Additionally, studies that used multiple cueing methods, such as visual, auditory, and haptic, but did not report the effectiveness of each method separately, were also excluded. This was done to isolate the specific impact of haptic cueing on gait outcomes and avoid potential confounding effects from other cueing methods.

2.3. Outcomes

The primary outcome measures were gait as measured on spatio-temporal gait parameters, primarily stride length (m), gait velocity (m/s), and cadence (steps/min). Secondary gait measures included swing time, stance time, single and double limb support time, and clinical assessments of gait such as the Timed Up and Go (TUG) test and the Freezing of Gait Questionnaire (FOG-Q). Additionally, studies that measured the number of FOG (Freezing of Gait) episodes and the percent time frozen were considered. Other outcomes included subjective ratings of disease severity, assessed through standardized clinical tools such as the Movement Disorder Society - Unified Parkinson's Disease Rating Scale (MDS-UPDRS – part III) or Hoehn & Yahr stage.

2.4. Study selection

After searching the databases, the results were imported into EndNote, where duplicates were removed. Before screening stages, irrelevant studies were removed, and specific keywords were applied to filter records. The remaining studies were then imported to Covidence systematic review software (www.covidence.org) for title and abstract screening, followed by full-text screening. Two independent reviewers (SMD and PC) conducted the screening, and any disagreements were resolved by a third party (GK or KS).

2.5. Data extraction and analysis

The two independent reviewers developed and applied a data extraction form. The extracted data were summarised, including; (1) study characteristics (author, year of publication), (2) participant characteristics (number of participants, age, gender, disease severity, and disease duration), (3) intervention characteristics, (e.g., type of haptic cueing, device type, placement, cue frequency), program duration and implementation (e.g., training, use in medication "on" or "off" phase), and (4) outcome measures including gait analysis systems and main results. The authors of the relevant studies were contacted to obtain any missing information.

The review manager (RevMan 5.4) (https://training.cochrane.org/revman) was used for the meta-analysis. Due to variations in study designs, only RCTs were included in the meta-analysis. A random-effects model with 95 % confidence intervals was used to calculate the pooled mean differences (MD) for the main outcomes: gait velocity, stride length, and cadence. Between-study heterogeneity was assessed using the I^2 statistic.

2.6. Quality and risk of bias assessment

Given the heterogeneity of study designs in this review, including both RCTs and non-RCTs, the Downs and Black tool [23] was used to assess the ROB. This tool includes five main domains: (1) reporting, (2) external validity, (3) internal validity (bias), (4) internal validity confounding (selection bias), and (5) statistical power. The two independent reviewers rated the items on the tool, and any differences in ratings were resolved through consensus, with the involvement of a third party when necessary.

3. Results

3.1. Literature search

Initially, a total of 25689 articles were identified. After removing 3528 duplicates and 16829 irrelevant studies, 5332 studies were screened in Covidence systematic review software. Sixty full-text studies were assessed for eligibility, and 31 studies were excluded, with reasons detailed in the PRISMA flow diagram below (Fig. 1). The remaining 29 articles met the eligibility criteria and were included in the review.

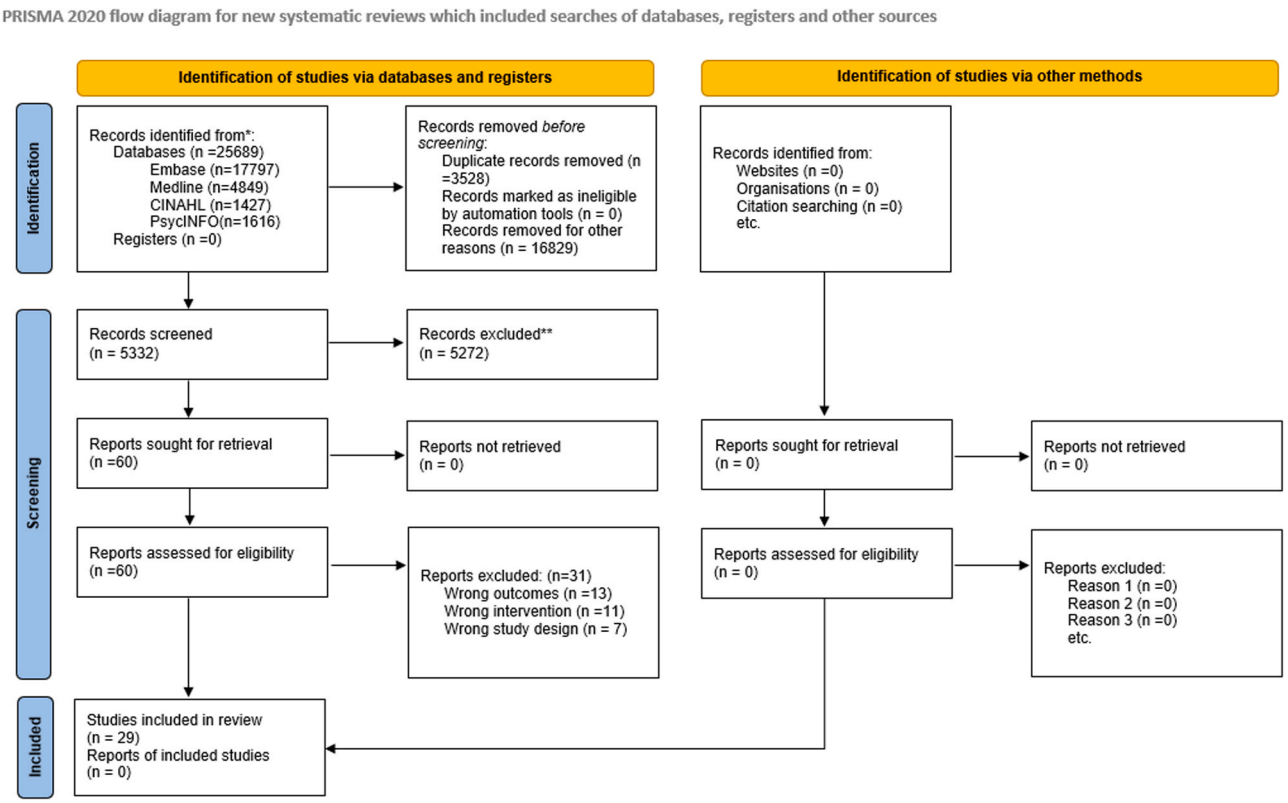

Fig. 1. PRISMA flow diagram for systematic review. PRISMA indicates Preferred Reporting Items for Systematic Reviews and Meta-Analyses.

3.2. Methodological quality

Using the Downs and Black tool, four studies were rated as having strong methodological quality, 19 as moderate, and six as limited (Supplementary material 2).

3.3. Participant characteristics

Participant and intervention characteristics of the included studies are presented in Table 1. This review includes a total of 661 participants with PD. From the studies that reported age as mean ± SD, the calculated mean age of the participants with PD was 65.57 ± 8.68 years, ranging from 55 to 70.71 years. According to the studies that reported the number of males and females, the calculated male-to-female ratio was 409–234. Disease duration was reported in all studies except those by [24] and [25] with values ranging from 3.8 to 15 years.

3.4. Study characteristics

Four studies were conducted in the USA [26,38,39,41] and Italy [18,31,34,46]. Three studies were conducted in Canada [25,36,37] Thailand [24,42,45], India [40,48,49] and the UK [35,44,50] while two were conducted in the Netherlands [17,27]. Two studies were conducted across multiple countries, including the UK, Belgium, and the Netherlands [28,30], while one study was conducted in both India and the USA [33]. Additional studies were conducted in Egypt [32], Belgium [43], Iran [29], and China [47].

Among the included studies, four were RCTs [32,34,42,45], and 25 were pre-post-intervention studies. Three RCTs had control groups with no vibration (placebo) [34,42,45], while one used a routine physiotherapy program as the control [32].

3.5. Intervention characteristics

A total of 17 studies used vibrations as the sole intervention [18,26,29,31–34,36,40,42,44–50]. Three studies used both vibrating and visual cues [25,27,38], while four studies combined vibrating and auditory cues [17,39,41,43]. Five studies used all three cue types (vibration, visual, and auditory) [24,28,30,35,37].

Some of the studies ($n = 14$) [18,24,25,27,28,30,31,35–38,40,43,44] used vibration as open-loop cueing, where the vibration was delivered rhythmically based on the walking cadence of the participants. Ten studies used closed-loop cueing [26,29,32,33,39,41,46–49] where the vibration was delivered according to specific gait events such as heel strike, toe-off and/or swing phase. One study [17] used both open and closed-loop cueing.

Various devices were used to apply the haptic cues or vibrations, including shoes [32,33,36,40,45,48–50], insoles [26,37], socks [17], anklets [18], wrist bands as well as devices attached to the wrist [27,28,30,38,43], a wearable postural stabilizer [34], a lumbar orthosis [29], vibrotactile units attached to the waistband [24,46], sternum [47]and custom-made vibratory devices [25,31,39,41,42,44]. One study did not report the device used to generate haptic cues [35].

The site of haptic cue application varied, as shown in Fig. 2. Seven studies applied the cueing to the wrist [27,28,30,38,39,41,43], and six to the sole of the foot [17,26,32,36,37,47]. Five other studies applied cueing to muscle tendons, with the posterior aspect of the lower leg being a common site for stimulation. This included soleus [31,34], Achilles tendons [42,45], tricep surae tendon [25], and gastrocnemius [44]. One of these studies also applied vibration to the tibialis anterior and erector spinae muscles [31]. Other sites of cue application were the dorsum of the foot [33,40], medial aspect of the heel [40], above the medial and lateral malleoli [48,49], the abdomen [24], the sternum [50], pelvis [35], and the lumbar region [29,46]. The study by Volpe et al. [34] also applied cueing to the seventh cervical vertebra in addition to the soleus tendon.

Table 1
Characteristics of the studies included in the review.

Study	Study characteristics		Characteristics of participants with PD	Intervention Characteristics							Outcomes		Main findings
Author, Year	Design	Sample size	Age, (mean± SD), Gender(G) (M/F), Disease duration (DD) (yrs), Disease progression (DP) (H&Y/UPDRS)	Device Name	Cueing location	Cue type	Intervention timing and follow-up	Setting	Cue Delivery – (CD), CL- Closed loop, OL- Open loop Cue frequency (CF)	Medication status	Gait Evaluation techniques	Outcome parameters	
Novak & Novak, 2006 [26]	Pre-post intervention	N = 16 8 PD 8 H	Age = 61.4 ± 12.4 G = 5 M/3 F DD = 6 ± 3.9 DP = (HY 2.4 ± 0.2, UPDRS 29.7 ± 8.5)	Insole	Sole (1 VD under the heel and 2 below the forefoot)	Vibration	One day No follow up	Lab	CD - CL (During stance phase) CF - 70 Hz	ON	Gait Logger (JAS Research. Inc., Boston, MA) connected to the foot switches with 4 force sensors on each foot (B & L Engineering, Inc., Tustin, CA).	Stride length, Gait velocity, Cadence, Stance duration, Stance CV (Coefficient of variation), Swing duration, Swing CV, Double support duration, Double support CV, Walking distance, Stride duration	Step-synchronized vibratory stimulation on the soles enhances gait stability in people with PD and significant balance impairments.
Van Wegen et al.,2006 [27]	Pre-post intervention	N = 17 17 PD	Age = 63.4 ± 10.3 G = 12 M/5 F DD = 7.7 ± 5.1 DP = (HY 2.5 ± 0.9, UPDRS 49 ± 813.7)	Wrist band	Wrist	Rhythmic somatosensory and visual flow.	One day,1.5 h No follow up	NR	CD - OL CF - 1.1 Hz	ON	NR	Stride frequency (Cadence)	RSC can be effectively applied to reduce stride frequency while keeping the walking speed constant, resulting in a longer stride length.
Rochester et al.,2007 [28]	Pre-post intervention	N = 153 153 PD	Age = 67.06 ± 7.54 G = 88 M/65 F DD = 8.25 ± 5.09 DP = (HY-NR, UPDRS 56.03 ± 16.01)	Wrist band	Wrist	Vibratory, auditory and visual cue	One day Follow up after 3 weeks	Home	CD- OL CF -NR	ON	Vitaport Activity MonitorR (VAM) (TEMEC Instruments Inc)	Velocity, Step amplitude, Cadence	Provides new evidence for the positive effects of cueing on dual-task performance and suggests that performance with cues can be generalized to functional activities and also to the home environment in which testing took place.
Ghoseiri et al.,2009 [29]	Pre-post intervention	N = 14 14 PD	Age = 59.9 ± 9.1 G = 12 M/2 F DD = 5.9 ± 4.2 DP = (HY 2.5 ± 0.7, UPDRS NR)	Vibratory lumbar orthosis	Lumbar region	Vibration	One day No follow up	NR	CD - CL (During heel contact) CF - 97 Hz	ON	Digital chronometer	Walking velocity and the time to complete the 10 m walking test.	The study demonstrated a significant increase in walking velocity with the vibratory lumbar orthosis compared to no vibration.
Nieuwboer et al.,2009 [30]	Pre-post intervention	N = 133 133 PD (68 freezers, 65 non-freezers)	Age = 66.6 ± 7.52 G = 78 M/55 F DD = 8.2 DP = (HY NR, UPDRS III 33.6)	Wrist band	Wrist	Vibratory, auditory and visual cue	NR	NR	CD - OL CF - NR	ON	The Vitaport Activity Monitor (VAM; TEMEC Instruments Inc, Kerkrade, the Netherlands)	Turn time	Somatosensory cues help people with PD complete complex turns more quickly in a home setting, benefiting both freezers and non-freezers.

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Table 1 (*continued*)

Study	Study characteristics		Characteristics of participants with PD	Intervention Characteristics							Outcomes		Main findings
De Nunzio et al.,2010 [31]	Pre-post intervention	N = 30 15 PD 15 H	Age = 68.4 ± 10.9 G = 7 M/8 F DD = 5.36 DP = (HY 2.46, UPDRS III 26.73)	Bands with two vibrating units around ankles and waist	Tibialis anterior muscle, Soleus muscle and the erector spinae	Vibration	One day, 0.5 h No follow up	Lab	CD - OL CF −100 Hz	ON	GAITriteÓ, CIR Systems, USA	Stride length, step cadence, velocity, support base width, stance phase and swing phase.	Alternate vibration of the paraspinal muscles increases walking velocity in people with PD by increasing both cadence and stride length. These effects are comparable to or even greater than those seen in healthy individuals.
El-Tamawy et al.,2012 [32]	Double-blind RCT	N = 30 30 PD	Age = 62.5 ± 6.1 G = 21 M/9 F DD = G1:4.0 ± 0.9 G2:3.8 ± 0.9 DP = (HY G1:2.8 ± 0.5 G2: 2.6 ± 0.4, UPDRS NR)	Shoe	Feet	Vibration	8 weeks, 51–70 min session, 3 times per week Follow up after 6 weeks	Lab	CD - CL (During swing phase) CF - NR	ON	Qualysis ProReflex motion capture (Qualysis Medical AB, Sweden) system	Cadence, Stride length, walking speed, walking distance, degrees of hip flexion, knee flexion and ankle dorsiflexion	Enhanced proprioceptive feedback improves gait kinematics and increases the angular movement of lower limb joints in people with PD.
Winfree et al.,2013 [33]	Pre-post intervention	N = 4 2 PD 2 H	Age = 57.25 ± 6.70 G = 1 M/1 F DD = 12.5 DP = NR	Shoe (PD Shoe)	Sole Two vibrators at heel and one at the toe of each sole	Vibration	1 week, 5 days, nine sessions Follow up after the 1-week intervention.	Lab	CD - CL (During stance phase) CF - 175 Hz	NR	PDShoe	TUG, BBS, FOGQ, Step duration, Stance to swing, peak heel pressure timing(% GC), Time on heel sensor (%GC), Peak toe pressure timing (% GC), Time on toe sensor (%GC)	This short intervention study demonstrated statistically significant improvements in the timing of peak heel pressure, peak toe pressure, time spent on the heel sensor, and the stance-to-swing ratio after only one week of therapy.
Volpe et al.,2014 [34]	Double-blind, double-dummy, parallel-group RCT	N = 40 40 PD	Age = Active 66.5(64.0; 78.0), Placebo 69.5 (65.0; 73.8) G = Active 7 M/ 13 F, Placebo 9 M/11 F DD = Active 3.0, Placebo 6.5 DP = HY Active 6.0, Placebo 3.0, UPDRS NR)	wearable postural stabiliser (Equistasi)	Seventh cervical vertebra and each soleus muscle-tendon	Vibration	8 weeks, 60 min daily sessions a week Follow up at two-time points. T1- within 1 week after the 2-month therapy period. T2–2 months after T1.	Hospital setting	CD – NA (vibration was not synchronized with the gait cycle) CF- NR	ON	NA	UPDRS II, UPDRS III, BBS, TUG, ABC, FES, PDQ−39, Sway area, Sway path, Mean COP velocity	This pilot RCT suggests that a physiotherapy program with perturbation-based training and focal mechanical vibration from a wearable stabilizer is safe and well-tolerated. While it lacks superiority in most primary endpoints, it effectively improves balance confidence, disability, and fall rates, enhancing QOL.
McCandless et al.,2016 [35]	Pre-post intervention	N = 20 20 PD	Age = 68 (49 – 84) G = 14 M/6 F DD = 11.5 DP = NR	Vibration device	Anteriorly over the right side of the pelvis	Vibratory, auditory and visual	One day No follow up	Lab	CD - OL CF - 70 beats/ min	OFF	Qualisys motion analysis system (Qualisys Medical AB, Gothenburg, Sweden)	Percentage of freezing episodes, first step length, second step length, forward COM velocity, sideways COM velocity,	The Laser Cane (Visual cues) and the walking stick (Vibratory cues) could benefit people with PD with gait initiation difficulties.

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Table 1 (*continued*)

Study	Study characteristics		Characteristics of participants with PD	Intervention Characteristics							Outcomes		Main findings
												number of forward/ backward sways and the number of sideways sways, forward COP velocity (m/s) side to side COP velocity (m/s).	
Otis et al.,2016 [36]	Pre-post intervention	N = 21 12 PD 9 H	Age = 67.7 ± 10.07 G = 10 M/2 F DD = 10.67 ± 6.05 DP = (HY 2.5 ± 0.88, UPDRS 43.42 ± 14.9)	Shoe	Sole	Vibration	One day No follow up	Lab	CD - OL CF- NR	ON	NA	TUG	The study found that the proposed enactive insole may help lower fall risk by providing rhythmic vibrotactile cues during walking on various types of soil.
Pereira et al.,2016 [25]	Pre-post intervention	N = 16 16 PD	Age = 70.71 ± 7.77 G = 14 M/2 F DD = NR DP = (HY NR, UPDRS III 25.73 ± 3.10)	Custom-made vibratory devices	Tricep surae tendons	Vibration and visual	One day No follow up	Lab	CD - OL CF−100 Hz	ON	Zeno Walkway-e ProtoKinetics®	Mean duration (and standard error) of the first FOG episode and subsequent FOG episodes during the three assessed conditions	Applying vibration to the gastrocnemius tendon of the less affected leg after a FOG episode begins reduces its severity. However, when vibration is applied before a FOG episode, it has no beneficial effects.
Ayena et al.,2017 [37]	Pre-post intervention	N = 21 12 PD 9 H	Age = 67.7 ± 10.07 G = 10 M/2 F DD = 10.67 ± 6.05 DP = (HY 2.5 ± 0.88, UPDRS 43.42 ± 14.9)	Insole (ACHIILE system)	Sole of the right foot.	Vibratory, auditory and visual	One day No follow up	Lab	CD - OL CF- Pulses of 50 ms	ON	NA	TUG	The results for vibrotactile cueing were inconsistent, though they showed promise in improving gait regulation. Auditory cues may be more effective in reducing fall risk across various walking surfaces for people with PD, and auditory cues are generally more effective than visual cues.
Thompson et al.,2017 [38]	Pre-post intervention	N = 12 12 PD	Age = 63.5 ± 9.5 G = 7 M/5 F DD = 5.4 ± 4.55 DP = (HY NR, UPDRS III 34.9 ± 16.5)	Wrist-based wireless device (ArmSense device)	Dorsal wrist	Vibration and visual	One day No follow up	A gymnasium	CD - OL CF - NR	ON	Video analysis	Step length, lateral trunk sway, Cadence and velocity	Wrist vibration cues may be more effective than visual cues for altering and sustaining gait characteristics, even though the vibration cue is indirect. During comfortable walking speeds, vibration cues increased arm swing and led to adjustments in step length and

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Table 1 (*continued*)

Study	Study characteristics		Characteristics of participants with PD	Intervention Characteristics							Outcomes		Main findings
													cadence, while trunk sway remained unaffected.
Mancini et al.,2018 [39]	Pre-post intervention	N = 43 43 PD (25 freezers, 18 non-freezers)	Age = Freezers - 69 ± 7, non-freezers - 70 ± 7 G = Freezers 14 M/4 F, non-freezers 19 M/ 6 F DD = Freezers −9.3 ± 6.5, non-freezers - 8.2 ± 4.7 DP = (HY NR, UPDRS III Freezers −47.1 ± 10.1, Non-freezers - 43.6 ± 11.6)	A miniature vibrotactile transducer attached to the wrist (VibroGait)	Wrist	Vibration and auditory	One day No follow up	Clinic	CD-CL(During stance phase) CF – 200–300 Hz	OFF	Inertial sensors (Opal, APDM Inc.)	FOG ratio, percentage of time spent freezing during the task, number of turns, Average turn peak velocity and average turn jerkiness.	Objective freezing measures, including the percentage of time spent freezing and the FOG-ratio, showed significant improvement during turns with both open-loop and closed-loop cueing compared to baseline.
Aggarwal et al.,2019 [40]	Pre-post intervention	N = 17 17 PD	Age = 55 ± 10.1 G = 13 M/4 F DD = NR DP = Mean and SD NR	Shoe (PDShoe)	Dorsum of the foot and on medial aspect of the heel	Vibration	2 weeks, 10 sessions (5 days per week) Follow up in two weeks	Hospital	CD - OL CF - NR	ON	NA	UPDRS III, TUG test, BBS, 10MWT(Steps), 10MWT(Seconds), PDQ−39, FOG-Q,FES-I	Step-synchronized vibration led to improvements in FOG, evidenced by better TUG and FES-I scores, enhanced balance as indicated by changes in BBS, and a higher QOL as reflected in PDQ−39 self-reports.
Fino & Mancini, 2020 [41]	Pre-post intervention	N = 43 43 PD	Age = 70 ± 7.3 G = 33 M/10 F DD = 8.6 ± 5.6 DP = NR	Miniature vibrotactile transducer (VibroGait unit)	Wrist	Vibration and auditory	One day No follow up	Clinic	CD - CL (During stance phase) CF - 200–300 Hz	OFF	Inertial sensors (Opal, APDM Inc.)	Gait speed, Stride length, Stride time, Step time (SD), Step time (Asymmetry), Weight transfer, Early swing, Late swing	Closed-loop tactile cueing induced gait stability, specifically during the weight transfer phase. Whereas open-loop auditory cueing had no effect on gait stability
Rossi et al.,2020 [18]	Pre-post intervention	N = 27 15 PD 12 H	Age = 61 ± 7.3 G = NR DD = 9 ± 4.9 DP = (HY NR, UPDRS 43.5 ± 15.23)	Anklets (WEARHAP-PD)	Ankle	Vibration	One day No follow up	Lab	CD - OL CF - 250 Hz	ON	Vicon Motion Systems Ltd., UK	Stride velocity, Stride length, Stride height, FOG time	The WEARHAP-PD device is an affordable, safe, and user-friendly wearable designed to enhance certain walking parameters in people with PD under regular pharmacological treatment.
Phuenpathom et al.,2022 [42]	RCT	N = 60 60 PD	Age = 62.78 ± 4.85 G = 34 M/26 F DD = 10.26 ± 2.79	Custom-made vibratory eccentric mass device	Both Achilles tendons	Vibration, Pressure stimulation	NR	Lab	CD – NA (vibration was not synchronized with the gait	ON	GAITRite® (Version 3.95, CIR Systems Inc., Clifton, NJ 07012, USA)	MDS UPDRS III in ON period, TUG test, Percent FOG (%), Freezing episodes (times), Freezing	Combined vibratory and pressure stimulation could be effective in addressing FOG. The results

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Table 1 (*continued*)

Study	Study characteristics		Characteristics of participants with PD	Intervention Characteristics							Outcomes		Main findings
			DP = (HY 2.57 ± 0.47, UPDRS NR)						cycle) CF −100 Hz			episodes(seconds), Stride velocity, Stride length, Mean stride lengths of 3 strides before a freeze, Coefficient of variation of stride velocity (%), Coefficient of variation of stride length (%),Coefficient of variation of 3 strides before a freeze	emphasize the immediate effects of dual stimulation as a possible alternative or supplementary treatment for FOG.
Suputtitada et al.,2022 [24]	Pre-post intervention	N = 20 20 PD	Age = 66 ± 11.2 G = 9 M/11 F DD =NR DP = HY 2.1 ± 0.9, UPDRS NR)	Device attached to the waist band	Abdomen	Vibration, Auditory and Visual	NR	Lab	CD - OL CF - NR	OFF	A 2-metre RS foot scan embedded in the centre of the walkway	Velocity, Stride length, Cadence	Using individual visual, auditory, or somatosensory cueing devices, or a combination of two cues, can immediately enhance gait mobility in people with PD.
Klaver et al.,2023 [17]	Pre-post intervention	N = 40 40 PD	Age = 66 (60–74) G = 27 M/ 13 F DD = 11 DP = (HY 2, UPDRS ON: 38, OFF 51)	Socks	Feet, medially at the arch underneath the patient's feet	Vibration and auditory	One day No follow up	Lab	CD - CL (At initial contact) & OL both CF−183 Hz	Both	MVN Awinda motion capture system (Xsens, Enschede, the Netherlands	Velocity, Step size, Cadence, SLSP, DLSP, Percent time frozen (%), Number of FOG episodes	While cueing did not enhance FOG at the group level, both tactile and auditory cueing were effective in improving FOG for many individuals.
Lheureux et al.,2023 [43]	Pre-post intervention	N = 10 10 PD	Age = 68.3 ± 9.3 G = 6 M/4 F DD = 5.6 ± 3.2 DP = (HY 2, UPDRS 62.8 ± 26.2)	Vibrotactile unit attached to the wrist	Wrist	Vibration and auditory	One day No follow up	Lab	CD - OL CF - NR	ON	Inertial Measurement Units (IMeasureU Research, VICON, United Kingdom)	Gait velocity, Cadence, Step length, Mean stride duration, Coefficient of variation in stride duration variability (%), α-DFA, α-DFA Z-score	Similar findings were observed for RAS and RVS concerning the spatiotemporal gait parameters and stride duration variability of people with PD, both in terms of magnitude and temporal organization
Li et al.,2023 [44]	Pre-post intervention	N = 17 17 PD	Age = 74.5 (60−84) G = 14 M/3 F DD = 9.6 DP = NR	Wearable 'GaitThaw' movement-tracking cueing device	Gastrocnemius muscle of both legs	Vibration	One day No follow up	Clinic	CD - OL CF - NR	ON	IMU	Step frequency (cadence), Freeze time total (secs), Freeze time (% total)	This study shows improved gait and FOG with responsive vibration cueing in PD and presents a framework for real-time gait analysis and FOG detection on embedded devices.
Phuenpathom et al.,2024 [45]	RCT	N = 40 40 PD	Age = Active 72 ± 7.2 Placebo 71.2 ± 7.2 G = Active16M/ 4 F, Placebo10M/ 10 F	FOG shoe	Both Achilles tendons	Vibration, Pressure stimulation	One day No follow up	Lab	CD – NA (vibration was not synchronized with the gait cycle) CF – 100 Hz	ON	Strideway® System (Version 7.8, Tekscan, Inc., Boston, MA, United States)	Percentage of time spent in FOG, Spatiotemporal gait parameters(velocity, stride length, their respective coefficients of variation and	The FOG shoe with combined vibratory and pressure stimulation could decrease FOG episodes.

(*continued on next page*)

Table 1 (*continued*)

Study	Study characteristics		Characteristics of participants with PD	Intervention Characteristics							Outcomes		Main findings
			DD = Active 12.1 ± 3.2, Placebo 12.4 ± 3.2 DP = HY Active 3.1 ± 0.6, Placebo 3 ± 0.6, UPDRS NR)									cadence) peak plantar pressure, plantar pressure during heel-strike and push-off, heel contact time, force time integral, mean length of the three strides taken immediately before onset of a freeze	
Bowman et al., 2024 [46]	Pre-post intervention	N = 07 07 PD	Age = 70.4 ± 8.1 G = 7 M/0 F DD = 12 ± 5.6 DP = (HY 2.7 ± 03 UPDRS 49.1 ± 13.5)	Belt with vibrotactile units	Waist (in correspondence with PSIS, lateral iliac crests and ASIS)	Vibration	Three consecutive days No follow up	Lab	CD – CL (Either at loading response or push off) CF – 100–150 Hz	ON	Motion analysis system and four force platforms (SMART-TD and P6000, BTS S.p.A., Milan, Italy)	Cadence, Stride duration, Double support, stance, single support, swing time	Participants showed short-term improvements in functional tests and instrumental assessments following the step-synchronised vibrotactile biofeedback.
Cen et al.,2024 [47]	Pre-post intervention	N = 33 33 PD	Age = 67.5 ± 8.8 G = 18 M/15 F DD = 7.5 ± 4.4 DP = (HY 2.5 ± 0.6, UPDRS III 36.0 ± 15.7)	vibrotactile foot device	Sole	Vibration	One day No follow up	Lab	CD - CL (During stance phase) CF - 200 Hz	OFF	Opal inertial sensor unit (128 Hz; Mobility Lab; APDM Inc., Portland, OR, USA) worn on bilateral wrists, ankles, and the trunk (sternal and lumbar region)	Freezing episodes, Percent time freeze, Cadence, Double support, Stride time, Stride velocity, Stride length, Turn duration, Turn velocity	The vibrotactile foot device appears to be an effective tool for reducing the severity of freezing episodes and improving gait regulation in individuals with PD who frequently experience freezing.
Khatavkar et al., 2024a [48]	Pre-post intervention	N = 10 10 PD	Age = 65.1 ± 9.17 G = 10 M/0 F DD = 11.8 ± 4.31 DP = (UPDRS II 23.8 ± 6.92, UPDRS III 43.2 ± 10.97)	Instrumented shoe	Above the malleolus on medial and lateral sides	Vibration	One day No follow up	Lab	CD – CL (Only at heel strike)) CF - 200 Hz	Both	instrumented shoe and the foot insoles	Foot to Ground angle at heel strike	The instrumented shoe that estimated the foot to ground angle at heel strike to deliver the vibrotactile cueing mitigated the FOG quantified by a reduction in the ratio of time spent freezing to the total walking time and the number of FOGs.
Khatavkar et al., 2024b [49]	Pre-post intervention	N = 08 08 PD	Age = 66.13 ± 7.04 G = 08 M/0 F DD = 12.63 ± 4.31 DP = (UPDRS II 15.87 ± 4.82, UPDRS III 27.75 ± 7.69)	Instrumented shoe	Above the malleolus on medial and lateral sides	Vibration	One day No follow up	Lab	CD – CL (If the foot strike angle is observed above a threshold) CF - 230 Hz	ON	instrumented shoe and the foot insoles	Kinetic and kinematic gait parameters such as vertical ground reaction force, center of pressure, toe clearance, and foot strike angle	There is potential of a Foot strike angle based cueing device for toe clearance improvement in people with PD.

(*continued on next page*)

Table 1 (*continued*)

Study	Study characteristics		Characteristics of participants with PD	Intervention Characteristics						Outcomes		Main findings
				CUE1	Sternum	Vibration	3* 2- week intervention	Home	CD – NA (vibration was not synchronized with the gait cycle) CF - NR	ON	NA	
Azoidou et al., 2025 [50]	Pre-post intervention	N = 10 10 PD	Age = 66.0 ± 9.83 G = 5 M/5 F DD = 3.90 ± 2.47 DP = (HY 2.90 ± 0.57, UPDRS III 45.40 ± 12.22)				blocks over 9 weeks Follow up at 3,6 and 9 weeks				Effectiveness outcomes: MDS-UPDRS Part-III and its subcategories, Functional Gait Assessment (FGA), TUG, and dual-task TUG Feasibility outcomes: recruitment rate, compliance, drop-out rates, tolerability and safety	CUE1 vibrotactile device shows potential in enhancing motor function, balance, and gait, lowering the risk of falls, and alleviating both motor fluctuations and non-motor symptoms.

Abbreviations: PD – Parkinson's Disease, SD – Standard Deviation, H – Healthy, G – Gender, M - Male, F - Female, DD - Disease duration, DP - Disease progression, H&Y - Hoehn and Yahr, UPDRS - Unified Parkinson's Disease Rating Scale, CD - Cue delivery, CL - Closed loop, OL - Open loop, CF - Cue frequency, VD - Vibratory device, NR - Not reported, NA – Not applicable, TUG - Timed up and go, FES - Falls efficacy scale, FOG - Freezing of gait, RSC - Rhythmic somatosensory cueing, GC - Gait Cycle, ABC – Activity Specific Balance Confidence Scale, PDQ-39 – Parkinson's Disease Questionnaire-39, BBS – Berg Balance Scale, COP – Center of Pressure, COM – Center of Mass, NA – Not Applicable, 10MWT – 10 Meter Walk Test, IMU – Inertial Measurement Unit, QOL – Quality of life, PSIS - Posterior Superior Iliac Spine, ASIS – Anterior Superior Iliac Spine

Since most of the included studies were pre-post interventions, the intervention duration was often limited to a single session [17,18,25–29,31,35–39,41,43–45,47–49]. However, a few studies applied the intervention over a longer period, ranging from three consecutive days [46] to eight weeks [32,34].

The majority ($n = 20$) of the studies did not include a follow-up assessment, while a few ($n = 6$) [28,32–34,40,50] measured follow-up outcomes after one [33] to nine [50] weeks post-intervention. One study [34] conducted its first follow-up (T1) eight weeks after the initial assessment and a second follow-up two months later from T1.

Twenty studies were conducted in the ON medication phase [18,25–32,34,36–38,40,42,43,45,46,49,50], and four were conducted in the OFF medication phase [24,39,41,47]. Two studies were conducted in both the ON and OFF phases [17,48], while three studies did not specify the medication phase during the intervention [33,35,44].

Of the included studies, only five [17,33,39,40,47] assessed participants' peripheral sensation prior to applying the haptic cueing device. One study [17] used vibrating socks, which served as the intervention tool or a Rydel-Seiffer tuning fork to assess sensation at the dorsal aspect of the first metatarsophalangeal joint and the medial malleolus of both feet. Another study [39] used a 128-Hz tuning fork on the feet, while the remaining three studies assessed sensation using their respective intervention devices [33,40,47].

3.6. Gait analysis methods

Only one study used Vicon Motion Systems Ltd., UK, and Nexus version 2.7 for gait data capture and analysis [18]. The study by Thompson et al. [38] used video analysis for gait data capture, but did not provide specifications. Three studies used instrumented shoes that served both as the intervention and as the method for gait analysis [33,48,49]. Other methods of gait data capture included the Vitaport Activity MonitorR (VAM) (TEMEC Instruments Inc) [28,30], a 2-metre RS foot scan embedded in the centre of the walkway [24], the Gait Logger (JAS Research. Inc., Boston, MA) [26], the Qualisys motion analysis system (Qualisys Medical AB, Gothenburg, Sweden) [32,35], four force platforms and a motion analysis system [46], Strideway® System (Version 7.8, Tekscan, Inc., Boston, MA, United States)[45], GAITRite® [31,42], Zeno Walkway e-ProtoKinetics® [25], the MVN Awinda motion capture system (Xsens, Enschede, the Netherlands) [17], IMUs [43,44], inertial sensors [39,41,47], and a digital chronometer [29].

3.7. Meta analysis

Due to the heterogeneity in study designs and intervention types, the primary outcome measures reported in RCTs only were considered for the pooled analysis. Moreover, since baseline outcome values were higher in the control groups in some RCTs, change scores (post-intervention minus pre-intervention) were used to compare group effects in the forest plots (Fig. 3).

The included RCTs compared the intervention group receiving haptic cueing with either no treatment or a regular physiotherapy program. Two RCTs [42,45] assessed immediate effects, while one [32] assessed the effects after six weeks of treatment. Three RCTs [32,42,45], comprising a total of 100 participants (50 experimental and 50 control), were included in the meta-analysis of gait velocity and stride length.

The pooled results showed a significant improvement in gait velocity (MD = 6.78; 95 % CI: 4.13–9.43; Z = 5.01; P < 0.00001) with a low heterogeneity ($I^2 = 0$ %; P = 0.31). Similarly, stride length showed a statistically significant improvement (MD = 10.31; 95 % CI: 5.08–15.54; Z = 3.86; P = 0.0001) with low heterogeneity ($I^2 = 28$ %; P = 0.36).

Two RCTs ($n = 35$) [32,45] were included in the meta-analysis of cadence. The pooled results did not show a statistically significant effect (MD = 13.84; 95 % CI: −2.73–30.42, Z = 1.64; P = 0.10), and the heterogeneity was high ($I^2 = 78$ %; P = 0.03).

3.8. Qualitative analysis

A qualitative analysis is presented below, considering all included studies. For the RCTs, we extracted and reported results from the intervention group only in Tables 2–4, and *p*-values were reported where within-group statistical comparisons for the intervention group were available.

3.9. Main spatiotemporal gait parameters

3.9.1. Gait velocity

Fourteen studies measured gait velocity (m/s) [17,18,24,26,28,29,32,38,41–43,45–47] as an outcome measure. The majority [18,26,28,29,32,38,42,43,45,46] were conducted during the ON medication phase, three during the OFF phase [24,41,47], and one [17] during both ON and OFF phases. Of these, three RCTs with strong methodological quality [32,42,45] demonstrated improvements in gait velocity following vibrations. Five additional pre-post interventional studies also reported improvements, though with moderate methodological quality [18,24,26,29,46]. The magnitude of improvement varied across studies (Cohen's *d* ranging from 0.45 to 3.11), and the methods used to measure gait velocity also differed across studies.

In contrast, four studies [17,38,43,47] found no significant improvement, while two reported reduced gait velocity [28,41] with haptic cues. One study [41], which utilized Inertial sensors (Opal, APDM Inc.), reported a reduction in gait velocity with closed-loop tactile cueing, observing decreases in both single-task and dual-task conditions ($p < 0.05$). This study was conducted during the OFF-medication phase and was assessed as having limited methodological quality (Table 2).

3.9.2. Stride length/ Step length

Eight studies measured stride length [24,26,31,32,41,42,45,47] and four measured step length [35,38,43,46] as an outcome measure. Three of the RCTs [32,42,45] reported significant improvements in stride length following the application of haptic cueing. Six other pre-post interventional studies also found similar findings [24,26,31,38,46,47].

However, two studies reported that the vibration had a decreasing effect on stride length, [35,41]. These studies had moderate [35] and limited [41] methodological quality and variability in their interventions. Notably, both were conducted in the OFF-medication phase (Table 3).

3.9.3. Cadence

Ten studies measured cadence [17,24,26–28,32,38,43,45,47] as an outcome measure. Two RCTs [32,45] reported a significant increase in cadence with haptic cue interventions. Two other pre-post-interventional studies reported similar findings [43,47].

In contrast, three studies [27,28,38] found that cadence decreased with haptic cue interventions. These were all pre-post interventional studies that used wrist-based devices for cueing.

Three additional studies [17,24,26] found no significant difference in cadence before and after the haptic cue intervention. All were pre-post-intervention studies [17,24,26]. The devices used included a waistband-attached device [24], insole [26], and socks [17]. The studies varied in medication status: ON [26], OFF [24], and both phases [17] (Table 4).

3.10. Other spatiotemporal gait parameters

3.10.1. Stance and swing phase duration

Two studies [26,46] assessed stance and swing duration, reporting a significant reduction in stance duration following haptic cueing interventions.

3.10.2. Single and double limb support time

Among the three studies [17,46,47] that assessed single and double limb support time, only one study [46] reported a significant reduction in double limb support time.

3.10.3. Stride time variability

Stride time variability was evaluated in three studies [26,43,47]. One study [26] reported a significant decrease in stride time variability, indicating more consistent gait timing post-intervention.

3.11. Other gait-related outcomes

3.11.1. FOG time or episodes

FOG time or episodes were assessed in eight studies [17,18,25,39,42,45,47,48] with varying results. Six studies found a significant reduction ($p < 0.001$) in freezing episodes and percent time frozen with vibrotactile cues [18,39,42,45,47,48].

Pereira et al. [25], found vibration on the less affected limb reduced the first FOG episode duration ($p < 0.05$) but not the subsequent episodes. Klaver et al. [17] reported no significant group-level effects on FOG duration or frequency.

3.11.2. FOG questionnaire

The Freezing of Gait Questionnaire was used in two studies [33,40] with mixed results. One study [33] reported significant reductions in FOG, while the other [40] found no significant reductions ($p = 0.07$).

3.11.3. Joint kinematics

Only one RCT [32] assessed joint kinematics, reporting greater increases in hip flexion (Cohen's $d = 5.35$), knee flexion (Cohen's $d = 2.53$), and ankle dorsiflexion (Cohen's $d = 2.14$) during mid-swing in the intervention group compared to controls. This study also reported associated increases in gait velocity, stride length and cadence.

3.12. Clinical tests

3.12.1. Timed up and go test

The TUG test was employed in seven studies [33,34,37,40,42,45,50], with six reporting significant reductions in completion time with haptic cueing. Two studies [40,50] reported a significant reduction in TUG time both post-intervention and at follow-up compared to pre-intervention, indicating sustained improvements.

In contrast, Ayena et al. [37] found no significant positive effect of cueing on TUG time for both healthy elderly and participants with PD.

3.12.2. Berg balance scale

Three studies included the BBS as an outcome measure. One study reported significant improvements in BBS for a participant with DBS (31−50), while a participant with FOG showed no change [33]. Another study [34] showed increased scores in both intervention and control groups post-intervention. A third study reported significant post-intervention and follow-up improvements [40].

3.12.3. 10-meter walk test

Two studies included the 10-meter walk test as an outcome measure [29,40]. One study reported a significant reduction in the time to complete the test with vibratory orthosis ($p = 0.001$) [29]. In contrast, the other study found no significant improvements in the test, with no changes observed post-intervention or at follow-up compared to baseline [40].

3.12.4. The activity-specific balance confidence

One study [34] used the ABC scale and found short-term improvements in the intervention group at assessment point one (T1), which were not retained at assessment point two. Similar results were seen in the control group using a placebo device.

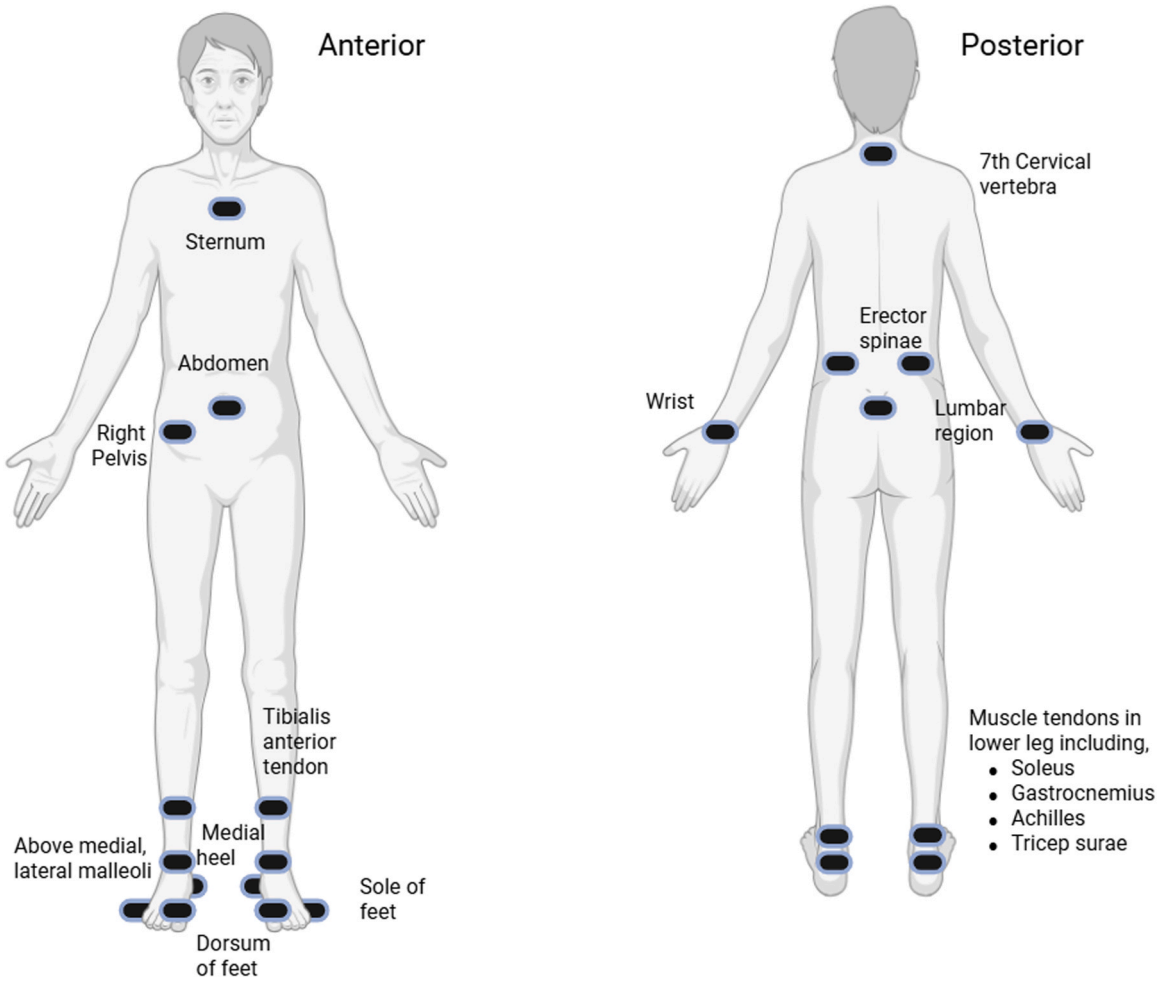


Fig. 2. Anatomical locations where haptic cues were applied in the studies.

3.13. Additional outcomes

3.13.1. Risk of falling/ falls efficacy

Five [34,36,37,40,50] studies assessed the impact of haptic cueing on fall risk, with most reporting significant improvements. These included reduced fall risk indicators, improved balance confidence, and functional gait assessments, though some effects were not sustained at follow-up.

3.13.2. Quality of life measured by the PDQ-39 questionnaire

Two studies assessed QOL using the PDQ-39. One reported significant improvement in the intervention group (66.0–39.0 post-intervention; 53.0 at follow-up) with smaller changes in the control group (63.0–58.0; 59.0 at follow-up) [34]. The other also showed significant post-intervention and follow-up improvements [40].

3.13.3. UPDRS part III in ON medication state

Four studies [34,42,45,50] evaluated haptic cueing effects on UPDRS scores; an RCT reported a significant reduction in UPDRS Part III scores in the intervention group compared to controls [45]. Two other studies [34,50] also showed clinically meaningful improvements, while one study found no significant change [42].

4. Discussion

This review investigated the effects of haptic cues on gait, balance, risk of falls, QOL, and subjectively evaluated disease severity in people with PD. A total of 29 studies were reviewed, including four RCTs, and the results suggest that haptic cueing can potentially improve gait parameters in individuals with PD. However, the long-term retention of these improvements remains uncertain. There was insufficient evidence to determine the long-term effectiveness of haptic cueing on outcomes such as QOL, joint kinematics, risk of falling, or UPDRS scores, as most studies only assessed the immediate effects of the intervention.

The meta-analysis demonstrated significant improvements in gait velocity and stride length following haptic cueing interventions. However, these findings should be interpreted with caution, as only three RCTs were included in the pooled analysis. While the studies involved participants of similar ages and disease severity, they differed in several aspects, including, but not limited to, the methods used to assess gait outcomes and the duration of intervention.

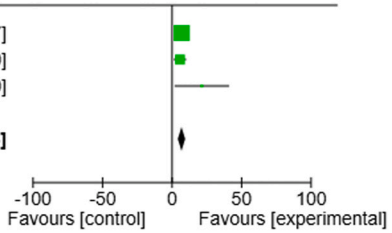
The four RCTs with strong methodological quality included in the review showed improvements in gait velocity [32,42,45], stride length [32,42,45] cadence [32,45] and the TUG test [34,45] following vibration. These findings were also shown in some pre-post interventional studies with moderate methodological quality. Although some studies have reported increased cadence with vibration [32,43,45], this does not necessarily indicate an overall improvement in gait, as a higher cadence can sometimes worsen gait quality. However, two studies [32, 45] revealed an increase in cadence, accompanied by improvements in stride length and gait velocity. When considered alongside enhancements in other gait parameters, this suggests a more positive effect on gait quality. In the included studies, several factors contributed to the challenges in achieving optimal methodological quality. Even though the Downs and Black tool [23] was utilized to assess the ROB, as it is recommended for both randomized and non-randomized studies, some

a) Gait velocity

Study or Subgroup	Experimental Mean	SD	Total	Control Mean	SD	Total	Weight	Mean difference IV, Random, 95% CI
El-Tamawy et al.,2012	10.56	5	15	3.61	4.24	15	63.8%	6.95 [3.63 , 10.27]
Phuenpathom et al.,2022	7.45	6.21	15	1.77	6.43	15	34.3%	5.68 [1.16 , 10.20]
Phuenpathom et al.,2024	21.7	38.86	20	0.3	22.13	20	1.8%	21.40 [1.80 , 41.00]
Total (Wald[a])			**50**			**50**	**100.0%**	**6.78 [4.13 , 9.43]**

Test for overall effect: Z = 5.01 (P < 0.00001)

Heterogeneity: Tau² (REML[b]) = 0.00; Chi² = 2.37, df = 2 (P = 0.31); I² = 0%



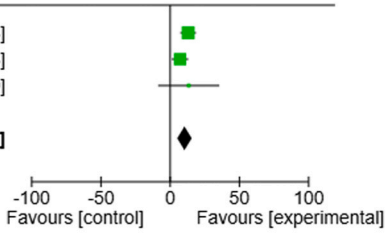
Footnotes
[a]CI calculated by Wald-type method.
[b]Tau² calculated by Restricted Maximum-Likelihood method.

b) Stride length

Study or Subgroup	Experimental Mean	SD	Total	Control Mean	SD	Total	Weight	Mean difference IV, Random, 95% CI
El-Tamawy et al.,2012	19	6.4	15	6	9.22	15	48.6%	13.00 [7.32 , 18.68]
Phuenpathom et al.,2022	8.78	7.72	15	1.67	8.87	15	46.0%	7.11 [1.16 , 13.06]
Phuenpathom et al.,2024	16.8	43.07	20	3.4	26.17	20	5.3%	13.40 [-8.69 , 35.49]
Total (Wald[a])			**50**			**50**	**100.0%**	**10.31 [5.08 , 15.54]**

Test for overall effect: Z = 3.86 (P = 0.0001)

Heterogeneity: Tau² (REML[b]) = 6.25; Chi² = 2.05, df = 2 (P = 0.36); I² = 28%



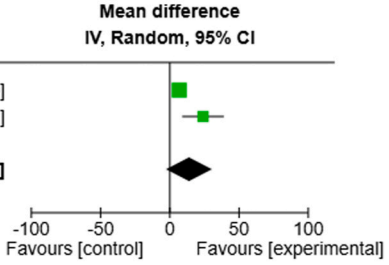
Footnotes
[a]CI calculated by Wald-type method.
[b]Tau² calculated by Restricted Maximum-Likelihood method.

c) Cadence

Study or Subgroup	Experimental Mean	SD	Total	Control Mean	SD	Total	Weight	Mean difference IV, Random, 95% CI
El-Tamawy et al.,2012	10.74	6.71	15	3.94	5.52	15	59.1%	6.80 [2.40 , 11.20]
Phuenpathom et al.,2024	28.5	25.28	20	4.5	23.1	20	40.9%	24.00 [8.99 , 39.01]
Total (Wald[a])			**35**			**35**	**100.0%**	**13.84 [-2.73 , 30.42]**

Test for overall effect: Z = 1.64 (P = 0.10)

Heterogeneity: Tau² (REML[b]) = 116.09; Chi² = 4.65, df = 1 (P = 0.03); I² = 78%



Footnotes
[a]CI calculated by Wald-type method.
[b]Tau² calculated by Restricted Maximum-Likelihood method.

Fig. 3. Forest plots showing the mean differences between experimental (haptic cueing) and control groups in randomized controlled trials (RCTs): (a) gait velocity (m/s), (b) stride length (m), and (c) cadence (steps/min). Random-effects meta-analysis was used.

ROB analysis criteria were not applicable to certain study designs. Given the limited availability of high-quality evidence, pre-post interventional studies were included in this review, which may introduce bias and limit the generalizability of the findings.

Among the studies ($n = 12$) that reported positive outcomes in gait velocity, step/stride length, and cadence following vibration, most ($n = 7$) [18,26,31,32,42,47,49] applied stimulation to the lower limb, including the feet, ankles or areas around the Achilles tendon.

Table 2
Summary of the studies that assessed gait velocity as an outcome measure.

Effect	Study	Pre-intervention Mean ± SD (m/s)	Post-intervention Mean ± SD (m/s)	*p-value*	Calculated Effect size (Cohen's *d*)
Increased	[18]	NR	NR	0.038	IC
	[24]	0.61 ± 0.32	0.82 ± 0.27	< 0.001	0.71
	[26]	1.02 ± 0.20	1.11 ± 0.20	0.0001	0.45
	[42]	0.35 ± 0.04	0.43 ± 0.04	NR	2.00
	[32]	0.25 ± 0.04	0.36 ± 0.03	0.001	3.11
	[29]	0.85 ± 0.16	0.95 ± 0.16	NR	0.63
	[46]	0.68 ± 0.12	0.87 ± 0.27	0.043	0.90
	[45]	0.44 ± 0.23	0.66 ± 0.31	NR	0.80
Decreased	[28]	0.96 ± 0.24	0.92 ± 0.24	0.006	0.16
	[41]	0.88 ± 0.22	0.74 ± 0.28	NR	0.56
No difference	[38]	NR	NR	0.658	IC
	[17]	NR	NR	NR	IC
	[43]	1.36 ± 0.24	1.45 ± 0.28	0.074	0.34
	[47]	0.7 ± 0.2	0.7 ± 0.2	0.119	0

Abbreviations: IC – Incalculable, NR- Not reported

Table 3
Summary of the studies that assessed stride length or step length as an outcome measure.

Effect	Study ID	Pre-intervention Mean ± SD (m)	Post-intervention Mean ± SD (m)	*p-value*	Calculated Effect size (Cohen's *d*)
Increased	[38]*	NR	NR	0.002	IC
	[24]	0.69 ± 0.17	0.84 ± 0.19	≤ 0.001	0.84
	[26]	1.170 ± 0.24	1.24 ± 0.30	0.0002	0.26
	[42]	0.39 ± 0.05	0.48 ± 0.04	NR	1.98
	[32]	0.80 ± 0.05	0.99 ± 0.04	0.005	4.19
	[31]	NR	NR	< 0.005	IC
	[45]	0.54 ± 0.27	0.71 ± 0.32	NR	0.57
	[47]	0.7 ± 0.2	0.8 ± 0.2	0.033	0.5
	[46]*	0.88 ± 0.14	1.05 ± 0.17	0.028	1.09
Decreased	[35]* FS	0.163 ± 0.013	0.126 ± 0.013	0.047	2.85
	[41] ST	0.93 ± 0.21	0.86 ± 0.25	NR	0.30
	[41] DT	0.86 ± 0.22	0.80 ± 0.26	NR	0.25
No difference	[35]* SS	0.314 ± 0.046	0.242 ± 0.042	0.252	2.61
	[43]*	0.71 ± 0.09	0.72 ± 0.10	NR	0.10

Abbreviations: IC – Incalculable, NR- Not reported, ST- Single task, DT – Dual task, FS – First step, SS – Second step, *step length

Table 4
Summary of the studies that assessed cadence as an outcome measure.

Effect	Study ID	Pre-intervention Mean ± SD (Steps/min)	Post-intervention Mean ± SD (Steps/min)	*p-value*	Calculated Effect size (Cohen's *d*)
Increased	[32]	95.13 ± 5.19	105.87 ± 4.26	0.001	2.26
	[43]	115.3 ± 37.73	119.78 ± 8.05	0.017	0.16
	[45]	77.5 ± 12.1	106 ± 22.2	< 0.0001	1.59
	[47]	114.5 ± 12.5	116.0 ± 12.9	0.518	0.11
Decreased	[38]	NR	NR	< 0.01	IC
	[27]	56.4 ± 12.0	49.8 ± 7.8	NR	0.65
	[28] ST	104.85 ± 11.7	100.73 ± 13.23	< 0.0001	0.33
	[28] DT	105.20 ± 14.22	101.77 ± 13.35	< 0.0001	0.25
No difference	[24]	51.53 ± 12.98	59.71 ± 9.19	1.000	0.73
	[26]	104.9 ± 8.9	109.2 ± 10.2	0.03	0.45
	[17] CL	108.89 ± 7.69	107.0 ± 9.23	NR	0.22
	[17] CL	108.89 ± 7.69	108.0 ± 9.23	NR	0.10

Abbreviations: IC – Incalculable, NR- Not reported, ST-Single task, DT-Dual task, CL-Closed-loop, OL-Open-loop

Conversely, among the studies reporting negative outcomes ($n = 5$), most ($n = 4$) [27,28,38,41] applied vibration cues to the wrist. This suggests that cue location might play an important role in optimising gait responses, though the ideal site for haptic cue application remains unclear. Further exploration of the most effective cue location, such as the feet versus the wrist, could enhance the precision of the intervention.

Moreover, all studies that reported negative effects on gait velocity, stride length, and cadence used more than one cue type, such as visual, auditory, or combined cues, along with haptic cues. Although only haptic cue outcomes were considered for this review, this intervention design may help explain the variability in results. Studies that exclusively used vibration as a cue type reported more positive results, suggesting that a focused intervention may be more effective in improving gait.

Most studies were conducted in the ON-medication phase, with only two studies conducted in both ON and OFF-medication phases [17,48]. Notably, both studies reporting reduced effects on stride length following vibration were conducted in the OFF-medication phase. This

implies that medication status may moderate the effectiveness of vibration cues, with greater variability in responses observed during the OFF-medication phase.

Studies applied haptic cues in both open-loop (consistent, rhythmic) and closed-loop (event-triggered) formats. Recent advances in wearable technology have enabled promising new methods for implementing both open and closed-loop cueing [51]. Some studies ($n = 14$) in this review utilized open-loop cueing, while others ($n = 10$) used closed-loop cueing, predominantly targeting the stance phase of gait. Only one study [32] targeted the swing phase and reported positive outcomes in gait velocity, stride length, and cadence. Despite mixed results, this review found that closed-loop cueing generally yielded more positive outcomes.

Intervention duration is a critical factor in determining the long-term effectiveness of haptic cues. Many studies focused on single-session interventions to assess the immediate effects of vibration cues. Only six studies assessed outcomes over extended periods, with durations ranging from three days to eight weeks. According to Nieuwboer [16], the complete impact on gait mobility may not be achieved with the immediate application of a cue, and more favourable outcomes may be observed with extended training periods using cues. Therefore, further studies with longer intervention durations are needed to determine if improvements can be sustained and to assess changes over time.

This review highlights the diverse methodologies used to assess gait in individuals with PD following haptic cue interventions, with varying methodologies across studies. One key aspect influencing the variability in findings is the use of different gait analysis technologies. For example, only one study utilised Vicon Motion Systems Ltd. [18] for gait analysis, a well-established, precise tool. In contrast, others used less sophisticated methods, such as video analysis [38] or digital chronometers [29]. Studies using highly precise systems like Vicon or Qualisys motion capture generally reported more reliable and consistent results. At the same time, those relying on simpler tools (e.g., video analysis or digital chronometers) were more prone to variability and potential measurement error. This inconsistency in data collection methods could explain some of the discrepancies observed in the effectiveness of haptic cueing on gait outcomes.

Only a few studies focused on other gait parameters, such as single and double limb support time and stride time variability. Assessing variability in gait provides valuable information about a person's movement patterns, although these measures are not yet fully integrated into clinical settings [52]. One study [26] showed significant reductions in stride variability following vibrations indicating that haptic cueing can contribute to a more rhythmic and regular pattern. The possibility that haptic cueing can enhance temporal gait consistency suggests the potential for benefits in related parameters, such as walking with confidence or reducing falls.

The mixed results on FOG time/episodes and the scores on the FOG questionnaire highlight the complexity of this motor symptom in PD. For instance, the study by Pereira et al. [25], showed that haptic cues reduced the duration of the first FOG episode but had no significant impact on subsequent episodes. This suggests that while vibration may have an immediate effect on FOG, its efficacy may diminish with prolonged use or require optimization to sustain benefits over multiple episodes. However, this study has limited methodological quality, and the results should be interpreted with caution. Moreover, Klaver et al.'s [17] lack of significant findings at the group level underscores the need for further investigation into individual variability in response to haptic cues for FOG, as the intervention may not benefit all patients equally.

Only one study [32], a RCT, investigated the effects of vibrations on joint kinematics, reporting significant improvements in hip and knee flexion, and ankle dorsiflexion during the mid-swing phase. Notably, the same study also demonstrated increases in gait velocity, stride length and cadence following vibration. These concurrent improvements in both spatiotemporal parameters and joint kinematics suggest a potential link between enhanced joint motion and overall gait performance. In particular, increased hip and knee flexion, along with ankle dorsiflexion, are essential for effective foot clearance and for reducing the risk of stumbling or tripping during walking. Therefore, integrating joint kinematic assessments into future studies, especially using motion capture systems, would provide a comprehensive understanding of how haptic cues influence the biomechanical aspects of gait in PD.

In addition to gait improvements, several studies in this review examined secondary outcomes related to motor performance, balance, and QOL. Consistent improvements were noted in the TUG test and the BBS, though BBS improvements were not always unique to the intervention group. Results were mixed for other balance measures, with significant gains in some tests like the 10-meter walk test and ABC scale scores, though these effects sometimes diminished over time. Quality of life improvements, measured by PDQ-39, were seen post-intervention; however, similar improvements in control groups suggest potential non-specific effects, such as increased attention to movement. Mixed results were also seen in UPDRS III scores, indicating a variability in the impact on motor symptoms. Overall, while haptic cueing interventions appear to positively impact secondary outcomes, the presence of similar improvements in control groups indicates a placebo effect highlighting the need for further studies to clarify the specific role of haptic cues.

The review also identified potential limitations in the existing literature on haptic cueing on gait in PD. One is the absence of conducting an advanced sensory screening of the participants, as haptic cues are intended to stimulate peripheral sensations. The plantar cutaneous mechanoreceptors appear to play a crucial role in supporting balance control during human movement [53]. However, only five studies assessed peripheral sensation in participants prior to intervention, and none utilized gold-standard sensory assessments. Klaver et al. [17], mentioned that future study participants should be screened for sensory testing, and that the vibrating device should be applied in a test trial before any actual implementation occurs. They also highlighted that this is especially relevant for people with PD as they have decreased vibration sensitivity of the plantar aspect of the feet compared to age-matched healthy participants [17].

Another research gap in the current literature is the predominant use of laboratory settings in the included studies as opposed to examining cueing in home or outdoor environments. In the advanced phases of the condition, continuous monitoring of patients over an extended duration is essential to gain a comprehensive understanding of symptoms and their variations, given the biphasic medication response [54]. This extended monitoring is challenging to achieve in a clinical setting. Additionally, the influence of attention on performance, particularly regarding symptoms like FOG, can result in an inaccurate clinical picture. Thus, future research should investigate the efficacy of haptic cueing in patients' home environments, where real-world monitoring is possible.

5. Study limitations

This systematic review provides a comprehensive evaluation of the effects of haptic cueing on gait and other motor outcomes in PD, offering valuable insights by including a wide range of studies and outcome measures. However, it is limited by including pre-post interventional studies without control groups, variability in study designs and methodologies, and a lack of long-term follow-up data. The inability to fully blind participants and assessors, as well as the inconsistent reporting of peripheral sensory function, may introduce bias. While haptic cueing shows potential for improving gait, its effects on secondary outcomes like balance, fall risk, and QOL are inconsistent and understudied. Overall, the review highlights gaps in the current literature and provides direction for future research.

6. Conclusion

Haptic cueing appears to be a promising intervention for improving gait in people with PD, with many studies demonstrating positive short-

term effects. However, most included studies focused primarily on immediate outcomes, leaving long-term effects largely unexplored. Furthermore, as the majority of studies were conducted in controlled, laboratory-based settings, future research should evaluate the effects of haptic cueing in real-world environments. Another important recommendation is to incorporate advanced sensory screening of participants before the intervention to gain deeper insights into individual responses to haptic cues. To strengthen the evidence base and minimise potential biases, high-quality RCTs are essential. Additionally, future research should investigate the sustained impact of haptic cueing on gait, QOL, balance, and other functional outcomes to provide a more comprehensive understanding of its effectiveness.

CRediT authorship contribution statement

Preetika B. Chand: Writing – review & editing, Visualization, Validation, Project administration, Investigation, Data curation. **Shanshika P. Maddumage Dona:** Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Karen Sullivan:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Conceptualization. **Alexander Lehn:** Writing – review & editing, Visualization, Validation, Supervision, Project administration. **Nadeesha Kalyani:** Writing – review & editing, Visualization, Validation, Supervision, Project administration. **Catherine Haden:** Writing – review & editing, Visualization, Validation, Resources, Project administration, Investigation, Data curation. **Graham K. Kerr:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Conceptualization.

Funding sources

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gaitpost.2025.08.069.

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