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DIGITAL BIOMARKERS FOR PARKINSON'S DISEASE MONITORING: WEARABLE SENSORS, SMARTPHONE APPLICATIONS, AND MACHINE LEARNING ANALYTICS

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ABSTRACT

Parkinson's disease (PD) affects approximately 10 million people globally and is characterised by progressive motor symptoms — tremor, rigidity, bradykinesia, and postural instability — alongside a spectrum of non-motor manifestations including cognitive decline, autonomic dysfunction, and sleep disorders. Current clinical assessment relies on periodic in-clinic evaluation using rating scales such as the Movement Disorder Society Unified Parkinson's Disease Rating Scale (MDS-UPDRS), which captures a brief snapshot of motor function and is subject to inter-rater variability and recall bias. Digital biomarkers derived from wearable inertial sensors, smartwatches, smartphones, and voice analysis have emerged as objective, continuous, and ecologically valid measures of PD symptom severity that complement and potentially extend traditional clinical assessment. This review analyses 52 studies of digital biomarker development and validation for PD monitoring published between 2016 and 2024, evaluating sensor modalities,

machine learning approaches, and clinical validation status. Implications for PD monitoring in Uzbekistan's neurology services are discussed.

Keywords: Parkinson's disease; digital biomarkers; wearable sensors; tremor; gait analysis; machine learning; remote monitoring

1. INTRODUCTION

Parkinson's disease is the second most prevalent neurodegenerative disorder globally, with incidence increasing substantially with age and prevalence projected to double by 2040 as population ageing accelerates (GBD 2016 Parkinson's Disease Collaborators, 2018). The cardinal motor features — resting tremor, bradykinesia, rigidity, and postural instability — arise from progressive degeneration of dopaminergic neurons in the substantia nigra and are the primary targets of pharmacological and surgical treatment. Optimising PD therapy requires accurate, longitudinal assessment of motor symptom severity and treatment response — a requirement that is difficult to meet through periodic clinic visits that capture only a brief, potentially unrepresentative snapshot of the patient's daily motor function.

Digital biomarkers — quantitative physiological or behavioural measures collected through digital technologies during the activities of daily living — offer a solution to this assessment gap. Inertial measurement units (IMUs) in smartwatches and dedicated wearable devices can continuously monitor tremor amplitude, gait parameters (step length, cadence, stride velocity), postural sway, and bradykinesia metrics with temporal resolution and ecological validity impossible to achieve in the clinic. Smartphone-based assessments — tapping tests, voice analysis, walking tests activated through mobile applications — provide semi-structured digital assessment of PD symptoms that can be

performed daily at home, generating longitudinal datasets orders of magnitude richer than conventional clinic visit data (Bhidayasiri et al., 2023).

Machine learning applied to these continuous and semi-continuous data streams can identify symptom patterns, detect motor fluctuations (the 'on-off' phenomenon characteristic of advancing PD), predict clinical rating scale scores, and potentially identify pre-symptomatic PD from subtle motor and autonomic signals. The aim of this review is to synthesise the evidence on digital biomarkers for PD monitoring, evaluate the clinical validation status of leading approaches, and identify priorities for implementation in neurology services with limited specialist capacity.

2. MATERIALS AND METHODS

A systematic search of PubMed, Scopus, and IEEE Xplore identified 52 studies of digital biomarker development and validation for PD monitoring published between 2016 and 2024. Studies were included if they reported validation of a digital measure against an established clinical standard (MDS-UPDRS, H&Y staging, or expert clinical assessment) in a PD patient sample of at least 20 participants. Studies were categorised by sensor modality (IMU wearable, smartwatch, smartphone, or voice analysis), machine learning method, and clinical outcome.

Correlation coefficients between digital biomarker output and MDS-UPDRS scores were extracted as the primary validity metric. Studies providing longitudinal or home-based validation were distinguished from those providing single-session laboratory validation, given the substantially greater clinical relevance of the former.

3. RESULTS

IMU-based wrist tremor monitors demonstrated correlation with MDS-UPDRS tremor subscores of r = 0.72–0.91 in included studies, with the highest correlations observed for devices worn continuously over 24–48 hours compared with single-session assessments. Gait analysis using bilateral ankle-worn IMUs showed significant correlations with MDS-UPDRS gait and postural instability subscores (r = 0.68–0.87) and detected motor fluctuations between on and off states with sensitivity of 82–94% and specificity of 78–91%. Smartphone tapping tests correlated with bradykinesia ratings (r = 0.70–0.88), while voice analysis demonstrated sensitivity of 75–91% for PD versus healthy control discrimination. Longitudinal home-based monitoring studies — available in 14 of 52 included studies — consistently demonstrated that home-based digital biomarker data provided richer characterisation of motor fluctuations than clinic-based assessment, identifying on-off transitions missed in 60–80% of clinic visits in three studies using continuous monitoring.

4. DISCUSSION

The results confirm that digital biomarkers from wearable and smartphone-based technologies provide clinically meaningful, objective measures of PD motor symptoms that correlate significantly with established rating scales. The superior characterisation of motor fluctuations through continuous home monitoring — compared with periodic clinic visits — has direct implications for treatment optimisation, particularly for the timing and dosing of levodopa therapy in advanced PD. For Uzbekistan, where neurological specialist density is limited and patients often travel significant distances for clinic appointments, digital biomarker-enabled remote PD monitoring offers the potential to reduce the

frequency of in-person visits while improving the quality of monitoring data available to treating neurologists.

5. CONCLUSION

Digital biomarkers derived from wearable sensors and smartphone applications provide objective, continuous, and ecologically valid measures of Parkinson's disease motor severity that significantly extend traditional clinical assessment capabilities. IMU-based tremor and gait monitoring, smartphone tapping tests, and voice analysis demonstrate clinically meaningful correlations with established rating scales and superior detection of motor fluctuations compared with clinic visit assessment. Implementation in Uzbekistan's neurology services could significantly improve PD management quality and access, particularly for patients in regions remote from specialist neurology centres. Future research priorities include longitudinal validation in diverse populations, regulatory pathway development, and integration with existing neurology clinic workflows.

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