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(REVIEW ARTICLE)

EVALUATING THE TRANSLATIONAL READINESS OF CONSUMER WEARABLES IN PARKINSON'S DISEASE: FROM MEASUREMENT TO CLINICAL UTILITY

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ABSTRACT

Parkinson's disease (PD) is characterized by substantial temporal variability in motor and non-motor manifestations, whereas conventional clinical assessments provide only intermittent observations of disease status. Consumer wearable devices offer an opportunity to capture longitudinal physiological and behavioral information in patients' everyday environments. However, measuring a physiological signal does not necessarily establish clinical validity or utility. Consumer wearables can capture movement characteristics, tremor, gait, physical activity, sleep-related measures, and cardiovascular signals, but the evidence remains heterogeneous. Technical feasibility and associations with clinical assessments substantially outnumber studies demonstrating improved clinical decision-making or patient outcomes. Major barriers include device heterogeneity, proprietary algorithms, inconsistent outcome definitions, limited reference values, laboratory-to-real-world performance gaps, adherence challenges, and difficulties integrating continuous data into clinical workflows. Consumer wearables therefore currently have stronger evidence as complementary monitoring tools than as independent systems for clinical decision-making. Their future clinical role will depend on reproducible digital biomarkers, clinically meaningful reference values, real-world validity, prospective evidence of clinical utility, and sustainable implementation. A five-stage translational framework, measurement capability, clinical validity, clinical interpretability, clinical utility, and implementation readiness, is used to distinguish technological promise from demonstrated clinical value.

Keywords: Parkinson's Disease, Consumer Wearables, Digital Biomarkers, Digital Health, Clinical Utility, Wearable Sensors

1 INTRODUCTION

Parkinson's disease (PD) is a progressive neurodegenerative disorder characterized by substantial heterogeneity in motor and non-motor manifestations and marked variability over time [1]. Symptoms may fluctuate with medication state, activity, and daily circumstances, making brief clinical assessments an incomplete representation of a patient's experience [2]. Although clinical examination and standardized instruments such as the Movement Disorder Society-

Unified Parkinson's Disease Rating Scale (MDS-UPDRS) remain fundamental to PD diagnosis and management [3], they provide only intermittent observations. Patient-reported diaries can extend monitoring into the home environment but are limited by recall, reporting burden, incomplete recording, and difficulty documenting brief or unpredictable events [4].

Consumer wearable technologies offer an opportunity to address this temporal limitation. Accelerometers, gyroscopes, photoplethysmography (PPG), and other sensors incorporated into wrist-worn devices, rings, footwear, and related platforms can generate repeated or continuous measurements during everyday life [5]. These technologies have been investigated for tremor, bradykinesia, dyskinesia, gait impairment, freezing of gait (FoG), physical activity, sleep, and cardiovascular parameters [5]. Their potential value lies not simply in collecting more data, but in providing longitudinal observations in the patient's natural environment, where symptom patterns may not be apparent during a brief clinical examination.

However, measurement capability does not necessarily establish clinical value. A sensor may capture wrist oscillations without demonstrating specificity for Parkinsonian tremor, while a digital measure may correlate with a clinical rating scale without an established threshold for clinically meaningful change [6]. Even a validated measure may have uncertain clinical utility if acting on its output has not been shown to improve patient management or outcomes [7]. Furthermore, consumer wearables differ in sensors, sampling characteristics, processing pipelines, algorithms, and data-access policies, limiting direct generalization across platforms [8].

This review examines the current evidence for consumer wearable monitoring of motor and non-motor manifestations of PD and evaluates the extent to which wearable-derived measurements have progressed from technical measurement toward clinical validity, interpretability, utility, and implementation.

2 WEARABLE MONITORING OF MOTOR AND NON-MOTOR MANIFESTATIONS

2.1 Tremor and Bradykinesia

2.1.1 Tremor

Tremor is among the most intuitive targets for wearable monitoring because its rhythmic characteristics can be quantified using inertial sensors [9]. Accelerometers measure linear acceleration, while gyroscopes capture angular velocity [5], and these signals can be analyzed using frequency-domain methods or machine-learning algorithms to characterize oscillatory movement. Research has demonstrated that wearable-derived movement measures can identify tremor-related characteristics and may correlate with clinician-based assessments, supporting the feasibility of continuous monitoring outside the clinic [10]. Detection of oscillatory movement, however, is not equivalent to identification of Parkinsonian tremor [13]. Eating, writing, typing, dressing, and manipulating objects can generate movement patterns that overlap with tremor-related signals. Clinical performance therefore depends not only on sensitivity to oscillatory movement but also on the ability to discriminate pathological tremor from normal activity. Consumer devices also differ in sensor characteristics and proprietary signal-processing algorithms, so performance reported for one platform cannot automatically be generalized to another [13]. Wearable tremor monitoring is consequently best regarded as a complementary measure, with future studies needing free-living validation, false-positive and false-negative reporting, and evidence that the information adds clinical value beyond conventional assessment.

2.1.2 Bradykinesia

Bradykinesia presents a more complex measurement problem because it encompasses slowness, reduced amplitude, and decrement rather than a single physiological signal [14]. Wearable studies have therefore examined movement velocity, amplitude, frequency, arm swing, repetitive movement characteristics, and overall mobility. Associations with conventional assessments support longitudinal monitoring, but a wearable parameter may capture only one component of the broader clinical construct and should not be interpreted as equivalent to the full assessment.

2.2 Motor Fluctuations and Treatment-Related Motor States

Continuous wearable monitoring may offer particular value for capturing motor fluctuations that are difficult to observe during periodic clinical assessments. By providing movement data across the day, wearables may help characterize changes in motor performance in relation to medication timing and identify patterns that are not evident during clinic visits. However, their clinical value depends on whether these temporal patterns can reliably distinguish treatment-related motor states, such as wearing-off and dyskinesia, from ordinary variations in daily movement [15]. The key question is therefore not simply whether wearables can detect fluctuations, but whether the information they provide can support more accurate and effective treatment decisions. Prospective studies should consequently determine

whether wearable-informed medication adjustments lead to measurable improvements in symptom control, adverse effects, quality of life, or other patient-centered outcomes.

2.3 Gait, Mobility, and Freezing of Gait

2.3.1 Gait and mobility

Gait dysfunction is a major determinant of disability and falls in PD and is therefore an important target for remote monitoring [16]. Wearable systems can quantify walking speed, cadence, stride characteristics, gait variability, asymmetry, and other aspects of mobility. Sensor placement influences the information obtained: wrist-worn devices may provide indirect measures of mobility, whereas sensors located at the waist, ankle, shoe, or insole can capture lower-limb dynamics more directly [17]. Commercially available devices therefore differ in their capacity to measure specific gait parameters.

2.3.2 Freezing of gait

Freezing of gait (FoG) is particularly challenging because episodes are episodic, context-dependent, and often triggered by turning, gait initiation, obstacles, or restricted spaces [18]. Algorithms developed under standardized laboratory conditions may therefore encounter substantially greater variability during everyday activity. This creates a fundamental distinction between laboratory accuracy and real-world validity: high sensitivity during predefined walking tasks does not establish equivalent performance during unrestricted daily activity [19]. Future studies should evaluate FoG during prolonged free-living monitoring and report sensitivity, specificity, false-positive rates, episode duration, adherence, and relationships with clinically important outcomes such as falls.

2.4 Sleep and Autonomic Physiology

2.4.1 Sleep

Wearable monitoring also extends to sleep and cardiovascular/autonomic physiology [20; 21]. Sleep disturbances in PD include insomnia, fragmented sleep, excessive daytime sleepiness, and REM sleep behavior disorder (RBD) [22]. Consumer wearables can estimate sleep-related parameters using combinations of movement and cardiovascular signals and offer the practical advantage of repeated monitoring across many nights without a dedicated laboratory environment [23]. These estimates, however, should not be regarded as equivalent to polysomnography because sleep states are inferred indirectly and performance varies across devices and algorithms. Increased nocturnal movement may provide useful longitudinal information, but it should not be interpreted as an independent diagnostic test for RBD; clinical evaluation and, when appropriate, polysomnography remain necessary.

2.4.2 Cardiovascular/ Autonomic physiology

PPG sensors incorporated into consumer watches and rings can continuously estimate heart rate and may permit calculation of heart rate variability (HRV) [21]. These measures are potentially relevant because autonomic dysfunction is an important component of PD. Nevertheless, HRV is influenced by age, physical activity, sleep, medications, cardiovascular disease, respiratory patterns, and psychological stress [24]. An isolated abnormal HRV measurement therefore cannot be considered a specific digital biomarker of PD-related autonomic dysfunction [24]. Greater potential may lie in longitudinal and multimodal monitoring, in which cardiovascular measures are interpreted alongside symptoms, activity, medication exposure, and other physiological parameters. Whether such monitoring improves detection or management remains insufficiently established.

Table 1 summarizes the principal clinical domains investigated using consumer wearable technologies in Parkinson's disease, together with the parameters measured, reference standards, monitoring settings, evidence demonstrated, and key limitations:

Table 1: Overview of wearable and sensor-based technologies for monitoring key clinical domains in Parkinson's disease.

Clinical domain	Wearable/sensor	Main parameter(s)	Reference/comparator	Monitoring setting	Evidence demonstrated	Key limitation
Tremor	Accelerometer/gyroscope	Frequency, amplitude, tremor burden	Clinical assessment/reference sensor	Laboratory/free-living	Quantification and association with clinical measures	Specificity and device heterogeneity
Bradykinesia	Accelerometer/gyroscope/smartwatch	Movement amplitude, velocity, frequency, arm swing	Clinical assessment/MDS-UPDRS	Laboratory/free-living	Association with motor impairment	Does not reproduce the full clinical construct
Dyskinesia/motor fluctuations	Inertial sensors/smartwatch	Abnormal movement, activity changes	Clinical assessment/medication state	Free-living	Longitudinal characterization	Clinical actionability insufficiently established
Gait/FoG	Waist/ankle/footwear/inertial sensors	Speed, cadence, stride, variability, asymmetry, FoG	Video/clinical assessment/reference system	Laboratory/free-living	Detection and quantification of gait abnormalities	Laboratory-to-real-world gap
Physical activity	Wrist/hip/other activity sensors	Steps, activity duration, mobility	Actigraphy/clinical measures	Free-living	Longitudinal activity profiling	Not disease-specific
Sleep	Smartwatch/ring/actigraphy	Sleep duration, fragmentation, sleep-wake pattern	PSG/actigraphy	Home/laboratory	Repeated longitudinal sleep estimation	Indirect estimation; not equivalent to PSG
Autonomic/cardiovascular	PPG	HR, HRV	ECG/clinical assessment	Free-living/laboratory	Continuous physiological monitoring	Multiple confounders; limited disease specificity

Collectively, these applications demonstrate broad measurement capability, but the clinical maturity of individual wearable-derived measures varies substantially. The next question is therefore not simply what wearables can measure, but how those measurements should be evaluated for clinical relevance

3 FROM WEARABLE MEASUREMENT TO CLINICALLY MEANINGFUL DIGITAL BIOMARKERS

The clinical maturity of a consumer wearable should not be determined solely by its ability to generate sensor data. A clinically meaningful digital biomarker requires progression through five related but distinct stages: measurement capability, clinical validity, clinical interpretability, clinical utility, and implementation readiness. This framework distinguishes technological feasibility from demonstrated clinical value.

The first stage, measurement capability, asks whether the device can reliably capture the physiological or behavioral signal of interest. An accelerometer, for example, may reliably detect rhythmic wrist movement without establishing that the movement represents Parkinsonian tremor [25]. The second stage, clinical validity, asks whether the wearable-derived measurement represents the intended clinical phenomenon and requires comparison with an appropriate reference standard, such as a standardized clinical assessment, clinician rating, physiological measurement, or established measurement method. Importantly, validity demonstrated under controlled conditions should not automatically be extrapolated to free-living environments.

The third stage, clinical interpretability, concerns whether a valid measurement can be translated into clinically meaningful information for an individual patient. Statistical changes in tremor burden, gait variability, activity, or other parameters do not necessarily indicate clinically important deterioration. Interpretation therefore requires appropriate reference values, individualized baselines, understanding of within-person variability, and clinically meaningful thresholds.

The fourth stage, clinical utility, asks whether using the wearable-derived information improves clinical decision-making or patient outcomes. A wearable may identify changes associated with medication response, for example, but clinical utility requires evidence that incorporating this information into care improves outcomes such as symptom control, adverse effects, quality of life, or functional status [7]. This represents a substantially higher evidentiary threshold than technical validation or correlation with conventional clinical measures.

The final stage, implementation readiness, concerns whether a clinically useful technology can be integrated sustainably into routine care. Adherence, cost, data privacy, interoperability, cybersecurity, clinician workload, and integration with existing health-information systems are relevant considerations [8; 26]. These stages are progressive but non-interchangeable: a device may measure a signal without validating it, validate a measure without establishing its clinical meaning, establish meaning without demonstrating benefit, or demonstrate benefit without being ready for routine implementation.

4 METHODOLOGICAL, TRANSLATIONAL, AND CLINICAL CHALLENGES

Several barriers currently limit the translation of consumer wearable measurements into routine clinical practice. These limitations extend beyond sensor accuracy and concern reproducibility across devices, interpretation at the individual-patient level, performance under real-world conditions, and the ability to translate wearable-derived information into meaningful clinical decisions.

Device and algorithm heterogeneity is a fundamental challenge. Commercial platforms differ in sensor configuration, sampling characteristics, signal-processing procedures, proprietary algorithms, and access to raw data, making results obtained from one device difficult to generalize to another [27]. Differences in sensor placement, sampling frequency, preprocessing, outcome definitions, reference standards, and algorithm versions can further limit comparability between studies [13]. A digital outcome may therefore reflect characteristics of a particular device or processing pipeline rather than a transferable measurement. Greater standardization of device specifications, processing procedures, outcome definitions, and reporting practices is needed to facilitate independent validation and meaningful comparison.

Proprietary processing introduces a related problem. Consumer devices frequently provide derived scores rather than raw physiological signals, limiting the ability to reproduce analyses or determine how a clinically relevant measure was generated. Although commercial algorithms do not necessarily need to be open source, sufficient methodological transparency is required to evaluate whether an observed change represents a genuine change in the clinical phenomenon of interest. This is particularly relevant in PD, where movement signals are strongly influenced by activity and context [28].

A second major challenge is the transition from controlled validation to free-living performance. Many algorithms are developed or tested during standardized tasks under supervised conditions. Such studies establish whether a sensor can detect a predefined signal but may not reproduce the complexity of everyday behavior [19; 29]. During daily life, patients encounter different surfaces, environmental conditions, concurrent activities, walking aids, and medication-related fluctuations that may alter the signals on which an algorithm was trained [30]. This problem is especially important for gait and freezing of gait. Validation should therefore distinguish laboratory performance from prolonged free-living performance and examine whether results remain stable across environments, disease stages, medication states, and patterns of daily activity.

Longitudinal monitoring also introduces data-completeness and adherence challenges. Charging requirements, connectivity, device positioning, comfort, and sustained wear can affect the amount and quality of usable data. Wear time, missing-data rates, charging interruptions, connectivity failures, device abandonment, and reasons for discontinuation should therefore be reported systematically [31]. Adherence is not merely a usability characteristic; for a longitudinal monitoring system, insufficient wear can directly compromise the validity and interpretability of the resulting dataset.

Even when measurements are technically reliable, their clinical meaning at the individual level remains uncertain because changes in movement, gait, activity, or tremor may reflect disease progression, normal within-person variability, changes in daily routine, or unrelated factors [7]. Therefore, clinically meaningful thresholds and individualized longitudinal baselines are needed, and validation should reflect the intended clinical purpose—for example, a measure designed to monitor medication response should be evaluated against relevant medication-related outcomes rather than only general disease-severity measures. Ultimately, however, the key translational question is whether wearable-derived information improves clinical care: correlation with the MDS-UPDRS or clinician ratings demonstrates association but does not show that using the measurement benefits patients. Prospective studies should therefore compare conventional care with care incorporating wearable data and determine whether this approach improves medication optimization, reduces motor complications and falls, enhances quality of life and functional independence, or improves healthcare utilization and patient and clinician experience [7; 32].

Finally, implementation determines whether clinically useful measurements can become part of routine care. Continuous monitoring can generate more information than clinicians can manually review, making data reduction and clinically meaningful summaries essential [8; 33]. Integration with electronic health records may facilitate interpretation alongside medication schedules, clinical assessments, and patient-reported outcomes, but interoperability alone will not ensure adoption. Data governance, privacy, cybersecurity, reimbursement, responsibility for reviewing abnormal results, and clinician workload must also be considered.

5 DISCUSSION

The evidence reviewed indicates that consumer wearable technology has developed faster than its clinical translation [7]. Across tremor, bradykinesia, dyskinesia, gait, sleep, physical activity, and cardiovascular monitoring, studies increasingly demonstrate the feasibility of capturing signals relevant to PD [13]. However, the strength of evidence varies according to the clinical target, device, reference standard, and monitoring environment.

The five-stage framework highlights why reported accuracy alone is insufficient to establish clinical value. A wearable measurement may be technically reliable without being disease-specific, may correlate with a conventional clinical assessment without reproducing the full clinical construct, and may be clinically valid without an established threshold for meaningful change [34]. Even a well-validated digital biomarker may have limited clinical value when there is no evidence-based action that can be taken in response to its output [35]. The central question should therefore move from whether a device can measure a symptom toward what additional information the measurement provides and whether that information changes clinical management.

In this context, the current evidence does not support replacing conventional neurological assessment with consumer wearables. Their most defensible near-term role is clinician-supervised digital augmentation, in which longitudinal wearable information complements rather than replaces clinical examination [36]. This approach is particularly relevant to manifestations that fluctuate between clinic visits, where repeated real-world observations may provide information unavailable during a brief assessment. At the same time, continuous monitoring should not be assumed to improve care simply because it increases the amount of available data [7; 37]. Clinically useful systems must transform high-volume measurements into standardized, interpretable outputs that can be incorporated into existing clinical workflows.

The next phase of research should therefore move beyond technical validation toward prospective evaluation of clinical utility. Studies should determine whether wearable-informed decisions improve outcomes that matter to patients and

clinicians, while also establishing reproducible measures, clinically meaningful thresholds, real-world validity, and feasible implementation pathways. The value of consumer wearables in PD will ultimately depend less on the quantity of data collected than on whether those data provide reliable information that can be interpreted and acted upon in routine care.

6 CONCLUSION

Consumer wearable devices have considerable potential to extend Parkinson's disease monitoring beyond intermittent clinical encounters by providing longitudinal information on movement, activity, gait, sleep, and selected physiological parameters. However, the ability to measure a physiological signal does not establish clinical validity, interpretability, utility, or implementation readiness. Current evidence is strongest for technical feasibility and associations with conventional clinical measures, whereas evidence demonstrating improved clinical decision-making and patient outcomes remains more limited.

The five-stage framework of measurement capability, clinical validity, clinical interpretability, clinical utility, and implementation readiness provides a structured way to identify where wearable-derived measures currently stand and what evidence is required for further translation. The future success of consumer wearables in PD should therefore not be judged by how much data they can collect, but by whether those data can be transformed into reliable, interpretable, and actionable clinical information that improves patient care.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Disclosure of conflict of interest

The authors declare that they have no financial or non-financial conflicts of interest.

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