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Gait asymmetry in Parkinson's disease – a systematic review and meta-analysis (AsymmGait-Parkinson study)

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Gait asymmetry (GA) in people with Parkinson's disease (pwPD) has been inconsistently reported, leading to uncertainty about its prevalence and clinical significance. GA may relate to motor symptoms' lateralization and the effects of dopaminergic medication. The aim of this study was to systematically summarize the current literature and perform a meta-analysis to investigate the differences between GA in pwPD compared to healthy individuals and to evaluate the effect of dopaminergic medication on GA. The review was registered in PROSPERO database (ID: CRD42021285067). The searching was conducted in the PubMed, Cochrane Library, Lilacs, PEDro and Scopus databases. The primary search resulted in 551 studies. After removing the duplicates, 451 studies remained for the analysis. After checking the full text, 42 studies with 2111 pwPD were included in this review. The meta-analysis showed that pwPD exhibited greater asymmetry in step length, step time, and swing time, particularly in the OFF state, with moderate effect sizes. Dopaminergic medication was associated with reduced swing time asymmetry. Temporal aspects of GA, particularly swing time asymmetry, was most sensitive to detect differences in GA between pwPD and healthy controls and to indicate an effect of dopaminergic medication. The inconsistent findings across studies highlight the need for standardization in GA measurement. Understanding the neural mechanisms underlying GA may improve targeted therapies. Further research should explore GA in more challenging walking conditions and in free-living environments to enhance the clinical understanding of gait disturbances in PD.

A substantial proportion of individuals diagnosed with Parkinson's disease (pwPD) manifest unilateral motor symptoms, with a reported prevalence exceeding 65%[1,2]. The asymmetrical appearance of motor signs is a hallmark of Parkinson's disease (PD) and is considered a "red flag" and a supporting finding for PD diagnosis according to the criteria of the Movement Disorder Society[3] and UK Brain Bank criteria list[4], respectively.

Several pathophysiological mechanisms may underlie asymmetrical manifestations in PD, including: (i) uneven depletion of dopamine in the substantia nigra[5,6], (ii) asymmetrical striatal dysfunction affecting basal ganglia and cortical circuits[7–9], and (iii) reduced integrity of transcallosal fibers connecting pre-supplementary and supplementary motor areas[10]. Symptoms that are pronounced on one side of the body result in a motor performance deficit of the affected limb[11–13], which can, due to the influence of interlimb coordination, also impact the performance of the less affected limb.

Gait asymmetry (GA) is a key motor feature in pwPD[14]. It can be defined as the differences between right and left lower limbs during walking, as evidenced by parameters measured bilaterally[15]. Nearly half of pwPD show step length differences between sides[16]. GA, gait variability and impaired gait adaptability are associated with freezing of gait (FOG), a major cause of falls in PD[10,17–19]. Furthermore, pwPD who have experienced falls demonstrate a higher prevalence of GA compared to those without a history of falling[20,21]. Therefore, it is

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clinically relevant to understand how asymmetric movements affect gait and to identify which gait parameters are asymmetrical in pwPD.

GA results in impaired coordination of bilateral gait control, disrupting stepping during both the single- and double-support phases[22]. These phases are characterized by increased medial–lateral sway during standing, which contributes to the instability observed in pwPD[23]. When the most affected limb supports body weight in single stance, balance is compromised due to deficits in the most affected limb, increasing swing time asymmetry of the contralateral limb[24]. Moreover, prolonged double support periods may be indicative of challenges in transitioning to subsequent steps[25]. Additionally, there is reduced beta band synchronization during single stance of the most affected limb[26], which is associated with motor area activation and information processing[27]. This may reflect adaptive changes, as pwPD increased cortical activity asymmetry than neurologically healthy individuals (NHI) during gait initiation[28].

Asymmetry is recognized as one of three independent domains of Parkinsonian gait[29]. However, the literature contains conflicting results regarding the degree of asymmetry of different gait features, which limits our understanding of its underlying mechanisms and clinical relevance. While some studies reported greater asymmetry in spatial (i.e., step length) and temporal (i.e., step time) features[10], others found asymmetry in only one of those domains when compared to NHI[30–32]. Some evidence suggests that while kinematic parameters are asymmetric, kinetic parameters such as ground reaction forces remain symmetric during unobstructed walking in pwPD[33]. Furthermore, the effects of dopaminergic medication, specifically ON vs. OFF states, on GA in pwPD are not fully elucidated. While some studies have reported an improvement in GA during ON-state[34,35], others have found no significant difference in step length asymmetry between ON and OFF-states[34,36].

This study addresses these discrepancies in the literature related to GA in pwPD by summarizing the spatial-temporal, muscular, kinetic and neural asymmetries between the step with most and least affected limbs. The aims of this systematic review with meta-analysis are (i) to investigate which gait features are asymmetric in pwPD compared to NHI and (ii) to evaluate whether medication ON-state reduces GA compared to the OFF-state. In addition, the study examines whether the differing findings across studies are attributable to methodological differences, such as sample size, Parkinson's disease stage, or other factors. Clarifying these aspects may improve the understanding of the underlying mechanisms of GA and to support the development of tailored interventions to reduce GA in this population.

Method

Protocol and registration

The protocol of this systematic review was registered in the PROSPERO database (CRD42021285067). This review followed the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines[37] and Cochrane Handbook for Systematic Reviews of Interventions[38].

Search strategy

A systematic literature search was conducted in PubMed, Cochrane Library, Lilacs, PEDro and Scopus up to November 2025. Additional searches included Google Scholar (Google LLC) when the full text was not available, and authors' contacts for unpublished material. Furthermore, the references of the identified trials, relevant review articles, and current treatment guidelines were also screened. Search terms combined (i) "Parkin*", (ii) ("asymm*" or "symm*"), and (iii) ("gait" or "walk*" or "locomotion" or "mobility"), in the title, abstract and keywords. Search strategies were adapted for each database. Full strategies are in Supplementary Table 1.

Study selection and eligibility

Eligibility followed the PICOS framework[37]: (i) Population: pwPD; (ii) Intervention: not applicable; (iii) Comparison: NHI or pwPD in ON vs. OFF-states; (iv) Outcome: GA between left and right body sides; (v) Study design: randomized, non-randomized controlled, or non-controlled trials.

Studies were included if they: (1) assessed GA during unobstructed overground walking. The studies that analyzed GA only during challenging environments, such as obstacle avoidance or dual tasking, were not included in this systematic review. In mixed-condition studies, only data from unobstructed walking were extracted; (2) compared bilateral performance (lower limbs or brain) using kinematic, kinetic, EMG, and/or neural measures; (3) included a control group; (4) were original peer-reviewed articles; and (5) were written in English. No date restrictions were applied.

Studies were excluded if they: (1) had < 10 participants per group; (2) focused on virtual environments, non-dopaminergic medication effects, or neurosurgical interventions (e.g., deep brain stimulation); (3) used animal models; (4) involved only treadmill walking, given the impact of treadmill gait on spatial-temporal parameters compared with overground walking in pwPD[39–41]; (5) developed new GA instruments/methods; (6) unavailable GA data; or (7) used robotic or purely descriptive methods.

Quality assessment

Mendeley (Mendeley Ltd., NY, USA) was used for reference management and duplicate removal. Three researchers (FBS, JRC, APSC) independently screened titles, abstracts, and keywords, applying the inclusion/exclusion criteria. Disagreements were resolved by consensus to ensure inter-rater reliability.

Study quality was assessed using a published appraisal tool[42](see Supplementary Table 2), which evaluates internal/external validity and result generalizability. Criteria were scored as 1 (met), 0.5 (unclear), or 0 (not met). Studies scoring > 7 were considered low quality and were excluded after consensus review. For high-quality studies, average scores from the three evaluators were calculated.

Data extraction and analysis

One author (APSC) extracted the data, verified by two others (FBS and MHF). Extracted information included sample demographics, clinical characteristics, experimental procedures (e.g., ON/OFF-states during GA acquisition and gait protocol), GA outcomes, and main GA findings during unobstructed walking in pwPD and variables correlated.

Quantitative data analysis

Meta-analysis compared GA in three conditions: "PD ON vs. NHI", "PD OFF vs. NHI", and "PD ON vs. PD OFF". Only studies involving self-selected speed were included. Data were grouped according to ON and OFF-states. If a study included additional groups (e.g., FOG vs. non-FOG), only non-FOG data were used. For intervention studies, only pre-intervention data were extracted. In studies comparing footwear conditions, only data from the "with footwear" condition were included[43].

Mean and standard deviation values of asymmetry outcomes (i.e., GA index values) were compiled for analysis. Analyses assessed asymmetry in step length, step time, swing time, and stance time between pwPD and NHI. An additional analysis compared ON vs. OFF effects on step length, step time, and swing time asymmetry in pwPD.

The meta-analysis was conducted using R (version 4.3.1; R Foundation for Statistical Computing, Vienna, Austria; https://www.r-project.org/)[44] and RStudio (version 2023.06.1, Posit, Boston, MA, USA). Standardized mean differences (SMDs) with 95% confidence intervals (CIs) using random effects were calculated for the outcomes. Hedges' g was used to adjust SMDs for small sample bias, with effect sizes classified as small (≥ 0.2), medium (≥ 0.5), and large (≥ 0.8)[45]. Between-study heterogeneity was assessed using the restricted maximum-likelihood estimator for τ^2, the Q-profile method for confidence intervals of τ^2 and τ, and the I^2 statistic[46], with thresholds of 25%, 50%, and 75% representing low, moderate, and high heterogeneity, respectively[47]. Statistical significance was set at $p < 0.05$.

Results

Study selection

Figure 1 shows the study selection process. Forty-two studies were included in this review[10,16,31,34–36,43,48–82] of which 19 were also included in the meta-analysis. Table 3 in the Supplementary Material presents details such as authors, publication year, country, title, and journal.

Quality assessment

Table 4 of Supplementary Material presents the results of the methodological quality appraisal for each study, including the value for each question evaluated and the total score for each paper. The 42 studies have an average score of 10 (range: 7–13), with 61.9% scoring above 70% of the maximum score.

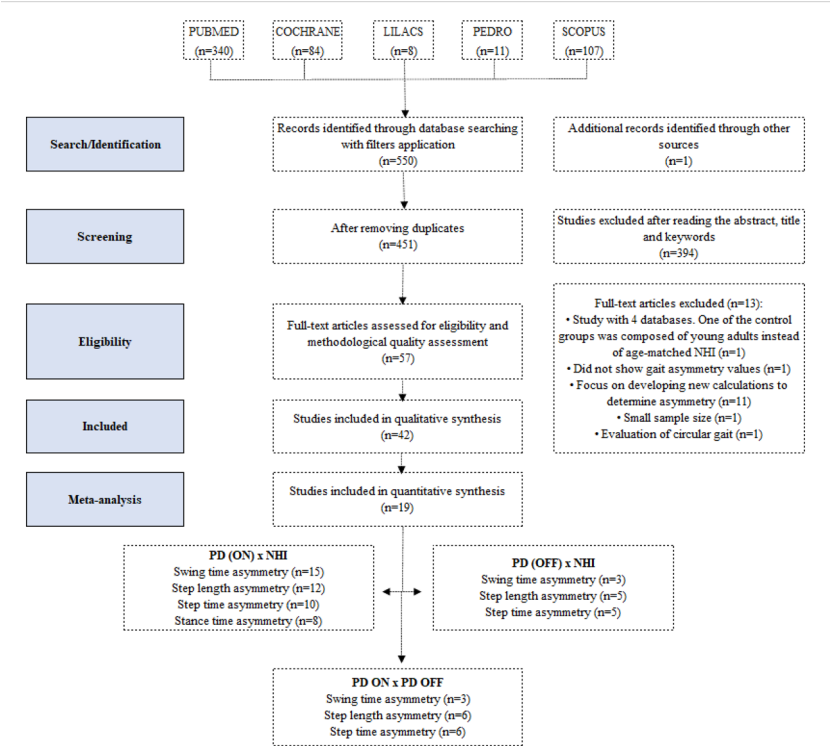

Fig. 1. Flowchart including literature search and selection steps following PRISMA statement.

Authors	Age (years)	Sex (Male/Female)	MDS-UPDRS or UPDRS III (points)	UPDRS asymmetry	HY	MAS (*R*/L)	Disease duration (years)
Arippa et al. (2022)[80]	• PD = 68.9 ± 9.3 • NHI = 66.0 ± 8.3	37/24 28/19	ON = 19.9 ± 9.3	NM	NM	NM	7.7 ± 5.6
Bailo et al. # (2024)[74]	• PD = 72.5 • NHI = 70.5	14/8 4/6	ON = 31 (13.2; 42.9)	0.3 (0.1; 0.9) $	2 (1.5; 2.5)	10/12	NM
Baltadjieva et al. (2006)[48]	• PD = 59.9 ± 13.0 • NHI = 62.1 ± 11.0	24/11 13/9	NM	NM	1–2.5.5 (HY 1 = 8; HY 1.5 = 4; HY 2 = 20; HY 2.5 = 3)	NM	1.5 ± 0.9
Barbieri et al. (2018a)[31]	• PD = 70.3 ± 6.0 • NHI = 70.7 ± 7.5	NM	OFF = 29.1 ± 7.7 ON = 24.1 ± 6.2	*	< 3	3/10	NM
Barbieri et al. (2025)[81]	• PD = 64.0 ± 10.3 • NHI = 62.7 ± 8.0	18/6 10/8	OFF = 26.4 ± 12.0 ON = 24.8 ± 13.6	See Table 2 in Barbieri's article	HY 1 = 1; HY 2 = 14; HY 3 = 7; HY 4 = 1	OFF = 12/9 (Undetermined = 1) ON = 10/12 (Undetermined = 2)	10.0 ± 6.1
Barbosa et al. (2024)[36]	• PD = 60.5 ± 8.1 • NHI = 60.7 ± 8.8	10/7 20/14	21.8 ± 8.9	NM	2.1 ± 0.2	NM	12.1 ± 5.1
Brodie et al. (2015)[73]	• PD = 67.1 ± 4.1 • NHI = 65.9 ± 6.9 • YC = 29.6 ± 6.6	7/3 6/5 5/4	NM	NM	1–4	NM	7.1 ± 4.2
Buckley et al. (2019)[75]	• PD = 69.2 ± 9.9 • NHI = 71.6 ± 6.8	47/23 35/29	36.9 ± 12.3	NM	NM	NM	NM
Danoudis et al. (2012)[76]	• PD + FOG=68.1 ± 1.7 • PD-FOG = 68.4 ± 8.4 • NHI = 69.7 ± 5.0	14/2 9/1 9/1	23.2 ± 5.4 15.9 ± 3.6	NM	3.8 ± 0.8 2.1 ± 0.6	NM	12.4 ± 5.0 (3–23) 2.3 ± 2.4 (1–8)
De Bartolo et al. (2020)[64]	• DP = 72.5 ± 9.2 • NHI = 72.1 ± 5.6 • YA = 32.3 ± 5.9	14/6 8/12 8/12	35.05 ± 16.9	NM	NM	NM	NM
Del Din et al. (2016)[77]	• PD = 69.1 ± 8.3 • NHI = 69.8 ± 7.2	34/13 27/23	32.0 ± 10.1	NM	HY 1 = 5; HY 2 = 39; HY 3 = 3	NM	NM
Del Din et al. (2016)[35]	• PD = 66.9 ± 9.4 • NHI = 66.6 ± 7.7	20/10 15/15	19.5 ± 10.7	NM	HY 1 = 8; HY 2 = 20; HY 3 = 2	NM	within 4 months of diagnosis
Djurić-Jovičić et al. (2017)[78]	• PD = 59.8 ± 10.5 • NHI = 59.7 ± 11.8	24/16 21/19	15.8 ± 5.4	NM	1–1.5.5 (1.16 ± 0.2)	NM	1.3 ± 1.1
Ferreira et al. (2022)[65]	• PD(HY:1–2) = 68.0 ± 7.5 • PD(HY:2.5–3.5) = 70.4 ± 7.5 • NHI = 68.0 ± 6.0	21/21 13/8 18/45	24.7 ± 10.1 32.9 ± 9.7	NM	1–2 2.5–3.5	NM	5.2 ± 3.6 5.5 ± 3.8
Fling et al. (2018)[10]	• PD = 68.7 ± 8.0 • NHI = 71.4 ± 8.1	26/13 7/13	40.1 ± 13.6	NM	2.4 ± 0.6	NM	7.1 ± 5.7
Galna et al. (2015)[79]	• PD = 67.0 ± 10.4 • NHI = 69.4 ± 7.7	81/40 78/106	25.5 ± 10.4	NM	HY 1 = 28; HY 2 = 72; HY 3 = 21	NM	6.3 ± 4.6 (months)
Gilmore et al. (2019)[34]	• PD = 65.29 ± 7.17 • NHI = 63.09 ± 8.09	41/21 7/4	OFF = 29.6 ± 9.8 ON = 16.4 ± 8.2	NM	NM	NM	8.9 ± 4.1
Godi et al. (2021)[66]	• PD = 70.0 ± 7.8 • NHI = 71.5 ± 8.2	159/139 40/44	NM	NM	2.5 ± 0.6 (1–4)	NM	7.6 ± 5.4
Grajić et al. (2015)[49]	• PD = 59.83 ± 10.57 • NHI = 59.79 ± 11.85	24/16 23/20	15.8 ± 5.4	NM	1–1.5.5 (1.1 ± 0.2)	NM	1.3 ± 1.1
Hackney, Earhart (2010)[50]	• PD = 65.1 ± 9.5 • NHI = 65.0 ± 10.0	56/22 56/17	27.5 ± 9.2	NM	HY 0.5 = 1; HY 1 = 1; HY 1.5 = 11; HY 2 = 49; HY 2.5 = 8; HY 3 = 8	NM	8.2 ± 5.0
Iosa et al. (2016)[67]	• PD = 67.23 ± 10.65 • NHI = 61.57 ± 12.3	58.6%/41.4% 78.6%/21.4%	30 ± 10 (10–53)	NM	1–3	NM	7.6 ± 4.7
Keloth et al. (2021)[68]	• PD = 71.9 ± 8.6 • NHI = 67.2 ± 3.7 • YC = 27.9 ± 2.4	17/7 17/7 18/6	25.6 ± 10.9	NM	2.2 ± 0.9 (1–3)	NM	4.2 ± 3.1
Kleiner et al. (2018)[51]	• PD + FOG=64.8 ± 8.8 • NHI = 61.8 ± 5.1	NM	21.3 ± 7.8	NM	PD + FOG=2.7 ± 0.76	NM	NM
Koh et al. (2019)[52]	• PD = 63.1 ± 8.1 • NHI = 66.3 ± 5.8	21/20 11/12	22.3 ± 8.4	NM	1–3	NM	18.1 ± 21.9 months
Leavy et al. (2018)[53]	• PD = 75.0 ± 5.9 • NHI = 71.0 ± 6.0	21/28 27/20	40.0 ± 10.9	NM	HY 2 = 22; HY 3 = 27	NM	mean values = 6.0
Lee et al. (2020)[69]	• PD = 69.6 ± 5.7 • NHI = 71.4 ± 4.9	45/29 27/25	40.9 ± 13.3	NM	2.3 ± 0.3 (1–3)	NM	NM
Lencioni et al. (2021)[70]	• PD = 67.1 • NHI = 58.1	3/7 4/6	NM	NM	2–3	NM	6.7 (1.4–12.0)
Liu et al. (2022)[71]	• PD = 63.18 ± 8.1 • NHI = 61.52 ± 6.1	40/28 22/26	PD early stage = 34.5 ± 10.6 PD advantage stage = 46.6 ± 12.8	NM	PD early stage = 1–2 PD advantage stage = 3–4	NM	4 (2–5.7.7)

Continued

Authors	Age (years)	Sex (Male/Female)	MDS-UPDRS or UPDRS III (points)	UPDRS asymmetry	HY	MAS (R/L)	Disease duration (years)
Martinez et al. (2018)[54]	• PD = 57 ± 7.84 • NHI = 56.5 ± 12.4 • YC = 29.5 ± 3.63	10/1 8/4 9/7	15 ± 4.2	NM	Mild stage (not mentioned the values of HY)	7/4	4 ± 1.8
Miller et al. (1996)[55]	• PD = 71.0 ± 8.0 • NHI = 68.0 ± 7.0	NM	NM	NM	HY 2 = 15; HY 3 = 4	NM	7.2 ± 4.0
Morris et al. (2017a)[56]	• PD = 66.1 ± 9.9 • NHI = 68.8 ± 7.1	79/40 78/106	24.9 ± 10.4	NM	HY 1 = 28; HY 2 = 70; HY 3 = 21	NM	6.2 ± 4.7
Morris et al. (2017b)[57]	• PD = 69.8 ± 9.7 • NHI = 72.3 ± 6.7	46/21 49/54	37.2 ± 12.0	NM	NM	NM	Newly diagnosed idiopathic PD
Nanayakkara et al. (2025)[82]	• PD = 69.03 ± 5.3 • NHI = 73.58 ± 4.6	25/14 16/22	NM	NM	NM	NM	7.3 ± 6.0
Nanhoe-Mahabier et al. (2011)[58]	• PD + FOG=60.5 ± 7.9 • PD-FOG = 60.2 ± 9.2 • NHI = 57.9 ± 7.3	71%/29% 70%/30% 60%/40%	35.4 ± 8.9 30.6 ± 7.0	NM	2.4 ± 0.3 2.1 ± 0.3	NM	9.6 ± 3.6 7.7 ± 4.5
Pereira et al. (2019)[43]	• PD = 69.1 ± 7.2 • NHI = 70.8 ± 5.5	7/9 6/9	28.3 ± 7.2	NM	NM	NM	NM
Plotnik et al. (2007)[59]	• PD = 71.9 ± 1.5 • NHI = 69.1 ± 1.3 • YC = 26.3 ± 0.5	16/5 7/7 7/8	35.8 ± 2.6	NM	2–3 (2.3 ± 0.1)	NM	NM
Ren et al. (2015)[60]	• LPD = 67.3 ± 7.6 • RPD = 66.9 ± 5.8 • NHI = 62.3 ± 5.5	6/3 5/6 4/9	22.3 ± 6.9 20.2 ± 12.4	−0.3 ± 0.3 0.3 ± 0.4	HY 1.5 = 1; HY 2 = 5; HY 2.5 = 2; HY 3 = 1 HY 1 = 1; HY 2 = 6; HY 2.5 = 1; HY 3 = 3	0/9 11/0	3.7 ± 2.9 5.9 ± 4.7
Seuthe et al. (2024)[16]	• PD = 66.8 ± 10.0 • NHI = 69.6 ± 6.5	69/28 20/16	34.4 ± 14.1	**	HY 1 = 1; HY 2 = 61; HY 3 = 29; HY 4 = 6	NM	9.8 ± 6.8
Vervoort et al. (2015)[61]	• PIGD = 61.4 ± 10.9 • TD = 57.3 ± 8.8 • NHI = 57.7 ± 8.8	29/14 12/10 14/6	30.5 ± 13.9 26.2 ± 10.9	NM	1–3 1–3	26/17 14/8	7.2 ± 4.3 4.8 ± 2.7
Vervoort et al. (2016)[62]	• PD + FOG=65.8 ± 9.9 • PD-FOG = 58.2 ± 9.9 • NHI = 57.7 ± 8.8	1/12 31/29 14/6	38.3 ± 13.9 25.9 ± 12.0	NM	2.2 ± 0.8 2.0 ± 0.6	6/7 36/24	7.9 ± 5.4 5.8 ± 3.3
Wu et al. (2021)[72]	• PD = 65.6 ± 10.1 • NHI = 62.4 ± 6.4	22/10 17/13	22.9 ± 9.3	NM	1.73 ± 0.44	12 (37.5%)/20 (62.5%)	2.4 ± 1.3
Yogev et al. (2007)[63]	• PD = 71.9 ± 7.3 • NHI fallers = 76.3 ± 4.9 • NHI = 67.5 ± 3.5	81%/19% 47%/53% 55%/45%	20.4 ± 7.9 2.9 ± 1.9 0.2 ± 0.6	0.2 ± 0.1	2–3	NM	NM

Table 1. Demographic and clinical characteristics of the included studies. NHI: control group of neurological healthy elderly individuals; MAS: most affected side (disease dominance); EF: Elderly fallers; +FOG: presence of FOG; -FOG: absence of FOG; HY: Hoehn & Yahr Scale; L: left; LFOG: predominant symptoms in the left side with FOG; LPD: predominant symptoms in the left side without FOG; NM: not mentioned; PD: Parkinson's disease group; PIGD: postural instability and gait disorder; R: right; RFOG: predominant symptoms in the right side with FOG; RPD: predominant symptoms in the right side without FOG; TD: tremor dominant; YC: young control group. * Only informed that motor UPDRS items 20–23 and 25–26 was used to assess appendicular asymmetry. ** Motor symptom asymmetry as measured by MDS-UPDRS-III (items 3.3–3.8, 3.15–3.17); lower limb asymmetry (3.3, 3.7, 3.8, 3.17). # Values are median (5th percentile; 95th percentile). $ Leg asymmetry index: Ratio between the difference of the worst and best leg, and the sum of the worst and best leg.

The main sources of bias in the studies included in this review were: recruitment and sampling methods (47.6% partially reported), controlled covariates (95.2% not reported; only two partially), methodology reliability (80.9% not reported; eight included), internal validity (78.5% not reported; nine included), and clinical implications (47.6% partially or not reported).

Research paradigm

Publications per year

Figure 2 presents the annual distribution of publications. The earliest study was from 1996[55]. Only five were published between 2001 and 2010. Most studies ($n = 29$; ~70%) were published after 2015.

Sample characteristics

Demographic and clinical data are presented in Table 1. 2111 pwPD and 1595 NHI were assessed in the studies. Mean age was 66.4 ± 4.4 years for pwPD (range: 57–75) and 65.9 ± 4.9 years for NHI. Two studies[61,62] shared the same control group; data from Vervoort et al.[61] were used. Three studies did not report sex[31,51,55], and three presented it in percentages[58,63,67], resulting in ~1152 males and 682 females.

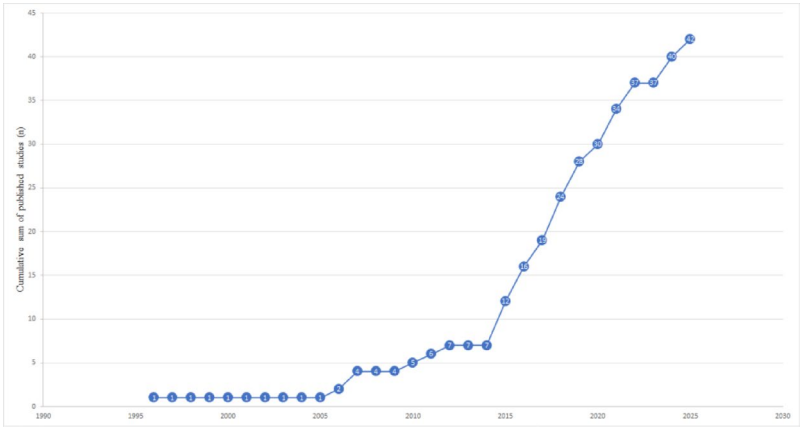

Fig. 2. Cumulative amount of the included articles per year.

Motor symptoms (UPDRS or MDS-UPDRS part III) were reported in 36 of 42 studies (Table 1). However, only 5 studies[16,31,60,63,81] analyzed motor symptom asymmetry. Hoehn & Yahr (HY) stage was reported in 34 studies; eight[34,43,54,57,64,75,80,82] did not. Thirteen articles[10,36,49,51,58,59,62,66,68,69,72,76,78] reported mean HY (2.2 ± 0.6); one[74] reported the median (HY: 2); eleven[16,35,48,50,53,55,56,60,77,79,81] reported counts by stage (HY 0.5: 1; HY 1: 81; HY 1.5: 16; HY 2: 393; HY 2.5: 14; HY 3: 126; HY 4: 7); and nine[31,52,61,63,65,67,70,71,73] according to the level of disease (HY < 3: 1; HY 1–3: 4; HY 2–3: 2; HY 1–4: 2).

Only eight studies reported the most affected side using UPDRS/MDS-UPDRS scores[31,54,60–62,72,74,81], with a slight predominance of right-sided (135 right vs. 123 left). Mean disease duration was 6.4 ± 2.9 years (minimum and maximum average: 1.3 and 12.4 years). Dopaminergic medication effects on gait were examined in 26 studies.

GA studies' comparison

About the comparison of GA in pwPD vs. NHI, five studies also compared GA in pwPD vs. young adu lts[54,59,64,68,73], and one article compared PD vs. older fallers[63]. Furthermore, six studies analyzed specific PD characteristics during GA analysis: three compared FOG vs. non-FOG[58,62,76], one compared clinical subtypes[61], one compared disease stages[65], and one examined the side of symptom onset[60].

A total of 22 studies assessed GA in the ON-state[16,35,43,50,53–57,60,64–66,68–70,73–75,77,79,80], eight in the OFF sta te[10,51,58,61,62,71,72,76], and five in both ON and OFF-states[31,34,36,67,81]. Furthermore, four studies[48,49,52,78] examined *de novo* pwPD, and three did not specify medication status[59,63,82].

Walking task

Table 2 summarizes walking tasks, GA calculation methods, and key findings. The most used protocol for gait assessment was walking over a period of 2 min (seven studies[54,56,57,59,63,75,79]. Other studies used 2–20 walking trials over distances ranging from 6 to 25 m, with 25 m[54,56,57,59,63,75,79], 10 m[16,35,50,53,67,77,80,81], and 8 m[10,43,52,55,58] being the most frequent.

GA index's calculation

Over 20 different indexes were used to assess GA in pwPD (Table 2), with only one study not reporting the index used[43]. The two most frequently used indexes were the asymmetry index[63](seven studies)[48,50,54,59,63,67,69] and factor analysis[83](five studies)[53,56,61,75,77]. Detailed formulas are in Supplementary Table 5. In addition, four studies[49,62,70,81] used conventional statistical analysis to compare the gait parameters between more and less affected side steps.

Outcomes analyzed

Table 3 summarizes the gait variables analyzed and those showing asymmetry. All studies included in this systematic review assessed at least one kinematic outcome related to GA, except for Keloth et al.[68] and Nanayakkara et al.[82]. The most frequently assessed were swing time ($n = 24$; 57.1%), step length ($n = 24$; 57.1%), step time ($n = 21$; 50%), stance time ($n = 13$; 30.9%), step width ($n = 4$; 10.3%), stride length ($n = 5$; 11.9%), and joint angle (e.g., angular velocity of ankle, knee and hip, $n = 6$; 14.2%).

Kinetic (e.g., heel-strike and toe-off forces)[48,54,82] and muscular (e.g., Root mean square)[55,68] asymmetries were assessed in only five studies (11.9%). No study examined neural asymmetry during gait, although two explored associations between interhemispheric connectivity and kinematic outcomes[10,62].

Overview of main findings of the systematic review

A summary of the main findings in the studies included in this systematic review is described in Fig. 3.

Authors	Number of participants	Status of medication	Gait protocol	GA index	Main findings
Arippa et al. (2022)[80]	• PD = 61 • NHI = 47	ON	• 6 × 10 m • Unobstructed walking • Self-selected speed	SIndex, CA, CO, TS and RO	• PD – greater asymmetry compared to NHI in terms of spatiotemporal and joint kinematics
Bailo et al. (2024)[74]	• PD = 22 • NHI = 10	ON	• 6-minute walk test (6MWT) • Self-selected speed	HR and iHR	• HR and iHR in the VT Direction: correlation with MDS-UPDRS III, akinesia/bradykinesia and worst leg impairment • No correlation: best leg impairment and leg asymmetry index • The iHR in the ML direction correlated only with MDS-UPDRS III and 6MWT
Baltadjieva et al. (2006)[48]	• PD(de novo) = 35 • NHI = 22	de novo	• 4 × 20 m • Unobstructed walking • Self-selected speed	GI	• PD – greater asymmetry in gait temporal parameters, but not in the ground reaction forces
Barbieri et al. (2018a)[31]	• PD = 13 • NHI = 13	OFF/ON	• 5 × 10 m (per condition) • Unobstructed walking • Walking with obstacle avoidance • Self-selected speed	SI	• GA - no effects of groups for all GA variables
Barbieri et al. (2025)[81]	• PD = 23 • NHI = 18	OFF/ON	• 20 × 10 m • Unobstructed walking • Self-selected speed	More vs. less affected side	• PD – significant hip, knee, and ankle angular asymmetries, while no limb differences were observed in NHI • The more affected side in PD had smaller joint movement amplitudes than the less affected side • Dopaminergic medication had limited effects on reducing asymmetry
Barbosa et al. (2024)[36]	• PD = 17 • NHI = 34	OFF/ON	• 3 × 7 m (comprising going, turning and returning) • Self-selected speed	IA	• Asymmetry was not different across levodopa administration neither comparing PD and NHI
Brodie et al. (2015)[73]	• PD = 10 • NHI = 11 • YC = 9	ON	• 5 × 22 m • Self-selected speed • Unobstructed walking with and without auditory cues (cued with varying paired-step asymmetries of: −10%, − 5%, 0%, + 5%, and + 10%)	MA and AA	• Baseline: No difference in GA between PD and NHI • Symmetric cues – did not provide more symmetric gait
Buckley et al. (2019)[75]	• PD = 70 • NHI = 64	ON	• 2 min (25 m) • Self-selected speed	Based on[109] and AS	• The kinematic variables of asymmetry discriminated mildly the PD and NHI • Upper body variables should be measured with spatiotemporal characteristics
Danoudis et al. (2012)[76]	• PD + FOG=16 • PD-FOG = 10 • NHI = 10	OFF	• 4 × 8.3 m • Unobstructed walking with normalized step length: 100%, 75%, 50% and 25%	Asymmetry	• Step length affects GA and gait coordination of gait • PD + FOG-greater asymmetry vs. PD-FOG (step length and swing time) and NHI (swing and step time) • No differences between PD-FOG and NHI at preferred speed
De Bartolo et al. (2020)[64]	• PD = 20 • NHI = 20 • YA = 20	ON	• 2 × 18 m (per condition) • Self-selected speed • 7 conditions: without music and with six different music tracks	Percentage of overlapping between curve accelerations of right and left sides	• Gait patterns (not GA) were altered by listening to music depending by the musical genre=among the three groups
Del Din et al. (2016)[77]	• PD = 47 • NHI = 50	ON	• Ambulatory environment: 4 × 10 m • Free-living (7 days) • Self-selected speed	Based on[109]	• PD and NHI – greater GA in unobstructed walking vs. ambulatory environment • PD – greater GA in both conditions vs. NHI
Del Din et al. (2016)[35]	• PD = 30 • NHI = 30	ON	• 4 × 10 m • Unobstructed walking • Self-selected speed	Asymmetry	• Body-worn monitor is more sensitive data for asymmetry features
Djurić-Jovičić et al. (2017)[78]	• PD = 40 • NHI = 40	de novo	• 6 × 8–9 m (per condition) Self-selected speed • Unobstructed walking • Unobstructed walking + motor DT (carrying a glass of water) • Unobstructed walking + cognitive DT (serial 7 subtraction)	Asymmetry	• Asymmetry of step time – an indicator to classify the disease in early stages
Ferreira et al. (2022)[65]	• PD(HY:1–2) = 42 • PD(HY:2.5–3.5) = 21 • NHI = 63	ON	• 3 × 8.5 m • Self-selected speed	SI	• ML algorithms have potential both to PD diagnosis and stage identification • Less importance weight to the asymmetry parameters
Fling et al. (2018)[10]	• PD = 39 • NHI = 20	OFF	• 3 × 8 m • Unobstructed walking • Self-selected speed	RI	• PD – greater asymmetry in step time and length vs. NHI • PD-lower transcallosal fiber tract integrity of the pre-SMA and S1 associated with greater asymmetry in step length asymmetry
Galna et al. (2015)[79]	• PD = 121 • NHI = 184	ON	• 2 min (25 m) • Unobstructed walking • Self-selected speed	Asymmetry	• PD – greater asymmetry in step time, swing time and stance time vs. NHI
Gilmore et al. (2019)[34]	• PD = 62 • NHI = 11	OFF/ON	• Self-selected speed • Forward (5 × 18 m) and backward (4 × 10 m) unobstructed walking	"PKMAS" Software	• Forward walking: a) ON – lower step time asymmetry vs. OFF b) PD – greater asymmetry in step length and swing time vs. NHI (both in ON and OFF) • backwards walking: PD-greater asymmetry in step time and swing time vs. NHI (both in ON and OFF)

Continued

Authors	Number of participants	Status of medication	Gait protocol	GA index	Main findings
Godi et al. (2021)[66]	• PD = 298 • NHI = 84	ON	• 4 × 8.6 m • Barefoot walking • Self-selected speed	Asymmetry=|ln(left/right)| * 100	• Step and swing time asymmetry: greater in PD than NHI • Asymmetry variables have low discriminative accuracy to discriminate between PD and NHI compared to the other variables
Grajić et al. (2015)[49]	• PD = 40 • NHI = 43	de novo	• 6 × 8–9 m • Unobstructed walking • Self-selected speed	Side of disease onset vs. contralateral leg	• Gait symmetry in PD remained preserved • PD (side onset) x NHI (left side): PD is more asymmetric
Hackney, Earhart (2010)[50]	• PD = 78 (FOG and Non-FOG) • NHI = 74	ON	• 3 × 10 m (per condition) • Self-selected speed • Unobstructed forward and backward walking with and without DT (counting backward)	GI	• Freezers – greater GA vs. non-freezers • Greater asymmetry in swing time during all challenging conditions (backward and DT)
Iosa et al. (2016)[67]	• PD = 70 • NHI = NM	ON (all) OFF (n = 15)	• 5 × 10 m • Self-selected speed	SRI and GI	• GI was higher in PD vs. NHI. However, SRI was small for PD vs. NHI
Keloth et al. (2021)[68]	• PD = 24 • NHI = 24 • YC = 24	ON	• Self-selected speed • Straight-line walking (greater than 2 m)	AI	• AI-PD was higher than NHI • PwPD-AI value was higher according to the sub-phases of gait cycler
Kleiner et al. (2018)[51]	• PD + FOG=33 • NHI = 14	OFF	• 6 × 9 m (per condition) • Self-selected speed • Unobstructed walking with and without cognitive DT	Step length asymmetry	• PD + FOG – greater asymmetry in step length during unobstructed walking + cognitive DT
Koh et al. (2019)[52]	• PD = 41 • NHI = 23	de novo	• 2 × 8 m (per condition) • Self-selected speed • Unobstructed walking	SA	• PD – no difference between NHI for swing time and step length asymmetry • PD-shoulder and elbow asymmetries affects arm swing asymmetry • Asymmetries in spatial and temporal parameters – no predicted arm swing asymmetry
Leavy et al. (2018)[53]	• PD = 49 • NHI = 47	ON	• 6 × 10 m • Unobstructed walking • Self-selected speed	Based on[109]	• No correlation between perceived walking difficulties and GA parameters
Lee et al. (2020)[69]	• PD = 74 • NHI = 52	ON	• 3 × 15 m (per condition) • Walking in self-selected speed, 20% slower and 20% faster than self-selected speed	GI	• PD patients demonstrated higher GA at slower and preferred speeds than controls
Lencioni et al. (2021)[70]	• PD = 10 • NHI = 10	ON	• 5 x • Self-selected speed • Controls performed additional trials at slower velocities	More vs. less affected side	• No effects of lower limb were found on spatiotemporal parameters • PD-symmetry in gait stability, although both limbs showed larger MoS values compared to NHI
Liu et al. (2022)[71]	• PD = 68 • NHI = 48	OFF	• 3 × 5 m • Self-selected speed	SA	• PD – greater step length asymmetry, asymmetry of arm-swing angle and asymmetry of arm-swing velocity than NHI
Martinez et al. (2018)[54]	• PD = 11 • NHI = 12 • YC = 16	ON	• 5 min (25 m) • Self-selected speed	GI	• PD – greater GA vs. NHI and YC • No difference between groups for kinematic and kinetic variables in both legs • GA – predicted by the affected side related to clinical onset, cognitive status and motor scale
Miller et al. (1996)[55]	• PD = 19 • NHI = 18	ON	• 2 × 8 m walks (speed not mentioned)	LCEAs	• The PD group had a significantly lower shape symmetry in the MG and TA muscles • The VL symmetry was similar in the PD and NHI groups • After a gait training program involving RAS, PD group had improvements in TA symmetry
Morris et al. (2017a)[56]	• PD = 119 • NHI = 184	ON	• 2 min (25 m) – per condition • Self-selected speed • Unobstructed walking with and without cognitive DT (digit span)	Based on[109]	• GA is unable to predict cognitive decline
Morris et al. (2017b)[57]	• PD = 67 • NHI = 103	ON	• 2 min (25 m) • Self-selected speed • Free-living walking assessment continuously for 7 days	Asymmetry	• Free-living – greater asymmetry in step length vs. laboratory in both groups • Body worn monitors are more sensitive in detecting asymmetry features
Nanayakkara et al. (2025)[82]	• PD = 39 • NHI = 38	NM	• Timed Up and Go (TUG) # • Self-selected speed	AsyCoP	• PD – exhibits increased asymmetry between the left and right foot • PD – demonstrate distinct and asymmetric plantar pressure patterns compared to NHI
Nanhoe-Mahabier et al. (2011)[58]	• PD + FOG=12 • PD-FOG = 15 • NHI = 15	OFF	• 6 × 8 m • Unobstructed walking • Self-selected speed	Step length and swing asymmetry	• No spatial stepping asymmetry among groups • No temporal stepping asymmetry freezers vs. non-freezers • Freezers and non-freezers – greater asymmetry in temporal stepping parameters vs. NHI • Correlation between UPDRS score and spatial stepping asymmetry
Pereira et al. (2019)[43]	• PD = 16 • NHI = 15	ON	• 3 × 8 m (per condition) • Self-selected speed • Walking barefoot and with habitual footwear	NM	• Walking with habitual footwear-greater GA in NHI, but not in PD

Continued

Authors	Number of participants	Status of medication	Gait protocol	GA index	Main findings
Plotnik et al. (2007)[59]	• PD = 21 • NHI = 14 • YC = 15	NM	• 2 min (25 m) • Self-selected speed	GI	• PD – higher GA than NHI • PCI was moderately correlated with GA
Ren et al. (2015)[60]	• LPD = 9 • RD = 11 • NHI = 13	ON	• 3 x condition • Self-selected speed • Unobstructed walking with eyes-open, egocentric reference point (walk toward a subjectively perceived center of a target) and vision-occluded	Asymmetry	• PD – direction of veering depends on the side of PD onset • LPD and RPD – no GA compared to NHI • LPD – lower GA in egocentric reference point vs. eyes-open
Seuthe et al. (2024)[16]	• PD = 97 • NHI = 36	ON	• 10 × 10 m • Unobstructed walking • Self-selected speed	IA	• Step length, swing time and stance time asymmetry was greater in PD than NHI • PD had higher asymmetry during gait, but not during turning • No correlations between symptom laterality and GA or turning asymmetry
Vervoort et al. (2015)[61]	• PIGD = 43 • TD = 22 • NHI = 20	OFF	• At least 40 steps • Unobstructed walking • Self-selected speed	Based on[109]	• No differences in GA between PIGD and TD • No differences in GA between NHI and PD (PIGD and TD)
Vervoort et al. (2016)[62]	• PD + FOG=13 • PD-FOG = 60 • NHI = 20	OFF	• 10 × 6 m • Self-selected speed • Unobstructed walking with and without DT (auditory version of Stroop task)	Dominant x non-dominant leg	• PD – greater asymmetry in step length during DT vs. NHI (no significant) • PD-hypo- and hyper-brain connectivity vs. controls in DT-related neural networks
Wu et al. (2021)[72]	• PD = 32 • NHI = 30	OFF	• 7 m • Self-selected speed • Unobstructed walking with 180° turning and returned to their initial place	Same index as "step time or length or swing asymmetry"	• PD and NHI - no difference in any of the assessed gait parameters • Early-stage PD: presented increased variability but still symmetrical gait pattern
Yogev et al. (2007)[63]	• PD = 21 • EF = 15 • NHI = 11	NM	• 2 min (25 m) – per condition • unobstructed walking without and with DT (serial 7 subtractions out loud)	GI	• PD and NHI fallers-greater GA vs. healthy controls • PD and NHI fallers – increased GA in DT condition • GA-associated with gait speed and gait variability in DT walking; no correlation with asymmetry of PD classic motor symptoms

Table 2. Gait protocols, GA index and main findings of the studies included in the review. NHI: control group of neurological healthy elderly individuals; DT: dual task; EF: Elderly fallers; +FOG: presence of FOG;-FOG: absence of FOG; LCEA: latency corrected ensemble average; LFG: predominant symptoms in the left side with FOG; LPD: predominant symptoms in the left side without FOG; LSWT: leg with the long swing time; MA: mean asymmetry – Brodie et al. (2015); MG: medial gastrocnemius; PD: Parkinson's disease group; PIGD: postural instability and gait disorder; RFOG: predominant symptoms in the right side with FOG; RPD: predominant symptoms in the right side without FOG; SSWT: leg with the short swing time; TA: tibialis anterior; TD: tremor dominant; VL: vastus lateralis; SMA: supplementary motor areas; S1: primary somatosensory cortice; YC: young control group; NM: not mentioned; de novo: without medication (de novo patients); Asymmetry=|right measure-left measure|; AI-Asymmetry index=100-([higher value of sEMG RMS/lower value of sEMG RMS] * 100); AS: auto symmetry-Moe-Nilssen & Helbostad (2004); GA – GA-Plotnik et al. (2005); GI – GA=|ln(SSWT/LSWT)|; HR= Harmonic ratio-Lowry et al. (2009); iHR= Improved harmonic ratio – Pasciuto et al. (2017); IA – Index of Asymmetry=(right side – left side)/(right side + left side); LCEA – latency corrected ensemble average-Miller et al. (1996); RI – ratio index=1-|left/right| * 100; SA – Symmetry angle-Zifchock et al. (2008); SI – Symmetry index-Robinson, Herzog, Nigg (1987); SIndex = ABS (2 x [right - left]/[right +left] x 100); SIratio – Maximum angular velocity ratio-Zampieri et al. (2010); SRI-Symmetry ratio index=ratio between longer step and shorter step within 1 stride; Step time or length or swing asymmetry=([max time-min time]/max time) * 100%; Symmetric index=[(value of LASL-value of MASL)/(value of LASL+value of MASL)] * 100; AsyCoP = (CoP left - CoP right)/(CoP left + CoP right); CA – Cyclogram Area (degrees^2) = Area enclosed by the curve obtained from the left–right angle diagram (Hershler, Milner, 1980); CO – Cyclogram orientation (degrees) = the absolute value of the angular difference ϕ between the perfect symmetry line (45◦ line) and the orien- tation of the principal axis of inertia, which is the direction of the eigenvector of the inertial matrix for the cyclogram points in the x–y (left vs. right joint angle) reference system (Goswami, 2003; Goswami, 1998); TS – Trend Symmetry (dimensionless) = Calculated to assess the similarity of two waveforms (i.e., right and left leg angular trend across the gait cycles for each joint) by means of an eigenvector analysis (Crenshaw, Richards, 2006); RO – Range offset = A measure of the differences in operating range of each limb, is calculated as the absolute value of the difference between the average of the right-side waveform from the average of the left-side waveform (Crenshaw, Richards, 2006). #For Analysis: TUG overall performance and 3 m walking segment of the TUG test. .

Authors	Asymmetry variables investigated	Results
Arippa et al. (2022)[80]	*Kinematic* • Step length asymmetry • Stance phase asymmetry • Swing phase asymmetry • Double support phase asymmetry Sagittal kinematics of hip, knee and ankle angles during the gait cycle to calculate: • Cyclogram area • Cyclogram orientation • Trend symmetry • Range offset	PD = ↑ step length and double support asymmetry compared to NHI PD = ↑ range offset at hip joint level compared to NHI PD = ↑ cyclogram orientantion and trend symmetry at the ankle joint compared to NHI
Bailo et al. (2024)[74]	*Kinematic* • HR • IHR both metrics for trunk acceleration in AP, ML and VT directions	PD: ↓ Harmonic Ratio and Improved Harmonic Ratio vertical asymmetry compared to NHI
Baltadjieva et al. (2006)[48]	*Kinematic* • Swing time asymmetry *Kinectic* • Heel strike force asymmetry • Toe-off force asymmetry	PD: ↑ swing time asymmetry compared to NHI PD = NHI: Heel-strike force asymmetry and Toe-off force asymmetry
Barbieri et al. (2018)[31]	*Kinematic* • Step length asymmetry • Step time asymmetry • Step width asymmetry • Step velocity asymmetry • Double support asymmetry	PD = NHI
Barbieri et al. (2025)[81]	"*Kinematic* • Step length asymmetry • Stride length asymmetry • Step time asymmetry • Relative stance phase duration asymmetry The gait cycle curves for ankle, knee, and hip joint angles and the pelvis segment in three anatomical planes of movement: • Sagital (flexion/extension) • Frontal (abduction/adduction) • Transverse (internal/external rotation)"	OFF and ON = ↓ Step length, step time and stride length for the most affected limb compared to least affected limb. OFF = ↑ Hip and knee flexion and dorsiflexion for the least affected limb than most affected limb. ON = ↑ Hip and knee flexion for the least affected limb than most affected limb.
Barbosa et al. (2024)[36]	*Kinematic* • Step length asymmetry • Step time asymmetry • Stance Time asymmetry • Swing Time asymmetry	PD = NHI
Brodie et al. (2015)[73]	*Kinematic* Mean asymmetry (MA) Absolute paired-step asymmetry (AA) both metrics applied for in step time	PD = NHI
Buckley et al. (2019)[75]	*Kinematic* • Step length asymmetry • Step time asymmetry • Swing time asymmetry • Stance time asymmetry Head and pelvis acceleration • Auto symmetry (AP, ML, VT) • HR (AP, ML, VT)	The kinematic variables of asymmetry discriminated mildly the PD and NHI Similar coupling between upper body accelerations and lower body spatiotemporal characteristics in both groups.
Danoudis et al. (2012)[76]	*Kinematic* • Step length asymmetry • Step time asymmetry • Swing time asymmetry	PD + FOG: ↑ step length asymmetry compared to NHI ↑ swing time asymmetry compared to NHI ↑ step time asymmetry compared to NHI PD-FOG = NHI
Continued		

Authors	Asymmetry variables investigated	Results
De Bartolo et al. (2020)[64]	*Kinematic* • Pelvis ROM asymmetry: Sagittal angles (tilt) Frontal angles (obliquity) Transversal angles (rotation)	Rotation and Obliquity asymmetry: different between groups
Del Din et al. (2016)[77]	*Kinematic* • Step length asymmetry • Step time asymmetry • Swing time asymmetry • Stance time asymmetry	PD: ↑ swing time and step length asymmetry compared to NHI
Del Din et al. (2016)[35]	*Kinematic* • Step length asymmetry • Step time asymmetry • Swing time asymmetry • Stance time asymmetry	PD: ↑ step length asymmetry compared to NHI
Djurić-Jovičić et al. (2017)[78]	*Kinematic* • Step length asymmetry • Step time asymmetry • Stride time asymmetry	Step time asymmetry: an indicator to classify PD in early stages
Ferreira et al. (2022)[65]	*Kinematic* • Step length asymmetry • Step width asymmetry • Step time asymmetry • Step velocity asymmetry • Step double support asymmetry • Step single support asymmetry	Asymmetry parameters had less importance to classify and rate PD
Fling et al. (2018)[10]	*Kinematic* • Step length asymmetry • Step time asymmetry	PD: ↑ step time and step length asymmetry compared to NHI
Galna et al. (2015)[79]	*Kinematic* • Step length asymmetry • Step time asymmetry • Swing time asymmetry • Stance time asymmetry	PD: ↑ step time, swing time and stance time asymmetry compared to NHI
Gilmore et al. (2019)[34]	*Kinematic* • Step length asymmetry • Step time asymmetry • Swing time asymmetry	PD: ↑ step length and swing time asymmetry compared to NHI ON: ↓ step time asymmetry compared to OFF
Godi et al. (2021)[66]	*Kinematic* • Step time asymmetry • Swing time asymmetry	PD: ↑ step time and swing time asymmetry compared to NHI
Grajić et al. (2015)[49]	*Kinematic* • Cyclo time • Stride length • Swing time • Coefficient of variation (CT, SL, ST) Right x Left side for all variables	PD: ↑ CT, ST and CV-SL (PD onset x NHI left side) NHI: ↑ CV-ST (PD other x NHI right side)
Hackney, Earhart (2010)[50]	*Kinematic* • Swing time asymmetry	PD: ↑ swing time asymmetry compared to NHI
Iosa et al. (2016)[67]	*Kinematic* • Step length asymmetry (SRI) • Swing time asymmetry (GI)	PD: ↑ swing time asymmetry compared to NHI
Keloth et al. (2021)[68]	*EMG* bilateral muscle asymmetry of RMS - TA bilateral muscle asymmetry of RMS - MG	PD: ↑ MG and TA asymmetry compared to NHI for total gait cycle
Kleiner et al. (2018)[51]	*Kinematic* • Step length asymmetry	PD: ↑ step length asymmetry compared to NHI
Koh et al. (2019)[52]	*Kinematic* • Step length asymmetry • Swing time asymmetry • Symmetry angle of shoulder • Symmetry angle of elbow	PD = NHI for swing time and step length
Leavy et al. (2018)[53]	*Kinematic* • Step length asymmetry • Step time asymmetry • Swing time asymmetry	The asymmetry parameters were not good at differentiating the groups
Lee et al. (2020)[69]	*Kinematic* • Swing time asymmetry	PD: ↑ swing time asymmetry compared to NHI
Continued		

Authors	Asymmetry variables investigated	Results
Lencioni et al. (2021)[70]	*Kinematic* • Spatiotemporal (gait speed, stride length, cadence and step width) • Margin of Stability (MoS - AP and ML) for all variables according to lower limb (more and less affected)	PD = NHI
Liu et al. (2022)[71]	*Kinematic* • Step length asymmetry • Arm-swing angle asymmetry • Arm-swing velocity asymmetry	PD: ↑ step length, arm swing angle and arm swing velocity asymmetry compared to NHI
Martinez et al. (2018)[54]	*Kinematic* • Swing time asymmetry • Variables below were presented according to R and L sides: Stride time Stance time Swing time CV of stride, stance and swing time Percentage of stance time Percentage of swing time *Kinetic* • Variables below were presented according to R and L sides: Heel-peak force Mid-stance force Toe-off force Time to heel peak Time to mid-stance force Time to toe-off force	PD = NHI for all parameters PD: ↑ swing time asymmetry compared to young adults
Miller et al. (1996)[55]	*Kinematic* • Single-limb support symmetry *EMG* • Magnitude (shape) and phase (timing) symmetry from LCEA of MG, TA and VL muscles	PD = NHI - single-limb support asymmetry PD: ↓MG and TA asymmetry compared to NHI
Morris et al. (2017a)[56]	*Kinematic* • Step length asymmetry • Step time asymmetry • Swing time asymmetry • Stance time asymmetry	PD: asymmetry parameters were unable to predict cognitive decline in early PD
Morris et al. (2017b)[57]	*Kinematic* • Step length asymmetry • Step time asymmetry • Swing time asymmetry • Stance time asymmetry	Temporal asymmetry parameters were strongly associated with asymmetry domain for laboratory and free-living conditions for both groups
Nanayakkara et al. (2025)[82]	*Kinetic* • 72 CoP features of asymmetry	PD - ↑ asymmetry between left and right feet PD - CoP located around the heel and forefoot areas, with greater occupation in one foot NHI - ↑ CoP trajectory in the heel and metatarsal, with relatively balanced density between the two feet
Nanhoe-Mahabier et al. (2011)[58]	*Kinematic* • Step length asymmetry • Step time asymmetry	PD: ↑ step time asymmetry compared to NHI
Pereira et al. (2019)[43]	*Kinematic* • Step length asymmetry • Step time asymmetry • Swing phase asymmetry • Stance phase asymmetry • Step velocity asymmetry • Step width asymmetry	Habitual footwear: PD less asymmetric than NHI for step velocity
Plotnik et al. (2007)[59]	*Kinematic* • Swing time asymmetry	PD: ↑ swing time asymmetry compared to NHI and young adults
Ren et al. (2015)[60]	*Kinematic* • Stride length asymmetry	PD = NHI
Continued		

Authors	Asymmetry variables investigated	Results
Seuthe et al. (2024)[16]	*Kinematic* • Step length asymmetry • Swing time asymmetry • Stance time asymmetry • Turning time asymmetry • Number of steps asymmetry	PD: ↑ step length, swing time and stance time asymmetry compared to NHI
Vervoort et al. (2015)[61]	*Kinematic* • Step length asymmetry • Step time asymmetry • Swing time asymmetry • Stance time asymmetry	PD = NHI
Vervoort et al. (2016)[62]	*Kinematic* • Step length asymmetry • Step time asymmetry • Stance time asymmetry • Swing time asymmetry • Double support time asymmetry	PD = NHI
Wu et al. (2021)[72]	*Kinematic* • Stride length asymmetry • Stride time asymmetry • Stance phase time asymmetry • Swing phase time asymmetry • Heel strike angle asymmetry • Toe-off angle asymmetry • ROM asymmetry - ankle joint, knee joint and hip joint	PD = NHI
Yogev et al. (2007)[63]	*Kinematic* • Swing time asymmetry	PD: ↑ swing time asymmetry compared to NHI

Table 3. Gait variables investigated in each study according to kinematic, kinetic, muscular (EMG) and/or neural gait feature. The third column shows the results presented only for GA values when comparing NHI and pwPD or GA with correlate variables. HR: Harmonic Ratio; IHR: Improved Hamonic Ratio; AP: anteroposterior; ML: mediolateral; VT: vertical; CT: cyclo time; SL: stride length; ST: swing time; MG: medial gastrocnemius; TA: tibialis anterior; VL: vastus lateralis; RMS: root mean square; ROM: Range of Motion.

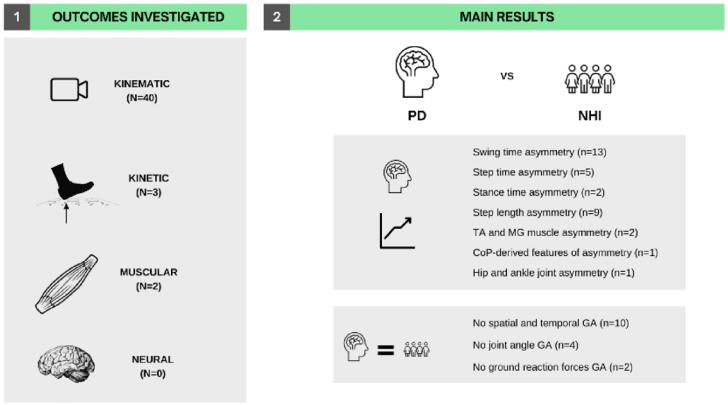

Fig. 3. On the left there are the type of outcomes and the respective number of studies that investigated each one. On the right, the number of studies showing significant (or non-significant) results in GA when comparing people with PD vs. NHI. The arrow graphic represents significant greater asymmetry in people with PD compared to NHI. Although some studies investigated brain functions may related to GA, no study directly assessed neural asymmetry during walking.

Kinematic outcomes

Most studies reported greater GA in temporal and spatial gait parameters in pwPD compared to NHI. However, 10 studies reported no differences in GA between pwPD and NHI[31,36,52,54,60–62,70,72,73]

Regarding temporal parameters, the studies placed particular emphasis on the investigation of swing time and step time. A greater degree of swing[16,34,48–50,59,63,66,67,69,76,77,79] and step time[10,58,66,76,79] asymmetry was observed in pwPD compared to NHI during unobstructed walking. Only two studies reported greater stance time asymmetry in pwPD[16,79].

Step length asymmetry was a consistent spatial parameter analyzed by the studies. PwPD exhibited a greater step length asymmetry compared to NHI[10,16,34,35,51,60,76,77,80]. Additionally, only one study reported greater step velocity asymmetry[43] and other for double support time[82] in pwPD compared to NHI. Furthermore, Barbieri

et al.[31] found that NHI had greater step velocity than pwPD in both the most and least affected limbs. No study reported asymmetry for step width.

Joint angle asymmetries were investigated in six studies[52,64,71,72,80,81]. One reported increased lower-limb asymmetry in pwPD[80]. The range offset at hip level, the cyclogram orientation and trend symmetry at the ankle joint were greater in pwPD compared to NHI[80]. Differences were also found in trunk and upper-limb movement: pwPD showed reduced trunk rotation/obliquity asymmetry[64], increased arm-swing angle asymmetry[71], and arm swing asymmetry[52].

Few studies compared the effects of dopaminergic medication on spatial and temporal GA in pwPD[31,34,36]. PwPD exhibited significantly lower asymmetry of step time under in ON vs. OFF-state[34,35]. In addition, in OFF-state, the step time was increased for the least affected limb compared to the most affected limb[31]. However, no consistent improvements of medication were found for step time[36], stance time[36] and swing time[34,36]. Step length was the only spatial parameter compared between medication states and showed no improvement with medication in two studies[34,36].

Kinetic outcomes

Only three studies assessed kinetic asymmetry during gait in pwPD[48,54,82]. With respect to peak forces, consistent findings showed no significant differences between pwPD and NHI. Baltadjieva et al.[48] reported no group differences in heel-strike or toe-off force asymmetry between the limbs with longer and shorter swing times in *de novo* PD patients. Martinez et al.[54] found no differences between groups in peak forces at heel-strike, mid-stance, or toe-off, nor in the timing of these events for right and left feet. However, Nanayakkara et al.[82] reported greater asymmetry in CoP-derived features captured from smart pressure insoles in pwPD compared to NHI.

Muscular outcomes

Two studies investigated muscular asymmetry during walking[55,68]. Using latency-corrected ensemble averages, Miller et al.[55] observed greater symmetry in the medial gastrocnemius and tibialis anterior in NHI compared to pwPD. Supporting this, Keloth et al.[68] reported significantly higher average asymmetry index for the same muscles in pwPD across the full gait cycle.

Neural outcomes

No study directly assessed neural asymmetry during gait in pwPD. However, two studies[10,62] examined associations between GA and neuroimaging findings. Fling et al.[10] found that greater step length asymmetry was associated with reduced transcallosal fiber integrity in the pre-supplementary motor area and primary somatosensory cortex. In contrast, Vervoort et al.[62] reported no significant associations between GA (kinematic outcomes) and neural connectivity.

Meta-analysis

The GA index values used for meta-analysis are presented in the Supplementary Table 6.

PD OFF vs. NHI (controls)

Swing time, step time and step length asymmetry were assessed in three[31,34,36], five[10,31,34,36,58] and five[10,31,34,36,58] studies, respectively (Fig. 4 – a, b, c). Compared to NHI, pwPD in the OFF-state exhibited significantly greater swing and step time asymmetries (moderate effect sizes; no heterogeneity). No significant difference was observed for step length asymmetry.

PD ON vs. NHI (controls)

Step length, swing time, step time, and stance time asymmetries were analyzed in 12[16,31,34–36,43,65,67,75,77,79,80], 15[16,31,34–36,43,50,54,66,67,69,75,77,79,80], 10[31,34–36,43,65,66,75,77,79] and 8[35,36,43,75,77,79,80] studies, respectively (Fig. 4 – d, e, f, g). PwPD in the ON-state showed significantly greater asymmetry across all parameters compared to NHI (small effect sizes). Heterogeneity was high for step length, swing time, and stance time, and moderate for step time.

PD ON vs. PD OFF

Four studies compared ON vs. OFF-states[31,34,36,81](Fig. 4 – h, i, j). Swing time asymmetry was significantly greater in the OFF-state (no heterogeneity). No differences were found for step length and time asymmetries.

Discussion

This systematic review and meta-analysis of 42 studies examined GA during overground walking in pwPD compared to NHI. We also examined the effects of dopaminergic medication (ON vs. OFF states) on GA. Except for two studies[68,82], all others evaluated kinematic parameters, while kinetic and muscular asymmetries remain limited. Notably, no study has directly compared hemispheric neural activity during the most and least affected steps (which were defined according to symptom predominance as assessed by the UPDRS), highlighting a significant research gap. Nevertheless, previous studies have associated GA with asymmetric brain function. Asymmetric degeneration of dopaminergic and non-dopaminergic pathways[1,7], as well as lateralized motor cortex activity[84], may also explain GA in pwPD. The left hemisphere is often more affected in PD[7], potentially reducing right-side muscle activity[68]. Fling et al.[10] proposed that reduced transcallosal connectivity between the pre-supplementary motor area (pre-SMA) and primary somatosensory cortex underlies GA. In their study, greater temporal and spatial asymmetries, particularly with step length asymmetry, were associated with reduced microstructural integrity of callosal white matter tracts connecting these regions.

PwPD consistently exhibited greater temporal asymmetries, including swing, step, and stance time, in both ON and OFF-states. Step length asymmetry appeared only in the ON-state, possibly due to limited number of

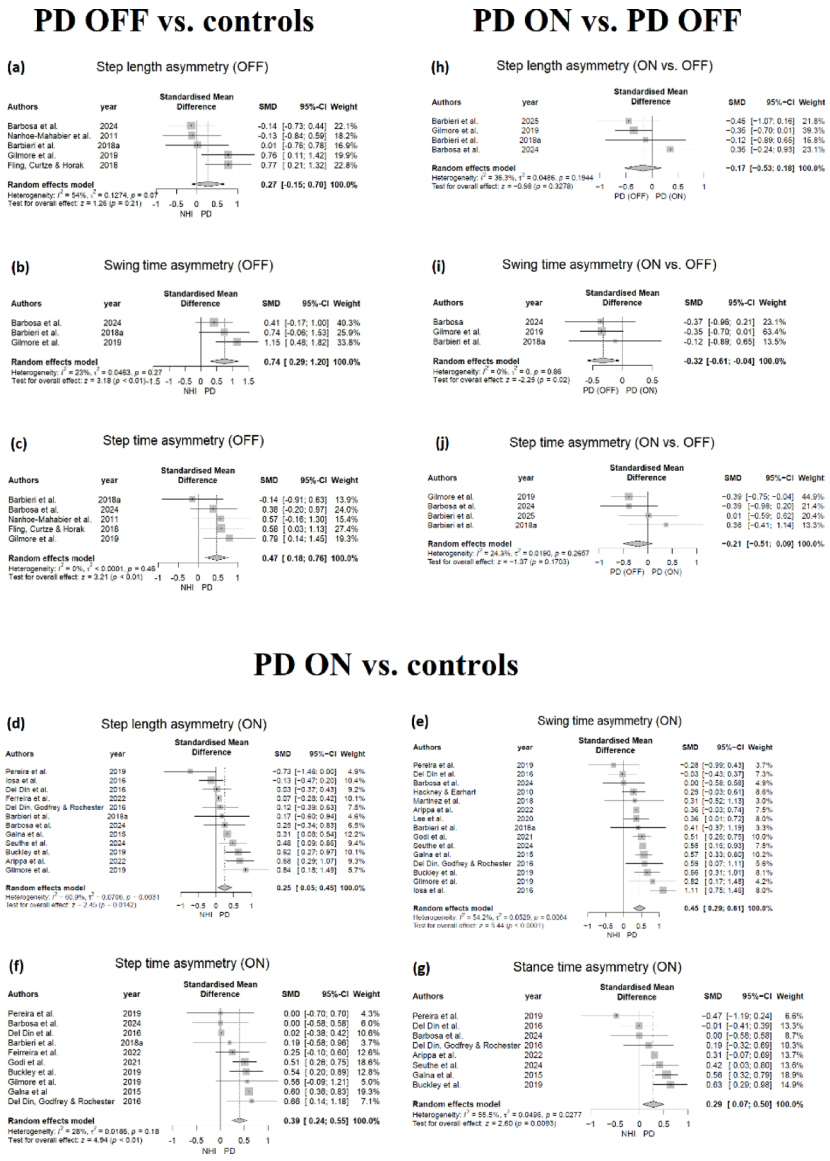

Fig. 4. Forest plots of gait asymmetry (GA) measures—step length, swing time, step time, and stance time asymmetry—comparing people with Parkinson's disease (pwPD) in OFF and ON dopaminergic states versus neurologically age-matched healthy individuals (NHI), and between ON and OFF states. PD: people with Parkinson's disease; NHI: neurologically age-matched healthy individuals; SMD: Standardized mean difference; CI: Confidence interval.

studies and moderate heterogeneity in the OFF-state. Meta-analysis was not feasible for kinetic and muscular outcomes due to the small sample, though available evidence indicates increased muscular asymmetry, particularly in the medial gastrocnemius and tibialis anterior during swing and single support phases[68].

The pronounced asymmetry in temporal gait parameters may reflect impaired temporal processing[85] and disrupted internal rhythmic timing[86] in pwPD. Internal timing deficits are considered potential markers of striatal and frontal dysfunction in PD[87], altered spinal pathways[68], basal ganglia circuitry dysfunction[88], and distinct cortical activity between hemispheres[89,90]. From a biomechanical perspective, temporal asymmetries may also be influenced by gait speed, given that gait speed is mathematically the product of step length and cadence—and that both step length differences and swing time asymmetry were observed. However, gait speed was not controlled for in the meta-analyses, as GA index values were used. Notably, none of the included studies normalized gait asymmetry measures to walking speed. Therefore, it is reasonable to suspect that swing time asymmetry may partly reflect differences in gait speed.

To explore this possibility, we compared gait speed between pwPD and NHI using data from nine studies included in the meta-analysis (Supplementary Table 7). PwPD exhibited significantly reduced gait speed compared with NHI ($p = 0.017$). Bradykinesia—typically asymmetric and prominent in the lower limbs in pwPD—may directly contribute to reduced gait speed and affected temporal gait asymmetries[89–91]. In addition, stride length, stride time, swing time, and stride time variability are closely related to gait speed, particularly

at slower walking speeds[92]. Reduced gait speed prolongs swing time, increasing the time in single support and potentially reflecting impairments in gait stability and balance control. Thus, swing time asymmetry may arise, at least in part, from deficits in balance-control mechanisms. Future studies should normalize GA measures to walking speed to avoid overestimation of temporal asymmetries in PD.

While our results confirm greater GA in pwPD, particularly temporal asymmetries, the effect size was small, with moderate-to-high heterogeneity. About a quarter of the studies reported no kinematic asymmetry, and two found no kinetic asymmetry. Variables like step width, joint angles, and double support time showed no consistent differences. Heterogeneous methodologies and potentially symmetrical progression of some gait parameters may explain inconsistencies. Consequently, asymmetry variables are not the best predictors for disease diagnosis and discriminate pwPD from NHI[65,66]. Future studies should assess GA across varied contexts while rigorously controlling potential confounding factors to improve the consistency and clinical relevance of findings.

Dopaminergic medication partly improves GA

Regarding our second aim, which compared GA between ON and OFF medication states in pwPD, we found that dopaminergic medication improved swing time asymmetry, but not step length or step time asymmetry. These findings should be interpreted with caution due to the limited number of studies available ($n = 3$ per domain). Levodopa may promote compensatory neural reorganization, reducing asymmetrical neurodegeneration and dopamine loss in the basal ganglia[7]. Neural overactivation in both cortices appears more pronounced in the OFF-state[93]. Santos et al.[94] reported that dopaminergic medication enhances cortico-muscular coherence in the alpha band, which coincides with improvements in stride length, speed, and step-timing coordination, making pwPD (ON-state) walk more similarly to NHI. These authors suggest that dopamine strengthens the motor cortex–muscle oscillatory coupling, possibly improving sensory feedback processing via basal ganglia and related circuits, and facilitating sensorimotor integration. The observed medication effects on GA align with improvements in gait rhythmicity[95] and timing deficits[96], indicating a direct influence of dopamine on GA in pwPD. These results suggest that dopaminergic medication may be an effective strategy for reducing GA in pwPD, providing novel insights into the potential benefits of gait interventions for pwPD.

Methodological quality and wide variability among experimental protocols

Overall, the included studies demonstrated high methodological quality. Research aims were clearly stated, key outcomes were well defined, methodologies were appropriately selected and sufficiently detailed for replication, and findings were generally supported by the results. However, recruitment and sampling methods were often inadequately described. Only two studies controlled for covariates, and most provided limited information regarding the reliability and internal validity of their methods. Additionally, clinical implications were not addressed in more than half of the studies. These methodological limitations introduce potential biases and warrant caution in interpreting and applying the current evidence.

The experimental protocols used to assess GA in PD showed substantial heterogeneity, particularly regarding sample characteristics, gait tasks, and asymmetry indexes. Notably, most studies included nearly twice as many men as women across varying disease stages. This is relevant since women with HY stage I present lower gait speed than men, but while women's gait speed remains stable over time, men show progressive worsening[97].

Although most studies focused on mild to moderate PD (HY stages I–III), a few included participants at more advanced stages (HY stage IV)[16,66,71,73]. While motor symptoms in PD typically remain asymmetric[97,98], gait deterioration, including reduced velocity[97], is strongly associated with disease progression[99]. Advanced stages, particularly HY stage IV, are often accompanied by severe disability[97,98], FOG, high variability, postural instability, and reliance on assistive devices[100]. Including individuals with advanced PD may offer insights into GA progression but could introduce bias when analyzed alongside earlier stages.

All studies included in this systematic review employed overground, unobstructed walking at self-selected speeds, but protocols varied widely in walking distance (6–25 m), trial duration (2–5 min), testing environment (laboratory, clinical corridor, free-living conditions), and number of trials (2–20). This lack of protocol standardization complicates comparisons and likely limits the number of studies eligible for meta-analysis, reducing statistical power in some outcomes. Establishing standardized protocols for gait assessment in pwPD would enhance comparability and strengthen future meta-analytic findings.

At least 20 distinct asymmetry indexes were reported. No consensus exists regarding the optimal index to quantify GA in PD. One crucial aspect is that the indexes are based on the selection of a single side as the reference point (the one most affected by disease)[101]. However, there is a striking mismatch between the side with the larger step length during walking and the side with greater motor symptoms, as assessed by MDS-UPDRS-III[16]. Only seven studies in this review identified the most affected side using standardized clinical scales. The use of different reference sides (right vs. left or most vs. least affected) for the same dataset leads to inconsistent results, hinders comparisons across studies, and may obscure asymmetry by lowering index values[102]. Developing a standardized, clinically meaningful asymmetry index could improve PD assessment and gait-related interventions.

Clinical implications, study limitations and future directions

Temporal aspects of gait, particularly swing time asymmetry, were the most sensitive measures for detecting GA in pwPD when compared with NHI and between ON and OFF states. Accordingly, we recommend including these measures in future studies. From a clinical perspective, these findings support the inclusion of temporal asymmetry metrics in gait assessments, as they capture interlimb deficits and asymmetries that may be relevant to walking stability and functional mobility. In particular, monitoring swing time asymmetry may assist clinicians in evaluating treatment effects and in guiding individualized gait rehabilitation strategies aimed at improving

walking safety and efficiency and reducing GA in pwPD. To further enhance their clinical applicability, future studies should employ discriminative analyses to determine thresholds that distinguish normal from pathological levels of asymmetry, thereby establishing clinical meaningful cut-off parameters of GA.

This review has some limitations: (i) due to the diversity of asymmetry indices used, studies in the meta-analysis were grouped by asymmetry variable rather than by calculation method; (ii) ON vs. OFF-states was only tested within the included studies, but an inclusion criterion in this systematic review was that the studies should include NHI. So, there might be more literature available having an ON vs. OFF comparison not included here; (iii) some meta-analyses were based on a small number of studies, which may have limited statistical power.

Future research should explore GA in real-world and challenging contexts. GA appears to be more pronounced in free-living environments compared to laboratory settings[77], yet little is known about asymmetry in real-world contexts. Additionally, obstacle navigation and dual-tasking have exacerbated GA in pwPD[31,50,103–105]. These tasks require rapid motor adaptation and increased sensorimotor integration[106,107], which may exceed the available resources in pwPD, especially given basal ganglia impairments in adaptive control[108]. Exploring GA under these conditions should be a priority for future studies.

Conclusions

This systematic review with meta-analysis has shown that pwPD have greater GA than NHI, with temporal parameters—particularly swing time asymmetry—being the most sensitive. Dopaminergic medication offers partial improvement, highlighting potential for therapeutic interventions.

Data availability

The datasets generated and/or analyzed during the current study are available upon request from the corresponding author.

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References

1. Riederer, P. & Sian-Hülsmann, J. The significance of neuronal lateralisation in Parkinson's disease. *J. Neural Transm.* **119**, 953–962 (2012).
2. Hipp, G. Das Luxemburger Parkinson-Kohortenprogramm: Neue Strategien für eine umfassende Studie zur Erfassung von Biodaten und klinischen Daten. *Basal Ganglia.* **5**, XVI (2015).
3. Postuma, R. B. et al. MDS clinical diagnostic criteria for Parkinson's disease. *Mov. Disord.* **30**, 1591–1601 (2015).
4. Hughes, A. J., Daniel, S. E., Kilford, L. & Lees, A. J. Accuracy of clinical diagnosis of idiopathic Parkinson's disease: A clinico-pathological study of 100 cases. *J. Neurol. Neurosurg. Psychiatry* **55**, 181–184 (1992).
5. Booij, J. et al. [123I]FP-CIT SPECT shows a pronounced decline of striatal dopamine transporter labelling in early and advanced Parkinson's disease. *J. Neurol. Neurosurg. Psychiatry* **62**, 133–140 (1997).
6. Kaasinen, V. et al. Personality traits and brain dopaminergic function in Parkinson's disease. *Proc. Natl. Acad. Sci. U. S. A.* **98**, 13272 (2001).
7. Claassen, D. O. et al. Cortical asymmetry in Parkinson's disease: Early susceptibility of the left hemisphere. *Brain Behav.* **6**(12), e00573 (2016).
8. Clower, D. M., Dum, R. P. & Strick, P. L. Basal ganglia and cerebellar inputs to "AIP". *Cereb. Cortex* **15**, 913–920 (2005).
9. Middleton, F. A. & Strick, P. L. Basal ganglia and cerebellar loops: Motor and cognitive circuits. *Brain Res. Rev.* **31**, 236–250 (2000).
10. Fling, B. W., Curtze, C. & Horak, F. B. Gait asymmetry in people with Parkinson's disease is linked to reduced integrity of callosal sensorimotor regions. *Front. Neurol.* **9**, 215 (2018).
11. Lafargue, G., D'Amico, A., Thobois, S., Broussolle, E. & Sirigu, A. The ability to assess muscular force in asymmetrical Parkinson's disease. *Cortex* **44**, 82–89 (2008).
12. Penko, A. L. et al. Asymmetrical pedaling patterns in Parkinson's disease patients. *Clin. Biomech.* **29**, 1089–1094 (2014).
13. Spagnolo, F. et al. The choice of leg during pull test in Parkinson's disease: Not mere chance. *Front. Neurol.* **11**, 302 (2020).
14. Plotnik, M. & Hausdorff, J. M. The role of gait rhythmicity and bilateral coordination of stepping in the pathophysiology of freezing of gait in Parkinson's disease. *Mov. Disord.* **23**(Suppl 2), S444–S450 (2008).
15. Viteckova, S. et al. Gait symmetry measures: A review of current and prospective methods. *Biomed. Signal Process. Control* **42**, 89–100 (2018).
16. Seuthe, J. et al. Gait asymmetry and symptom laterality in Parkinson's disease: Two of a kind?. *J. Neurol.* **271**, 4373–4382 (2024).
17. Plotnik, M., Giladi, N., Balash, Y., Peretz, C. & Hausdorff, J. M. Is freezing of gait in Parkinson's disease related to asymmetric motor function?. *Ann. Neurol.* **57**, 656–663 (2005).
18. Smulders, K., Esselink, R. A., Bloem, B. R. & Cools, R. Freezing of gait in Parkinson's disease is related to impaired motor switching during stepping.. *Mov. Disord.* **30**, 1090–1097 (2015).
19. Frazzitta, G., Pezzoli, G., Bertotti, G. & Maestri, R. Asymmetry and freezing of gait in parkinsonian patients. *J. Neurol.* **260**, 71–76 (2013).
20. Lord, S. et al. Predicting first fall in newly diagnosed Parkinson's disease: Insights from a fall-naïve cohort. *Mov. Disord.* **31**, 1829–1836 (2016).
21. Wood, B. H., Bilclough, J. A., Bowron, A. & Walker, R. W. Incidence and prediction of falls in Parkinson's disease: A prospective multidisciplinary study.. *J. Neurol. Neurosurg. Psychiatry* **72**, 721–725 (2002).
22. Plotnik, M., Giladi, N. & Hausdorff, J. M. Bilateral coordination of walking and freezing of gait in Parkinson's disease. *Eur. J. Neurosci.* **27**, 1999–2006 (2008).
23. Costa, T. M. et al. Gait and posture are correlated domains in Parkinson's disease. *Neurosci. Lett.* **775**, 136537 (2022).
24. Guadagnin, E. C., Barbieri, F. A., Simieli, L. & Carpes, F. P. IS Muscular and functional performance related to gait symmetry in older adults? a systematic review. *Arch. Gerontol. Geriatr.* https://doi.org/10.1016/j.archger.2019.103899 (2019).
25. Nieuwboer, A. et al. Abnormalities of the spatiotemporal characteristics of gait at the onset of freezing in Parkinson's disease.. *Mov. Disord.* **16**, 1066–1075 (2001).
26. Tamás, G., Pálvölgyi, L., Takáts, A., Szirmai, I. & Kamondi, A. Delayed beta synchronization after movement of the more affected hand in essential tremor. *Neurosci. Lett.* **405**, 246–251 (2006).
27. Chung, J. W., Ofori, E., Misra, G., Hess, C. W. & Vaillancourt, D. E. Beta-band activity and connectivity in sensorimotor and parietal cortex are important for accurate motor performance. *Neuroimage* **144**, 164–173 (2017).

28. Faria, M. H. et al. (A)symmetry during gait initiation in people with Parkinson's disease: A motor and cortical activity exploratory study. *Front. Aging Neurosci.* https://doi.org/10.3389/fnagi.2023.1142540 (2023).
29. Arcolin, I. et al. Proposal of a new conceptual gait model for patients with Parkinson's disease based on factor analysis. *Biomed. Eng. Online* **18**, 70 (2019).
30. Roemmich, R. T. et al. Locomotor adaptation and locomotor adaptive learning in Parkinson's disease and normal aging. *Clin. Neurophysiol.* **125**, 313–319 (2014).
31. Barbieri, F. A. et al. Obstacle avoidance increases asymmetry of crossing step in individuals with Parkinson's disease and neurologically healthy individuals. *J. Mot. Behav.* **50**, 17–25 (2018).
32. Ravi, D. K. et al. Does subthalamic deep brain stimulation impact asymmetry and dyscoordination of gait in Parkinson's disease?. *Neurorehabil. Neural Repair* **35**, 1020–1029 (2021).
33. Nanhoe-Mahabier, W. et al. Split-belt locomotion in Parkinson's disease with and without freezing of gait. *Neuroscience* https://doi.org/10.1016/j.neuroscience.2013.01.038 (2013).
34. Gilmore, G., Gouelle, A., Adamson, M. B., Pieterman, M. & Jog, M. Forward and backward walking in Parkinson disease: A factor analysis. *Gait Posture* **74**, 14–19 (2019).
35. Del Din, S., Godfrey, A. & Rochester, L. Validation of an accelerometer to quantify a comprehensive battery of gait characteristics in healthy older adults and Parkinson's disease: Toward clinical and at home use. *IEEE J. Biomed. Health Inform.* **20**, 838–847 (2016).
36. Barbosa, R. et al. 3D kinematics quantifies gait response to levodopa earlier and to a more comprehensive extent than the MDS-Unified Parkinson's Disease Rating Scale in patients with motor complications. *Mov. Disord. Clin. Pract.* **11**, 795–807 (2024).
37. Moher, D., Liberati, A., Tetzlaff, J. & Altman, D. G. Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *PLoS Med.* **6**, e1000097 (2009).
38. Higgins, J. & Green, S. Cochrane Handbook for systematic reviews of interventions | Cochrane Training. https://training.cochrane.org/handbook/archive/v6.3
39. Bello, O. Spatiotemporal parameters of gait during treadmill and overground walking in Parkinson ' s disease. *J. Parkinsons Dis.* **4**, 33–36 (2014).
40. Ambrus, M. & Sanchez, J. A. Gait & posture walking on a treadmill improves the stride length-cadence relationship in individuals with Parkinson' s disease. *Gait Posture* **68**, 136–140 (2019).
41. Lu, C. et al. Gait & Posture Overground versus treadmill walking in Parkinson ' s disease: Relationship between speed and spatiotemporal gait metrics. *Gait Posture*. **93**, 96–101 (2022).
42. Galna, B., Peters, A., Murphy, A. T. & Morris, M. E. Obstacle crossing deficits in older adults: A systematic review. *Gait Posture* **30**, 270–275 (2009).
43. Pereira, M. P., Orcioli-Silva, D., de Sousa, P. N., Beretta, V. S. & Gobbi, L. T. B. The effects of habitual footwear in gait outcomes in people with Parkinson's disease. *Gait Posture* **68**, 111–114 (2019).
44. R Core Team. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria. at (2023). https://www.r-project.org/
45. Cohen, J. Statistical Power Analysis for the Behavioral Sciences. *Stat. Power Anal. Behav. Sci.* https://doi.org/10.4324/9780203771587 (2013).
46. Borenstein, M., Hedges, L. V., Higgins, J. P. T. & Rothstein, H. R. *Introduction to Meta-Analysis. Principles and Practice of Clinical Trials* (John Wiley & Sons, Ltd Registered, 2009). https://doi.org/10.1007/978-3-319-52636-2_287.
47. Higgins, J. P. T. Measuring inconsistency in meta-analyses. *BMJ* **327**, 557–560 (2003).
48. Baltadjieva, R., Giladi, N., Gruendlinger, L., Peretz, C. & Hausdorff, J. M. Marked alterations in the gait timing and rhythmicity of patients with de novo Parkinson's disease. *Eur. J. Neurosci.* **24**, 1815–1820 (2006).
49. Grajić, M., Stanković, I., Radovanović, S. & Kostić, V. Gait in drug naïve patients with de novo Parkinson's disease–altered but symmetric. *Neurol. Res.* **37**, 712–716 (2015).
50. Hackney, M. E. & Earhart, G. M. The effects of a secondary task on forward and backward walking in Parkinson's disease. *Neurorehabil. Neural Repair* **24**, 97–106 (2010).
51. Kleiner, A. F. R. et al. Analyzing gait variability and dual-task interference in patients with Parkinson's disease and freezing by means of the word-color Stroop test. *Aging Clin. Exp. Res.* **30**, 1137–1142 (2018).
52. Koh, S. B., Park, Y. M., Kim, M. J. & Kim, W. S. Influences of elbow, shoulder, trunk motion and temporospatial parameters on arm swing asymmetry of Parkinson's disease during walking. *Hum. Mov. Sci.* **68**, 102527 (2019).
53. Leavy, B., Löfgren, N., Nilsson, M. & Franzén, E. Patient-reported and performance-based measures of walking in mild-moderate Parkinson's disease. *Brain Behav.* **8**, e01081 (2018).
54. Martínez, M., Villagra, F., Castellote, J. M. & Pastor, M. A. Kinematic and kinetic patterns related to free-walking in Parkinson's disease. *Sensors (Switzerland)* **18**(12), 4224 (2018).
55. Miller, R. A., Thaut, M. H., McIntosh, G. C. & Rice, R. R. Components of EMG symmetry and variability in parkinsonian and healthy elderly gait. *Electroencephalography and Clinical Neurophysiology/Electromyography and Motor Control* **101**, 1–7 (1996).
56. Morris, R. et al. Gait rather than cognition predicts decline in specific cognitive domains in early Parkinson's disease. *The Journals of Gerontology: Series A* **72**, 1656–1662 (2017).
57. Morris, R. et al. A model of free-living gait: A factor analysis in Parkinson's disease. *Gait Posture* **52**, 68–71 (2017).
58. Nanhoe-Mahabier, W. et al. Walking patterns in Parkinson's disease with and without freezing of gait. *Neuroscience* **182**, 217–224 (2011).
59. Plotnik, M., Giladi, N. & Hausdorff, J. M. A new measure for quantifying the bilateral coordination of human gait: Effects of aging and Parkinson's disease. *Exp. Brain Res.* **181**, 561–570 (2007).
60. Ren, X. et al. Veering in hemi-Parkinson's disease: Primacy of visual over motor contributions. *Vision Res.* **115**, 119–127 (2015).
61. Vervoort, G. et al. Distal motor deficit contributions to postural instability and gait disorder in Parkinson's disease. *Behav. Brain Res.* **287**, 1–7 (2015).
62. Vervoort, G. et al. Dual-task-related neural connectivity changes in patients with Parkinson' disease. *Neuroscience* **317**, 36–46 (2016).
63. Yogev, G., Plotnik, M., Peretz, C., Giladi, N. & Hausdorff, J. M. Gait asymmetry in patients with Parkinson's disease and elderly fallers: When does the bilateral coordination of gait require attention? *Exp. Brain Res.* **177**, 336–346 (2007).
64. De Bartolo, D. et al. Effect of different music genres on gait patterns in Parkinson's disease. *Neurol. Sci.* **41**, 575–582 (2020).
65. Ferreira, M. I. A. S. N., Barbieri, F. A., Moreno, V. C., Penedo, T. & Tavares, J. M. R. S. Machine learning models for Parkinson's disease detection and stage classification based on spatial-temporal gait parameters. *Gait Posture* **98**, 49–55 (2022).
66. Godi, M., Arcolin, I., Giardini, M., Corna, S. & Schieppati, M. A pathophysiological model of gait captures the details of the impairment of pace/rhythm, variability and asymmetry in Parkinsonian patients at distinct stages of the disease. *Sci. Rep.* **11**, 21143 (2021).
67. Iosa, M. et al. Loss of fractal gait harmony in Parkinson's disease. *Clin. Neurophysiol.* **127**, 1540–1546 (2016).
68. Keloth, S. M., Arjunan, S. P., Raghav, S. & Kumar, D. K. Muscle activation strategies of people with early-stage Parkinson's during walking. *J. Neuroeng. Rehabil.* **18**(1), 133. (2021).
69. Lee, M., Youm, C., Noh, B., Park, H. & Cheon, S. M. Gait characteristics under imposed challenge speed conditions in patients with Parkinson's disease during overground walking. *Sensors* **20**(7), 2132 (2020).

70. Lencioni, T. et al. Strategies for maintaining dynamic balance in persons with neurological disorders during overground walking. *Proc. Inst. Mech. Eng. H* **235**, 1079–1087 (2021).
71. Liu, P. et al. Quantitative assessment of gait characteristics in patients with Parkinson's disease using 2D video. *Parkinsonism Relat. Disord.* **101**, 49–56 (2022).
72. Wu, Z. et al. Mild Gait impairment and its potential diagnostic value in patients with early-stage Parkinson's Disease. *Behav. Neurol.* 6696454 (2021). (2021).
73. Brodie, M. A. D. et al. Symmetry matched auditory cues improve gait steadiness in most people with Parkinson's disease but not in healthy older people. *J. Parkinsons Dis.* **5**, 105–116 (2015).
74. Bailo, G. et al. Characterization of walking in mild Parkinson's Disease: Reliability, validity and discriminant ability of the six-minute walk test instrumented with a single inertial sensor.. *Sensors* **24**(2), 662 (2024).
75. Buckley, C., Galna, B., Rochester, L. & Mazzà, C. Upper body accelerations as a biomarker of gait impairment in the early stages of Parkinson's disease. *Gait Posture*. **71**, 289–295 (2019).
76. Danoudis, M., Iansek, R. & Simpson, P. Freezing of gait in Parkinson's disease: Further insights into pathophysiological mechanisms. *Park. Relat. Disord.* **18**, 543–547 (2012).
77. Del Din, S., Godfrey, A., Galna, B., Lord, S. & Rochester, L. Free-living gait characteristics in ageing and Parkinson's disease: Impact of environment and ambulatory bout length. *J. Neuroeng. Rehabil.* **13**, 46 (2016).
78. Djurić-Jovičić, M., Belić, M., Stanković, I., Radovanović, S. & Kostić, V. S. Selection of gait parameters for differential diagnostics of patients with de novo Parkinson's disease. *Neurol. Res.* **39**, 853–861 (2017).
79. Galna, B., Lord, S., Burn, D. J. & Rochester, L. Progression of gait dysfunction in incident Parkinson's disease: Impact of medication and phenotype. *Mov. Disord.* **30**, 359–367 (2015).
80. Arippa, F. et al. A study on lower limb asymmetries in Parkinson's disease during gait assessed through kinematic-derived parameters. *Bioengineering* **9**(3), 120 (2022).
81. Barbieri, F. A. et al. Inter-limb gait asymmetry in people with Parkinson ' s disease. *Hum. Mov. Sci.* **103**, 103399 (2025).
82. Nanayakkara, T. et al. Multi-domain CoP feature analysis of functional mobility for Parkinson's Disease detection using wearable pressure insoles. *Sensors (Basel)* **25**(18), 5859 (2025).
83. Lord, S. et al. Independent domains of gait in older adults and associated motor and nonmotor attributes: Validation of a factor analysis approach. *J. Gerontol. A Biol. Sci. Med. Sci.* **68**, 820–827 (2013).
84. Heinrichs-Graham, E., Santamaria, P. M., Gendelman, H. E. & Wilson, T. W. The cortical signature of symptom laterality in Parkinson's disease. *Neuroimage (Amst)*. **14**, 433 (2017).
85. Jones, C. R. G. & Jahanshahi, M. Motor and perceptual timing in Parkinson's disease. *Adv. Exp. Med. Biol.* **829**, 265–290 (2014).
86. Tolleson, C. M. et al. Dysrhythmia of timed movements in Parkinson's disease and freezing of gait. *Brain Res.* **1624**, 222 (2015).
87. Ashoori, A., Eagleman, D. M. & Jankovic, J. Effects of auditory rhythm and music on gait disturbances in Parkinson's Disease. *Front. Neurol.* **6**, 234 (2015).
88. Debaere, F., Wenderoth, N., Sunaert, S., Van Hecke, P. & Swinnen, S. P. Cerebellar and premotor function in bimanual coordination: Parametric neural responses to spatiotemporal complexity and cycling frequency. *Neuroimage* **21**, 1416–1427 (2004).
89. Bologna, M., Paparella, G., Fasano, A., Hallett, M. & Berardelli, A. Evolving concepts on bradykinesia. *Brain* **143**, 727–750 (2020).
90. Monje, M. H. G. et al. Motor onset topography and progression in Parkinson's disease: The Upper Limb Is First. *Mov. Disord.* **36**, 905–915 (2021).
91. Paparella, G. et al. Interhemispheric imbalance and bradykinesia features in Parkinson's disease. *Brain Commun.* **6**, fcae020 (2023).
92. Frenkel-toledo, S. et al. Effect of gait speed on gait rhythmicity in Parkinson ' s disease: variability of stride time and swing time respond differently. *J. neuroeng. rehabilitation* **2**, 1–7 (2005).
93. Koren, O. et al. Dopaminergic medication reduces interhemispheric hyper-synchronization in Parkinson's disease. *Parkinsonism Relat. Disord.* **97**, 39–46 (2022).
94. Santos, P. C. R., dos, Heimler, B., Koren, O., Flash, T. & Plotnik, M. Dopamine improves defective cortical and muscular connectivity during bilateral control of gait in Parkinson's disease.. *Commun. Biol.* **7**(1), 495 (2024).
95. Hausdorff, J. M., Balash, J. & Giladi, N. Effects of cognitive challenge on gait variability in patients with Parkinson's disease. *J. Geriatr. Psychiatry Neurol.* **16**, 53–58 (2003).
96. Malapani, C. et al. Coupled temporal memories in Parkinson's disease: A dopamine-related dysfunction. *J. Cogn. Neurosci.* **10**, 316–331 (1998).
97. Vila, M. H., Pérez, R., Mollinedo, I. & Cancela, J. M. Analysis of gait for disease stage in patients with Parkinson's Disease. *Int. J. Environ. Res. Public Health* **18**, 720 (2021).
98. Miller-Patterson, C. et al. Motor asymmetry over time in Parkinson's disease. *J. Neurol. Sci.* **393**, 14–17 (2018).
99. Corrêa, P. S. et al. Is the dopaminergic loss associated with gait and postural impairments in subjects with Parkinson's disease at different motor stages?. *Eur. J. Neurosci.* **50**, 3889–3895 (2019).
100. Hoehn, M. M. & Yahr, M. D. Parkinsonism: Onset, progression and mortality. *Neurology* **17**, 427–442 (1967).
101. Cabral, S. et al. A global gait asymmetry index. *J. Appl. Biomech.* **32**, 171–177 (2016).
102. Zifchock, R. A., Davis, I., Higginson, J. & Royer, T. The symmetry angle: A novel, robust method of quantifying asymmetry. *Gait Posture* **27**, 622–627 (2008).
103. Orcioli-Silva, D. et al. Double obstacles increase gait asymmetry during obstacle crossing in people with Parkinson's disease and healthy older adults: A pilot study. *Sci. Rep.* **10**(1), 2272 (2020).
104. Barbieri, F. A. et al. Obstacle circumvention and eye coordination during walking to least and most affected side in people with Parkinson's disease. *Behav. Brain Res.* **346**, 105–114 (2018).
105. Corradini, J. R. et al. Dual tasking reduces gait asymmetry of trajectory deviation during obstacle circumvention in people with Parkinson's disease. *Hum. Mov. Sci.* **83**, 102938 (2022).
106. Snijders, A. H. et al. Obstacle avoidance to elicit freezing of gait during treadmill walking. *Mov. Disord.* **25**, 57–63 (2010).
107. Vitório, R., Lirani-Silva, E., Orcioli-Silva, D., Beretta, V. S. & Gobbi, A. S. O. T. B. Electrocortical dynamics of usual walking and the planning to step over obstacles in Parkinson's disease. *Sensors* **23**, 1–13 (2023).
108. Cools, R., Barker, R. A., Sahakian, B. J. & Robbins, T. W. L-Dopa medication remediates cognitive inflexibility, but increases impulsivity in patients with Parkinson's disease. *Neuropsychologia* **41**, 1431–1441 (2003).
109. Lord, S. et al. Independent domains of gait in older adults and associated motor and nonmotor attributes: Validation of a factor analysis approach. *J. Gerontol. A Biol. Sci. Med. Sci.* **68**, 820–827 (2013).

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Aline Prieto Silveira-Ciola: Conceptualization, Data curation, Formal analysis, Investigation, Methodology and Writing – original draft.Jana Seuthe: Assistance on meta-analysis and writing (review of the manuscript).Daniel Boari Coelho: writing (review of the manuscript).Murilo Henrique Faria: Data curation, Formal analysis and writing (review of the manuscript).Felipe Balistieri Santinelli: Data curation, Formal analysis and writing (review of the manuscript).Christian Schenstedt: Supervision and writing (review of the manuscript).Fabio Augusto Barbieri: Supervision, Conceptualization, Writing (original draft) and Writing (review of the manuscript).

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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