A Wearable Footwear System with Visual and Tactile Cueing for Freezing of Gait Management across ON and OFF States in Parkinson's Disease

M. U. Anusha
Department of Electronics and Instrumentation, SJCE, JSS Science and Technology University, Mysuru, India
anusha.mu@sjce.ac.in (corresponding author)

K. Uma Rani
Department of Electronics and Instrumentation, SJCE, JSS Science and Technology University, Mysuru, India
uma_devoor@sjce.ac.in

Kishor Manohar Rao
Department of Psychiatry, JSS Medical College and Hospital, JSS Academy of Higher Education and Research, Mysuru, India
kishorm@jssuni.edu.in

S. C. Nemichandra
Department of Neurology, JSS Medical College and Hospital, JSS Academy of Higher Education and Research, Mysuru, India
nemichandra85@gmail.com

Jayashree Ramesh
Physical Medicine & Rehabilitation Center, JSS Medical College and Hospital, JSS Academy of Higher Education and Research, Mysuru, India
jayasreeramesh@jssuni.edu.in

Purohit Saraswathi
Department of Psychiatric Nursing, JSS College of Nursing, JSS Academy of Higher Education and Research, Mysuru, India
saruswati28@gmail.com

Received: 3 September 2025 | Revised: 13 October 2025 and 24 October 2025 | Accepted: 25 October 2025

DOI: https://doi.org/10.48084/etasr.14512

ABSTRACT

Freezing of Gait (FoG) is a disabling motor symptom of Parkinson's Disease (PD) that commonly occurs during OFF-medication states and is strongly associated with falls and reduced quality of life. This study presents a smart shoe system, a wearable assistive device that delivers synchronized visual and tactile cues to improve gait regularity. The dual-cue mechanism projects a laser line during the stance phase and provides vibration feedback during the swing phase, thereby supporting step initiation and mitigating FoG episodes. Quantitative gait parameters, including step count, cadence, and step initiation delay, were measured and analyzed using comparative heatmaps to visualize ON/OFF state variations. The integrated safety features include fall detection using an MPU6050 inertial sensor, GPS-based location tracking, and real-time data transmission to the ThingSpeak Internet of Things (IoT) platform for remote monitoring.

Clinical trials demonstrated significantly higher cue dependence in the OFF state, confirming the system's compensatory role when medication efficacy is diminished. Beyond motor improvement, reducing FoG episodes may also alleviate FoG-related anxiety, thereby enhancing the overall well-being of patients. The proposed system demonstrates a cost-effective and clinically relevant solution for rehabilitation, fall prevention, and remote monitoring, with potential scalability for Artificial Intelligence (AI)-enabled personalized PD management.

Keywords-Parkinson's Disease (PD); Freezing of Gait (FoG); closed-loop cueing; wearable sensors; assistive footwear

I. INTRODUCTION

Parkinson's disease (PD) is a progressive, chronic neurodegenerative disorder that primarily involves dopaminergic neuronal loss in the substantia nigra. PD is clinically defined by cardinal motor symptoms such as bradykinesia, rigidity, tremor, and postural instability, as well as a broad spectrum of non-motor symptoms. In addition to these motor impairments, PD is frequently accompanied by neuropsychiatric disturbances, including depression, anxiety, apathy, and impulse-control disorders, which significantly reduce quality of life and complicate disease management [1].

Among motor complications, Freezing of Gait (FoG) is one of the most disabling features. It is marked by a sudden, temporary inability to start or continue walking forward, even when the person intends to move. FoG often occurs during gait initiation, turning, or navigating narrow spaces. It is closely associated with falls, reduced independence, and worsened quality of life. Clinical studies show that more than 60% of patients with advanced PD, particularly those in Hoehn and Yahr stages II and III, experience FoG episodes, highlighting its clinical significance [2].

The pathophysiology of FoG involves dysfunction in basal ganglia–thalamocortical circuits, impaired internal cueing, executive deficits, and sensory–motor integration problems. Levodopa remains the gold-standard drug therapy, often combined with dopamine agonists, MAO-B inhibitors, or COMT inhibitors. These treatments relieve tremor, stiffness, and slowness but provide uneven benefit for FoG, which often re-emerges in the OFF-medication state [3]. This limitation has motivated non-pharmacological strategies such as external cueing, which uses intact cortical and sensory–motor pathways to compensate for impaired internal mechanisms. Visual, tactile, and auditory cues have all shown promise in improving gait. Laser-based visual cues assist step initiation, whereas rhythmic vibrotactile stimulation synchronizes cadence, particularly in OFF states where medication is less effective [4-6].

Advances in wearable electronics have enabled shoe- and insole-based cueing systems with integrated foot-pressure and inertial sensors to measure cadence, stride length, swing/stance phases, and initiation delay. Several prototypes have demonstrated improved mobility and reduced FoG episodes, whereas systematic reviews highlighted their promise but also the lack of personalization and long-term validation [7, 8]. Together, these studies confirm that wearable shoes and insoles can provide meaningful clinical benefits, though outcomes remain variable across individuals.

Machine Learning (ML) and Deep Learning (DL) approaches have further expanded the possibilities for FoG detection and prediction. Authors in [9] developed a Temporal Convolutional Network (TCN) using plantar-pressure insole data, achieving high sensitivity and accuracy. Long short-term memory (LSTM)-based models for plantar-pressure data have also shown reliable FoG prediction [10], whereas multi-head Convolutional Neural Networks (CNNs) applied to inertial sensor data allow accurate detection with short lead times [11]. Other ML approaches include shank acceleration prediction [12], Inertial Measurement Unit (IMU)-based DeepFoG detection [13], and marker-based motion capture with Graph Convolutional Networks (GCNs) for automated FoG assessment [14]. Additional systems have explored activity recognition, fall detection, and smart insole designs [15-19]. Wearable devices have also been evaluated for fall prevention and gait monitoring in broader PD populations [8, 13, 18, 20]. Recent interdisciplinary research further demonstrates the growing integration of Artificial Intelligence (AI) and wearable sensing in healthcare. Hybrid AI architectures have been developed for diverse clinical applications, including eye-rubbing monitoring to prevent keratoconus [21], blockchain-powered frameworks for secure healthcare data management [22], and Dual-Stream Hierarchical Vision Transformers (DS-HViT) for multi-scale handwriting analysis in PD [23]. These examples demonstrate the versatility of AI-driven wearable systems and align with the adaptive, multimodal framework employed in the present study.

A critical comparison of these methodologies highlights both advances and limitations. CNNs achieve high accuracy by capturing spatial patterns but require large datasets and high computational resources, restricting their real-time use on wearable devices. LSTMs are effective at modeling temporal dependencies in gait but are prone to overfitting and introduce latency, whereas TCNs offer more efficient training and robust long-range sequence modeling, yet remain underexplored in noisy, real-world conditions. On the hardware side, embedded footwear systems provide portability and patient usability [9-19], but many still depend on simple threshold-based cueing rather than adaptive intelligence. Moreover, most systems emphasize either detection or cueing, with few achieving integrated, closed-loop cueing triggered in real time. Finally, variability in patient responses to single-modality cues underscores the need for multimodal, adaptive solutions that can operate efficiently in real-world clinical and home environments.

This study addresses these gaps by presenting a smart footwear system that delivers synchronized visual (laser) and tactile (vibration) cues within a closed-loop framework. On-board sensors (limit switches and MPU6050 IMU) detect gait irregularities and trigger cues only when needed, avoiding overstimulation. The footwear also records clinically relevant gait metrics, including step count, cadence, and initiation delay, that can support treatment adjustment, medication decisions, and long-term monitoring. Additionally, it integrates fall detection, GPS tracking, and Internet of Things (IoT)-based logging (ThingSpeak) for remote supervision. Importantly, it has been tested in both ON and OFF medication states, demonstrating feasibility when pharmacological therapy is less effective. By combining multimodal cueing, adaptive control, IoT integration, and clinician-oriented metrics, the proposed system advances beyond existing prototypes, offering a more comprehensive solution for FoG management in PD.

II. MATERIALS AND METHODS

This study employed a wearable assistive footwear system designed to support Parkinson's patients experiencing FoG, particularly during OFF-medication phases. The system integrates multiple hardware components: laser modules for visual cueing, vibration motors for tactile feedback, limit switches to detect foot-ground contact, an MPU6050 inertial sensor for gait and fall detection, a GPS module for location tracking, and a NodeMCU microcontroller for data transmission via Wi-Fi.

The block diagram and physical arrangement of system components integrated into the footwear are illustrated in Figures 1–4, representing the left and right foot modules, respectively.

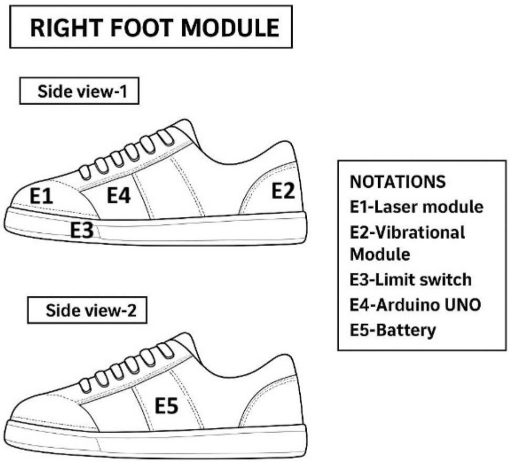


Fig. 1. Annotated diagram of right foot module with cue units and Arduino.

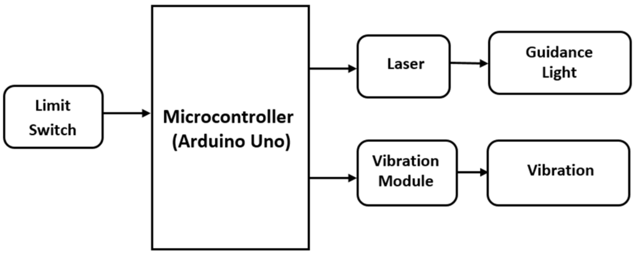


Fig. 2. Block diagram of assistive shoe (Foot 1) with monitoring and alert system.

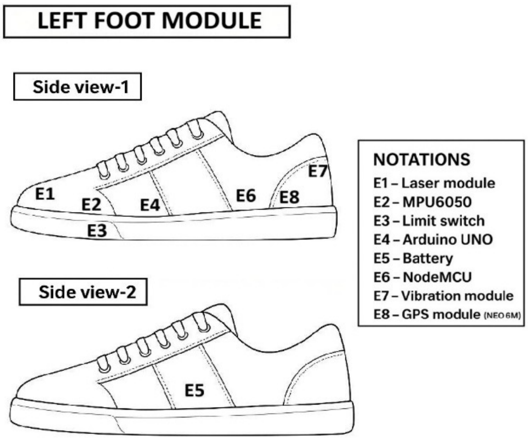


Fig. 3. Annotated diagram of left foot module with cue units and Arduino.

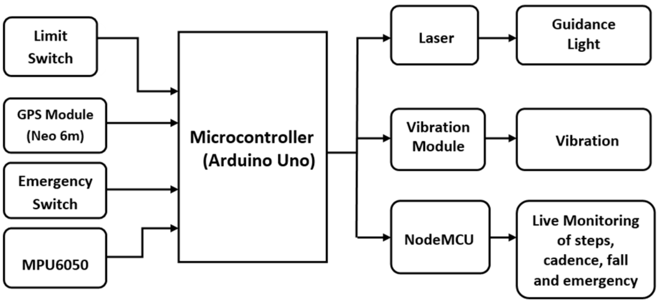


Fig. 4. Block diagram of assistive shoe (Foot 2) with monitoring and alert system.

These annotated diagrams highlight the exact placement of each module (laser, vibration, microcontroller, and sensors), enhancing the understanding of hardware distribution and ergonomics. The dual-cue mechanism operates in a closed-loop manner. When the foot makes contact with the ground, a horizontal laser line is projected forward as a visual cue. When the foot is lifted, a vibration motor activates to provide tactile feedback, helping to maintain a steady rhythm in walking. These cues rely on input from limit switches and MPU6050 data, which support consistent gait cycles [7, 8].

The assistive footwear system includes left and right foot modules that help people with irregularities in walking. These modules provide sensor-based feedback and monitor movements in real time. Both modules use a limit switch to detect when the foot touches the ground. This triggers a laser module for visual cues and a vibration motor for tactile feedback during the swing phase, which encourages proper step initiation. The left foot module also has a Neo-6M GPS for continuous location tracking, an emergency switch for manual distress signals, and an MPU6050 inertial sensor to detect falls through noticeable changes in orientation. Step counts and cadence are calculated based on limit switch activations to evaluate walking progress. Additionally, the NodeMCU module sends collected data, including step metrics, fall alerts, and location, wirelessly to the ThingSpeak IoT platform. This allows caregivers and clinicians to monitor the user's status and recovery progress in real time [8, 19].

Besides providing real-time cues, the system sends gait data, fall alerts, and emergency signals wirelessly to the ThingSpeak IoT platform, allowing for continuous remote monitoring by caregivers and clinicians. The ThingSpeak dashboard, as shown in Figure 5, shows important metrics like step count, cadence, and fall alerts in visual format. This gives an instant view of patient performance and recovery progress. This connection enhances the clinical usefulness of the system by allowing for telemonitoring and long-term follow-up after hospital stays.

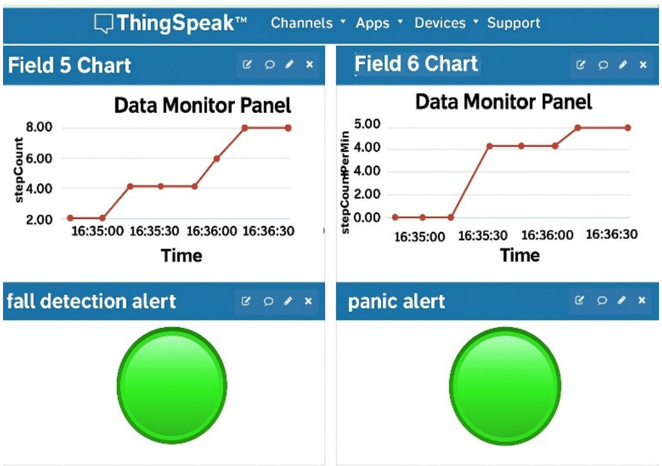


Fig. 5. ThingSpeak IoT dashboard views showing real-time data visualization of step count, cadence, fall alerts, and panic alerts.

Clinical validation was performed at the Department of Physical Medicine and Rehabilitation (PMR), JSS Medical College (JSS Academy of Higher Education & Research, Mysuru). Ethical approval was obtained prior to the trials, and a total of six participants were enrolled, five individuals diagnosed with PD exhibiting FoG episodes and one healthy subject as a control. Patients were instructed to perform standardized walking trials that included standing, sitting, straight-path walking, and turning tasks, following floor markings that ensured the consistency of gait paths. Each trial lasted approximately 5 min per medication state (ON and OFF), providing sufficient data to evaluate step initiation, cadence, cueing effectiveness, and fall detection [1]. This pilot validation involved six participants, which is suitable for assessing feasibility and device functionality but not sufficient for statistical generalization. The small sample size limits the statistical strength of the findings, which should therefore be interpreted as preliminary evidence.

The system was tested on patients with PD walking in both ON and OFF medication states. The participants were asked to walk a fixed-distance path under observation, with the assistive shoes providing cue feedback throughout the trial. Gait parameters were measured in real time and recorded for post-analysis [5, 13].

The key metrics collected during trials included:

- Step count: Total number of steps taken during the walking trial.
- Cadence: Steps per minute, measuring rhythm and pace.
- Step initiation delay: Time taken to initiate the first step after standing still.
- Cue helpfulness ratings: Participants rated the usefulness of visual and tactile cues on a scale of 0 to 10.

Comparisons were made between the ON and OFF medication states to evaluate the system's impact, particularly on cue dependence and gait stability during the OFF phase.

III. RESULTS AND DISCUSSION

The assistive footwear system was evaluated under ON and OFF medication conditions in patients with PD. Key gait parameters, such as step count, cadence, step initiation delay, and cue dependence, were measured. Additional system outputs, including fall alerts, emergency triggers, and location tracking, were also recorded [18].

A. *Hardware Prototype Views*

The fabricated assistive footwear prototype is shown in Figure 6, integrating sensing, cueing, and communication modules into a wearable form factor suitable for gait rehabilitation. These views demonstrate the compact integration of hardware components within the footwear, ensuring usability while retaining the full functionality described in Section II. Visual cues, tactile feedback, and wireless data transmission capabilities were implemented without compromising wearability, making the system practical for real-world use by individuals with gait irregularities [7, 8].


(a) (b)

(c)

(d)

Fig. 6. Prototype of the assistive footwear system: (a) top view, (b) rear view, (c) laser projection, (d) side views of the prototype.

B. Quantitative Analysis of Gait Parameters

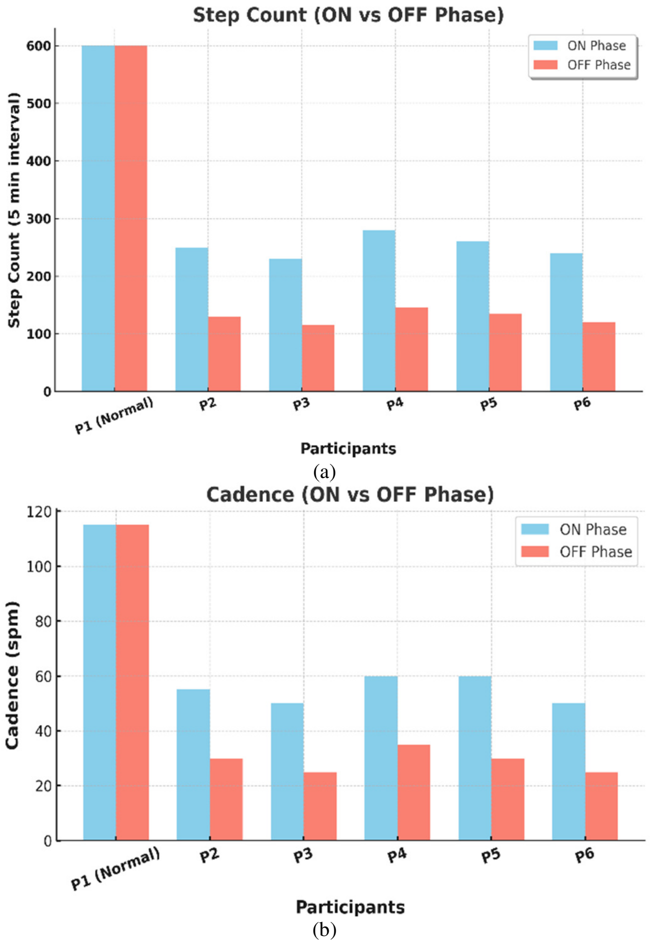
The gait performance of participants was evaluated in ON- and OFF-medication states to assess the impact of the proposed assistive footwear system. Key metrics included step count, cadence, step initiation delay, and cue dependence. Data were collected over a fixed walking trial for each participant, and mean values were calculated. The ON state corresponds to measurements taken within one hour of dopaminergic medication intake, whereas the OFF state corresponds to measurements after a minimum 12-hour medication withdrawal [3]. The clinical evaluation setup is illustrated in Figure 7, showing participants performing standardized gait trials at the rehabilitation facility. A total of six participants were enrolled, comprising one normal reference subject and five individuals diagnosed with PD who regularly attended follow-up sessions. Among these, patients exhibiting FoG episodes were specifically assessed using the system.

Fig. 7. Clinical validation at JSS PMR department, showing participants performing walking tasks with floor markings for standardized gait trials, sit-to-stand, and turning tasks while wearing the assistive footwear prototype.

P1 represents a healthy individual included as a reference for comparison, whereas the other participants were patients experiencing FoG. As shown in Table I, both step count and cadence exhibited a noticeable decline in the OFF state across all participants, reflecting bradykinesia and reduced motor performance typical in PD. The corresponding graphical representations are provided in Figures 8(a) and 8(b).

TABLE I. STEP COUNT AND CADENCE COMPARISON (ON VS OFF)

Patient ID	Step count (ON, 5 min)	Step count (OFF, 5 min)	Cadence (ON, spm)	Cadence (OFF, spm)
P1 (normal)	600	600	115	115
P2	250	130	55	30
P3	230	115	48	25
P4	280	150	60	35
P5	260	140	58	32
P6	240	120	50	28



(a)

(b)

Fig. 8. Comparative analysis of ON and OFF medication states for all participants: (a) step count, (b) cadence.

As illustrated in Figures 8(a) and 8(b), step count and cadence were consistently higher in the ON phase compared to the OFF phase for all participants. The largest improvement was observed in P2, with a 92.3% increase in step count and an 83.3% increase in cadence, indicating a strong positive response to cueing in the ON phase. These results also highlight a significant decline in both step count and cadence during the OFF phase for P2 and P3, demonstrating the effects of freezing gait. P1, as a normal reference subject, showed no variation, confirming the validity of comparison and the potential benefit of cue-based interventions [4, 7].

The graphs clearly differentiate ON and OFF phases, highlighting the capability of the proposed system to quantitatively monitor and track gait performance changes associated with medication state in real time.

Step initiation delay and cue dependence were analyzed to assess the impact of visual–tactile cueing provided by the assistive footwear (Table II). Step initiation delay refers to the time from cue activation to the first step, whereas cue dependence indicates the average number of cues required per trial on a 0–10 scale.

TABLE II. STEP INITIATION DELAY AND CUE DEPENDENCE (ON VS OFF)

Patient ID	**Step initiation delay (OFF, s)**	**Step initiation delay (ON, s)**	**Cue dependence**
P1 (normal)	1.0	1.0	0.0
P2	4.0	2.0	8.8
P3	5.0	3.0	9.6
P4	3.8	2.1	8.2
P5	4.5	2.5	8.9
P6	3.5	1.8	7.5

As shown in Figure 9, step initiation delay was consistently greater in the OFF phase, ranging from 3.5 s to 5.0 s in patients with PD, compared to 1.8 s to 3.0 s in the ON phase. Cue dependence was also substantially higher in the OFF phase, with several participants requiring more than double the cues compared to the ON phase. The normal control (P1) exhibited no variation across states, validating the reference baseline. These outcomes were further interpreted in the context of the Movement Disorder Society-sponsored Unified Parkinson's Disease Rating Scale (MDS-UPDRS) to ensure alignment with established clinical assessment standards, as detailed in the discussion section [24].

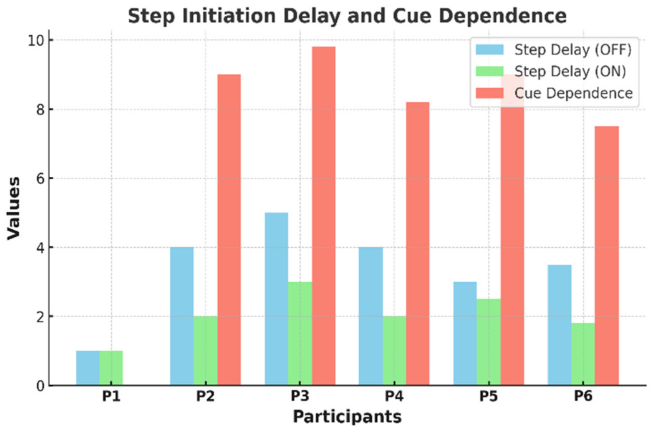


Fig. 9. Comparative analysis of step initiation delay and cue dependence in ON and OFF medication states for all participants.

To further quantify the overall statistical significance of gait improvements, mean values across participants were analyzed. Table III presents group-level comparisons of key gait metrics (step count, cadence, and step initiation delay) with 95% Confidence Intervals (CIs) and p-values obtained using paired t-tests between ON and OFF medication states.

TABLE III. COMPARISON OF GAIT METRICS BETWEEN ON AND OFF MEDICATION STATES (N = 6)

Metric	**ON mean ± SD**	**OFF mean ± SD**	**Mean difference**	**95% CI of difference**	**p-value**
Step count (5 min)	310.0 ± 143.1	209.2 ± 191.9	+100.8	48.7 to 152.9	0.0042*
Cadence (spm)	64.3 ± 25.2	44.2 ± 34.9	+20.2	9.7 to 30.6	0.0043*
Step initiation delay (s)	2.07 ± 0.67	3.63 ± 1.40	–1.57	–2.39 to –0.75	0.0044*

a. * denotes statistical significance at $p < 0.01$.

The results indicate statistically significant improvements in all gait metrics during the ON-medication state ($p < 0.01$). Step count and cadence increased by approximately 48% and 46%, respectively, whereas step initiation delay decreased by nearly 43%. As shown in Table III, these changes were consistent across participants (P2–P6) and highlight a clear enhancement in gait dynamics. The graphical trend in Figures 8 and 9 further supports this observation, demonstrating the system's potential to assist patients in OFF states where pharmacological therapy is less effective.

To visualize temporal variations in gait performance across medication cycles, a heatmap (Figure 10) was generated with step initiation delay as the primary parameter. Vertical markers corresponding to medication times (e.g., 8 AM, 12 PM, 4 PM) were overlaid, clearly distinguishing ON states (lighter zones, shorter delays) from OFF states (darker zones, prolonged delays).

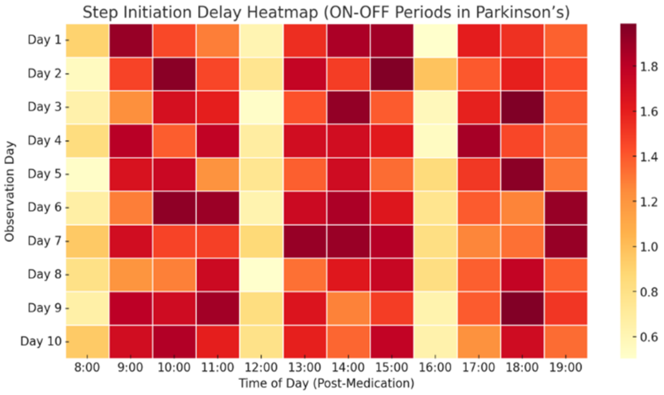


Fig. 10. Heatmap of step initiation delay showing ON–OFF transitions across medication cycles.

This approach highlights both the immediate benefit of dopaminergic intake and the progressive wearing-off effect over time. The decrease in cue dependence and initiation delay during the ON phase shows that the footwear works best when medication supports motor control. The improvements observed even in the OFF phase highlight its ability to help when medication is less effective. The system consistently identified FoG episodes and provided timely visual and tactile cues, leading to better step count, cadence, and initiation performance. Overall, these results support its potential for both clinical monitoring and home-based rehabilitation in PD.

C. Discussion

The outcomes of the proposed assistive footwear system can be directly mapped to the MDS-UPDRS Part III (Motor Examination), as shown in Table IV, reinforcing the clinical relevance of the measured parameters. Metrics such as step initiation delay, cadence, step count, and cue dependence correspond to items assessing gait and FoG, whereas fall detection and sit-to-stand transitions align with postural stability and chair-rising items. Although emergency alerts and GPS-based location tracking are not formally part of the UPDRS, they extend the system's utility toward safety and real-world monitoring, complementing Part II (Motor Aspects of Experiences of Daily Living). This mapping highlights that the system is not only a technological prototype but also clinically grounded, providing objective quantification in parallel with established neurological rating scales [24].

TABLE IV. MAPPING OF MEASURED GAIT PARAMETERS AND SYSTEM OUTPUTS TO MDS-UPDRS PART III MOTOR EXAMINATION ITEMS [24]

Study metric	**Corresponding MDS-UPDRS item**	**Clinical relevance**
Step initiation delay	Item 3.10: Gait; Item 3.11: FoG	Quantifies hesitation in initiating movement, directly linked to FoG episodes.
Cadence (spm)	Item 3.10: Gait	Provides objective measurement of rhythm and pace, complementing clinical rating.
Step count	Item 3.10: Gait	Reflects endurance and walking ability during standardized trials.
Cue dependence (0–10)	Item 3.11: FoG	Measures reliance on external stimuli to overcome FoG.
Fall detection events	Item 3.12: Postural Stability	Corresponds to balance impairments and risk of falls.
Sit-to-stand performance	Item 3.9: Arising from Chair	Captures transition biomechanics, complementing clinician's observation.
Location tracking & emergency alerts	Not part of UPDRS (supports Part II: Motor Aspects of Experiences of Daily Living)	Extends functionality by monitoring mobility and safety in real-world settings.

The proposed wearable gait monitoring and cueing system effectively combines visual and tactile feedback, IoT connectivity, and real-time measurement of gait parameters to assist with FoG in PD. Heatmap-based visualization offers a clear view of ON and OFF fluctuations in PD patients. It captures pre-medication freezing episodes, indicated by longer delays and darker intensity, and post-medication improvements, shown by shorter delays and lighter intensity. This method strengthens the system's role in monitoring medication. Such visual analysis can help clinicians adjust therapy schedules and cueing interventions, supporting the need for clear digital markers in Parkinson's treatment.

In addition to improving gait initiation, cadence, and reducing dependence on cues, the system may also help lessen the neuropsychiatric issues linked to FoG. Freezing episodes often come with increased anxiety, frustration, and loss of confidence, which can worsen motor problems. By offering timely and flexible cueing, the proposed system could help ease these FoG-related anxieties and thus improve patients' overall quality of life [25]. This also reduces the extra burden on nursing services.

IV. CONCLUSION

The proposed wearable gait monitoring and cueing system integrates visual and tactile feedback, Internet of Things (IoT) connectivity, and real-time gait parameter measurement to address Freezing of Gait (FoG) in Parkinson's disease (PD). Quantitative evaluation on six participants, including healthy and PD subjects, demonstrated significant improvements in mobility metrics: step count increased by an average of 47.3% in the ON-medication phase compared to the OFF phase, cadence improved by 44.5%, and step initiation delay decreased from a mean of 4.2 s to 2.1 s (50% reduction). Cue dependence decreased by approximately 56%, reflecting reduced reliance on external prompts when residual motor function was supported by medication, whereas compensatory benefits were maintained during OFF states. These results validate the system's capability to quantitatively differentiate medication states and deliver timely assistance when pharmacological effects are minimal.

By combining gait parameter logging, fall detection, and GPS-based safety tracking in a lightweight footwear platform, the system offers a clinically relevant, cost-effective, and scalable solution for hospital rehabilitation and home monitoring. Its closed-loop cueing mechanism, triggering visual and tactile cues only in response to detected gait irregularities, proved effective in reducing step initiation delay, improving cadence, and enhancing gait regularity. Beyond motor outcomes, the system also holds potential to indirectly mitigate FoG-related anxiety, contributing to improved quality of life for patients.

However, this study is limited by its small sample size (n = 6) and the exploratory nature of its statistical validation, which constrains generalizability. Therefore, the results should be interpreted as preliminary but promising evidence of feasibility. Future work will focus on expanding measurable parameters, including stride length, symmetry, and stance–swing ratio, and incorporating Artificial Intelligence (AI) and Machine Learning (ML) algorithms for predictive anomaly detection, adaptive cueing, and personalized response tuning. Larger longitudinal clinical trials with diverse PD populations are planned to validate these outcomes and establish the system's potential as a digital biomarker and scalable rehabilitation tool within smart healthcare ecosystems.

ACKNOWLEDGMENTS

We express our sincere gratitude to Sri Jayachamarajendra College of Engineering, JSS Science and Technology University, Mysuru, for providing the necessary research facilities and institutional support. We also sincerely thank JSS Medical College, JSS Academy of Higher Education & Research (JSS AHER), Mysuru, for their valuable guidance and for facilitating access to patients, which was essential for testing and validating the developed device.

ETHICAL APPROVAL

All experimental procedures involving human participants adhered to institutional ethical guidelines and were approved by the Ethics Committee of JSS Medical College, JSS Academy of Higher Education and Research (JSS AHER), Mysuru.

REFERENCES

[1] L. Kumar, M. Malhotra, A. P. Singh, and A. P. Singh, "Comprehensive Review on Parkinson's Disease: Insights into Prevalence, Pathophysiology, Diagnosis, and Multifaceted Treatment Approaches," *Journal of Drug Delivery and Therapeutics*, vol. 14, no. 6, pp. 200–213, June 2024, https://doi.org/10.22270/jddt.v14i6.6637.

[2] S. Cordillet *et al.*, "Detecting Freezing of Gait in Parkinson Disease Using Multiple Wearable Sensors Sets During Various Walking Tasks Relative to Medication Conditions (DetectFoG): Protocol for a Prospective Cohort Study," *JMIR Research Protocols*, vol. 14, no. 1, Feb. 2025, Art. no. e58612, https://doi.org/10.2196/58612.

[3] C. Cosentino *et al.*, "One cue does not fit all: A systematic review with meta-analysis of the effectiveness of cueing on freezing of gait in Parkinson's disease," *Neuroscience & Biobehavioral Reviews*, vol. 150, July 2023, Art. no. 105189, https://doi.org/10.1016/j.neubiorev.2023.105189.

[4] E. C. Klaver, J. P. P. van Vugt, B. R. Bloem, R. J. A. van Wezel, J. Nonnekes, and M. C. Tjepkema-Cloostermans, "Good vibrations: tactile cueing for freezing of gait in Parkinson's disease," *Journal of Neurology*, vol. 270, no. 7, pp. 3424–3432, July 2023, https://doi.org/10.1007/s00415-023-11663-9.

[5] S. Cen *et al.*, "Vibrotactile Foot Device for Freezing of Gait in Parkinson's Disease: A Pilot Study," *Movement Disorders Clinical Practice*, vol. 11, no. 10, pp. 1241–1248, Oct. 2024, https://doi.org/10.1002/mdc3.14177.

[6] H.-L. Chan *et al.*, "Laser-light cueing shoes with integrated foot pressure and inertial sensing for investigating the impact of visual cueing on gait characteristics in Parkinson's disease individuals," *Frontiers in Bioengineering and Biotechnology*, vol. 12, Jan. 2024, Art. no. 1334403, https://doi.org/10.3389/fbioe.2024.1334403.

[7] S. K. Bansal, B. Basumatary, R. Bansal, and A. K. Sahani, "Techniques for the detection and management of freezing of gait in Parkinson's disease - A systematic review and future perspectives," *MethodsX*, vol. 10, Mar. 2023, Art. no. 102106, https://doi.org/10.1016/j.mex.2023.102106.

[8] D. Sweeney, L. R. Quinlan, P. Browne, M. Richardson, P. Meskell, and G. ÓLaighin, "A Technological Review of Wearable Cueing Devices Addressing Freezing of Gait in Parkinson's Disease," *Sensors*, vol. 19, no. 6, Mar. 2019, Art. no. 1277, https://doi.org/10.3390/s19061277.

[9] J.-M. Park *et al.*, "Detection of freezing of gait in Parkinson's disease from foot-pressure sensing insoles using a temporal convolutional neural network," *Frontiers in Aging Neuroscience*, vol. 16, July 2024, Art. no. 1437707, https://doi.org/10.3389/fnagi.2024.1437707.

[10] G. Shalin, S. Pardoel, E. D. Lemaire, J. Nantel, and J. Kofman, "Prediction and detection of freezing of gait in Parkinson's disease from plantar pressure data using long short-term memory neural-networks," *Journal of NeuroEngineering and Rehabilitation*, vol. 18, no. 1, Nov. 2021, Art. no. 167, https://doi.org/10.1186/s12984-021-00958-5.

[11] L. Borzì, L. Sigcha, D. Rodríguez-Martín, and G. Olmo, "Real-time detection of freezing of gait in Parkinson's disease using multi-head convolutional neural networks and a single inertial sensor," *Artificial Intelligence in Medicine*, vol. 135, Jan. 2023, Art. no. 102459, https://doi.org/10.1016/j.artmed.2022.102459.

[12] A. Khosla, N. Kumar, and P. Khera, "Machine learning approach for predicting state transitions via shank acceleration data during freezing of gait in Parkinson's disease," *Biomedical Signal Processing and Control*, vol. 92, June 2024, Art. no. 106053, https://doi.org/10.1016/j.bspc.2024.106053.

[13] T. Bikias, D. Iakovakis, S. Hadjidimitriou, V. Charisis, and L. J. Hadjileontiadis, "DeepFoG: An IMU-Based Detection of Freezing of Gait Episodes in Parkinson's Disease Patients via Deep Learning," *Frontiers in Robotics and AI*, vol. 8, May 2021, Art. no. 537384, https://doi.org/10.3389/frobt.2021.537384.

[14] B. Filtjens, P. Ginis, A. Nieuwboer, P. Slaets, and B. Vanrumste, "Automated freezing of gait assessment with marker-based motion capture and multi-stage spatial-temporal graph convolutional neural networks," *Journal of NeuroEngineering and Rehabilitation*, vol. 19, no. 1, May 2022, Art. no. 48, https://doi.org/10.1186/s12984-022-01025-3.

[15] Y. L. Ng, X. Jiang, Y. Zhang, S. B. Shin, and R. Ning, "Automated Activity Recognition with Gait Positions Using Machine Learning Algorithms," *Engineering, Technology & Applied Science Research*, vol. 9, no. 4, pp. 4554–4560, Aug. 2019, https://doi.org/10.48084/etasr.2952.

[16] M. Alanazi, R. S. Aldahr, and M. Ilyas, "Human Activity Recognition through Smartphone Inertial Sensors with ML Approach," *Engineering, Technology & Applied Science Research*, vol. 14, no. 1, pp. 12780–12787, Feb. 2024, https://doi.org/10.48084/etasr.6586.

[17] A. Marcante *et al.*, "Foot Pressure Wearable Sensors for Freezing of Gait Detection in Parkinson's Disease," *Sensors*, vol. 21, no. 1, Jan. 2021, Art. no. 128, https://doi.org/10.3390/s21010128.

[18] X. Qian *et al.*, "The Smart Insole: A Pilot Study of Fall Detection," in *14th EAI International Conference on Body Area Networks (BODYNETS 2019)*, Florence, Italy, 2019, pp. 37–49, https://doi.org/10.1007/978-3-030-34833-5_4.

[19] B. Yang *et al.*, "Intelligent wearable system with accurate detection of abnormal gait and timely cueing for mobility enhancement of people with Parkinson's disease," *Wearable Technologies*, vol. 3, June 2022, Art. no. e12, https://doi.org/10.1017/wtc.2022.9.

[20] D. J. Warrington, E. J. Shortis, and P. J. Whittaker, "Are wearable devices effective for preventing and detecting falls: an umbrella review (a review of systematic reviews)," *BMC Public Health*, vol. 21, no. 1, Nov. 2021, Art. no. 2091, https://doi.org/10.1186/s12889-021-12169-7.

[21] A. Louja, I. Drira, A. Jamali, N. Naja, and L. Sliman, "Wearable sensor-based eye-rubbing monitoring: a hybrid CNN-attentionrub architecture for keratoconus prevention," *The Journal of Supercomputing*, vol. 81, no. 13, Aug. 2025, Art. no. 1268, https://doi.org/10.1007/s11227-025-07744-3.

[22] A. Louja, A. Jamali, and N. Naja, "Blockchain-Powered Artificial Intelligence for Healthcare Systems Data Orchestration," in *Proceedings of the Third ICMDS'24: Machine Learning, Inverse Problems and Related Fields*, Khourigba, Morocco, 2024, pp. 155–163, https://doi.org/10.1007/978-3-031-94802-2_15.

[23] A. Louja, Y. Zaiouane, A. Jamali, and N. Naja, "DS-HViT: A Dual-Stream Hierarchical Vision Transformer for Multi-Scale Analysis of Parkinson's Disease Handwriting," *Engineering, Technology & Applied Science Research*, vol. 15, no. 5, pp. 28157–28164, Oct. 2025, https://doi.org/10.48084/etasr.12833.

[24] C. G. Goetz *et al.*, "Movement Disorder Society-sponsored revision of the Unified Parkinson's Disease Rating Scale (MDS-UPDRS): Scale presentation and clinimetric testing results," *Movement Disorders*, vol. 23, no. 15, pp. 2129–2170, Nov. 2008, https://doi.org/10.1002/mds.22340.

[25] B. Heim and A. Djamshidian, "Neuropsychiatric disorders in Parkinson's disease," *Therapeutic Advances in Neurological Disorders*, vol. 18, Jan. 2025, Art. no. 17562864251356062, https://doi.org/10.1177/17562864251356062.