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Joint Angle Gait Features Outperform Scalar Gait Metrics in Differentiating Parkinson's Disease from Essential Tremor

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Abstract

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By Savannah Ngo

Introduction: Essential tremor (ET) and Parkinson's disease (PD) are frequently mistaken for each other due to overlapping clinical features, particularly those associated with tremor. Gait analyses may enhance differential diagnostic accuracy, especially in cases where the overall clinical presentation is consistent with both ET or PD. This study evaluates whether 3D kinematic motion captures provide reliable diagnostic markers for PD and ET.

Methods: 524 patients with PD or ET were analyzed. 3D kinematic motion capture recorded joint position, angle, and orientation for 42 joints throughout the gait cycle. Symmetry metrics for each joint were derived by computing the correlation between bilateral joint trajectories. Three models for predicting PD and ET were developed: (1) The Benchmark Model included standard quantifications of gait. (2) The Kinematic Model included the covariates from the Benchmark Model and the mean and extent of joint motion. (3) The Kinematic Model with Asymmetry included the derived symmetry covariates alongside covariates from Models 1 and 2. All models were created using cross-validated elastic net and performance was evaluated using sensitivity, specificity, accuracy, and area under the curve (AUC).

Results: The AUCs were 0.803 (95% CI: 0.765, 0.841) for the Benchmark Model, 0.923 (95% CI: 0.899, 0.946) for the Kinematic Model, and 0.931 (95% CI: 0.908, 0.953) for the Kinematic Model with Asymmetry. The symmetry metrics made up 7 out of the top 10 predictors in the Kinematic Model with Asymmetry.

Discussion: These findings highlight the potential of 3D kinematic motion capture in improving diagnostic accuracy for ET and PD. Additionally, derived features such as symmetry provide predictive value beyond standard gait parameters.

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Table of Contents

1 Introduction

Parkinson's Disease (PD) and Essential Tremor (ET) are among the most common neurological disorders with 1.8% and 4.6% prevalence in adults over 65 years of age for PD and ET respectively.[1] Given their prominence, clinicians must often diagnose and discern between the two disorders. Distinguishing between PD and ET, however, can pose a challenge due to the vast commonalities between the two diseases. The primary symptom, tremor, (rest, postural, kinetic, and intention) is shared between patients with PD and ET.[1,2] As such, studies have found that 30-50% of ET diagnoses may be incorrect,[3] with one study reporting 37% of patients misdiagnosed as ET.[4] Another study found that 56.3% of patients diagnosed with PD in primary care could have their medication withdrawn without deterioration,[5] providing a clue that the diagnosis of underlying basal ganglia degeneration was incorrect. Despite many approaches being tested to improve differential diagnosis,[6] the problem persists.[7]

It is possible that gait analyses could improve differential diagnostic accuracy, particularly in cases where the overall clinical presentation aligns with either essential tremor (ET) or Parkinson's disease (PD).

Currently, most clinical centers address gait in movement disorders in three approximate tiers. Standard care in most academic movement disorders typically involves expert observation with ordinal gait scores, such as the MDS-UPDRS-III.[8] Second-tier assessments often include gait summary metrics like gait speed or stride length, commonly measured using "gait mat" pressure-sensitive monitoring equipment.[9] The highest level of assessment involves detailed movement

features derived from 3D kinematic data[10] or body-worn sensors,[11] both capable of capturing individual joint angle excursion over the gait cycle.

Many studies have utilized gait summary metrics, such as speed, step time, and postural transitions, to differentiate PD from ET and other disorders.[12,13] These approaches have yielded promising results, achieving classification accuracies ranging from 75% to 89%.[12,13]

Here, we used a large sample of movement disorders patients (N=524) assessed with 3D kinematic motion capture testing in our center[10,14,15] to investigate whether detailed movement features derived from joint angle motion during gait could improve differentiation beyond performance with typically used summary measures of gait, including step width, average cadence, and support time. Specifically, we compare the predictive power of three models; the first containing only gait summary metrics, the second retains the gait summary metrics and adds in mean and range from the motion captures, and the third retains all the covariates from the previous models and includes symmetry metrics derived from the motion captures. The inclusion of symmetry metrics in the third model reflects clinical knowledge that ET typically presents bilaterally (symmetrically), whereas PD often begins with unilateral tremors that may later progress to a bilateral presentation.[2] Our findings, described below, highlight the potential of detailed movement features derived from 3D kinematic motion capture to improve diagnostic accuracy, offering a possible complement to standard clinical criteria in cases where diagnosis is challenging.

2 Methods

All statistical analyses and visualizations, including feature extraction, symmetry calculations, and modeling, were performed using R statistical software (version 4.2.3).

2.1 Participants

524 patients diagnosed with PD or ET were included in the study. Of these 524 individuals, 189 were diagnosed with ET and 335 with PD. All available cases were included in this study.

2.2 Data Collection

Data were collected at a motional analysis facility located within the Emory University School of Medicine (Atlanta, GA). Infrared-reflective spheres measuring 12 mm in diameter for the upper body and 19 mm for the lower body were adhered to 42 anatomical landmarks across the body.[10,14,15] Marker positions were recorded in real time using synchronized video capture. Each marker was then automatically identified by comparing its relative spatial position within the cluster of markers.[10,14,15] An example of the kinematic data collection is shown in Figure 1.

Figure 1. Clinical Motion Capture Facility. (A) Markers placed on anatomical landmarks enable measurement of their position throughout the gait cycle. (B) After data collection, software identifies and triangulates marker positions. (C) The motion analysis facility at Emory University.

The resulting observations were marker angle, rotation, and elevation positions over the course of the patients' average gait for several joints on both the left and right side of the body. Figure 2 provides a visualization of the data over the course of the gait cycle for six of the 42 joint positions captured. In Figure 2, each black line is the position for a particular joint and individual. The blue and pink lines in each plot show a representative participant with PD (pink) and ET (blue).

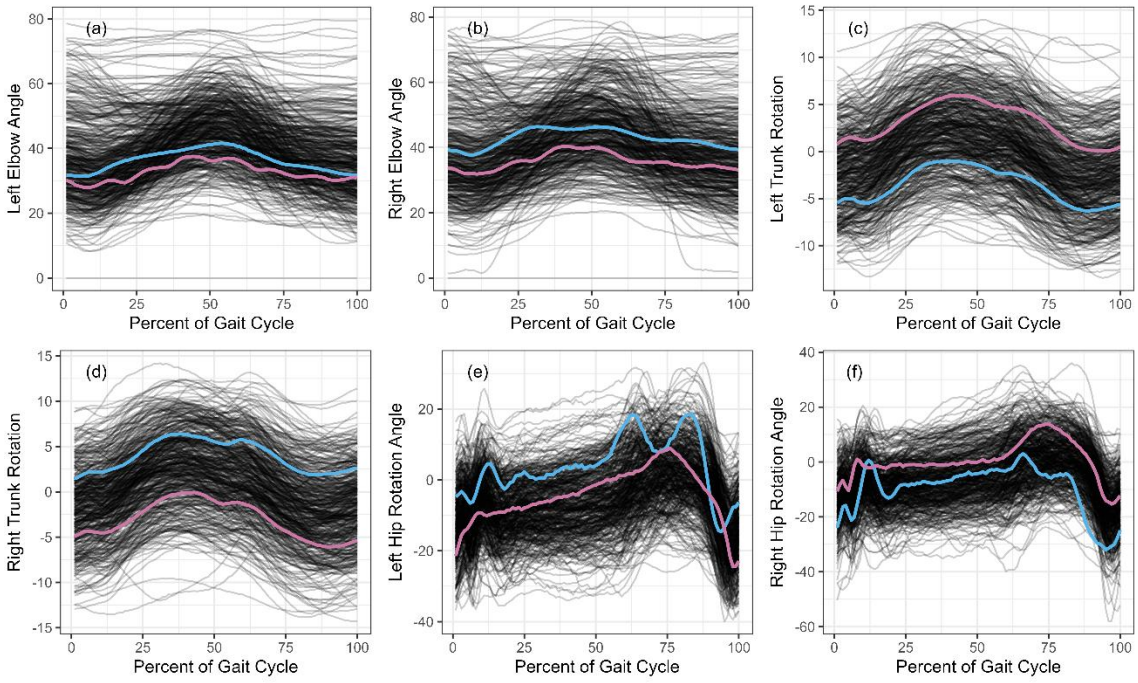

Figure 2. A subset of the joint position data used in this analysis. (a) Left elbow angle. (b) Right elbow angle. (c) Left trunk rotation. (d) Right trunk rotation. (e) Left hip rotation angle. (f) Right hip rotation angle. The pink line represents position for a single participant with PD. The blue line represents position for a single participant with ET.

In addition to the gait kinematic curves partially depicted in Figure 2, summary metrics of gait (e.g., step width, step length, forward velocity, etc.) and scalar demographic covariates (e.g., age, gender) were collected.

2.3 Deriving Features from Kinematic Motion Captures

For each participant, we derived characteristics of gait from curves like those depicted in Figure 1. Mean and range values were computed individually for each joint by calculating the mean and the total range of graphs. Gait symmetry was assessed for bilateral joints using Pearson correlation coefficients, calculated between left- and right-side joint trajectories at each 1% increment of the gait cycle. High positive correlations indicated strong bilateral symmetry, while lower or negative correlations were indicative of asymmetrical movement patterns

2.4 Modeling

To determine if the features from kinematic motion captures are useful in predicting PD versus ET, and to see if symmetry measures increase that predictive power, three models were created: (1) the Benchmark Model included standard gait measures, such as step width and average cadence. (2) The Kinematic Model included the covariates from the Benchmark Model, as well the extracted mean joint position and range of joint motion. (3) The Kinematic Model with Asymmetry expanded on both other models by adding the symmetry measures derived from the correlation between left- and right-side joint movements.

To identify which gait metrics best distinguish between Essential Tremor (ET) and Parkinson's Disease (PD), we employed an elastic net regression model. Elastic net is an interpretable machine learning approach that simultaneously performs predictive modeling and variable selection. It identifies and retains variables most strongly associated with the outcome while

excluding those that contribute minimally to prediction accuracy. This method effectively integrates features of both LASSO regression, which targets model sparsity (i.e. fewer predictors) with ridge regression, which is better at handling correlated variables. Tuning parameters for the model were selected using cross validation, and modeling was implemented using the cv.glmnet function from the glmnet package in R.

The performance of the models was evaluated using sensitivity, specificity, accuracy, and area under the curve (AUC). These metrics were chosen to assess the models' ability to correctly classify patients as either PD or ET, with sensitivity and specificity being particularly important in clinical settings.

3 Results

The demographic characteristics of the patient study population are displayed in Table 1. The median age for ET patients was 71 and the median age for PD patients was 67. Moreover, 42% of ET patients were female, while 31% of the PD patients were female.

Table 1. Patient Demographics and Summary Gait Characteristics

	Essential Tremor Patients ***N* = 189**	**Parkinson's Disease Patients** ***N* = 335**	**Total** ***N* = 524**
Age (years)	71 (63, 75)	67 (59, 72)	68 (60, 74)
Gender Female	80 (42%)	103 (31%)	183 (35%)

Median (IQR); n (%)

The derived symmetry metrics, computed as correlations between left- and right-side joint joints, revealed clear distinctions between the two disorders. Figure 3 illustrates a subset of these symmetry metrics, where each point represents a specific joint. Points falling directly on the diagonal dotted line correspond to joints with equivalent symmetry (or asymmetry) between ET and PD, whereas points above the line indicate more symmetry in ET and those below the line indicate more symmetry in PD. Notably, we observe points falling above the line, aligning with previous knowledge that ET presents symmetrically whilst PD presents asymmetrically.

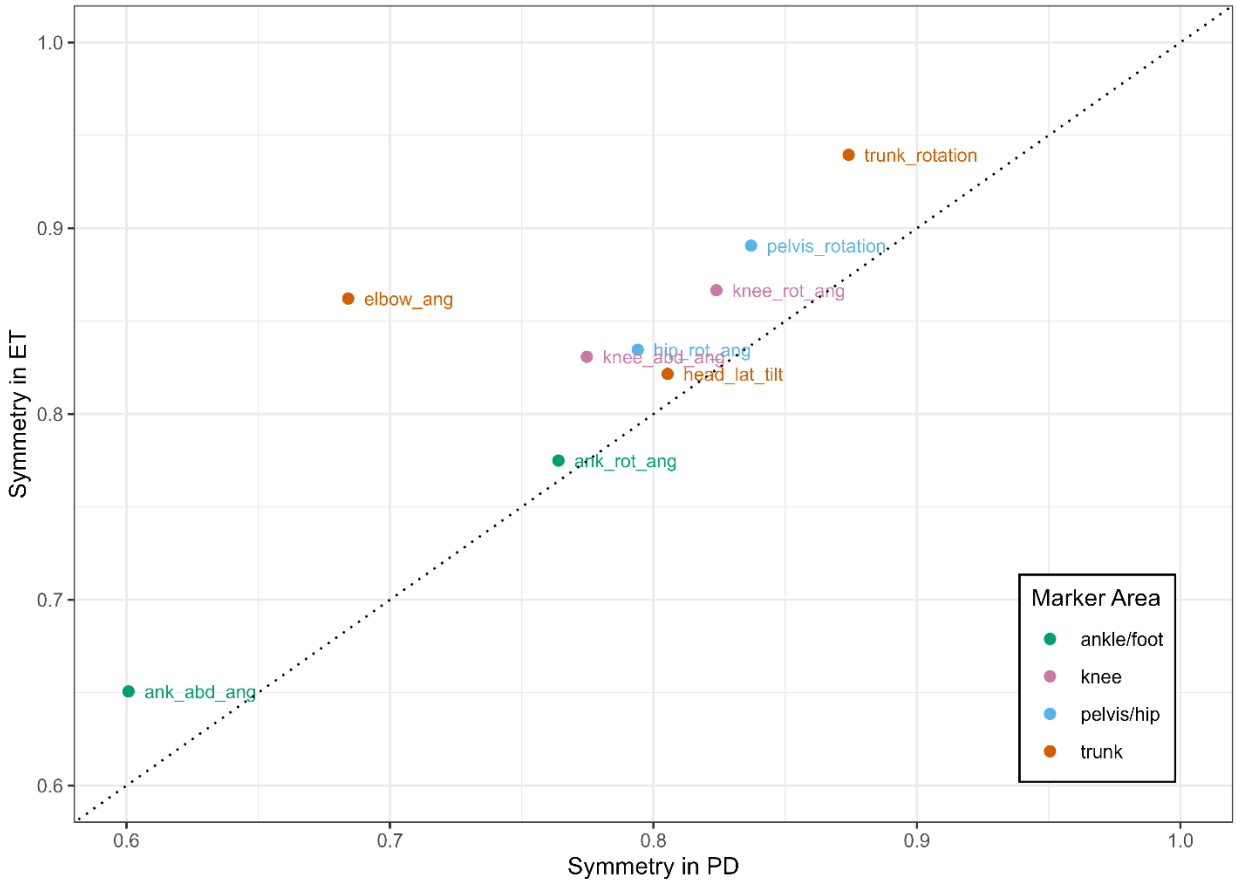

Figure 3. Correlation plot of top symmetry predictors in PD vs ET.

The sensitivity, specificity, AUC, and accuracy were greatest in the Kinematic Model with Asymmetry. Specifically, The Benchmark Model's sensitivity and specificity were 0.524 and 0.848, respectively. The AUC was 0.803 (95% CI: 0.765, 0.841) and the accuracy was 0.731. For The Kinematic Model, the sensitivity and specificity were 0.751 and 0.904, respectively. The AUC was 0.923 (95% CI: 0.899, 0.946) and the accuracy was 0.849. For the Kinematic Model with Asymmetry, the sensitivity and specificity were 0.762 and 0.925, respectively. The AUC was 0.931 (95% CI: 0.908, 0.953) and the accuracy was 0.865. Table 2 contains the performance for each model. Figure 4 contains the Receiver Operating Characteristic (ROC) curve with AUC included for each model.

Table 2. Model Performance

	Sensitivity	**Specificity**	**AUC (95% CI)**	**Accuracy**
Benchmark Model	0.524	0.848	0.803 (0.765, 0.841)	0.731
Kinematic Model	0.751	0.904	0.923 (0.899, 0.946)	0.849
Kinematic Model with Asymmetry	0.762	0.925	0.931 (0.908, 0.953)	0.865

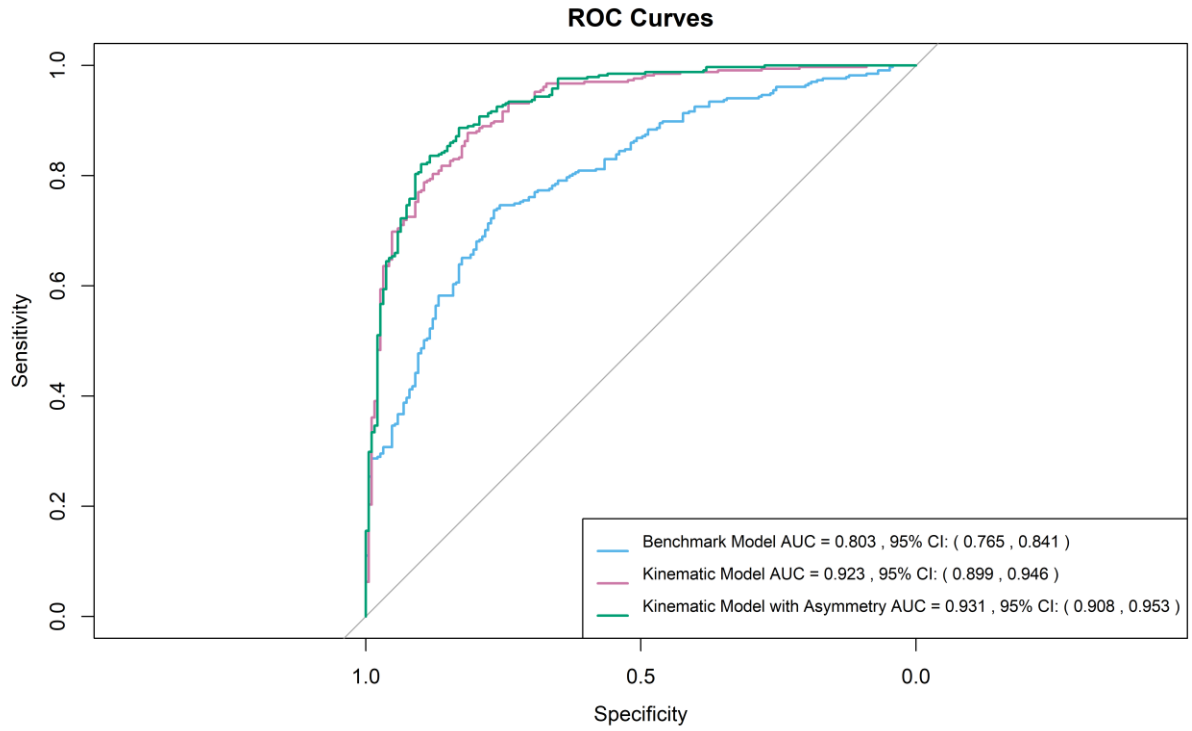

Figure 4. ROC curve comparing AUC for all 3 models.

Symmetry covariates comprised 7 out of the top 10 predictors for PD versus ET in the Kinematic Model with Asymmetry. Specifically, symmetry of the elbow angle, trunk rotation, angle of hip rotation, pelvis rotation, foot orientation, angle of knee abduction, and pelvis forward tilt were most indicative of PD versus ET. Table 3 compares the top predictors between the models.

Table 3. Comparison of Predictors Between the Kinematic Model and the Kinematic Model with Asymmetry

Kinematic Model		**Kinematic Model with Asymmetry**	
Coefficient	**Estimate**	**Coefficient**	**Estimate**
Gender	-0.767	Elbow angle symmetry	-1.437
Range of right pelvis forward tilt	0.312	Trunk rotation symmetry	-1.261

SD of right step length (cm)	0.195	gender	-0.712
Range of left trunk lateral tilt	-0.168	Hip rotation angle symmetry	-0.455
Range of right pelvis lateral tilt	0.120	Pelvis rotation symmetry	-0.382
Mean right shoulder abduction angle	-0.010	Foot orientation symmetry	-0.311
SD of left step length (cm)	0.094	Knee abduction angle symmetry	-0.229
Range of right trunk rotation	-0.092	Range of left trunk lateral tilt	-0.221
Range of right forward head tilt	0.090	Pelvis forward tilt symmetry	-0.200
SD of left step width	-0.068	Range of right pelvis forward tilt	-0.196

4 Discussion

4.1 Findings

This study demonstrates that incorporating data from 3D kinematic motion captures significantly enhances the diagnostic differentiation between Parkinson's disease (PD) and Essential Tremor (ET) compared to traditional summary gait metrics alone. The progressive improvement in model performance, from an AUC of .803 with standard gait metrics (Benchmark Model) to 0.923 when incorporating mean and range motion-derived features (Kinematic Model) and finally reaching 0.931 with the addition of symmetry measures (Kinematic Model with Asymmetry), underscores the diagnostic value of these covariates.

The Kinematic Model's improved performance from the Benchmark Model suggests that values of mean and range of joint position, extracted from motion captures, provide crucial information in differentiating between PD from ET. The Kinematic Model with Asymmetry's out-

performance of both other models highlights that bilateral gait symmetry is a potent biomarker for distinguishing PD from ET. Moreover, our analysis revealed that symmetry metrics, including those related to the elbow angle, trunk rotation, hip and pelvis rotations, foot orientation, knee abduction, and pelvis forward tilt, were among the top predictors. These findings suggest that subtle deviations in bilateral coordination between these joints, which may not be perceptible using traditional summary metrics, are captured effectively by taking the correlations between bilateral 3D kinematic motion captures.

4.2 Comparison with Previous Research

Commonly, expert clinical observation with ordinal scoring systems and summary metrics such as gait speed and stride length acquired through gait mats are used in assessing gait.[8,9] Although these metrics are clinically valuable, they may overlook the complexity of dynamic joint movements. Our study expands on the growing body of work surrounding 3D kinematic motion captures for assessing gait in PD and ET. Our findings align with previous research which demonstrates that motion captures are more useful in discriminating between PD and ET than the commonly used gait summary covariates alone.[12,13] Moreover, we find that correlation-derived symmetry measures can capture additional nuances of gait, providing even greater predictive power.

4.3 Clinical Implications

The enhanced diagnostic accuracy observed with the inclusion of 3D motion capture variables is promising for clinical practice. Implementing 3D kinematic motion capture in clinical settings could offer a non-invasive, objective tool to be paired with existing clinical assessments.

Moreover, the ability to detect subtle gait asymmetries may facilitate earlier interventions, potentially slowing disease progression.

4.4 Limitations

Despite these promising findings, limitations must be considered. Specifically, while the use of elastic net regularization provided robust variable selection, alternative modeling approaches could further elucidate the contributions of kinematic features. Moreover, this study uses cross-sectional gait data collected at a single time point. PD is known to progress asymmetrically in its early stages and may evolve toward bilateral involvement, potentially narrowing the diagnostic gap with ET over time. The lack of longitudinal follow-up limits the ability to assess the evolution of gait asymmetry and its role in disease diagnosis. Finally, this study does not consider whether patients were on or off medications. Dopaminergic therapy in PD can significantly alter gait features whilst medications used for ET may similarly affect motor output. Future research should aim to incorporate longitudinal assessments that track changes in gait asymmetry over time to better understand how progression impacts diagnostic utility. Additionally, studies should standardize or record medication states at the time of gait assessment to control for pharmacological effects on motor behavior.

5 Conclusion

In summary, this study demonstrates that incorporating advanced gait features from 3D kinematic motion capture, particularly symmetry measures, markedly improves the differentiation between PD and ET compared to conventional gait summary metrics. The progressive enhancement in model performance, from an AUC of 0.803 for standard measures to

0.931 when symmetry and mean/range metrics are included, underscores the potential of these derived features to capture subtle but significant differences in gait patterns. These findings not only reinforce the value of kinematic analyses in understanding movement disorders but also highlight the promising nature of including such methodologies as non-invasive diagnostic tools. Our results suggest that integrating continuous motion-derived features into clinical practice could help reduce misdiagnosis rates.

While the results of this study are compelling, further research is warranted to validate these findings. Moreover, future research may benefit from exploring alternative modeling methods as this study focused on a cross-validated elastic net approach.

Ultimately, integrating 3D kinematic motion capture as a tool for differentiating between PD and ET represents a significant advancement in the objective assessment of movement disorders. This approach has the propensity to improve clinical diagnostics by enabling earlier detection and, thus, improved patient outcomes.

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