Φysikotherapia • Issue 28, Volume 2 • April-June 2025 • https://doi.org/10.55742/SATK1721

Φysikotherapia

Associations between Kinetic and Kinematic Parameters and Functional Assessment Methods of Balance and Gait in Parkinson's Disease: A Critical Literature Review

Papakosta E[1], Lampropoulou S.[2]

1. M.Sc. candidate "Therapeutic Exercise", Department of Physiotherapy, School of Health Rehabilitation Sciences, University of Patras
2. Associate Professor, Department of Physiotherapy, School of Health Rehabilitation Sciences, University of Patras

Submitted: 31 March 2025 /
Revised: 22 April 2025 /
Accepted: 25 April 2025

ABSTRACT

Aim: The present study aims to elucidate the degree to which objective modalities of balance and gait assessment, including kinetic and kinematic analyses, correlate with the functional rating scales routinely employed in clinical practice for the evaluation of patients with PD.

Methods: The present study constitutes a narrative critical review of the literature and does not adhere to a formal PRISMA protocol. Electronic searches were conducted in the PubMed, ScienceDirect, and Google Scholar databases using the keywords "Parkinson's disease", "balance", "gait", "motion analysis", "force platform", "Vicon system" and "functional assessments". Articles published between 2015 and 2025 were considered eligible, provided that they focused on high-precision methods, such as kinetic and kinematic evaluations of postural control and gait in patients with PD, as well as studies that examined the quantitative associations of these measures with functional scales (mini-BESTest, BBS, FGA).

Results: A moderate correlation was observed between kinetic and kinematic parameters and the BBS ($r = -0.55$), while kinematic parameters recorded via inertial measurement units (IMU's) also demonstrated moderate correlations with the UPDRS ($r = -0.5$). Furthermore, the FGA demonstrated a strong correlation with gait speed ($r = 0.77$) and a moderate correlation with step length ($r = 0.54 – 0.59$), while an FGA score of ≤ 18 predicted falls within a six-month period (ICC= 0.81).

Conclusions: The integrative application of objective metrics and clinical assessment tools affords a multidimensional and more precise characterization of functional capacity in patients with PD. In early stages (H&Y 1-2), IMU's and force platforms detect subtle deviations, whereas in intermediate and advanced stages, the combined deployment of mini-BESTest/FGA alongside objective measurements is recommended for the timely prevention of falls.

Keywords: Parkinson's disease, gait, balance, functional assessments, motion analysis

Contact Information:
up1075912@ac.upatras.gr, lampropoulou@upatras.gr

INTRODUCTION

Parkinson's disease (PD) is characterized by a variety of motor disturbances, including impairments in balance and gait, which lead to a markedly increased risk of falls (Bao et al., 2023). It is estimated that approximately 60% of individuals with PD will experience at least one fall, an event directly associated with injury, reduced mobility, and a decline in quality of life (Sotirakis et al., 2024). Consequently, accurate and comprehensive assessment of balance and gait patterns is essential both for fall prevention and for monitoring disease progression (Bao et al., 2023).

Assessment of static and dynamic balance in patients with PD is typically conducted through clinical methods and standardized tests. Instruments such as the Berg Balance Scale (BBS), the mini-Balance Evaluation Systems Test (mini-BESTest), the Functional Gait Assessment (FGA), and the Timed Up and Go (TUG) test are widely employed to evaluate static and dynamic balance, as well as gait, in patients with PD. (Winser et al., 2019). Although these scales have been established as reliable and valid measures in PD (Bao et al., 2023), the subjective nature of examiner observation and their confinement to controlled laboratory or clinical settings undermine their external validity (Atrsaei et al., 2021). For instance, gait speed during daily activities has been shown to be up to 30% lower than speeds measured in a clinical assessment (Atrsaei et al., 2021). Moreover, functional scales often feature a limited scoring range (e.g. 0-4 or 0-56 points), resulting in ceiling and floor effects. For example, many patients in the early stages of PD obtain the maximum score on the BBS, thereby concealing subtle balance deficits (King et al., 2012). Likewise, 89% of patients with mild symptomatology are rated 0-1 (no/slight impairment) in the gait item of the Movement Disorder Society – Unified Parkinson's Disease Rating Scale (MDS-UPDRS), a scale internationally used for assessing disease severity and progression. Nevertheless, measurable gait deviations are recorded which the scale fails to detect (Hill et al., 2021).

With advances in technology, high-precision laboratory methods have been developed for the assessment of balance and gait, such as force platforms for analyzing Center of Pressure (CoP) displacements and wearable inertial measurement units (IMUs) for kinematic gait analysis (Horak et al., 2013). These techniques offer high – resolution quantitative measurements (e.g. centimeter – level accuracy) (Merlo et al., 2025). Studies have demonstrated that quantitative biomechanical parameters can detect balance impairments in the early stages of PD, before they become clinically apparent (Atrsaei et al., 2021; Bao et al., 2023). Specifically, pathological alterations in CoP variability during quiet standing have been documented in early PD, even prior to the emergence of overt symptoms (Taghizadeh et al., 2018). In contrast, conventional clinical tests typically only reveal deficits once they have progressed to a level that visibly impacts functional performance (Wodarski et al., 2023).

The correlation between these sensitive and high-precision assessment methods and functional recording data represents a major scientific concern. By examining this relationship, we can determine the extent to which clinical methods capture (or omit) critical aspects of balance and gait (Wodarski et al., 2023). At the same time, such analysis highlights the shortcomings of clinical tools with respect to the completeness and precision of the information they provide (Merlo et al., 2025). The present review evaluated the latest empirical findings that explore these dimensions in patients with PD.

The aim of the present study was to examine the extent to which objective and high-precision assessment methods for balance and gait, such as kinetic and kinematic analyses and data from specialized recording systems correlate with the functional scales employed in the evaluation of patients with PD. This work seeks to critically delineate the strengths and limitations of clinical instruments in terms of their accuracy and comprehensiveness in capturing the corresponding measurable parameters.

METHODS

The present study adopts a narrative critical literature-review approach, without formal application of a PRISMA protocol, and involves a targeted search of the PubMed, ScienceDirect and Google Scholar databases. English-language keywords («Parkinson disease», «balance», «gait», «motion analysis», «force platform», «Vicon system», «functional assessments»), were used to identify relevant publications from 2015 through 2025. Included articles investigated objective methods for assessing balance and gait in patients with PD, such as three – dimensional kinematic analysis (e.g. Vicon system), indirect force measurement systems (e.g. force platforms), or wearable inertial measurements units (IMUs), as well as studies that investigated the quantitative associations of these objective, high-precision measurements with established functional scales (e.g. mini-BESTest, BBS, FGA). All sources were drawn from peer-reviewed, English-language journals to ensure scientific rigor. Although a full systematic review was not conducted, a careful selection of representative studies spanning the main technological categories and featuring quantitative comparative analyses was performed to guarantee the validity and relevance of the literature synthesis.

RESULTS

High-precision and objective balance assessment versus clinical tests

Patients with Parkinson's disease (PD) frequently exhibit balance impairments, which are clinically evaluated using instruments such as the Berg Balance Scale (BBS), the single-leg stance test, the mini Balance Evaluation Systems Test (mini-BESTest) and the MDS-UPDRS Pull Test (Liu et al., 2020). By contrast, objective and high-precision assessment employs force platforms, which record Center of Pressure (CoP) excursions and ground reaction forces (GRF), and inertial measurement units (IMUs) that capture three-axis accelerations and angular velocities, thereby enabling precise quantification of both static sway and gait kinematics (King et al., 2012; Álvarez et al., 2020). Recent evidence demonstrates that while correlations between selected parameters from these objective and clinical methods are statistically significant, they tend to be moderate in strength (Bao et al., 2023; King et al., 2012; Picardi et al., 2020).

Specifically, the study by Bao et al. (2023), involving 46 patients with mild-moderate PD (H&Y 1-2), compared Berg Balance Scale (BBS) scores with stabilometric CoP indices during quiet standing under eyes - open and eyes - closed conditions on a force platform. The 95% prediction ellipse area of the CoP was negatively correlated with BBS ($r = -0.55$, $p = 0.001$), while the high – frequency slope of the sway power spectrum, reflecting rapid corrective adjustments, showed a moderate positive correlation with BBS ($r \approx 0.48$, $p = 0.001$). Structural metrics, such as the intersection point in the sway scatterplot, also exhibited moderate positive correlations ($r \approx 0.40$–$0,50$, $p \leq 0.01$).These findings indicate that the BBS explains only about 25% of the total variance in laboratory-derived measures, with clear clinical implications: although the functional scale broadly reflects balance ability, it fails to detect subclinical instabilities revealed by objective metrics, potentially delaying intervention and increasing fall risk. Similar results were reported by Liu et al. (2023), who found $r \approx 0.55$ between CoP ellipse area and BBS, while experimental interventions demonstrated that a reduction in sway corresponded to a clinically meaningful improvement of + 2.3 points on the Mini Balance Evaluation Systems Test (mini-BESTest) (Giardini et al., 2018). Additionally, regarding balance parameters, the study by Hasegawa et al. (2019), reported moderate correlations between the mini-BESTtest and stabilometric indices of CoP sway, with values ranging from $r= 0.5$ to $r = 0.58$. Furthermore, the "Sensory Orientation" subscale of the mini-BESTest demonstrated a moderate association with sway variability during quiet standing ($r = 0.45$), whereas the "Reactive Postural Control" subscale exhibited moderate correlations with parameters derived from the "Push and Release test" which evaluates automatic postural responses ($r = 0.4$-0.55). These findings highlight that, although the mini-BESTest represents a reliable and widely utilized clinical tool for balance assessment, its associations with biomechanical parameters remain moderate. This underscores the value of integrating laboratory-based measurements, which may provide complementary insigths and enrich the clinical evaluation of postural control in PD. Nevertheless, despite the exceptional precision of force platform for recording CoP and GRFs, their use is severely limited by high cost and space requirements, specialized laboratory facilities and trained personnel for calibration and operation are mandatory. Additionally, their limited portability confines measurements to brief trials (10-40 seconds) and precludes assessment in real – world settings (Merlo et al., 2025).

Accordingly, the findings indicate that in the early stages of PD (H&Y 1-2), where functional scales rapidly exhibit ceiling effects, CoP indices obtained through force platforms (Bao et al., 2023; Taghizadeh et al., 2018) capture subtle balance deviations. In intermediate stages (H&Y 2-3), the mini-BESTest, in conjunction with stabilometric indices of CoP displacement, demonstrates moderate yet clinically meaningful associations (Hasegawa et al., 2019). In advance stages (H&Y 3-4), increased postural instability is substantiated by CoP parameters that are directly linked to a heightened risk of falls (Kamieniarz et al., 2018).

High-precision and objective gait assessment versus clinical tests

Gait in PD is characterized by bradykinesia, manifesting as reduced walking speed, shorter step length, prolonged double-support time, and difficulty with gait initiation/termination and dual-task performance (Zhang et al., 2024). In routine clinical practice, gait is quantitatively assessed primarily via timed speed tests (e.g. the 10-Meter Walk Test) and functional gait scales (e.g. the Tinetti gait score), which nonetheless fail to yield detailed quantitative indices of the kinematic and postural control impairments that objective assessment methods can reveal. (De Pasquale et al., 2025).

Specifically, a central question is whether objective gait measurements reflect overall motor severity in PD as captured by the UPDRS and the Hoehn & Yahr stage. In the study by Curtze et al. (2016), 104 patients with mild-to-moderate functional impairment (stage 2-4), as classified by the H&Y, were evaluated on 34 gait and balance parameters using IMUs, and correlations were examined: (a) with subjective motor function (PDQ-39 Mobility, ABC scale) and (b) with clinical severity (UPDRS, Hoehn & Yahr). In the off-medication state, gait speed, turning angular velocity, and stride length exhibited the strongest correlations with UPDRS ($r \approx 0.5$) and with perceived difficulty ($r \approx 0.4–0.5$), whereas CoP variability showed a weaker association. By contrast, in the on-medication state these correlations were attenuated, highlighting the importance of the off-medication assessment to reveal "hidden" deficits. Moreover, Carlson-Kuhta et al. (2019) confirmed an inverse relationship ($r \approx -0.51$) (Beck et al., 2018) between turning angular velocity and stride length with UPDRS scores, while the SPARC index (Beck et al., 2018) offers a quantitative estimate of gait smoothness that corresponds to disease severity.

Several studies have implemented IMUs during Timed Up and Go (TUG) test, placing a sensor at the lumbosacral junction to capture metrics such as sit-to-stand velocity, acceleration at gait initiation, peak turning angular velocity, and double-support time, thereby enhancing the TUG's sensitivity to motor disturbances in PD (Zhang et al., 2024; Di Lazzaro et al.,2020; Bernad-Elazari et al.,2016). Furthermore, Wang et al. (2024) deployed ten body-worn sensors throughout the TUG to differentiate PD subtypes (tremor-dominant versus bradykinetic/instability-dominant) and to explore their relationship with clinical severity (UPDRS). They demonstrated that composite digital markers, such as peak turning angular velocity, can reliably distinguish the instability-dominant subtype from healthy controls at an early stage, while trunk-related measures, such as maximum sit-to-stand velocity, show an inverse correlation with disease severity. These findings underscore the capacity of wearable sensor technology to reveal subclinical gait alterations that conventional clinical tools fail to detect. Moreover, in the study by Hasegawa et al. (2019), which included patients with PD following at least 12 hours of medication withdrawal, measurements obtained via IMUs placed at multiple anatomical sites revealed moderate to strong correlations between the "Dynamic Gait" subscale of the mini-BESTest and kinematic gait parameters. Specifically, strong positive associations were observed with gait speed ($r = 0.77$) and stride length ($r = 0.61$), along with a moderate negative correlation with double support time ($r = -0.55$), indicating that the scale captures essential kinematic aspects of gait. Nevertheless, the overall findings underscore the complementary value of IMUs in detecting subclinical alterations in gait that remain undetected through conventional assessment tools.

However, although IMUs permit monitoring in natural environments through repeated or continuous measurements, they have certain limitations: (a) integrated accelerations accumulate, leading to positional drift unless regular re-calibration is performed, (b) incorrect sensor placement or tilt on the body substantially alters the recorded data, (c) algorithms designed to distinguish phenomena such as freezing of gait (FOG) require training on a broad patient cohort, otherwise yielding increased false positive and false negative rates and (d) while more affordable than laboratory systems, some of the most reliable IMU models are not universally available in all clinical settings (Prisco et al., 2024).

Additionally, in PD the Functional Gait Assessment (FGA) score has been shown to correlate closely with objective gait parameters measured via three-dimensional motion capture systems, the "gold standard" for kinematic gait analysis (albeit with limitations similar to those of force platforms) (Ehrhardt et al., 2020). Specifically, there is a strong positive correlation between gait speed and FGA score ($r \approx 0.77$), as well as moderate positive correlations with step length and cadence ($r \approx 0.54$–0.59) (Eldeeb & Abdelraheem, 2021). Conversely, temporal parameters, such as step duration and double-support time, are significantly and negatively correlated with FGA ($r \approx -0.59$ έως -0.65, $p < 0.01$), indicating that lower FGA scores are associated with slower, more prolonged gait patterns (Álvarez et al., 2020). Meanwhile, certain spatial parameters, such as step width, do not show a significant relationship with FGA scores (Pistacchi et al., 2017). The diagnostic utility of the FGA is further underscored by its ability to predict falls: and FGA score of ≤18 predicted the occurrence of falls within six months with 81% sensitivity and 80% specificity (Marques et al., 2021). Collectively, these results validate the FGA as a functional gait assessment tool in PD, mirroring indices of motor severity and fall risk.

Accordingly, the findings suggest that in the early stages of PD (H&Y 1-2), IMUs and 3D motion capture systems can detect subclinical gait alterations that are not readily captured by functional assessment scales (Zhang et al., 2024; McGuirk et al., 2022). In intermediate stages (H&Y 2-3), the use of IMUs during the execution of the TUG highlights moderate-to-strong associations with subscales of the mini-BESTest (Hasegawa et al., 2019; Curtze et al., 2016). In advanced stages (H&Y 3-4), the FGA (Marques et al., 2021), together with data derived from plantar pressure systems and force platforms (Merlo et al. 2025), is closely linked to the increased risk of falls, thereby constituting valuable tools for prognosis and rehabilitation.

DISCUSSION

The present review demonstrates that contrasting objective and clinical methods for assessing balance and gait in patients with Parkinson's disease (PD) reveals distinct strengths and limitations in both approaches.

Many conventional balance assessment scales (e.g. the BBS and the Tinetti scale) were originally developed for older adults at risk of falls and exhibit ceiling effects in early Parkinson's stages (H&Y 1–2) (Krzysztoń et al., 2018) and floor effects in advanced stages (H&Y 4–5) (Schlenstedt et al., 2016), thereby limiting their ability to detect deterioration or improvement beyond certain thresholds (Park et al., 2018). Moreover, their cumulative scoring does not distinguish discrete functional components (dynamic stability, reactive balance, foot-placement accuracy) and is influenced by the examiner's subjective judgment as well as by patient cooperation, fatigue, or stress at the time of testing (e.g. off-medication versus on-medication state) (Bao et al., 2023). In contrast, objective methods such as stabilography (kinetic recordings of center of pressure displacements) and three-dimensional motion capture systems deliver continuous or repeated high-resolution measurements (millimeters, degrees, milliseconds), capturing both the direction of sway (anteroposterior versus mediolateral) and the frequency spectrum of postural oscillations (high-frequency reflexive corrections versus low-frequency exploratory adjustments), detecting infrequent events (e.g. FOG), and enabling targeted intervention planning (De Pasquale et al., 2025). Among functional clinical tools, the mini-BESTest stands out for assessing a broader range of balance domains, exhibiting reduced ceiling/floor effects and greater sensitivity to clinical change (Krzysztoń et al., 2018). Likewise, the FGA has proven valuable for early fall prediction in PD, with scores ≤ 18 forecasting falls within six months with high sensitivity and specificity (Marques et al., 2021).

Therefore, depending on the severity of motor impairment, it appears that:

(a) In early stages (H&Y 1-2), where functional scales rapidly exhibit ceiling effects, the use of IMUs or three-dimensional motion capture systems enables the detection of subtle gait and balance deviations (Zhang et al., 2024; McGuirk et al., 2022).

(b) In intermediate stages (H&Y 2-3), the mini-BESTest combined with IMUs during the TUG offers a more comprehensive assessment framework, identifying deficits that the functional scale alone might not capture (Curtze et al., 2016; Mancini et al., 2025).

(c) In advanced stages (H&Y 3-4), where fall risk is high, force platforms and pedobarographic systems provide precise fall-risk assessment and facilitate the design of specialized rehabilitation programs (Kamieniarz et al., 2018).

Limitations and future directions

Cost and availability: Many clinical settings, particularly those outside major academic centers, lack the resources to implement large laboratory systems. Further investigation into the cost-effectiveness of IMU devices relative to improvements in fall-prediction accuracy is needed (Mancini et al., 2025; Prisco et al., 2024).

Protocol standardization: The absence of universally accepted protocols (e.g. number and placement of sensors, standardized walking speeds) impedes the comparability of gait data across different cohorts and research centers (Merlo et al., 2025). Development of international guidelines for the collection and analysis of IMU-derived gait metrics is therefore essential.

Large-scale, long-term studies: Most existing investigations involve small cohorts (< 50 patients) and relatively brief follow-up periods (6-12 months). To validate digital gait and balance markers as prognostic indicators of disease progression, prospective studies with larger samples and surveillance exceeding two years are warranted (Curtze et al., 2016; Mancini et al., 2025).

Patient acceptance and adherence: Deploying wearable sensors in everyday settings necessitates comprehensive patient training and ongoing evaluation of device comfort. Without sufficient user compliance, the quality and reliability of the collected data may be compromised (Prisco et al., 2024).

CONCLUSIONS

The incorporation of objective indicators into the assessment process, alongside traditional clinical methods, provides a more comprehensive and precise depiction of functional status in patients with PD. The principal challenge is to maintain an optimal balance between cost, accessibility, and measurement accuracy, with an emphasis on developing standardized protocols that yield comparable and clinically actionable outcomes.

Declarations

Funding: This work received no funding.

Conflicts of interest: The authors declare that they have no conflicts of interest.

Ethical approval: Not required for this review of published literature.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process: The authors declare that no generative Artificial Intelligence software (such as large language models, text-generation applications, etc.) was used in the drafting, structuring or data analysis processes of this work.

REFERENCES

1. Álvarez I, Latorre J, Aguilar M, Pastor P, Llorens R. (2020) Validity and sensitivity of instrumented postural and gait assessment using low-cost devices in Parkinson's disease. *J Neuroeng Rehabil*., 11;17 (1):149. doi: 10.1186/s12984-020-00770-7.
2. Atrsaei, A., Corrà, M.F., Dadashi, F. (2021) Gait speed in clinical and daily living assessments in Parkinson's disease patients: performance versus capacity. *npj Parkinsons Dis.,* 7;(24) https://doi.org/10.1038/s41531-021-00171-0.
3. Bao W, Tan Y, Yang Y, Chen K, Liu J. (2023) Correlation of balance posturographic parameters during quiet standing with the berg balance scale in patients with parkinson's disease. *BMC Neurol*., 6;23(1):362. doi: 10.1186/s12883-023-03386-1.
4. Bernad-Elazari H, Herman T, Mirelman A, Gazit E, Giladi N, Hausdorff JM. (2016) Objective characterization of daily living transitions in patients with Parkinson's disease using a single body-fixed sensor. *J Neurol*., 263(8):1544-51. doi: 10.1007/s00415-016-8164-6.
5. Curtze C, Nutt JG, Carlson-Kuhta P, Mancini M, Horak FB. (2016) Objective Gait and Balance Impairments Relate to Balance Confidence and Perceived Mobility in People With Parkinson Disease. *Phys Ther*.;96(11): 1734-1743. doi: 10.2522/ptj.20150662.
6. De Pasquale, P., Bonanno, M., De Marchis, C., et al. (2025). Beyond clinical scales: an observational study on instrumental gait analysis and biomechanical patterns in patients with Parkinson's disease. *Frontiers in Bioengineering and Biotechnology*, 13, 1541240.
7. Di Lazzaro G, Ricci M, Al-Wardat M, Schirinzi T, Scalise S, Giannini F, Mercuri NB, Saggio G, Pisani A. (2020) Technology-Based Objective Measures Detect Subclinical Axial Signs in Untreated, de novo Parkinson's Disease. *J Parkinsons Dis*., 10(1):113-122. doi: 10.3233/ JPD-191758.
8. Ehrhardt A, Hostettler P, Widmer L, Reuter K, Petersen JA, Straumann D, Filli L. (2020) Fall-related functional impairments in patients with neurological gait disorder. *Sci Rep*., 3;10(1):21120. doi: 10.1038/s41598- 020-77973-4.
9. Eldeeb, H.M., Abdelraheem, H.S. (2021) Functional gait assessment in early and advanced Parkinson's disease. *Egypt J Neurol Psychiatry Neurosurg*., 57, 145. https://doi.org/10.1186/s41983-021-00399-w.
10. Hasegawa N, Shah VV, Carlson-Kuhta P, Nutt JG, Horak FB, Mancini M. (2019) How to Select Balance Measures Sensitive to Parkinson's Disease from Body-Worn Inertial Sensors-Separating the Trees from the Forest. *Sensors*., 28;19(15):3320. doi: 10.339 0/s19153320.
11. Hill EJ, Mangleburg CG, Alfradique-Dunham I, Ripperger B, Stillwell A, Saade H, Rao S, Fagbongbe O, von Coelln R, Tarakad A, Hunter C, Dawe RJ, Jankovic J, Shulman LM, Buchman AS, Shulman JM. (2021) Quantitative mobility measures complement the MDS-UPDRS for characterization of Parkinson's disease heterogeneity. *Parkinsonism Relat Disord*., 84:105-111. doi: 10.1016/j.parkreldis. 2021. 02.006.
12. Horak FB, Mancini M. (2013) Objective biomarkers of balance and gait for Parkinson's disease using body-worn sensors. *Mov Disord*., 15;28(11):1544-51. doi: 10.1002/mds.25684.
13. Kamieniarz A, Michalska J, Brachman A, Pawłowski M, Słomka KJ, Juras G. (2018) A posturographic procedure assessing balance disorders in Parkinson's disease: a systematic review. *Clin Interv Aging*. 12;13:2301-2316. doi: 10.2147/CIA.S180894.
14. King LA, Priest KC, Salarian A, Pierce D, Horak FB. (2012) Comparing the Mini-BESTest with the Berg Balance Scale to Evaluate Balance Disorders in Parkinson's Disease. *Parkinsons Dis*., 2012:375419. doi: 10.1155/2012/375419.
15. Krzysztoń K, Stolarski J, Kochanowski J. (2018) Evaluation of Balance Disorders in Parkinson's Disease Using Simple Diagnostic Tests-Not So Simple to Choose. *FrontNeurol.*, 31;9:932. doi: 10.3389 /fneur. 2018.00932.
16. Marques LBF, Moreira BS, Ocarino JM, Sampaio RF, Bastone AC, Kirkwood RN. (2021) Construct and criterion validity of the functional gait assessment-Brazil in community-dwelling older adults. *Braz J Phys Ther*., 25(2):186-193. doi: 10.1016/j.bjpt. 2020.05.008.
17. Mancini, M., Afshari, M., Almeida, Q., Amundsen-Huffmaster, S., Balfany, K., Camicioli, R., Corcos, D. M. (2025). Digital gait biomarkers in Parkinson's disease: Susceptibility/risk, progression, response to exercise, and prognosis. *npj Parkinson's Disease, 11*(1), 51. https://doi.org/10.1038/ °s41531-025-00897-1.
18. McGuirk, T. E., Perry, E. S., Sihanath, W. B., Riazati, S., & Patten, C. (2022). Feasibility of markerless motion capture for three-dimensional gait assessment in community settings. *Frontiers in Human Neuroscience, 16*,867485. https://doi.org/10.3389/fnhum. 2022. 867485
19. Merlo A, Cavazzuti L, Bò MC, Cavallieri F, Bassi MC, Damiano B, Scaltriti S, Fioravanti V, Di Rauso G, Portaro G, Valzania F, Lusuardi M, Campanini I. (2025) Instrumental balance assessment in Parkin-

son's disease and parkinsonism. A systematic review with critical appraisal of clinical applications and quality of reporting. *Front Neurol*., 29;16:1528191. doi: 10.3389/fneur.2025. 1528191.

20. Park J, Koh SB, Kim HJ, Oh E, Kim JS, Yun JY, Kwon DY, Kim Y, Kim JS, Kwon KY, Park JH, Youn J, Jang W. (2018) Validity and Reliability Study of the Korean Tinetti Mobility Test for Parkinson's Disease. *J Mov Disord*., 11(1):24-29. doi: 10.14802/jmd.17058.
21. Pistacchi M, Gioulis M, Sanson F, De Giovannini E, Filippi G, Rossetto F, Zambito Marsala S. (2017) Gait analysis and clinical correlations in early Parkinson's disease. *Funct Neurol*., 32(1):28-34. doi: 10.11138/fneur/ 2017.32.1.028.
22. Prisco, G., Pirozzi, M. A., Santone, A., Esposito, F., Cesarelli, M., Amato, F., & Donisi, L. (2024). Validity of wearable inertial sensors for gait analysis: A systematic review. *Diagnostics (Basel), 15*(1), 36. https://doi.org/ 10.3390/diagnostics15010036
23. Schlenstedt C, Brombacher S, Hartwigsen G, Weisser B, Möller B, Deuschl G. (2016) Comparison of the Fullerton Advanced Balance Scale, Mini-BESTest, and Berg Balance Scale to Predict Falls in Parkinson Disease. *Phys Ther*., 96(4):494-501. doi: 10.2522 /ptj.20150249.
24. Sotirakis C, Brzezicki MA, Patel S, Conway N, FitzGerald JJ, Antoniades CA. (2024) Predicting future fallers in Parkinson's disease using kinematic data over a period of 5 years. *NPJ Digit Med*., 5;7(1):345. doi: 10.1038/s41746-024-01311-5.
25. Taghizadeh G, Martinez-Martin P, Fereshtehnejad SM, Habibi SA, Nikbakht N, Alizadeh NH, Salehi S, Mehdizadeh M. (2018) Psychometric properties of the Berg balance scale in idiopathic Parkinson' disease in the drug off-phase. *Neurol Sci*., 39(12):2175-2181. doi: 10.1007/s10072-018-3570-4.
26. Wang, H., Xu, Y., Chen, Z., & Pan, J. (2024). Instrumented Timed Up and Go with ten body worn sensors for motor-subtype differentiation in Parkinson's disease. *Journal of NeuroEngineering and Rehabilitation, 21*(1), 45. https://doi.org/10.1186/s12984-024-01023-7.
27. Winser SJ, Kannan P, Bello UM, Whitney SL. (2019) Measures of balance and falls risk prediction in people with Parkinson's disease: a systematic review of psychometric properties. *Clin Rehabil*., 33(12):1949-1962. doi: 10.1177/0269215519877498.
28. Wodarski P, Jurkojć J, Michalska J, Kamieniarz A, Juras G, Gzik M. (2023) Balance assessment in selected stages of Parkinson's disease using trend change analysis. *J Neuroeng Rehabil*., 2;20(1):99. doi: 10.1186/s12984-023-01229-1.
29. Zhang, W., Ling, Y., Chen, Z. (2024) Wearable sensor-based quantitative gait analysis in Parkinson's disease patients with different motor subtypes. *npj Digit. Med.*, 7,169 https://doi.org/10.1038/s41746-024-01163-z.