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Review

Systematic review of kinematic and kinetic parameters in Parkinson's disease, with and without freezing of gait

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ABSTRACT

Background: Parkinson's Disease (PD) is a chronic, progressive disorder, impairing gait, balance and overall functionality. Freezing of gait (FOG) is a debilitating and pervasive symptom of PD, presenting as an inability to make forward progression despite the intention to walk. Commonly seen within FOG are rigid movements and postural instability, inducing a fear of falling which can inhibit quality of life. The aim of this review was to identify the key biomechanical parameters that differentiate individuals with and without FOG during gait-related mobility tasks.

Methods: A search was conducted in EBSCOhost and SCOPUS up to May 2025 to retrieve studies measuring kinematic and kinetic parameters during gait mobility tasks in individuals with and without FOG. Methodological quality was assessed using a modified Downs and Black checklist. Overall quality of evidence was assessed using the GRADE system. Hedges' g effect sizes were reported as standardised mean differences and 95% confidence intervals.

Findings: Sixteen studies involving 513 participants (259 with FOG, 254 without FOG) were included. Results showed individuals with FOG produced delayed head rotation timing during turning, decreased hip range of motion and increased hip-knee and hip-ankle decomposition indices during backward walking. Moreover, results found postural instability and mechanical inefficiencies during walking in individuals with FOG.

Discussion: FOG involves more than spatiotemporal irregularities, and key biomechanical parameters such as joint range of motion, knee and hip flexion patterns, centre of mass displacement and ground reaction force patterns can provide clinical markers for assessing freezing severity and monitoring rehabilitation outcomes.

PROSPERO registration: CRD42024514366.

1. Introduction

Parkinson's Disease (PD) is the second most common neurodegenerative disorder globally (Kouli et al., 2018) affecting approximately 6.1 million people worldwide as of 2016 (Bloem et al., 2021). It is a chronic, progressive disorder that leads to impairments in gait, balance, and overall functionality limiting an individual's ability to perform everyday mobility-related activities such as walking and turning (Hariz and Forsgren, 2011). One of the most debilitating and pervasive symptoms of PD is freezing of gait (FOG) (Cronin et al., 2024) which affects approximately 50% of people in early-stage PD, becoming increasingly prevalent throughout the disease cycle (Conde et al., 2023). FOG was recently defined as the sudden inability to take an effective step either during gait initiation, walking or turning. FOG can present in different ways that is not just the complete absence of movement, such as trembling legs or shuffling with small steps (Gilat et al., 2026). Consequently, people with FOG represent a major contributor to falls, fear of movement, and thus can experience a reduced quality of life (Nutt et al., 2011).

FOG is a complex and multifactorial phenomenon with contributing factors such as medication status, disease duration, anxiety, visuomotor processing, executive functioning, and cortical dysfunction being implicated in the condition (Creaby and Cole, 2018). Clinical assessment tools such as the Movement Disorder Society Unified Parkinson's Disease Rating Scale (MDS-UPDRS), Freezing of Gait Questionnaire (FOG-Q) and New Freezing of Gait Questionnaire (NFOG-Q) have been shown to be

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effective when determining FOG frequency and severity, despite limitations such as recall bias and cognitive decline amongst patients (Creaby and Cole, 2018). However, they are unable to quantify movement characteristics that precede a freezing episode or affect overall gait performance.

Biomechanical assessments include objective and quantifiable measures to analyse human movement. Gait is achieved through coordinated muscle activation, joint and ground reaction forces (GRF) (kinetics), and movement (kinematics) (Rutz and Benninger, 2020). Biomechanics allows researchers to identify discrete changes in movement patterns, joint coordination, and compensatory mechanisms. Quantification of these parameters can aid understanding of motor control strategies and inefficiencies that can differentiate individuals with and without FOG. Previous research has outlined spatiotemporal differences such as decreased gait speed and stride length amongst individuals with FOG (Palmisano et al., 2022; Son et al., 2018). Differences in hip and knee range of motion (ROM), lower-limb decomposition index (DI), and increased variability and temporal asymmetry during gait have also been reported (Albani et al., 2014; Myers et al., 2020; Zanardi et al., 2021). Despite this, findings are inconsistent and are limited by small sample sizes, differences in reported outcome variables, disease confounders and methodological heterogeneity (Spildooren et al., 2019).

Pharmacological treatment is thought to be the most effective management strategy (McNeely and Earhart, 2011) despite ON-OFF periods and medication efficacy decreasing over time (Sivanandy et al., 2022). Freezing episodes are more frequently observed during OFF medication states, emphasising the significant role of the dopaminergic pathway. However, FOG also occurs during ON medication conditions, suggesting that it is not solely related to decreased striatal dopamine levels (McNeely and Earhart, 2011). As such, alternative pathways and mechanisms contribute to this phenomenon and should be considered. Pharmacological treatments often fail to alleviate FOG, emphasising the importance of understanding FOG through biomechanics to implicate key mechanical and neuromotor components (Creaby and Cole, 2018). This knowledge can help guide targeted rehabilitation strategies on a symptom that requires improved management strategies outside of pharmacology.

Research involving FOG in PD has evolved in stages. Early work primarily characterised FOG using clinical observation and patient reported severity scales. Subsequent studies increasingly examined spatiotemporal gait features, such as gait speed, stride length, cadence and variability, to identify aspects of movement associated with FOG (Palmisano et al., 2022; Son et al., 2018). More recent biomechanical work has extended its focus to segmental coordination, joint motion, centre of mass (COM) and GRF, enabling a more detailed understanding of the mechanical and motor control features distinguishing individuals with and without FOG. However, current biomechanical findings remain dispersed across tasks and outcome domains, limiting synthesis and clinical translation.

Despite heightened awareness surrounding FOG in PD, existing reviews have primarily focused on clinical features, neurophysiological mechanisms, or broader spatiotemporal gait impairments (Conde et al., 2023; Spildooren et al., 2019). Moreover, recent advances in PD mobility research increasingly use wearable sensors to quantify FOG and mobility within real world and home environments. These measures introduce contextual factors such as environmental variability, obstacles, and distractions which may act as confounding variables when assessing kinetic and kinematic mechanisms of FOG. As such, these approaches represent a distinct measurement context from the laboratory-based biomechanical studies synthesised in the present review. These studies were prioritised to provide greater methodological consistency.

To our knowledge, no systematic review has specifically synthesised the kinetic and kinematic biomechanical parameters that distinguish individuals with PD who experience FOG (PD with FOG) to those who do not (PD without FOG) during controlled gait-related mobility tasks. These tasks include walking, turning, and gait related functional transitions, which are representative of daily gait tasks, but are performed within a laboratory environment. Addressing this gap is important as biomechanical measures may provide objective markers of impaired motor control, help refine assessment beyond questionnaire-based tools, and inform targeted rehabilitation strategies. Therefore, the aim of this review was to identify the key biomechanical parameters (kinetic and kinematic) that differentiate individuals with PD, with and without FOG, during gait-related mobility tasks.

2. Methods

2.1. Protocol registration

This systematic review adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021) and was registered with the International Prospective Register of Systematic Reviews (PROSPERO, CRD42024514366).

2.2. Search strategy

The search was conducted in April 2024 and updated on 7th May 2025. The databases used were EBSCOhost (CINAHL Plus with Full Text, MEDLINE, SPORTDiscus with Full Text) and Scopus. Results were limited to the last 20-years (1 January 2004-date of search), journal articles ONLY, and English ONLY. A Population, Exposure and Outcome (PEO) framework was used to guide this systematic review (Hosseini et al., 2024): (P) individuals with PD; (E) the presence of FOG; (O) kinetic and kinematic gait parameters during gait-related mobility tasks.

Search terms involved four search fields combined using "AND" Boolean operators. An example of the search strategy used is shown in Table 1 (full database specific search strings are provided in Supplementary Material 1). A manual search of the reference lists of the final articles was checked based on article titles (followed by the abstract and full text where relevant) to check for other eligible studies. Studies focused solely on gait initiation were excluded as this task involves anticipatory postural adjustments distinct from freezing mechanisms during steady walking and turning

2.3. Eligibility criteria

Studies eligible for inclusion in this systematic review were studies

Table 1
Search strategy and results used in EBSCOhost (7th May 2025).

	Key Words in EBSCOhost (CINAHL Plus with Full Text, MEDLINE, SPORTDiscus with Full Text)	Hit Counts (07/05/2025)
(1)	"Activit* of daily living" OR "ADL" OR "ADLs" OR "Gait" OR "Gait initiation" OR "Walking" OR "Turn*" OR "Sit-to-stand" OR "STS" OR "TUG" OR "Timed up and go" OR "Functional capacity" OR "Functional mobility" (TX All Text)	1,938,661
(2)	"Parkinson's disease" OR "PD" OR "Parkinson*" OR "Parkinsons disease" OR "Parkinsonism" (AB Abstract)	273,992
(3)	"Freezing of gait" OR "FOG" OR "Gait freezing" OR "freezing episode*" OR "freezer" OR "freezing" (TX All Text)	106,501
(4)	"Kinetic*" OR "Kinematic*" OR "Electromyography" OR "EMG" OR "Myography" OR "Biomechanics" OR "Motion" OR "Motion capture" OR "Gait analysis" OR "Ground reaction force" OR "GRF" OR "Muscle activity" OR "Muscular activity" (TX All Text)	1,946,905
(5)	(1) AND (2) AND (3) AND (4)	952
(6)	Full Text ONLY	922
(7)	Date Limiter (2024-date search was conducted)	155
(8)	Academic Journals ONLY	151
(9)	English ONLY	151

available in full text, written in English, that focused on the target population (individuals with PD, with and without FOG). Individuals with FOG had to be classified using predefined criteria. FOG classification included: observation, clinical history, and/or self-reported questionnaires. Studies had to include kinetic and/or kinematic outputs whilst performing gait-related mobility tasks, including but not limited to: walking, turning, and transitional movements.

This review did not focus on basic, instrumental, and/or advanced activities of daily living, and as such any studies that reported on these activities were excluded. A study was also excluded if the reported outcomes were not applicable to the research question, or if it did not use an objective motion analysis approach capable of quantifying three-dimensional kinematic or kinetic data (for example, optical motion capture, infrared camera systems, or validated wearable inertial sensors). Finally, systematic reviews were excluded to reduce the risk of double counting results.

2.4. Selection of studies

The selection of studies was conducted independently by two researchers (LB and FK). Raayan software (Ouzzani et al., 2016) was used to collate results from EBSCOhost and Scopus. Duplicate studies across the databases were immediately refined. Titles and abstracts were evaluated in accordance with eligibility criteria and disagreements were resolved by a third reviewer (JB). In the second phase, two reviewers (LB and JB) studied the remaining articles full text. Studies were included or excluded in accordance with eligibility criteria.

2.5. Data extraction

Data extraction was completed by two reviewers (LB and FK) and inserted into a spreadsheet. The following study characteristics were extracted: authors, year of publication, study design, sample size, age, FOG classification method, medication condition/timing, if FOG trials were included, activities performed, relevant outcome measures, and main findings. Moreover, statistically different confounders between groups were extracted (disease duration, treatment duration, disease severity (MDS-UPDRS), Hoehn and Yahr (H&Y) scale, levodopa equivalent daily dose (LEDD), medication status and timing). All statistically significant kinetic or kinematic outcomes during different gait-related mobility tasks were extracted, including but not limited to: joint ROM, joint angles, DI, cycle timing, maximum anti-phase, toe clearance height, rotation timing, vertical GRF (vGRF), and COM metrics. The mean and standard deviation (SD) (and standard measurement units) were extracted for each variable. Missing data were calculated where possible. Other missing or unclear data was excluded from the narrative synthesis.

2.6. Quality assessment

A modified Downs and Black quality checklist (Downs and Black, 1998) was used in this review. Originally it was used to assess methodological quality of both randomised and non-randomised studies. Previously, authors have used this checklist with customised questions to make it applicable to their research question (Zanardi et al., 2021). As such, in line with a similar review conducted by Zanardi et al. (2021), the checklist was modified to include questions 1, 2, 3, 5, 6, 7, 10, 11, 12, 18, 20, 21 and 22. Studies were scored out of 14, and study quality was based on Ratcliffe et al. (2014). A study was deemed of high quality if it scored $\geq$66.8%, moderate quality 33.4%–66.7%, and low quality $\leq$33.3%. Two reviewers (LB and JB) worked through the final articles separately, scoring them in accordance with the checklist. Level of agreement between reviewers were calculated using Cohen's Kappa coefficient inter-rater reliability.

The overall quality of evidence was assessed using the GRADE (Grades of Recommendation, Assessment, Development and Evaluation) system (Guyatt et al., 2008). For each outcome, a priori ranking of 'low' was assigned to non-randomised control trials. Five domains of quality were assessed and used to 'downgrade' the quality of the outcome across all trials, domains included: (1) risk of bias; (2) inconsistency; (3) indirectness; (4) imprecision; and (5) publication bias. The quality of the finding was rated as 'very low' if one or more of the criteria were not met. Only observational studies with no major threats to validity (i.e. had not been downgraded) had the opportunity to be upgraded (Guyatt et al., 2008).

2.7. Data analysis

FOG biomechanics research can result in heterogeneity due to the movement task performed, protocols, outcome definitions, medication states, and study design. Therefore, a pooled meta-analysis was not performed. Instead, a structured narrative synthesis supported by study level effect size calculations were undertaken. Sources of heterogeneity were considered when interpreting findings.

Hedges' g was used to calculate the effect size for the difference between two means of statistically significant outputs. To calculate this, group means, SD, and sample size of all the relevant outputs that were statistically significant were extracted and calculated. Moreover, some studies reported effect sizes using Partial Eta Squared (η_p^2). These values were converted to Hedges' g. Effect sizes were interpreted in accordance with Cohen (1992), where 0.20–0.50 indicates a small effect, 0.51–0.80 a medium effect, and $>$ 0.80 a large effect. Effect sizes were reported using forest plots to visually present individual outcomes and directional trends. The 95% confidence intervals (CI) were calculated and presented for each effect size, showing the range of values that the true mean can be within (with 95% certainty). Hedges' g values were used descriptively to support task specific narrative synthesis. Cohen's Kappa coefficient inter-rater reliability was conducted in IBM SPSS statistics (Version 29.0) to assess the two reviewers' agreement. Inter-rater reliability is the consistency and/or agreement between individuals which arises through human disagreement, error, or variability (McHugh, 2012). Cohen's Kappa was scored referring to guidelines put forward by Landis and Koch (1977), where a rating between 0.41 and 0.60 indicates moderate agreement, 0.61–0.80 a substantial agreement, and 0.81–1.00 an almost perfect agreement.

3. Results

3.1. Studies inclusion

A total of 2017 studies were identified during the literature search. After adjusting for duplicates (n = 177), 1840 studies remained. From these, further studies were excluded using appropriate criteria. 92 full text articles were read, in which 78 were excluded using the same rationale as above. Accordingly, 14 studies were included. The second search was conducted using the same strategy, and 2 additional studies were added, totalling 16 studies to be included within this review. The search results and reason for exclusion can be seen in Fig. 1.

3.2. Methodological quality

The methodological quality of 16 studies was assessed and scored moderate to high quality (see Table 2). Common limitations identified across most studies were weaknesses in external validity, particularly in questions 11 and 12 of the assessment tool. The source population was frequently not reported, rendering these questions unable to be determined. In addition, the proportion of participants who agreed to take part was often not specified, resulting in a score of zero. Question 22 consistently received low scores across the included studies, indicating limitations in internal validity (selection bias) (Downs and Black, 1998). This was primarily due to studies failing to specify the time period over

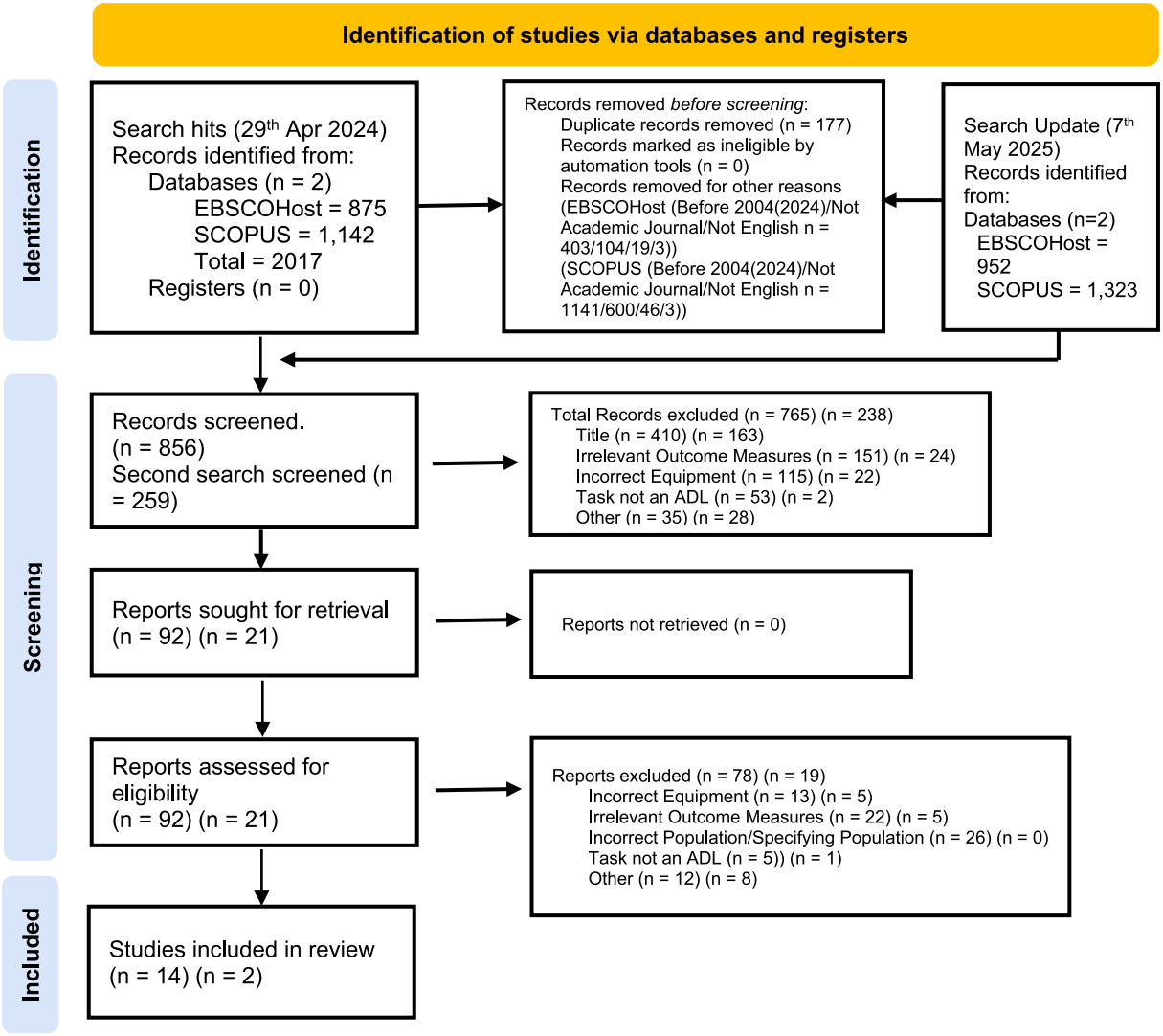

Fig. 1. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) flow chart for search strategy (Page et al., 2021).

Table 2
Methodological quality of included articles using 'Modified' Downs and Black Quality Assessment Checklist.

Studies	Quality Index Item Number														% Score	Quality
	1	2	3	5	6	7	10	11	12	18	20	21	22	Total (/14)		
Albani et al. (2014)	1	1	0	2	1	0	0	0	0	1	1	0	0	7	50.0%	**Moderate**
Bengevoord et al. (2016)	1	1	0	2	1	1	1	0	0	1	1	0	0	9	64.3%	**Moderate**
Choi et al. (2022)	1	1	1	2	1	1	1	1	0*	1	1	1	0	12	85.7%	**High**
McNeely and Earhart (2011)	1	1	0*	2	1	1	1	1	0	1	1	1	0	11	78.6%	**High**
Mezzarobba et al. (2018)	1	1	1	2*	0	0	1	0	0	1	1	1	0	9	64.3%	**Moderate**
Myers et al. (2020)	1	1	0	2	1	1	1	0	0	1	1	0	0	9	64.3%	**Moderate**
Palmisano et al. (2022)	1	1	1*	2	1	1	0	0	0	1	1	1*	0	10	71.4%	**High**
Park et al. (2020)	1	1	0	2	1	1	1	1	0	1	1	0*	0	10	71.4%	**High**
Pinto et al. (2020) **	1	1	0	na	1	1	1	0	0	1	1	na	0	7	58.3%	**Moderate**
Shida et al. (2023)	1	1	0*	2	1	1	1	0	0	1	1	0*	0	9	64.3%	**Moderate** *
Son et al. (2018)	1	1	0	2*	1	1	1	0	0	1	1	0	0	9	64.3%	**Moderate**
Son et al. (2022)	1	1	0	2	1	1	1	0	0	1	1	0	0	9	64.3%	**Moderate**
Spildooren et al. (2013)	1	1	1	2	1	1	1	0	0	1	1	1	0	11	78.6%	**High**
Urakami et al. (2021)	1	1	1	2	1	1	1	0	0	1	1	1	1	12	85.7%	**High**
Etoom et al. (2024) **	1	1	1	na	1	1	1	0	0	1	1	na	0	8	66.7%	**Moderate**
Los Angeles et al. (2024)	1	1	1	2	1	1	1	0	0	1	1	0	0	10	71.4%	**High**

Quality of studies was based on Ratcliffe et al. (2014). Studies were scored as high quality if they achieved a score > 66.8%, moderate quality if they scored between 33.4 and 66.7%, and low quality if they scored <33.3% (Zanardi et al., 2021).

* Disagreements between reviewers.

** Paper was scored out of 12 as there was no control group implemented, and as such questions 5 and 21 could not be assessed.

which participants were recruited (rationale for scoring can be seen in Supplementary Material 1). Inter-rater reliability, assessed using Cohen's Kappa, was calculated as 0.92 (Standard error = 0.03, $p < 0.001$), indicating almost perfect agreement between raters (McHugh, 2012).

3.3. Quality of evidence

The summary of evidence using GRADE assessment for the key kinetic and kinematic parameters in individuals with and without FOG are presented in Table 3. Study outcomes were rated very low largely due to their observational study design. Non-randomised controlled trials are initially assigned a 'low' rating and can only be upgraded if there is no major threat to validity. As such, study designs were limiting in the quality of evidence. Moreover, studies were consistently marked down due to risk of bias and imprecision metrics. Risk of bias was serious amongst most outcome measures due to statistically significant confounders between groups, whilst imprecision was often serious due to the small sample sizes commonly observed in clinical biomechanics research. The full rationale for summary of evidence scores can be found within Supplementary Material 1.

3.4. Study characteristics

Main study characteristics are presented in Table 4. Most papers used a between-groups design, comparing PD with FOG to PD without FOG. Certain papers included both ON and OFF medication conditions (Etoom et al., 2024; McNeely and Earhart, 2011; Palmisano et al., 2022; Pinto et al., 2020; Shida et al., 2023) making them a cross sectional, within groups design. Total sample sizes amongst included studies ranged from 20 to 63 participants. All papers investigated PD with FOG and PD without FOG, except Pinto et al. (2020) which solely investigated individuals with FOG during walking and dual-tasks conditions, whilst ON and OFF medication.

3.5. Hip kinematics

Albani et al. (2014) investigated kinematics and kinetics during OFF medication walking which produced significant differences between PD with FOG and PD without FOG in hip flexion/extension angles at initial contact (IC) (PD with FOG = 34.6° ± 6.4°, PD without FOG = 28.8° ± 5.9°), showing a large effect size (standardised mean difference (SMD) 0.91, CI 0.08 to 1.74) (all hip kinematic outputs are shown in Fig. 2). This was the only study to explore this output at IC. Fig. 2 reveals increased hip flexion minimum value in stance (SMD 0.56, CI -0.24 to 1.37). This finding outlines significantly increased flexion in PD with FOG (1.0° ± 9.9°) compared to PD without FOG (−4.5° ± 8.8°), showing the inability of the hip to go into extension during stance. Myers et al. (2020) investigated intersegmental coordination using DI. Interestingly, effect size was larger in forward walking (hip-knee (SMD 0.32, CI -0.33 to 0.97), hip-ankle (SMD 0.26, CI -0.39 to 0.91)) when compared to dual-task walking (hip-knee (SMD 0.23, CI -0.42 to 0.88), hip-ankle (SMD 0.10, CI -0.55 to 0.74)), when dual-task would be presumed to be a more complex and cognitively challenging activity, and would be expected to further inhibit intersegmental coordination.

Hip-knee DI during backward walking produced a large effect size (SMD 0.81, CI 0.14 to 1.48) and hip-ankle DI produced a medium effect during the same task (SMD 0.72, CI 0.06 to 1.39). These effect sizes are larger than those observed in forward and dual task activities. Backward walking was also investigated by Son et al. (2018) and Son et al. (2022) in the most affected side (MAS) and least-affected side (LAS). Research showed that hip ROM of the LAS during backward walking was found to have a large (SMD -0.90, CI -1.73 to −0.07) (Son et al., 2018) and a small effect size (SMD -0.47, CI -0.97 to 0.03) (Son et al., 2022). Interestingly, hip ROM of the LAS during backward walking presented the largest difference across all hip kinematics reported in this systematic review. Furthermore, Son et al. (2018) uncovered small differences in the MAS during backward walking (SMD -0.26, CI -0.75 to 0.24) but found no significant differences during normal walking on the MAS.

Choi et al. (2022) investigated severity of FOG during turning, a complex movement that requires cognitive and executive functioning. They reported that inner hip ROM of the outer step of the more affected side (OMA) during 180° turning was decreased amongst PD with FOG (46.76° ± 14.86°) in comparison to PD without FOG (56.44° ± 18.85°), producing a medium effect size (SMD -0.56, CI -1.09 to −0.03). Son et al. (2022) found similar results showing hip ROM of the MAS during 360° turning produced a small effect size in the same direction (SMD -0.34, CI -0.84 to 0.16). Investigating the LAS during 360° turning resulted in a small effect size (SMD -0.36, CI -0.86 to 0.15) (Son et al., 2022).

3.6. Knee kinematics

Shida et al. (2023) investigated FOG and medication on lower limb biomechanics and was the only paper to report a statistical difference in knee flexion kinematics across different phases of the gait cycle. A large effect size was reported before IC (SMD 1.02, CI 0.50 to 1.54) where PD with FOG produced increased knee flexion. A large difference was also observed for minimum knee flexion in terminal stance (SMD 1.05, CI 0.53 to 1.57) (see Fig. 3).

During backward walking, Son et al. (2022) reported negligible effect for knee ROM of the MAS (SMD -0.17, CI -0.67 to 0.32) but small effects for the LAS (SMD -0.33, CI -0.83 to 0.17), outlining increased knee ROM in individuals with FOG.

Only one study investigated knee ROM of the MAS during turning.

Table 3
Summary of evidence of key kinetic and kinematic parameters in individuals with PD, with and without FOG.

Outcome	N (# of studies)	Risk of Bias	Inconsistency	Indirectness	Imprecision	Publication Bias	Quality of Evidence (GRADE)
Hip Kinematics							
DI	44 (1)	Not Serious	Not Serious	Not Serious	Serious	None	⊕OOO Very low [b]
Hip ROM	108 (3)	Serious	Not Serious	Not Serious	Serious	None	⊕OOO Very low [a, b]
Knee Kinematics							
Knee ROM	48 (2)	Serious	Not Serious	Not Serious	Serious	None	⊕OOO Very low [a, b]
Ankle Kinematics							
Ankle ROM	168 (4)	Serious	Not Serious	Not Serious	Serious	None	⊕OOO Very low [a, b]
Miscellaneous Dependent Variables							
Toe-clearance height	89 (2)	Serious	Not Serious	Not Serious	Serious	None	⊕OOO Very low [a, b]
Head rotation timing	20 (1)	Serious	Not Serious	Not Serious	Serious	None	⊕OOO Very low [a, b]
Kinetics							
COM distance	26 (1)	Serious	Not Serious	Not Serious	Serious	None	⊕OOO Very low [a, b]
vGRF	50 (2)	Serious	Not Serious	Not Serious	Serious	None	⊕OOO Very low [a, b]

DI = Decomposition index; ROM = Range of motion; COM = Centre of mass; vGRF = Vertical ground reaction force.
[a] Serious risk of bias (confounding variables which statistically differed between groups).
[b] Serious imprecision (fewer than 400 participants included).

Table 4
Characteristics and summary of 16 studies ($n = 16$) (12 cross-sectional studies, 1 observational biomechanical study, 1 within-subject comparative study, 1 experimental study, and 1 dataset/validation study).

Authors and year	Study design	Total participants/ PD with FOG (M)/ PD without FOG (M)	Age (years) (mean ± SD)	FOG Classification Method	Disease Differences	ON/OFF Medication (Timing)	Activities Performed	FOG trials included?	Outcome measures	Main findings
Albani et al. (2014)	Observational (biomechanical)	25/ 14 (6) / 11 (7)	69.8 ± 6.3 / 65.3 ± 12.7	Scored ≥2 on item 14 (UPDRS-III), and observation	UPDRS-III >	OFF (≥12 h)	Self-paced walking	No	UPDRS-III motor score; 3-D gait kinematics (joint angles, segment coordination).	PD with FOG group had greater abnormalities in joint coordination and inter-segmental timing than PD without FOG, reflecting progression-related biomechanical deficits.
Bengevoord et al. (2016)	Cross-sectional	30/ 16 (12) / 14 (10)	68.71 ± 7.45 / 66.57 ± 7.37	NFOG-Q item 1	No statistical difference in groups	OFF (12–15 h)	180° walking turns	Yes	Centre of mass trajectory; gait velocity; turn duration and smoothness.	PD with FOG displayed greater COM displacement and irregular trajectories during 180° turns compared with PD without FOG, showing impaired dynamic stability.
Choi et al. (2022)	Cross-sectional	57/ 27 (15) / 30 (15)	68.05 ± 5.21 / 68.06 ± 4.62	NFOG-Q > 3 and ≤ 3, respectively	LEDD > UPDRS total scores > UPDRS-II scores >	OFF (≥12 h)	180° maximum speed turn, modified from TUG	No	Turn velocity, step count, and duration; NFOG-Q severity; UPDRS total/ II scores.	Higher FOG severity correlated with slower, less efficient turns and poorer balance, confirming turning sensitivity to FOG severity.
McNeely and Earhart (2011)	Within-subject comparative (pre–post medication)	20/ 10 (NR) / 10 (NR)	75.3 ± 1.4 / 74.0 ± 2.1	NFOG-Q item 3	LEDD >	OFF (13.1 ± 0.43), and ON	180° walking turns, modified from TUG	No	180° turning time and step count (modified TUG); NFOG-Q item 3.	Turning speed improved with medication but freezing persisted; some participants showed worsened stability, suggesting mixed motor effects.
Mezzarobba et al. (2018)	Cross-sectional	24/ 12 (8) / 12 (7)	70.3 ± 8.9 / 68 ± 12	FOG-Q item 1	No statistical difference in groups	ON	Walk, gait initiation, sit-to-walk, and dual task	No	Postural transition timing; gait initiation; step parameters.	PD with FOG showed delayed weight shift and reduced anticipatory postural adjustments versus PD without FOG, indicating deficits in motor planning.
Myers et al. (2020)	Cross-sectional	44/ 13 (5) / 31 (12)	64.2 ± 6.6 / 67.3 ± 9.2	NFOG-Q item 1	No statistical difference in groups	ON	Forward, backward, and dual task walking	No	Kinematic variables of forward, backward, and	PD with FOG exhibited smaller joint excursions and slower limb

(*continued on next page*)

Table 4 (*continued*)

Authors and year	Study design	Total participants/ PD with FOG (M)/ PD without FOG (M)	Age (years) (mean ± SD)	FOG Classification Method	Disease Differences	ON/OFF Medication (Timing)	Activities Performed	FOG trials included?	Outcome measures	Main findings
									dual-task walking.	velocities, especially under dual-task conditions, suggesting limited adaptive capacity.
Palmisano et al. (2022)	Cross-sectional	47/ 24 (16) / 23 (13)	64.5 ± (NR) / 66 ± (NR)	Clinical history and clinical evaluation	No statistical difference in groups	OFF (≥12 h) and ON (1–1.5 morning dose)	Quiet stance, self-paced walking	No	Trunk flexion/ extension angles; spine range of motion during stance and gait.	PD with FOG had reduced lumbar mobility and greater rigidity, implying axial stiffness contributes to FOG.
Park et al. (2020)	Cross-sectional	24/ 12 (7) / 12 (8)	66.67 ± 4.38 / 68.83 ± 6.00	NFOG-Q > 3	Disease duration > Treatment duration > UPDRS total > UPDRS-III scores > LEDD >	ON (2–3 h before testing)	360° and 540° turning	No	Turning angle (360°, 540°); duration; step number; NFOG-Q score.	More-affected-side turning was slower and required more steps in PD with FOG, revealing asymmetry-related motor control impairment.
Pinto et al. (2020)	Experimental (dual-task condition test)	32/ 32 (23) / N/A	65.13 ± 9.00	FOG-Q	N/A	OFF (4–12 h) and ON	Self-paced walking, dual task	No	Lower-limb joint range of motion across gait cycle; dual-task interference.	Dual-task walking reduced ROM and increased variability in PD with FOG, confirming attentional load exacerbates gait rigidity.
Shida et al. (2023)	Dataset / validation study	22/ 11 (8) / 11 (9)	62.72 ± 12.12 / 65.91 ± 8.82	NFOG-Q item 1	LEDD >	OFF (≥12 h) and ON	Self-paced walking	No	Full-body 3-D kinematics and kinetics; NFOG-Q item 1.	PD with FOG showed reduced step length, cadence, and hip–knee coordination; data provide normative reference for FOG biomechanics.
Son et al. (2018)	Cross-sectional	63/ 28 (18) / 35 (14)	68.6 ± 5.5 / 70.5 ± 5.2	NFOG-Q	MMSE > Symptom duration > Treatment duration > LEDD > H&Y >	OFF (≥12 h)	Forward and backward walking, 360° turning	No	Temporal-spatial gait parameters; FOG frequency; NFOG-Q.	FOG predominantly occurred during backward walking and turning, showing higher instability and slower velocity in PD with FOG.
Son et al. (2022)	Cross-sectional	26/ 10 (7) / 16 (11)	70.24 ± 6.21 / 71.52 ± 6.34	NFOG-Q	No statistical difference in groups	OFF (NR)	Forward and backward walking	No	Turn time, angle, stride length, step count.	Turning elicited more pronounced FOG characteristics than forward/ backward gait, supporting turn testing as a sensitive FOG probe.
Spildooren et al. (2013)	Cross-sectional	27/ 13 (NR) / 14 (NR)	68.1 ± 7.5 /	NFOG-Q item 1	No statistical	OFF (overnight withdrawal)	180° turning	Yes	Head–pelvis coupling; angular	PD with FOG displayed increased

(*continued on next page*)

Table 4 (*continued*)

Authors and year	Study design	Total participants/ PD with FOG (M)/ PD without FOG (M)	Age (years) (mean ± SD)	FOG Classification Method	Disease Differences	ON/OFF Medication (Timing)	Activities Performed	FOG trials included?	Outcome measures	Main findings
			66.7 ± 7.4		difference in groups				velocity; phase coordination index.	head–pelvis coupling and poor inter-segmental decoupling, contributing to freezing during directional change.
Urakami et al. (2021)	Cross-sectional	20/ 11 (6) / 9 (7)	75 (NR) / 75 (NR)	NFOG-Q	No statistical difference in groups	ON	Self-selected walking	No	Forward gait stability indices; stride-to-stride variability; COM acceleration.	PD with FOG showed greater anterior instability and stride variability, indicating persistent feedforward control deficits.
Etoom et al. (2024)	Cross-sectional	26/ 13 (NR) / 13 (NR)	66.92 ± 6.69 / 67.75 ± 4.17	FOG-Q score ≥ 2, and self-report of FOG, video footage of specific elements known to provoke FOG	No statistical difference in groups	ON	Self-selected walking	No	Vertical ground-reaction force parameters during walking.	PD with FOG presented lower peak GRF and asymmetrical loading, reflecting impaired propulsion and postural adjustment.
Los Angeles et al. (2024)	Cross-sectional	26/ 13 (NR) / 13 (NR)	NR	NFOG-Q	NR	OFF (NR) and ON	Self-selected walking	No	UPDRS-III motor score; 3-D gait kinematics (joint angles, segment coordination).	PD with FOG group had greater abnormalities in joint coordination and inter-segmental timing than PD without FOG, reflecting progression-related biomechanical deficits.

Significantly higher in PD with FOG compared to PD without FOG (>); Not reported (NR).
N = sample size; M = male; SD = standard deviation; PD = Parkinson's Disease; FOG = Freezing of Gait; UPDRS-III = Unified Parkinson's Disease Rating Scale part III (motor examination); NFOG-Q = New Freezing of Gait Questionnaire; FOG-Q = Freezing of Gait Questionnaire; LEDD = Levodopa Equivalent Daily Dose; UPDRS Total Score = Unified Parkinson's Disease Rating Scale Total Scores (combination of all sections of the UPDRS assessment); UPDRS-II = Unified Parkinson's Disease Rating Scale part II (motor experiences of daily living); MMSE = Mini-Mental State Evaluation; H&Y = Hoehn and Yahr scale; TUG = Timed Up and Go.

Son et al. (2022) showed a medium effect size (SMD -0.65, CI -1.16 to −0.14) during 360° turning movements, where PD without FOG had increased knee ROM. Moreover, Son et al. (2022) were the only study to investigate these parameters on the LAS, showing small effect sizes during turning (SMD -0.39, CI -0.89 to 0.11).

3.7. Ankle kinematics

Shida et al. (2023) was the only paper to investigate ankle plantar- and dorsi-flexion in specific phases of the gait cycle. PD with FOG presented with larger peak dorsiflexion in the swing phase (SMD 0.99, CI 0.48 to 1.50), and larger peak plantarflexion in loading response (SMD 1.11, CI 0.58 to 1.68). Myers et al. (2020) investigated ankle minimum cycle timing, producing small effects (SMD 0.41, CI -0.24 to 1.06) during forward walking, and negligible effects during dual-task walking (SMD -0.07, CI -0.71 to 0.58). Backward walking produced the largest effect size for ankle minimum cycle timing (SMD 0.89, CI 0.22 to 1.56), suggesting that the ankle minimum angle occurred later in the gait cycle in individuals with FOG (Myers et al., 2020). Furthermore, ankle ROM of the LAS during backward walking was investigated across two separate studies whilst participants were OFF medication (Son et al., 2018; Son et al., 2022). Both studies found larger ROM in individuals without FOG, with large (SMD -1.45, CI -2.33 to −0.57) and medium (SMD -0.67, CI -1.19 to −0.16) effect sizes observed in 2018 and 2022, respectively (see Fig. 4). Moreover, both studies outlined similar results in the MAS during backward walking, with large effect sizes seen (SMD -1.31, CI -2.18 to −0.44 (Son et al., 2018); SMD -0.88, CI -1.40 to −0.36 (Son et al., 2022)).

Choi et al. (2022) investigated ankle kinematics using ROM of the inner step of the more affected limb (IMA) during 180° turning movements. A medium effect size was established, (SMD -0.5, CI -1.02 to 0.03) once again suggesting larger ROM in individuals without FOG.

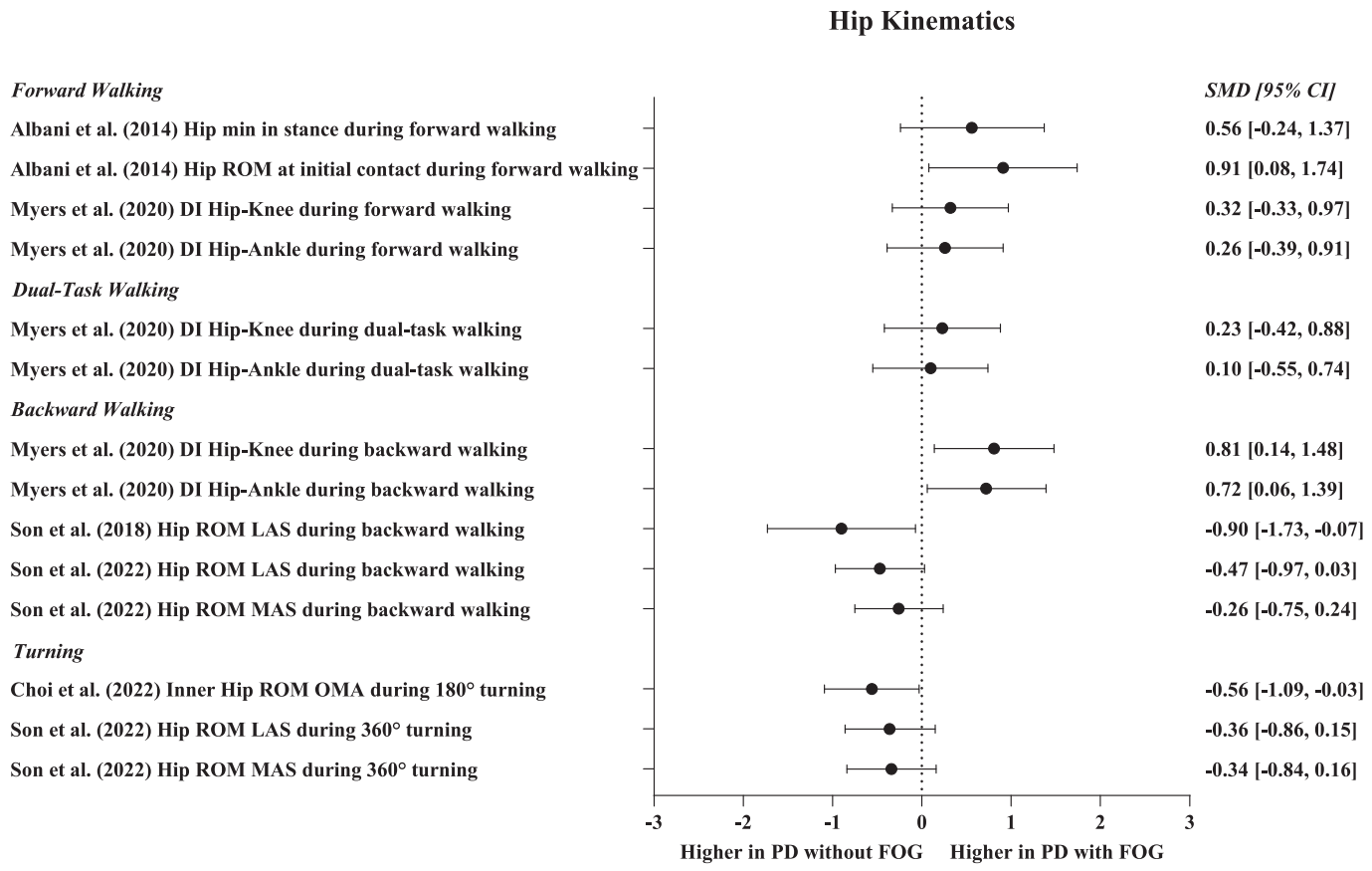

Fig. 2. Standardised mean difference (SMD) in hip kinematics between individuals with PD, with and without FOG. CI = Confidence Interval; min = Minimum; ROM = Range of Motion; DI = Decomposition Index; LAS = Least Affected Side; MAS = Most Affected Side; OMA = Outer Step of the Most Affected Side.

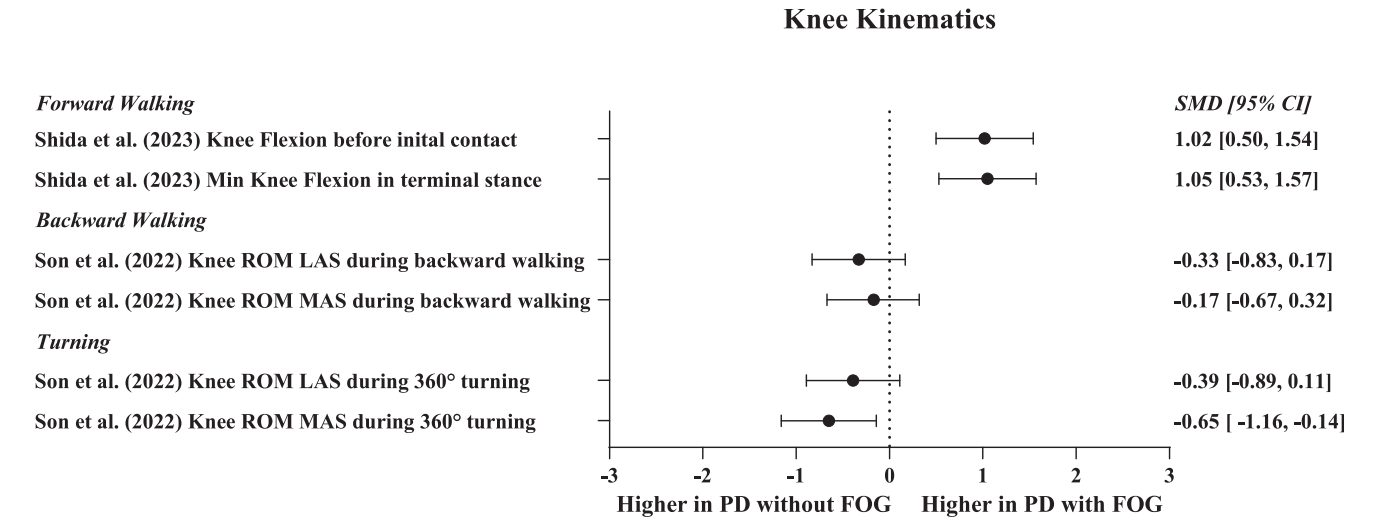

Fig. 3. Standardised mean difference (SMD) in knee kinematics between individuals with PD, with and without FOG. CI = Confidence Interval; Min = Minimum; ROM = Range of Motion; LAS = Least Affected Side; MAS = Most Affected Side.

3.8. Miscellaneous dependent variables

One study investigated mediolateral (ML) wrist amplitude during walking (Los Angeles et al., 2024). They found a large effect size (SMD 0.99, CI 0.48 to 1.50) as PD with FOG produced increased ML movement in the wrist. Another variable investigated during forward walking was toe-clearance height. Son et al. (2022) outlined small (SMD -0.37, CI -0.87 to 0.13) and medium (SMD -0.55, CI -1.06 to −0.05) effect sizes in the MAS and LAS, respectively, suggesting decreased toe-clearance height in individuals with FOG.

Researchers also investigated toe clearance height during backward walking. Son et al. (2022) and Son et al. (2018) outlined small (SMD -0.33, CI -0.83 to 0.17) and large (SMD -0.99, CI 0.48 to 1.50) effect sizes on the MAS in the same direction as observed in forward walking. However, differences were negligible during backward walking on the LAS (SMD -0.14, CI -0.64 to 0.36).

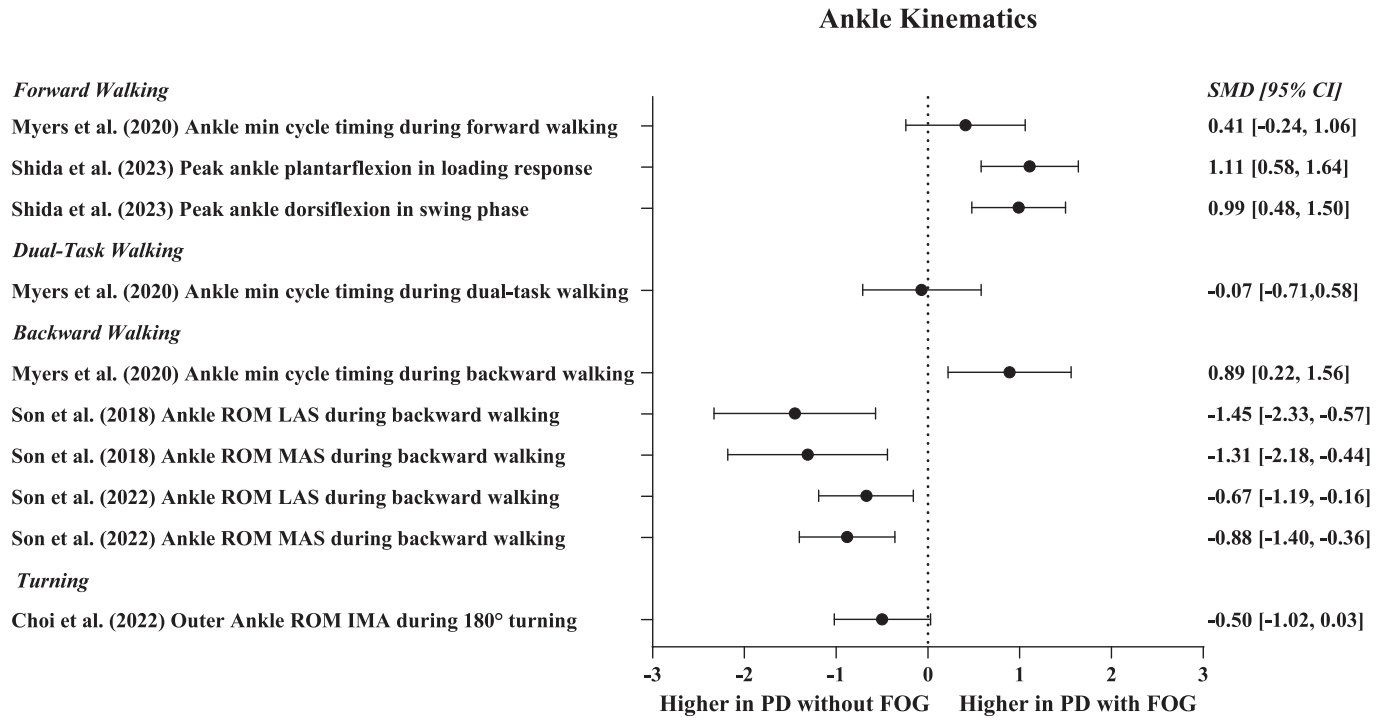

Fig. 4. Standardised mean difference (SMD) in ankle kinematics between individuals with PD, with and without FOG. CI = Confidence Interval; min = Minimum; ROM = Range of Motion; LAS = Least Affected Side; MAS = Most Affected Side; IMA = Inner Step of the Most Affected Limb.

Moreover, toe clearance height produced small effects during turning for the LAS (SMD -0.21, CI -0.71 to 0.29) and MAS (SMD -0.34, CI -0.84 to 0.16) (Son et al., 2022). Son et al. (2022) also investigated maximum anti-phase of the MAS and LAS during 360° turning. A small

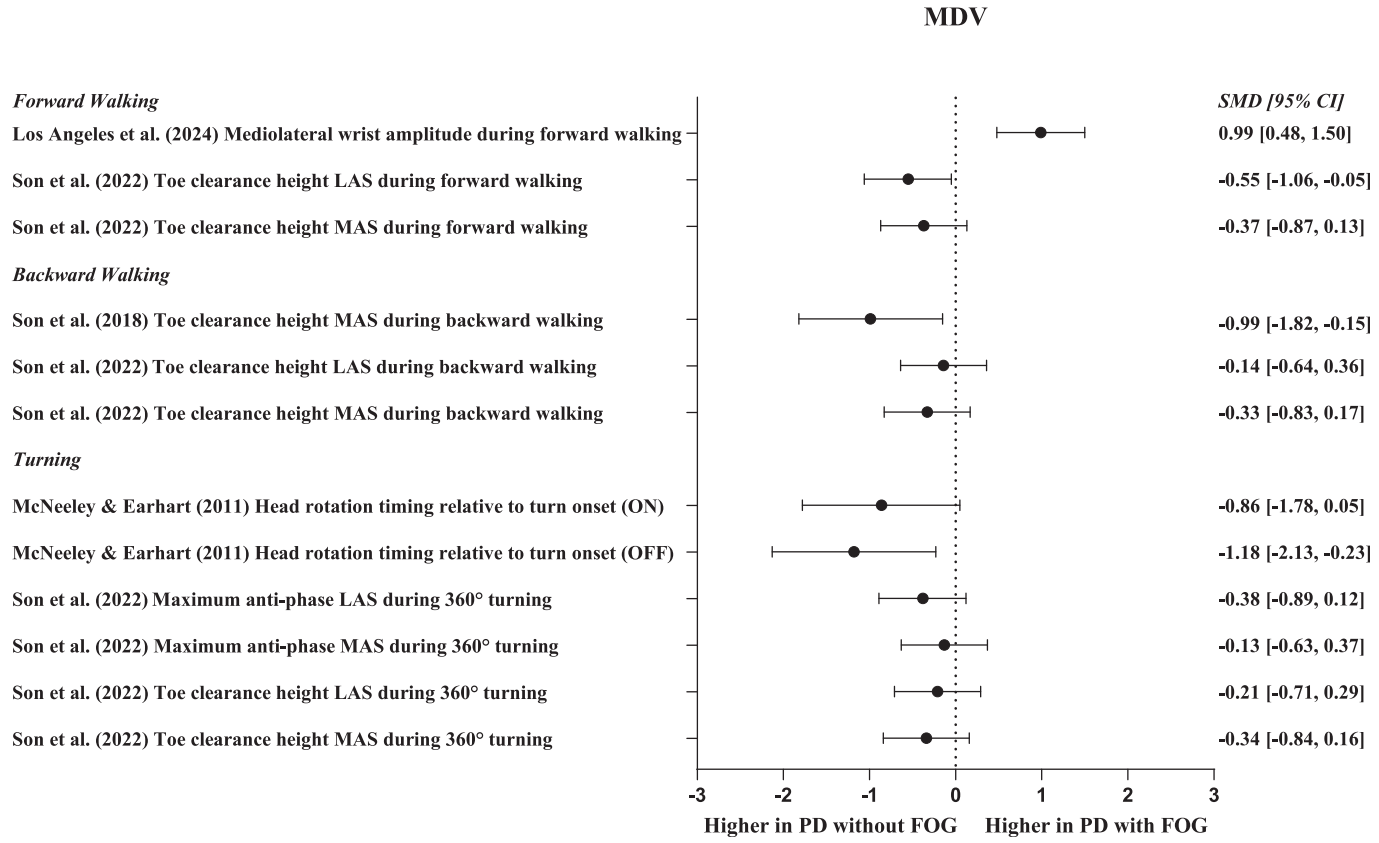

Fig. 5. Standardised mean difference (SMD) in miscellaneous dependent variables (MDV) between individuals with PD, with and without FOG. CI = Confidence Interval; LAS = Least Affected Side; MAS = Most Affected Side; ON = On Medication; OFF = Off Medication.

effect was seen during LAS turning (SMD -0.38, CI -0.89 to 0.12), suggesting PD without FOG have larger maximum anti-phase angle than PD with FOG. Further research was conducted by McNeely and Earhart (2011), investigating turning during ON and OFF medication conditions. They found significant differences in head rotation timing relative to turn onset in both ON (SMD -0.86, CI -1.78 to 0.05) and OFF (SMD -1.18, CI -2.13 to −0.23) conditions, where a longer delay occurred between initiation of head rotation and turn onset in PD with FOG (see Fig. 5).

3.9. Kinetics

Urakami et al. (2021) investigated forward gait instability in individuals with FOG. They found large significant differences between groups when comparing anterior-posterior (AP) COM-BOS (base of support) distance during forward gait (SMD -1.08, CI 2.02 to −0.13), suggesting significantly decreased AP COM-BOS distance in individuals with FOG. Margin of stability (MOS) was also utilised, showing medium differences between groups (SMD -0.70, CI -1.61 to 0.21).

Etoom et al. (2024) was the only paper to investigate vGRF magnitude. They found a large significant difference between groups during mid-stance (SMD 1.19, CI 0.35 to 2.02), suggesting increased vGRF magnitude in individuals with FOG. This difference switches during late stance (SMD -1.40, CI -2.26 to −0.54), suggesting increased vGRF magnitude in individuals without FOG.

Two studies investigated COM distance during turning (Park et al., 2020; Son et al., 2022). Park et al. (2020) investigated the OMA and IMA during both 360° and 540° turning and found a medium effect size for AP root mean square (RMS) COM distance of the IMA during 360° turning (SMD 0.70, CI -0.12 to 1.53). Son et al. (2022) agreed, also finding a medium effect size (SMD 0.57, CI 0.06 to 1.07) in this parameter (see Fig. 6).

Son et al. (2022) also found significant differences in the AP RMS COM distance during LAS turning (SMD 0.28, CI -0.22 to 0.78); however, Park et al. (2020) found no significant differences between groups in this parameter. Both studies found significant differences in ML RMS COM distance during both MAS and LAS turning. A large effect size was seen in Park et al. (2020) during LAS turning (SMD 1.32, CI 0.44 to 2.21) and a medium effect size was observed amongst groups during MAS turning (SMD 0.47, CI -0.34 to 1.28). Further research by Son et al. (2022) showed medium effect sizes in both MAS and LAS turning for ML RMS COM distance (SMD 0.33, CI -0.17 to 0.83).

Furthermore, Park et al. (2020) saw significant differences repeated during 540° turning movements with medium effect sizes seen in MAS turning in both ML COM (SMD 0.70, CI -0.12 to 1.53) and AP COM (SMD 0.76, CI -0.07 to 1.59). A large effect size was established in ML COM during LAS turning (SMD 1.05, CI 0.19 to 1.90).

4. Discussion

This was the first systematic review to examine the biomechanical differences between individuals with PD, with and without FOG, across laboratory-based mobility tasks. Clear kinetic and kinematic alterations were observed, indicating impairments in intersegmental coordination, compensatory joint strategies, and kinetic mechanisms. Reduced coordination during tasks such as backward walking and turning contributed to rigid movement patterns, whilst compensatory increases in hip and knee flexion and reduced joint motion reflected a stability-focused gait strategy. Altered COM displacement and inefficient GRF further demonstrated balance and propulsion deficits. Together, these findings highlight biomechanical mechanisms that contribute to gait instability and fall risk in individuals with FOG and directly address the aim of this review by identifying parameters that differentiate between two groups.

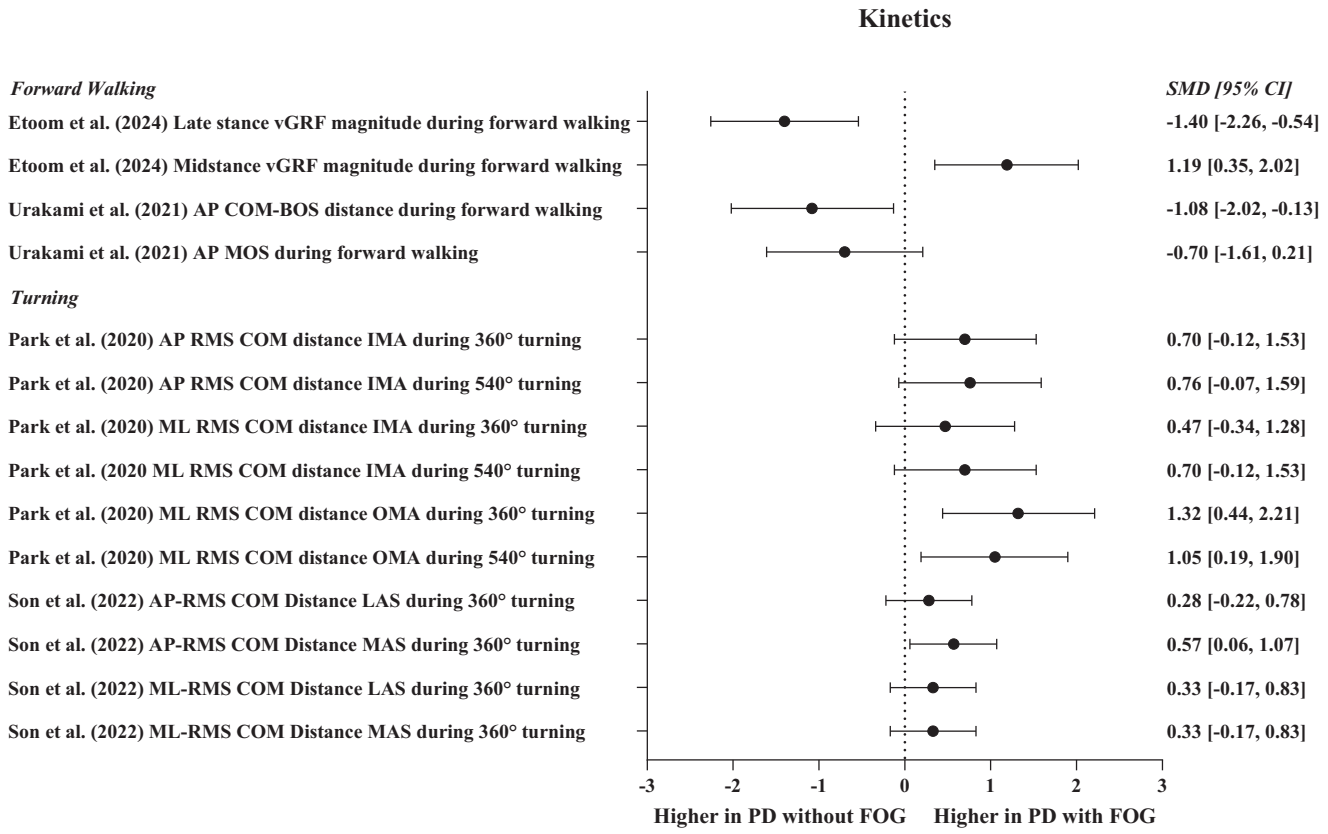

Fig. 6. Standardised mean difference (SMD) in kinetics between individuals with PD, with and without FOG. CI = Confidence Interval; vGRF = Vertical Ground Reaction Force; AP = Anterior-Posterior; COM = Centre of Mass; BOS = Base of Support; MOS = Margin of Stability; RMS = Root Mean Squared; IMA = Inner Step of the Most Affected Side; ML = Mediolateral; OMA = Outer Step of the Most Affected Side; LAS = Least Affected Side; MAS = Most Affected Side.

4.1. Intersegmental coordination

Complex tasks such as backward walking and turning induce reduced intersegmental coordination amongst PD with FOG. McNeely and Earhart (2011) showed a delay in head rotation timing relative to turn onset, reflecting an 'en-bloc' turning sequence, as opposed to the typical 'top-down' strategy, to maintain control over COM and reduce postural instability. Moreover, during turning PD with FOG also produced decreased hip ROM in the MAS (Choi et al., 2022), supporting more rigid turning in individuals with FOG.

Differences in hip kinematics amongst these groups were also seen during forward and backward walking, with individuals with FOG showing greater hip flexion at IC, and reduced hip extension during stance (Albani et al., 2014; Son et al., 2022). Myers et al. (2020) showed increased DI between hip-knee and hip-ankle segments during backward walking amongst those with FOG. These findings highlight a reduction in intersegmental coordination and coupling between joints, more commonly seen during complex tasks such as backward walking and turning which produce high cognitive load. Weaknesses in coordination could be trained using targeted and/or individualised programmes that involve repetition of intersegmental movements.

4.2. Compensatory mechanisms

To improve and maintain stability individuals with FOG apply compensatory mechanisms and adjustments during movement. Increased hip flexion during stance shows a reduced ability of the hip to enter extension in PD with FOG, a pattern also seen in the knee amongst individuals with FOG (Albani et al., 2014; Shida et al., 2023). In addition to this, increased knee flexion before IC may reduce vertical displacement of the COM, thus reducing stride length and limiting forward propulsion, resulting in a characteristic shuffling gait (Shida et al., 2023). Reduced ROM and delayed timing of the minimum joint angle at the ankle joint, seen during backward walking and turning tasks, may be compromising toe-clearance height resulting in the trips and falls commonly observed amongst individuals with FOG, as well as reducing push-off. These findings indicate a stiffness-driven gait strategy that prioritises stability over dynamic efficiency. Despite potentially improving stability, this strategy likely increases energy expenditure and disrupts rhythmic stepping, increasing likelihood of freezing episodes, fatigue, and subsequent fall risk.

4.3. Kinetics (COM and vGRF)

Kinetic parameters such as COM displacement and mechanical inefficiencies were shown amongst individuals with FOG. During turning, altered COM displacement in the ML and AP directions indicates balance difficulties as the individual struggles to maintain the COM within the narrow BOS (Park et al., 2020; Son et al., 2022; Urakami et al., 2021). These deficits reflect axial rigidity and uneven loading patterns that contribute to the rigid, unstable movement patterns seen amongst individuals with FOG. However, these findings were reported during both 360° and 540° turning movements. As such, the ecological validity of these movements should be considered when interpreting and applying these findings.

Moreover, increased vGRF during mid-stance and decreased propulsive forces during late stance amongst individuals with FOG suggests inefficient weight transfer and reduced forward momentum (Etoom et al., 2024). Thereby it shows that the imbalance between stability and propulsion arises from the interaction between biomechanical rigidity and compromised postural control.

4.4. Limitations

This review did not address the use of electromyography, which may provide valuable insight when comparing kinematics and kinetics to underlying muscle activity. This is due to the lack of literature investigating electromyography in PD with FOG. One paper was retrieved (Wang et al., 2014) but was not reported throughout the review as it yielded no significant differences in findings.

Furthermore, this systematic review focused on 3D motion capture systems within a laboratory environment only and did not include research using inertial measurement units and other wearable technologies. These approaches represent an important and rapidly developing area of FOG assessment (Cereatti et al., 2024) and future work should look to incorporate a wider scope of research that utilises these devices.

Small, observational study designs inherently carry a higher risk of bias, have limited control over confounding variables, and greater susceptibility to selection and measurement errors (Guyatt et al., 2008). Although publication bias was assessed using the GRADE assessment, its presence cannot be completely excluded and thus should be considered when interpreting included evidence. Overall, the GRADE assessment resulted in consistently very low-quality evidence, largely attributable to study design and sample size. This contributed to 'serious imprecision', thereby reducing confidence in the estimated effects; an issue well recognised in GRADE when wide CI and low event counts are present (Guyatt et al., 2008).

Statistical synthesis was limited by heterogeneity in study populations, methodologies, and reported outcomes. Research on FOG frequently present with confounding variables such as disease severity, disease duration, medication state, and cognition, as well as differences in ascertainment which may be representative of distinct motor control states. Alongside this, variations in task protocols, gait speed standardisation, and reported outcome measures meant that pooled inference was not supported, although effect sizes provided useful descriptive comparison.

Future research would benefit from greater methodological consistency in FOG ascertainment, reporting of outcome measures, as well as implementing rigorously designed and adequately powered studies. This will strengthen the evidence base and better determine the true effects of these measures.

4.5. Clinical and research implications

The biomechanical parameters within this review suggests the FOG involves more than spatiotemporal gait irregularities. Outlined are breakdowns in coordination and kinetic control that can be objectively quantified through motion analysis. Key biomechanical parameters such as lower-limb joint ROM, knee and hip flexion patterns, COM displacement and vGRF patterns may provide clinical markers for assessing freezing severity and monitoring rehabilitation outcomes. However, the low quality of evidence presented suggests that further research is required before including biomechanical parameters into clinical practice. With more research, we believe that biomechanical assessments could be included within clinical practice to complement traditional rating scales and assessments.

5. Conclusion

This systematic review demonstrates that individuals with FOG display biomechanical abnormalities, particularly during turning and backward walking movements. Findings including increased knee flexion, altered COM displacement, and inefficient mechanical properties can provide objective evidence for impaired coordination and kinetic control that differentiate PD with and without FOG.

The synthesis displays the value of biomechanical analysis to identify movement deficits within individuals with FOG, offering a foundation for developing standardised evaluation methods and individualised rehabilitation strategies that target biomechanical deficits. Future studies should validate these biomechanical markers in clinical settings and explore their responsiveness to therapeutic and pharmacological interventions to improve functionality.

CRediT authorship contribution statement

Lewis Ball: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Fuengfa Khobkhun:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jim Richards:** Writing – review & editing. **Glen Davison:** Writing – review & editing, Conceptualization. **Jake Bowd:** Writing – review & editing, Validation, Methodology, Investigation, Data curation, Conceptualization.

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Declaration of competing interest

The authors declare they have no known competing interests that could have influenced the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.clinbiomech.2026.106853.

Data availability

The data that supports the findings of this study are available in the supplementary material of this article.

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