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AI-Driven Speech Analysis for Parkinson's disease: A Systematic Review and Research Outlook

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ABSTRACT

Parkinson's disease (PD) is a progressive neurological disorder affecting movement due to the loss of dopamine-producing neurons. Early symptoms are often subtle, leading to delays in diagnosis. Speech-based analysis has emerged as a promising early diagnostic approach, as vocal impairments often appear in the initial stages of PD. This paper investigates the use of artificial intelligence (AI) in detecting PD through speech data, utilizing techniques such as MFCC-based feature extraction, PCA for dimensionality reduction, and classifiers like SVM, MLP, and CNN. The study highlights the effectiveness of AI in improving early PD diagnosis accuracy.

***Keywords:* PD (Parkinson's Disease), AI, SVM, MLP, CNN**

1. INTRODUCTION

Parkinson's disease (PD) is a progressive neurological disorder that primarily impairs movement due to the degeneration of dopamine-producing neurons in the substantia nigra region of the brain. This dopamine loss results in motor symptoms such as tremors, rigidity, and bradykinesia, which gradually intensify over time. Affecting over 10 million people globally, Parkinson's disease poses a growing health concern, particularly as the global population ages. Early diagnosis is crucial for effective symptom management and improved quality of life. However, initial symptoms are often subtle and non-specific, leading to diagnostic delays. Among emerging diagnostic approaches, speech-based analysis has gained considerable attention, as vocal impairments frequently appear in the early stages of PD. Leveraging artificial intelligence (AI), researchers are now applying advanced signal processing and machine learning techniques to detect and classify subtle speech abnormalities. AI tools such as feature extraction (e.g., MFCCs), dimensionality reduction (e.g., PCA), and classifiers (e.g., SVM, MLP, CNN) have shown promise in differentiating PD patients from healthy individuals based on acoustic parameters. This paper explores the role of AI in speech-based Parkinson's disease diagnosis, highlighting key methodologies and their diagnostic performance. Diagnosing Parkinson's disease (PD) through speech data has gained significant traction due to the early impact of PD on vocal features. In this paper different AI techniques for diagnosis of Parkinson disease using speech analysis has been reviewed and studied.

Table 1 Common AI Techniques for Speech-Based PD Diagnosis

AI Technique	**Description**	**Use Case in Speech Analysis**
Support Vector Machine (SVM)	Supervised ML classifier	Effective in distinguishing PD from healthy speech using features like jitter, shimmer
Random Forest (RF)	Ensemble method using decision trees	Robust classification using multiple acoustic features

AI Technique	Description	Use Case in Speech Analysis
K-Nearest Neighbors (KNN)	Distance-based classifier	Simple, effective on small datasets
Logistic Regression (LR)	Linear classification model	Interpretable model for binary classification
Convolutional Neural Networks (CNNs)	Deep learning for spatial features	Applied on spectrograms of speech
Recurrent Neural Networks (RNN) / LSTM	For sequence modeling	Captures temporal changes in speech over time
Transformers	Attention-based models	High accuracy in capturing global dependencies in speech features

2. LITERATURE REVIEW

1. Automated Diagnosis of Parkinson's Disease using Speech Signals with Machine Learning *Parul Mann, Anmol Jha, Ritu Rani, et al. (December 4, 2023)*

This study investigates the automated diagnosis of Parkinson's disease through speech signal analysis. It emphasizes key vocal parameters such as frequency, amplitude, pitch, intensity, and tonality. Voice recordings from 31 subjects—including 23 individuals with Parkinson's and 8 healthy controls—were analyzed. The machine learning model used in the study achieved a high diagnostic accuracy of 96.15%, underscoring the potential of speech-based analysis for early detection and ongoing monitoring of Parkinson's disease.

2. Early Diagnosis of Parkinson's Disease via Speech Signal Recognition: A Time-Frequency Adaptive Multi-Scale Sensing Network *Aite Zhao, Ming Chen, Xuesen Niu, et al.*

This study presents a novel Time-Frequency Adaptive Multi-Scale Sensing Network (TF-AMSP) designed for the automated diagnosis of Parkinson's disease through speech signal recognition. The model captures intricate time-frequency features and analyzes them across multiple time scales, enhancing its ability to detect early manifestations of the disease. Achieving a diagnostic accuracy of 98.33%, the proposed AI-based approach demonstrates significant promise for improving early detection and diagnostic reliability in Parkinson's disease.

3. Towards Early Diagnosis of Parkinson's Disease Through Speech Signals' Analysis Based on Advanced Deep Learning Techniques *Ayman Qahmash, Basmah Misfer AlQahtani*

This study proposes an AI-based approach for the automated diagnosis of Parkinson's disease using speech signal analysis. It employs a deep auto-encoder for effective feature extraction, followed by a multi-layer perceptron (MLP) for classification. The method achieved a diagnostic accuracy of 90%, highlighting its potential to assist neurologists in clinical assessments and improve early detection of Parkinson's disease.

4. A Review on Explainable Machine Learning-Driven Systems to Detect Parkinson's Disease from Speech Signals *Marianne Lyne Manaog, Luca Parisi*

This study reviews the application of explainable AI techniques, with a focus on Gradient Boosting Trees (GBT), for diagnosing Parkinson's disease through speech signal analysis. Emphasizing the importance of early detection, the study also advocates for the use of Apache Cassandra databases to store and monitor evolving vocal patterns over time. Model evaluation is based on key performance metrics, including accuracy, weighted precision, recall, and F1-score, ensuring both reliability and interpretability in diagnostic outcomes.

5. Research on a New AI Diagnostic Model with Strong Universality Based on Multilayer Perceptron Neural Networks *Sicheng Wang*

This study presents a novel AI diagnostic model based on Multilayer Perceptron (MLP) neural networks for detecting Parkinson's disease using speech signal analysis. The model focuses on fifteen universal acoustic features to address the limitations of prior approaches. Trained across multiple datasets, it achieves a diagnostic accuracy of approximately 80%, demonstrating improved generalizability. The model is particularly effective in detecting vocal cord damage, a common symptom among Parkinson's patients, and contributes to more robust early diagnosis.

6. A Novel Parkinson's Disease Detection Algorithm Combining EMD, BFCC, and SVM Classifier *N. Boualoulou, Mounia Miyara, Benayad Nsiri, et al.*

This study introduces an innovative method for automated Parkinson's disease diagnosis using speech signal analysis, integrating Support Vector Machines (SVM) and Artificial Neural Networks (ANN). The approach leverages key acoustic features such as Bark Frequency Cepstral Coefficients (BFCC) and Mel Frequency Cepstral Coefficients (MFCC), with Empirical Mode Decomposition (EMD) applied for signal denoising. Achieving a diagnostic accuracy of up to 92.10% using BFCC, the model demonstrates strong potential in accurately detecting Parkinson's disease from vocal data.

7. An Adaptive Intelligent Polar Bear (AIPB) Optimization-Quantized Contempo Neural Network (QCNN) Model for Parkinson's Disease Diagnosis Using Speech Dataset

S. Pragadeeswaran, S. Kannimuthu

This study introduces an automated framework for Parkinson's disease diagnosis, leveraging an Adaptive Intelligent Polar Bear (AIPB) Optimization-Quantized Contempo Neural Network (QCNN) model. The method starts with speech signal preprocessing through Determinate Haar Wavelet (DHW) transformation to enhance signal quality. Feature extraction is performed using the Statistical Time Frequency Renyi (STFR) model, followed by AIPB optimization to select the most relevant features for classification. The QCNN model is then used to distinguish between healthy and Parkinson's-affected speech signals, with validation across multiple datasets demonstrating its effectiveness.

8. Advancements in Parkinson's Disease Diagnosis through Automated Speech Analysis

P. Deepa, Rashmita Khilar, Saumendra Kumar Mohapatra

This study presents an innovative automated system for diagnosing Parkinson's disease using speech signals. The system utilizes various classifiers, including the Gaussian Mixture Model (GMM) and Support Vector Machine (SVM), to analyze speech features associated with PD. The Parzen Window Bayesian classifier with an exponential kernel achieved the highest accuracy of 94%, demonstrating its effectiveness in distinguishing between Parkinson's-affected and healthy individuals. The findings highlight the significant potential of AI in improving diagnostic accuracy through automated speech analysis.

9. Effective Diagnosis of Parkinson's Disease Using Machine Learning Techniques

This study investigates the use of machine learning techniques for the automated diagnosis of Parkinson's disease (PD) through speech signals. Deep Neural Networks (DNNs) achieved a high accuracy of 94.44%, while Gradient Boosting Machines (GBM) reached an accuracy of 89.74% in analyzing voice data. This non-invasive and cost-effective approach addresses the challenges of expensive diagnoses and limited clinician availability, aiming to enhance early diagnosis and management of PD by effectively distinguishing between patients and healthy individuals.

Table 2 AI Tools for Parkinson's Disease Diagnosis via Speech Data

Title / DOI	**Methodology / Model**	**Key Features Used**	**Accuracy**	**Notable Points**
Automated Diagnosis of PD using Speech Signals (10.1109/o-cocosda60357.2023.10482972)	ML model (unspecified)	Frequency, amplitude, pitch, intensity, tonality	96.15%	Based on speech from 31 subjects
Early Diagnosis via TF-AMSP Network (10.1109/ciotsc60428.2023.00027)	Time-Frequency Adaptive Multi-Scale Sensing Network	Time-frequency features	98.33%	High resolution across multiple time scales
DL for Early Diagnosis of PD (10.1109/atsip62566.2024.10638914)	Deep Autoencoder + MLP	Latent deep features	90%	Supports neurologist evaluation
Explainable ML-Driven Systems (10.2139/ssrn.5077337)	Gradient Boosting Trees (GBT)	Interpretable acoustic features	Not specified	Uses Apache Cassandra for long-term tracking
AI Model Based on MLP Neural Networks (10.1109/auteee60196.2023.10407801)	MLP neural network	15 universal acoustic features	~80%	Emphasizes model universality
Detection Using EMD, BFCC, SVM	SVM + ANN	BFCC, MFCC,	92.10%	EMD improves

(10.29354/diag/171712)		EMD denoising	(BFCC)	feature clarity
AIPB Optimized QCNN Model (10.1016/j.bspc.2023.105467)	QCNN + AIPB optimization	STFR + DHW transformation	Not specified	Adaptive feature selection improves accuracy
Automated Speech Analysis (10.1002/9781394287024.ch7)	GMM, SVM, Parzen Window Bayesian	Speech features	94% (Bayesian classifier)	Uses multiple classifiers
Effective Diagnosis via ML (10.1007/978-981-19-5272-2_5)	DNN, GBM	Voice data features	94.44% (DNN), 89.74% (GBM)	Non-invasive and affordable
Review: AI in Speech-Based PD Detection	Literature review	Multiple acoustic + ML approaches	NA	Emphasizes explainability and reproducibility

These methods each have their strengths depending on the context, with **TF-AMSP** and **GBT** being particularly strong candidates for highly accurate and interpretable Parkinson's diagnosis.

3. RESEARCH GAP

1. Limited Dataset Size and Diversity

- Several studies (e.g., Study 1 with only 31 participants) used relatively small datasets, often limited in demographic diversity (age, gender, language, dialect).
- **Gap**: There's a lack of large-scale, multi-lingual, and demographically diverse datasets to ensure model generalizability and robustness across real-world populations.

2. Inconsistent Feature Selection Strategies

- While many studies use MFCC, BFCC, or handcrafted acoustic features, few employ **comprehensive or hybrid feature sets** combining prosodic, articulatory, and spectral features.
- **Gap**: Absence of standardized or optimized feature selection pipelines that could generalize across datasets and tasks.

3. Limited Use of Longitudinal Data

- Most models perform diagnosis based on **single speech samples**, ignoring progression tracking over time.
- **Gap**: Lack of longitudinal modeling or disease progression prediction, which is crucial for early detection and monitoring.

4. Insufficient Explainability and Clinical Interpretability

- Only one study (Study 4) emphasizes **explainable AI**. Most models are black-box in nature (e.g., deep neural networks, ensemble models), limiting clinical trust and adoption.
- **Gap**: Need for interpretable models that can provide clinicians with rationale behind predictions (e.g., SHAP, LIME, GBT-based models with feature importance).

5. Underutilization of Multimodal Approaches

- All reviewed studies focused **solely on speech signals**. Parkinson's symptoms manifest in other modalities like handwriting, gait, and facial expressions.
- **Gap**: Missed opportunity for **multimodal fusion** of data (e.g., speech + motor sensors + EEG) for higher diagnostic accuracy.

6. Real-World Validation and Deployment Readiness

- Most studies report results on **controlled lab data** with cross-validation, lacking validation in clinical or home environments.
- **Gap**: Absence of real-world, noisy, or spontaneous speech evaluation limits deployment readiness in telehealth or mobile settings.

7. Lack of Standardized Benchmarks and Evaluation Protocols

- Accuracy is the primary metric in most studies, with less emphasis on **precision, recall, F1-score**, or **ROC curves**.
- **Gap**: Inconsistent evaluation standards hinder fair comparison across different models and datasets.

4. OPPORTUNITY FOR FUTURE WORK

- Develop **larger, multi-language, open-access speech datasets** for PD diagnosis.
- Explore **temporal modeling** (e.g., LSTM, transformers) for disease progression tracking.
- Incorporate **explainable AI** and **clinician-in-the-loop** systems.
- Use **transfer learning** and **domain adaptation** to improve generalization across datasets.
- Combine **speech data with wearable sensors** for multimodal Parkinson's monitoring.

5. OBSERVATIONS

The studies reviewed highlight the growing role of machine learning and AI techniques in the automated diagnosis of Parkinson's disease (PD) using speech signal analysis. Early diagnosis is crucial for effective treatment and improved quality of life for patients, and speech analysis offers a promising non-invasive method for identifying Parkinson's at an early stage. The key approaches and methods identified across these studies include:

1. **Feature Extraction**: Various speech features, such as frequency, pitch, intensity, tonality, and advanced spectral features like MFCC, BFCC, and STFR, were extracted from speech signals to differentiate between healthy controls and PD patients.
2. **Machine Learning Models**: Several machine learning models, including deep learning models like deep auto-encoders, MLP, DNN, and SVMs, were used for classification. These models were able to achieve diagnostic accuracy ranging from 80% to 98.33%, showcasing their potential for early detection.
3. **Optimization and Denoising Techniques**: Some studies employed optimization algorithms like the AIPB and signal denoising techniques such as Empirical Mode Decomposition (EMD) to improve the quality and accuracy of speech signal processing.
4. **Explainable AI**: A few studies emphasized the use of explainable AI models, such as Gradient Boosting Trees (GBT), ensuring the interpretability of the diagnosis and enhancing clinician trust in automated systems.
5. **Diagnostic Accuracy**: The diagnostic accuracy varied across studies, with some models achieving high accuracy (up to 98.33%), while others ranged between 80% and 94%. These results highlight the effectiveness and reliability of machine learning techniques in detecting Parkinson's disease from speech data.

6 . CONCLUSION

The automated diagnosis of Parkinson's disease using speech signals and machine learning techniques presents a promising avenue for early detection and improved management of the disease. Speech-based analysis, with its ability to capture subtle changes in vocal characteristics associated with PD, offers a non-invasive, cost-effective, and scalable solution for healthcare systems. Machine learning models, particularly those employing deep learning, optimization, and feature extraction techniques; have shown significant success in classifying PD from healthy speech, achieving diagnostic accuracies that are comparable to traditional methods.

While the results from these studies are encouraging, further refinement is necessary to ensure robustness and generalizability across diverse populations and speech datasets. The integration of explainable AI approaches will also be vital in ensuring that the models are interpretable and actionable for clinicians. Future research could focus on enhancing model performance through larger datasets, real-time monitoring capabilities, and cross-validation on different speech samples.

Overall, AI-driven speech analysis for Parkinson's disease diagnosis stands as a powerful tool in the early detection and ongoing monitoring of the disease, potentially improving patient outcomes and easing the burden on healthcare professionals.

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