

## Wearable inertial sensors for clinical gait analysis in Parkinson's disease: A test-retest reliability study

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### ARTICLE INFO

#### Article history:

Received 12 February 2025

Accepted as revised 26 August 2025

Available online 29 August 2025

#### Keywords:

Gait analysis, inertial measurement units, Parkinson disease, reproducibility of results, spatiotemporal analysis.

### ABSTRACT

**Background:** Parkinson's disease (PD) is a neurodegenerative disorder that significantly affects gait parameters. Accurate and reliable gait assessment tools are essential for monitoring disease progression and treatment efficacy. The G-Walk®, a wearable inertial measurement device, offers a convenient and portable solution for evaluating spatiotemporal gait parameters, but its reliability in individuals with moderate-stage PD remains underexplored.

**Objectives:** This study aimed to evaluate the test-retest reliability of the G-Walk® sensor system in assessing gait parameters in individuals with moderate-stage PD.

**Materials and methods:** Thirteen participants with idiopathic PD completed two walking trials on a 14-meter pathway, conducted 3 to 7 days apart. Gait parameters, including stride length, cadence, gait velocity, and limb support times, were recorded using the G-Walk® system. Intraclass correlation coefficients (ICCs), standard error of measurement (SEM), and minimal detectable change (MDC) were calculated.

**Results:** The G-Walk® system demonstrated excellent reliability for stride length (ICC=0.979), cadence (ICC=0.958), and gait velocity (ICC=0.997). Moderate reliability was observed for single limb support (ICC=0.699) and double limb support times (ICC=0.656). SEM and MDC values further supported the precision of the system for clinical applications.

**Conclusion:** The G-Walk® sensor system is a reliable tool for assessing gait parameters in individuals with moderate-stage PD, particularly for stride length, cadence, and gait velocity. Its portability and ease of use make it suitable for clinical settings to track disease progression and evaluate interventions.

### Introduction

Parkinson's disease (PD) is a progressive neurodegenerative disorder primarily affecting individuals over the age of 60, with a prevalence estimated at 2%-3% in this population.<sup>1</sup> The increasing prevalence with age is attributed to cumulative exposure to neurodegenerative factors, reduced neuronal resilience, and aging-related biological changes that exacerbate dopaminergic neuron vulnerability.<sup>2</sup> The disorder is characterized by the degeneration of dopaminergic neurons and  $\alpha$ -synuclein aggregation in the substantia nigra pars compacta within the basal ganglia, leading to dopamine deficiency.<sup>1</sup> This neurotransmitter plays a critical role in motor control, and its depletion results in hallmark motor symptoms such as bradykinesia, resting tremor, rigidity, and postural instability.<sup>3</sup> Among these symptoms, gait disturbances are

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doi: 10.12982/JAMS.2025.107

E-ISSN: 2539-6056

particularly significant, profoundly impacting the quality of life in individuals with PD.<sup>4</sup>

Gait abnormalities in individuals with PD typically manifest as reduced stride length, increased cadence, decreased gait velocity, reduced single limb support time, and increased double limb support time.<sup>5</sup> These spatiotemporal gait deficits contribute to a heightened risk of falls and injuries due to impaired balance and reduced stability during walking.<sup>6</sup> They also lead to reduced physical activity levels as individuals may avoid movement to minimize the risk of falling, which in turn exacerbates deconditioning and mobility limitations.<sup>7</sup> Additionally, the cumulative impact of these deficits diminishes the quality of life,<sup>4</sup> as individuals face increasing challenges in performing daily activities and maintaining social engagement. Moreover, these impairments are associated with increased morbidity, mortality, and economic burdens due to higher healthcare costs and social dependencies.<sup>8</sup> Consequently, the ability to accurately assess and monitor gait disturbances is crucial for managing the progression of PD and evaluating the efficacy of therapeutic interventions.

The G-Walk® sensor system, a wearable inertial measurement unit, has emerged as a promising tool for gait analysis. Unlike traditional optoelectronic systems that require extensive setups, fixed laboratory conditions,<sup>9</sup> and are limited by their dependence on walkway-based measurements, the G-Walk® offers portability, ease of use, and affordability, making it highly suitable for clinical applications and enabling gait assessments in more diverse and practical settings.<sup>10, 11</sup> The device measures key spatiotemporal gait parameters, such as stride length, cadence, and limb support times, using advanced sensor fusion technology.<sup>10</sup> This portable device is widely used in clinical and research settings to assess spatiotemporal gait parameters during walking tests, which are essential for assessing gait disturbances in various populations,<sup>10, 12</sup> including those with neurodegenerative diseases like PD.<sup>13</sup> Comparative studies have demonstrated its accuracy in assessing gait, showing comparable results to gold-standard tools like optoelectronic systems and the GAITRite system.<sup>9-11</sup> Despite its widespread use, however, there is limited research on its reliability in assessing gait parameters in individuals with moderate-stage PD, a group characterized by more pronounced gait abnormalities.

Reliability is a critical aspect of any measurement tool, particularly in clinical settings where consistent and accurate data are necessary for decision-making. A previous study on the G-Walk® primarily focused on populations with mild PD or healthy individuals, where the device has demonstrated high test-retest reliability.<sup>14</sup> In moderate-stage PD, clinical symptoms involve more severe gait impairments such as increased postural instability, motor variability, higher fall risk, and fluctuating motor performance due to Levodopa wearing-off effects.<sup>15</sup> These factors pose challenges for reliable assessment, making accurate monitoring in this subgroup essential and highlighting the need for further investigation into the device's consistency in this population.

This study aims to evaluate the test-retest reliability of the G-Walk® sensor system in individuals with moderate-stage PD, focusing on key gait parameters such as stride length, cadence, gait velocity, and limb support times. The findings are expected to inform clinical practice by identifying reliable parameters for tracking disease progression and tailoring therapeutic interventions. Although clinical assessments such as the MDS-UPDRS III and H&Y staging are commonly used, they are limited in their sensitivity to gait variability.<sup>14</sup> While the GAITRite® system, a pressure sensitive walkway, is considered the gold standard in gait parameter measurement and analysis, it presents several limitations: the examination mat requires a large space, is heavy to handle, and has a high initial cost.<sup>10</sup> These factors limit its practicality for routine clinical use. Additionally, the study incorporates the calculation of the standard error of measurement (SEM) and minimal detectable change (MDC) to provide a comprehensive understanding of the system's precision and clinical utility.

This research seeks to establish the G-Walk® as a reliable and accessible tool for monitoring gait impairments in moderate-stage PD, facilitating improved management and intervention strategies.

## Materials and methods

### Study design

This prospective study assessed the test-retest reliability of the G-Walk® sensor system during walking tasks in individuals with moderate-stage PD which defined as patients with a modified Hoehn and Yahr (H&Y) stage of 2.5 to 3. Stage 2.5 represents a transitional phase with bilateral symptoms and early postural instability that does not yet require assistance, while stage 3 involves bilateral involvement with mild to moderate postural instability, with patients remaining physically independent.<sup>16</sup>

### Participants

Thirteen participants with idiopathic PD were recruited from King Chulalongkorn Memorial Hospital, The Thai Red Cross Society, Bangkok, Thailand. Neurologists confirmed the diagnosis based on established clinical criteria. Participants were aged 60–75 years and in the “ON” phase of their PD medication cycle. Inclusion criteria required participants to have a modified H&Y stage of 2.5 to 3, the ability to walk 10 meters independently without assistive devices, and normal cognitive function, defined as a Thai Mental State Examination (TMSE) score >23.<sup>17</sup> Exclusion criteria included individuals with severe visual impairments that were not correctable with devices, as these may interfere with gait assessment. Participants with significant musculoskeletal disorders (e.g., arthritis, joint deformities), cardiovascular conditions (e.g., heart failure, arrhythmias), or neurological conditions (e.g., stroke, multiple sclerosis) unrelated to PD that impair gait patterns were also excluded. Additionally, individuals participating in other clinical trials that might affect gait parameters or interfere with study outcomes were not eligible.

### Sample size calculation

The required sample size was calculated using an online sample size calculator for intraclass correlation coefficient (ICC) hypothesis testing.<sup>18</sup> The minimum acceptable reliability (ICC<sub>0</sub>) was set at 0.50, and the expected reliability (ICC<sub>1</sub>) was set at 0.90. A significance level ( $\alpha$ ) of 0.05 and power (1- $\beta$ ) of 80% were used, with two repetitions per subject (k=2). Based on these parameters, the sample size was calculated to be 11 participants. To allow for a possible 10% dropout rate, this number was increased, resulting in a final sample size of 13 participants.

### Procedure

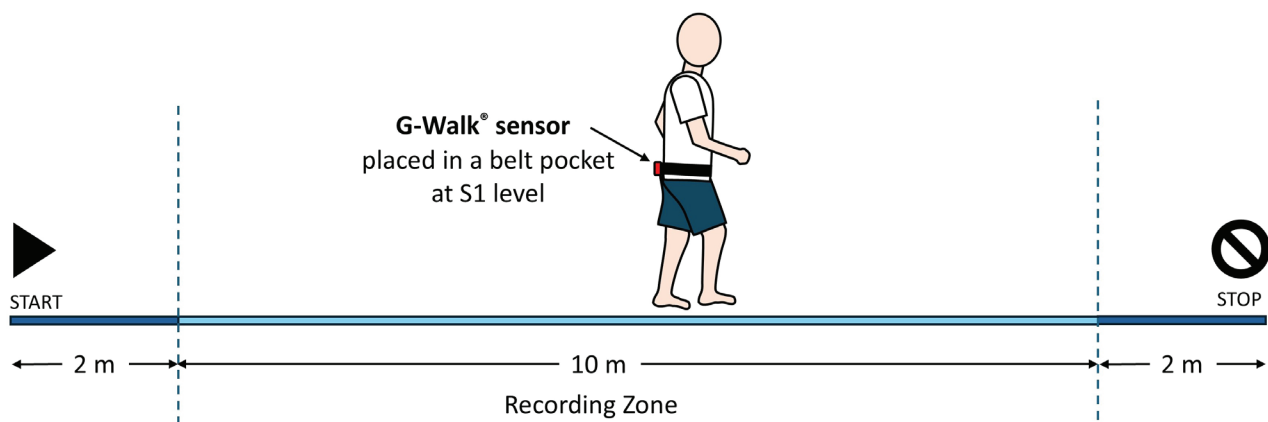
Relevant demographic and clinical data, including age, sex, weight, height, medical history, duration of disease, timing of medication intake, and any previous injuries or conditions affecting gait, were collected from participants with PD.

Test-retest assessments were conducted over two sessions, separated by an interval of 3 to 7 days, to ensure consistent testing conditions.<sup>19</sup> Practice trials aimed to reduce variability and ensure participants were comfortable with the walking task. Participants were instructed to walk at a self-selected, comfortable pace

along a 14-meter straight path. Excluding the initial and final 2 meters minimized errors due to acceleration and deceleration, focusing on stable walking performance (Figure 1).<sup>10</sup> Each participant completed two trials during each session. Participants were given a 2-minute rest or additional recovery time between trials to ensure accuracy and prevent fatigue.

The G-Walk® sensor (BTS G-Sensor2, BTS Bioengineering Company, Milan, Italy) was used to collect gait data. This portable device features a 4-sensor inertial platform, transmitting data via Bluetooth® 3.0 technology with a range of up to 60 meters. The accelerometer operates at frequencies of 4-1000 Hz, the gyroscope at 4-8000 Hz, and the magnetometer up to 100 Hz, with sensor fusion at a rate of 200 Hz. The portability of the device is enhanced by its compact dimension (70×40×18 mm) and lightweight design (37 grams). For optimal performance, the device was placed in a designated belt pocket aligned with the participant's S1 vertebra in a standing position.<sup>20, 21</sup>

Key gait parameters were recorded during the trials, including gait velocity (meters per second), cadence (steps per minute), stride length (meters), single limb support time (% gait cycle; %GC), and double-limb support time (% gait cycle; %GC). Averages were calculated from two trials for each parameter.



**Figure 1.** Study setup for gait assessment using the G-Walk®, a wearable inertial sensor system. Participants walked along a 14-meter pathway, with gait parameters recorded over the middle 10 meters to minimize acceleration and deceleration effects.

### Statistical analysis

Data analysis was conducted using SPSS version 29 (IBM Corp., Armonk, NY, USA). The Shapiro-Wilk test was used to assess the normality of the data, ensuring appropriate statistical tests were applied based on the distribution characteristics. Descriptive statistics summarized the demographic and clinical characteristics of participants, including age, sex, weight, height, medical history, duration of disease, modified H&Y stage, and TMSE scores.

To evaluate test-retest reliability, ICCs were calculated for gait parameters, including stride length, cadence, gait velocity, single limb support time, and double limb support time. The ICC<sub>[3,1]</sub> model, a two-way mixed effects model assessing absolute agreement for a single rater, was

selected, as measurements were obtained by the same rater across multiple sessions. ICC values were interpreted according to established guidelines: values less than 0.49 indicated poor reliability, 0.50-0.74 indicated moderate reliability, 0.75–0.89 indicated good reliability, and values greater than 0.90 indicated excellent reliability.<sup>22</sup>

Additionally, SEM was calculated to estimate the level of error in individual scores, using the formula:  $SEM = SD \times \sqrt{1-ICC}$ ,<sup>23</sup> where SD represents the standard deviation of the test scores, and ICC is the intraclass correlation coefficient. To determine the smallest change in a parameter that exceeds measurement error and reflects a meaningful change, the MDC was computed using the formula:  $MDC = 1.96 \times \sqrt{2} \times SEM$ .<sup>23</sup>

## Results

### Participant Characteristics

A total of 13 participants with PD were included in the study. The demographic and clinical characteristics are presented in Table 1. Regarding disease severity, six participants were classified as modified H&Y stage 2.5, while seven were classified as stage 3. Cognitive function, assessed using the TMSE, revealed a mean score of 28.62  $\pm$  1.61, indicating preserved cognitive function across the cohort.

Regarding medical history, 13 participants reported comorbid conditions that could potentially affect gait, including hypertension (N=2), orthostatic hypotension (N=1), and tachycardia (N=1). However, none of these conditions were active during the tests. No participants reported any previous injuries to the lower limbs or spine. Medication timing varied slightly among participants; however, all participants took their dopaminergic medication within one hour prior to the gait assessment.

**Table 1.** Demographic and clinical characteristics of participants with Parkinson's disease (N=13).

| Characteristics            | PD (N=13)         |
|----------------------------|-------------------|
| Sex, N (%)                 |                   |
| Male                       | 6 (46.2%)         |
| Female                     | 7 (53.8%)         |
| Age (year)                 |                   |
| Range                      | 60-75             |
| Mean $\pm$ SD              | 69.69 $\pm$ 5.71  |
| Weight (kg)                | 59.04 $\pm$ 14.20 |
| Height (cm)                | 160.23 $\pm$ 9.13 |
| Duration of disease (year) | 6.38 $\pm$ 3.07   |
| Modified H&Y stage, N (%)  |                   |
| Stage 2.5                  | 6 (46.2%)         |
| Stage 3                    | 7 (53.8%)         |
| TMSE scores                | 28.62 $\pm$ 1.61  |

**Note:** H&Y: Hoehn and Yahr, TMSE, Thai mental state examination.

### Test-retest reliability

The test-retest reliability of the gait parameters assessed using the G-Walk® sensor system is presented in Table 2. ICCs indicated excellent reliability for stride length (ICC=0.979; 95% CI [0.933-0.993]), cadence (ICC=0.958; 95% CI [0.871-0.988]), and gait velocity (ICC=0.997; 95% CI [0.991-0.999]). These results demonstrate a high level of consistency for these parameters across repeated measures.

Moderate reliability was observed for single limb support time (ICC=0.699; 95% CI [0.052-0.907]) and double limb support time (ICC=0.656; 95% CI [0.082-0.894]). The wider confidence intervals for these parameters reflect

greater variability and suggest the need for cautious interpretation when assessing temporal support times.

### Measurement precision and minimal detectable change

The SEM and MDC, as shown in Table 2, provide additional insights into the precision and clinical relevance of the gait parameter measurements. Stride length exhibited the lowest SEM (0.02 m) and MDC (0.06 m), followed by gait velocity (SEM=0.01 m/s; MDC=0.02 m/s).

In contrast, single limb support time and double limb support time demonstrated higher SEM (0.83% and 0.89%, respectively) and MDC (2.31% and 2.45%, respectively), as detailed in Table 2.

**Table 2.** Test-retest reliability results for gait parameters assessed using the G-Walk® sensor system.

| Gait parameter                 | Test<br>Mean $\pm$ SD | Retest<br>Mean $\pm$ SD | ICC <sub>[3,1]</sub><br>[95% CI] | SEM  | MDC  |
|--------------------------------|-----------------------|-------------------------|----------------------------------|------|------|
| Stride length (m)              | 1.12 $\pm$ 0.16       | 1.13 $\pm$ 0.16         | 0.979 [0.933-0.993]              | 0.02 | 0.06 |
| Cadence (steps/min)            | 113.04 $\pm$ 11.30    | 112.26 $\pm$ 10.67      | 0.958 [0.871-0.988]              | 2.25 | 6.24 |
| Gait velocity (m/sec)          | 1.04 $\pm$ 0.16       | 1.04 $\pm$ 0.16         | 0.997 [0.991-0.999]              | 0.01 | 0.02 |
| Single limb support time (%GC) | 38.79 $\pm$ 1.82      | 38.36 $\pm$ 1.22        | 0.699 [0.052-0.907]              | 0.83 | 2.31 |
| Double limb support time (%GC) | 11.21 $\pm$ 1.79      | 11.66 $\pm$ 1.23        | 0.656 [0.082-0.894]              | 0.89 | 2.45 |

**Note:** SEM: standard error of measurement, MDC: minimal detectable change, ICC: intraclass correlation coefficient, CI: confidence interval, %GC: percentage of the Gait cycle.

## Discussion

This study aimed to evaluate the reliability of the G-Walk® sensor system in measuring gait parameters in individuals with moderate-stage of PD. The findings demonstrated excellent test-retest reliability for gait parameters such as stride length, cadence, and gait velocity. These results align with a previous study that reported the reliability of the G-Walk® system in individuals with early-stage PD.<sup>10</sup> Additionally, a study assessing test-retest reliability using markerless motion capture systems and traditional motion capture systems in individuals with moderate-stage PD further supports the G-Walk® system's utility in this population.<sup>24</sup>

The high ICC values observed for stride length (0.979), cadence (0.958), and gait velocity (0.997) in this study indicate excellent reliability, consistent with prior research in the early stages of PD.<sup>14</sup> This can be attributed to the fact that the measurements were taken while the patients were in an "ON" phase of their PD medication, allowing them to maintain a consistent walking rhythm. Consequently, variations in stride length, cadence, and gait velocity were minimal<sup>25</sup>, resulting in highly stable gait parameters across repeated assessments. However, moderate reliability was observed for single limb support time (ICC=0.699) and double limb support time (ICC=0.656), which is lower than findings from an earlier study conducted with individuals in the early stages of PD.<sup>14</sup> A possible explanation for this difference is the progression-related postural instability frequently observed in moderate-stage PD.<sup>5</sup> Postural instability may introduce greater variability in limb support times due to increased reliance on compensatory mechanisms or fluctuations in motor control. This limitation may contribute to gait fluctuations and temporal alterations during walking,<sup>26</sup> thereby affecting the consistency of measurements during retesting. Another explanation involves the selective effect of dopamine on gait variability. A previous study found that double limb support time was not significantly influenced by dopaminergic medication, suggesting that dynamic postural control may be more closely associated with cholinergic pathways, particularly involving the pedunculopontine nucleus.<sup>27</sup>

Although the minimum acceptable reliability (ICC<sub>0</sub>) for sample size calculation in this study was set at 0.50, it is widely recognized that for key clinical gait parameters such as stride length, cadence, and gait velocity, a higher threshold of ICC ( $\geq 0.75$ ) is generally recommended to ensure clinical utility.<sup>28</sup> The rationale for selecting ICC<sub>0</sub> at 0.50 was to meet statistical requirements for hypothesis testing and to ensure sufficient sample size for detecting reliability across a range of gait parameters, including those expected to have moderate reliability. However, the actual ICC values observed for stride length (0.979), cadence (0.958), and gait velocity (0.997) in this study far exceeded the clinically relevant threshold, indicating that the G-Walk® system provides excellent reliability for these parameters in individuals with moderate-stage PD. This supports the clinical applicability of the device for monitoring disease progression and treatment response.

The calculated SEM and MDC allowed for a more detailed interpretation of measurement variability and responsiveness.<sup>23</sup> Stride length and gait velocity exhibited the smallest SEM (0.02 m and 0.01 m/s, respectively) and MDC (0.06 m and 0.02 m/s, respectively), suggesting their high sensitivity for detecting clinically meaningful changes. These findings reinforce their use as primary indicators in clinical settings for tracking disease progression and evaluating treatment efficacy in individuals with moderate-stage PD. Conversely, the higher SEM and MDC values for single and double limb support times indicate greater variability and a lack of stability in these parameters, potentially limiting their utility for short-term monitoring in this population. The SEM and MDC values observed in this study tend to be lower than those reported in previous research involving children with cerebral palsy using the G-Walk® system, which is the only other population with published MDC data for this device.<sup>12</sup> This comparison suggests that the G-Walk® system may have good sensitivity to detect meaningful changes in populations with different motor control impairments. However, further studies are needed to establish MDC values in other populations such as older adults or stroke patients.

A notable strength of this study is the use of a standardized protocol for test-retest assessments, ensuring consistency and minimizing measurement bias. The inclusion of individuals with moderate-stage PD provides critical insights into the application of the G-Walk® system in this specific population, addressing a gap in the existing literature. Additionally, the portability and ease of use of the G-Walk® system make it highly practical for clinical and community-based settings. The availability of detailed spatiotemporal gait data supports precise monitoring of disease progression and enables timely intervention. From a clinical application perspective, the findings highlight the potential of the G-Walk® system as a compact device for accurately and reliably assessing gait parameters in individuals with PD. It can serve as a convenient and appropriate tool in clinical settings. The obtained data can serve as benchmarks for evaluating and monitoring gait changes across different stages of the disease. Moreover, it aids physicians and physical therapists in using reliable information to plan appropriate treatment and care strategies for patients.

## Limitation

This study has certain limitations, including a sample size of 13 participants, which was calculated to meet statistical requirements for ICC hypothesis testing with adequate power. However, despite being statistically adequate, the sample size may still limit the generalizability of the findings to broader populations. Future studies with larger, more diverse cohorts are recommended to further validate these results and improve generalizability. Additionally, this study lacked a healthy control group for comparison. The inclusion of such a group in future research would provide a valuable baseline, allowing for direct comparison of gait parameter

reliability between individuals with PD and the general population. This addition would enhance the validity and clinical relevance of the findings by distinguishing disease-specific measurement variability from normal variability in gait parameters. Furthermore, the selection of patients who could walk without assistive devices makes the results specific to those with moderate-stage PD. Variations in medication timing and individual responses to Levodopa may also have influenced gait performance, potentially introducing variability into the results. Future research should aim to expand the sample size and include participants with more advanced stages of PD or severe gait impairments to provide more comprehensive and generalizable data. Longitudinal studies could also help to assess the responsiveness of the G-Walk® system to changes in disease severity or therapeutic interventions over time.

### Conclusions

In conclusion, this study highlights the excellent reliability of the G-Walk® sensor system for measuring key gait parameters such as stride length, cadence, and gait velocity in individuals with PD. In contrast, single and double limb support times showed only moderate reliability, indicating that these parameters should be interpreted with caution in clinical practice. The analysis of SEM and MDC highlights the accuracy and stability of repeated measurements, recommending the use of stable parameters like stride length and gait velocity as primary indicators for tracking changes in clinical settings. Future research is crucial for enhancing the utility of G-Walk® in evaluating gait parameters in PD.

### Ethical approval

The study was approved by the Institutional Review Board (COA No.1512/2024). Written informed consent was obtained from all participants prior to their participation.

### Funding

This work received no specific grant from any funding agency.

### Conflicts of Interest Statement

The authors declare no conflict of interest.

### CRedit authorship contribution statement

**Thanakorn Angkurasiripaiboon:** conceptualization, methodology, validation, formal analysis, investigation, writing: original draft, review and editing; **Chernkhuan Stonsaovapak:** writing: original draft, review and editing; **Maria Justine:** writing: original draft, review and editing; **Akkradate Siriphorn:** conceptualization, methodology, formal analysis, writing: original draft, review and editing

### Acknowledgements

The author gratefully acknowledges King Chulalongkorn Memorial Hospital, The Thai Red Cross Society, for providing access to its facilities for data collection. Sincere appreciation is also extended to the Department

of Rehabilitation Medicine, Chulalongkorn Hospital, for providing the instruments and equipment necessary for this study.

### References

- [1] Poewe W, Seppi K, Tanner CM, Halliday GM, Brundin P, Volkman J, et al. Parkinson disease. Nat Rev Dis Primers. 2017; 3: 17013. doi: 10.1038/nrdp.2017.13.
- [2] Reeve A, Simcox E, Turnbull D. Ageing and parkinson's disease: Why is advancing age the biggest risk factor? Ageing Res Rev. 2014;14(100):19-30. doi: 10.1016/j.arr.2014.01.004.
- [3] Bloem BR, Okun MS, Klein C. Parkinson's disease. Lancet. 2021; 397(10291): 2284-303. doi: 10.1016/S0140-6736(21)00218-X.
- [4] Zhao N, Yang Y, Zhang L, Zhang Q, Balbuena L, Ungvari GS, et al. Quality of life in parkinson's disease: A systematic review and meta-analysis of comparative studies. CNS Neurosci Ther. 2021; 27(3): 270-9. doi: 10.1111/cns.13549.
- [5] Zanardi APJ, da Silva ES, Costa RR, Passos-Monteiro E, Dos Santos IO, Kruel LFM, et al. Gait parameters of parkinson's disease compared with healthy controls: A systematic review and meta-analysis. Sci Rep. 2021; 11(1): 752. doi: 10.1038/s41598-020-80768-2.
- [6] Dibble LE, Addison O, Papa E. The effects of exercise on balance in persons with parkinson's disease: A systematic review across the disability spectrum. J Neurol Phys Ther. 2009; 33(1): 14-26. doi: 10.1097/NPT.0b013e3181990fcc.
- [7] Pickering RM, Grimbergen YA, Rigney U, Ashburn A, Mazibrada G, Wood B, et al. A meta-analysis of six prospective studies of falling in parkinson's disease. Mov Disord. 2007; 22(13): 1892-900. doi: 10.1002/mds.21598.
- [8] Albarmawi H, Zhou S, Shulman LM, Gandhi AB, Johnson A, Myers DE, et al. The economic burden of parkinson disease among medicare beneficiaries. J Manag Care Spec Pharm. 2022; 28(4): 405-14. doi: 10.18553/jmcp.2022.28.4.405.
- [9] Kleiner AFR, Pacifici I, Vagnini A, Camerota F, Celletti C, Stocchi F, et al. Timed up and go evaluation with wearable devices: Validation in parkinson's disease. J Bodyw Mov Ther. 2018; 22(2): 390-5. doi: 10.1016/j.jbmt.2017.07.006.
- [10] Vítečková S, Horáková H, Poláková K, Krupička R, Růžicka E, Brožová H. Agreement between the gaitrite® system and the wearable sensor bts g-walk® for measurement of gait parameters in healthy adults and parkinson's disease patients. PeerJ. 2020; 8: e8835. doi: 10.7717/peerj.8835.
- [11] De Ridder R, Lebleu J, Willems T, De Blaiser C, Detrembleur C, Roosen P. Concurrent validity of a commercial wireless trunk triaxial accelerometer system for gait analysis. J Sport Rehabil. 2019; 28(6). doi: 10.1123/jsr.2018-0295.
- [12] Yazıcı MV, Çobanoğlu G, Yazıcı G. Test-retest reliability and minimal detectable change for measures of wearable gait analysis system (g-walk) in children

- with cerebral palsy. *Turk J Med Sci.* 2022; 52(3): 658-66. doi: 10.55730/1300-0144.5358.
- [13] Harro CC, Shoemaker MJ, Coatney CM, Lentine VE, Lieffers LR, Quigley JJ, et al. Effects of nordic walking exercise on gait, motor/non-motor symptoms, and serum brain-derived neurotrophic factor in individuals with parkinson's disease. *Front Rehabil Sci.* 2022; 3: 1010097. doi: 10.3389/fresc.2022.1010097.
- [14] Bailo G, Saibene FL, Bandini V, Arcuri P, Salvatore A, Meloni M, 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 (Basel).* 2024; 24(2): 662. doi: 10.3390/s24020662.
- [15] Smulders K, Dale ML, Carlson-Kuhta P, Nutt JG, Horak FB. Pharmacological treatment in parkinson's disease: Effects on gait. *Parkinsonism Relat Disord.* 2016; 31: 3-13. doi: 10.1016/j.parkreldis.2016.07.006.
- [16] Goetz CG, Poewe W, Rascol O, Sampaio C, Stebbins GT, Counsell C, et al. Movement disorder society task force report on the hoehn and yahr staging scale: Status and recommendations. *Mov Disord.* 2004; 19(9): 1020-8. doi: 10.1002/mds.20213.
- [17] Muangpaisan W, Assantachai P, Sitthichai K, Richardson K, Brayne C. The distribution of thai mental state examination scores among non-demented elderly in suburban bangkok metropolitan and associated factors. *J Med Assoc Thai.* 2015; 98(9): 916-24.
- [18] Arifin WN. Sample size calculator (web) 2024 [cited 2024 Oct 31]. Available from: <http://wnarifin.github.io>.
- [19] Hutin E, Ghédira M, Mardale V, Boutou M, Santiago T, Joudoux S, et al. Test-retest and inter-rater reliability of the 20-meter ambulation test in patients with parkinson's disease. *J Rehabil Med.* 2023; 55: jrm00378. doi: 10.2340/jrm.v55.4381.
- [20] BTS. G-sensor2 hardware manual version 1.2.2. Milan, Italy: BTS Bioengineering Corp.; 2016.
- [21] BTS. G-walk user manual version 8.1.0. Milan, Italy: BTS Bioengineering Corp.; 2017.
- [22] Koo TK, Li MY. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *J Chiropr Med.* 2016; 15(2): 155-63. doi: 10.1016/j.jcm.2016.02.012.
- [23] Beninato M, Portney LG. Applying concepts of responsiveness to patient management in neurologic physical therapy. *J Neurol Phys Ther.* 2011; 35(2): 75-81. doi: 10.1097/NPT.0b013e318219308c.
- [24] Kluge F, Gaßner H, Hannink J, Pasluosta C, Klucken J, Eskofier BM. Towards mobile gait analysis: Concurrent validity and test-retest reliability of an inertial measurement system for the assessment of spatio-temporal gait parameters. *Sensors (Basel).* 2017; 17(7). doi: 10.3390/s17071522.
- [25] Ambrus M, Sanchez JA, Sanchez Miguel JA, Del-Olmo F. Test-retest reliability of stride length-cadence gait relationship in parkinson's disease. *Gait Posture.* 2019; 71: 177-80. doi: 10.1016/j.gaitpost.2019.05.009.
- [26] Peterson DS, Horak FB. Neural control of walking in people with parkinsonism. *Physiology (Bethesda).* 2016; 31(2): 95-107. doi: 10.1152/physiol.00034.2015.
- [27] Lord S, Baker K, Nieuwboer A, Burn D, Rochester L. Gait variability in parkinson's disease: An indicator of non-dopaminergic contributors to gait dysfunction? *J Neurol.* 2011; 258(4): 566-72. doi: 10.1007/s00415-010-5789-8.
- [28] Parati M, Ambrosini E, B DEM, Gallotta M, Dalla Vecchia LA, Ferriero G, et al. The reliability of gait parameters captured via instrumented walkways: A systematic review and meta-analysis. *Eur J Phys Rehabil Med.* 2022; 58(3): 363-77. doi: 10.23736/s1973-9087.22.07037-x.