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Intelligent Multi Sensor System for Parkinsonian Gait Pattern Analysis

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ABSTRACT: Parkinson's disease (PD) is a chronic neurodegenerative condition that progressively impairs motor function and results in distinctive abnormalities in gait patterns. Quantitative evaluation of gait signals provides an effective and objective method for early diagnosis as well as continuous monitoring of disease progression. In this study, a spatio-temporal deep learning framework is proposed to identify Parkinsonian gait using vertical ground reaction force (VGRF) signals acquired from pressure-sensitive insole sensors. The multi-sensor data are modeled as a graph structure to preserve the anatomical connectivity between plantar sensing locations. A Graph Convolutional Network (GCN) is employed to learn spatial pressure distribution characteristics across the foot, while a Long Short-Term Memory (LSTM) network captures temporal patterns present in gait cycles. An attention mechanism is incorporated to emphasize the most relevant temporal segments contributing to accurate classification. Experimental validation conducted on the PhysioNet gait dataset demonstrates promising performance, achieving 90% accuracy at the window level and 93% accuracy at the subject level, indicating strong discriminative ability. Analysis of spatial sensor relevance and temporal attention weights reveals clinically meaningful gait phases. The proposed framework provides an interpretable and dependable approach for gait-based screening and assessment of Parkinson's disease.

KEYWORDS: Parkinson's Disease, Gait Analysis, Spatio-Temporal Modeling, Graph Convolutional Network, Long Short-Term Memory, Vertical Ground Reaction Force.

I. INTRODUCTION

Parkinson's disease (PD) is a progressive neurodegenerative disorder that affects motor function due to the degeneration of dopaminergic neurons in the substantia nigra. The resulting deficiency of dopamine disrupts the regulation of voluntary movement, leading to symptoms such as bradykinesia, rigidity, tremor, and postural instability. These motor impairments significantly affect an individual's ability to perform daily activities and reduce overall quality of life. Among the various motor symptoms, gait impairment is one of the most clinically significant manifestations of PD. Walking, which is normally an automatic and coordinated activity, becomes increasingly irregular and unstable as the disease progresses. Patients typically exhibit reduced stride length, slower walking speed, shuffling steps, and impaired balance. In many cases, these gait abnormalities appear in the early stages of the disease, even before severe symptoms become evident. This makes gait an important and reliable indicator for early detection and monitoring of PD. Despite its importance, clinical evaluation of PD is largely based on observational methods and rating scales such as the Unified Parkinson's Disease Rating Scale (UPDRS). These methods depend heavily on clinician expertise and are inherently subjective. Subtle abnormalities in gait, particularly during the early stages of the disease, may not be consistently identified through visual assessment alone. This limitation highlights the need for objective and quantitative approaches for analyzing gait. Gait is a complex biomechanical process that involves coordinated interaction between the nervous system and the musculoskeletal system. A normal gait cycle consists of a sequence of repetitive phases that ensure stable and efficient locomotion. These phases are characterized by consistent timing and predictable force distribution across the foot. The gait cycle is defined as the time interval between two consecutive contacts of the same foot with the ground. It is broadly divided into stance and swing phases, which together form a continuous and coordinated movement pattern. Proper coordination between stance and swing phases ensures smooth and energy-efficient walking. Any disruption in this coordination reflects abnormalities in motor control. Stance phase (≈60% of the gait cycle): This phase occurs when the foot is in contact with the ground, providing

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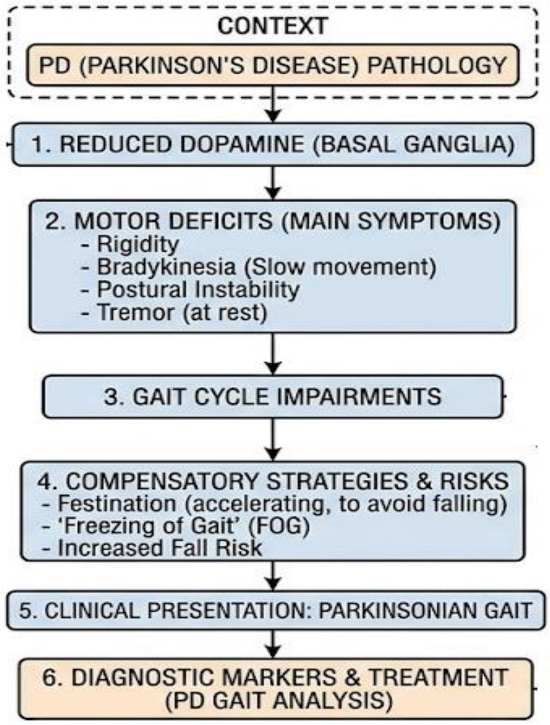
support and stability for the body. Parkinsonian gait is characterized by distinct abnormalities that arise from impaired motor coordination. The loss of dopaminergic control affects movement initiation and execution, leading to reduced stride length, slower walking speed, and a shuffling pattern. Patients often exhibit decreased arm swing and a stooped posture, which further contributes to instability. Modern gait analysis systems use wearable sensors such as pressure-sensitive insoles to record force signals during walking. In multi-sensor systems, sensors are distributed across different regions of the foot, enabling detailed measurement of force distribution over time. This results in high-dimensional data that captures both temporal variations and spatial relationships.

II. LITERATURE REVIEW

Machine learning approach to gait analysis for Parkinson's disease detection and severity classification AUTHORS: Mittal, R., Agarwal, N., Dubey, M., Pathak, V., Shukla, P., Rani, G., Vocaturo, E., and Zumpano, E. YEAR: 2025 DESCRIPTION: The study develops a ML-based framework for PD severity classification using ground reaction force signals obtained from PhysioNet and share datasets. Classification models, including Decision Tree, Random Forest, Extreme Gradient Boosting, and LightGBM, are evaluated against Hoehn and Yahr staging scores. Quantitative analysis of gait parameters in Parkinson's disease and the clinical significance AUTHORS: Yin, W., Gao, H., Liang, B., Liu, R., Liu, Y., Shen, C., Niu, X., and Wang. YEAR: 2025 DESCRIPTION: The study quantifies gait characteristics in PD by comparing 20 patients with 17 healthy controls and evaluating changes before and after levodopa administration. Gait analysis in the early stage of Parkinson's disease with a machine learning approach AUTHORS: Yin, W., Zhu, W., Gao, H., Niu, X., Shen, C., Fan, X., and Wang, C. YEAR: 2024 DESCRIPTION: The study employs a non-contact gait assessment system to quantify spatiotemporal gait characteristics in early-stage PD. Measured parameters, including stride length, gait speed, cadence, swing speed, and turning time, exhibit significant deviations in patients compared to healthy controls.



III. METHODOLOGY

The proposed system introduces a structured spatio-temporal framework for PD detection using VGRF signals. The system models gait as a graph-based temporal process. Multi-sensor signals are represented as nodes in a graph, where edges encode spatial relationships derived from sensor coordinates. GCN is applied to extract spatial features, followed by temporal modeling using LSTM. An attention mechanism is incorporated to identify the most informative segments

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of the gait sequence. The model outputs are calibrated to improve reliability, and predictions are aggregated to produce subject-level diagnoses.

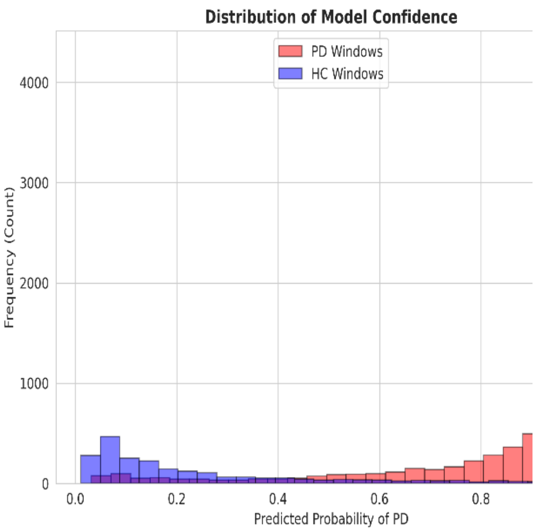
3.1 BLOCK SCHEMATIC

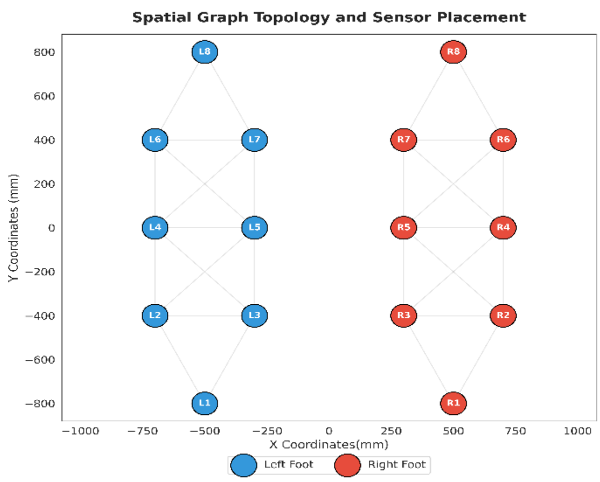
Direct learning from raw VGRF signals eliminates reliance on handcrafted feature extraction. Graph-based representation preserves spatial relationships among sensors based on physical topology. Spectral GCN captures force distribution patterns across anatomically relevant regions of the foot. Temporal modeling using LSTM effectively captures sequential dependencies and gait cycle dynamics. Attention mechanism highlights the most informative temporal segments, improving classification performance. Subject-level data splitting ensures realistic evaluation and prevents data leakage. Sliding window segmentation increases data utilization while preserving temporal continuity. Temperature scaling improves probability calibration, enhancing reliability for clinical decision-making. Subject-level prediction aggregation provides stable and clinically meaningful diagnosis. Integration of clinical feature extraction enables interpretability and correlation with biomedical indicators. Multi-seed evaluation improves robustness and reduces variance in model performance.

IV. RESULTS & DISCUSSION

The spatial modeling stage represents the 16 insole sensors as nodes in a graph structure, enabling the model to capture spatial dependencies in plantar pressure distribution. Fig. 4.3 illustrates the constructed sensor topology, where each node corresponds to a specific anatomical location on the foot and edges represent spatial relationships between sensors.

The graph structure preserves the physical arrangement of sensors across both feet, allowing the model to learn localized interactions between adjacent regions such as the heel, midfoot, and forefoot. Strong connections are formed between anatomically proximal sensors, while distant relationships are suppressed through distance-based thresholding. This design ensures that spatial feature propagation occurs primarily among physiologically meaningful sensor regions. Graph convolutional operations propagate information across neighboring sensors, enabling the model to capture regional pressure patterns during gait.





V. CONCLUSION

This study proposes a spatio-temporal deep learning framework for automated Parkinson's Disease (PD) detection using VGRF signals. By combining graph-based spatial modeling with temporal sequence learning, the system effectively captures the complex gait patterns associated with Parkinsonian movement. The results demonstrate high classification performance at both window-level and subject-level analyses, supported by strong ROC and Precision–Recall metrics. This dual-level evaluation enables accurate identification of localized gait abnormalities while ensuring consistent and reliable patient-level diagnosis. A key contribution of this work is enhancing the clinical interpretability of deep learning models. Through the integration of attention mechanisms and sensor importance analysis, the framework highlights critical gait phases and foot regions relevant for diagnosis. Additionally, the extracted clinical biomarkers—such as stride variability, gait asymmetry, and double support time—closely align with established neurological indicators of Parkinson's Disease.

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