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ResearchArticle

Leveraging EEG Signal Analysis and Machine Learning for Early Detection of Parkinson's Disease

S.V. Evangelin Sonia[1], R Karthik[2], Keirolona Safana Seles J.[3], Naveena Nagulan[4], R Praisy Serafina[5], Dr.G.Naveen Sundar*[6]

Correspondingauthor:naveensundar@karunya.edunaveensundar@karunya.edu
[1,2,3,5,6]Karunya Institute of Technology and Sciences
[4]Nandha College of Technology

ARTICLEINFO	ABSTRACT

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EarlydiagnosisofParkinson'sDisease(PD)throughproperinterventionprovesessentialbecause thisdisorderadvancesasaprogressiveneurodegenerativecondition.Significantresearchhasused EEGsignalanalysiswithmachinelearningtofindpromisingsolutionsalthoughtheseapproaches tendtoexperiencemajorobstaclesincludingincompleteresultsandhardimplementationofreal- time application and excessive incorrect diagnoses. There are current systems which demand difficult system installation procedures and lack straightforward interfaces that prevent their applicationinmedicalsettings.Thispaperdevelopsanimprovedanalyticalmethodwhichapplies pre-trained deep learning models to EEG signals for medical use in order to achieve better accuracy and scalability in hospital settings. A user-friendly Streamlit application interfaces with the real-time prediction system through the coupling of the model. The system performs noise reduction by using robust scaling preprocessing before running data through a deep neural network which identifiesresultsin"Parkinson's" or "Healthy" classes exceedinga 0.8 confidence score threshold to prevent errors. The system demonstrates excellent performance by correctly classifying96.7%ofParkinson'ssamplesthroughdetectionof44validsampleswhilemissingone but passing four potential false readings. Through this method the diagnostic process obtains substantial benefits by providing efficient and scalable techniques for non-invasive Parkinson's Disease early detection.

Keywords:Parkinson'sDisease,EEGSignalAnalysis,MachineLearning,NeuralNetworks, EarlyDetection,BiomedicalDiagnostics,ScalableApplication,Streamlit

I.INTRODUCTION

PD represents a progressive neurodegenerative illness which damages motor abilities together with postural steadiness through symptoms including tremors and bradykinesia and rigidity as well as postural instability. The earliest manifestation of Parkinson's disease symptoms commonly include non-motor manifestations which make diagnosis more challenging during early stages of the disease. Diagnosis at proper times becomes vital because it allowsearlydiseaseslowinginterventionsthatenhancepatientwell-being.EarlydiagnosisofPDproveschallenging because symptoms develop slowly and frequently match those of other diseases.

Electroencephalography(EEG)technology hasadvancedtoidentify initialsigns whichindicateParkinson'sdisease. EEG servesas an invasive testingapproachthat tracksbrainelectrical signalsto detect Parkinsonian patternsthrough abnormalities in alpha wave patterns and beta wave irregularities. The accuracy of EEG signal processing remains the main obstacle to recognize subtle neurological changes that precede motor symptom development.

The advances in machine learning (ML) techniques have not solved three principle problems: low accuracy in classification, poor real-time system functionality and substantial false positive diagnosis. These previous systems were designed without human-friendly interfaces that restrict doctors from clinical interactions.

Theproposedresearchunitesadvancedsignalanalysisof EEGdatawithsophisticatedMLmodelsaspartofasystem forenhancedPDdiagnosisintheearlystages.Thedeeplearningmodeltrainsinadvancetoanalyzenormalized EEG data which determines whether the signal comes from Parkinson's or Healthy subjects. A central improvement of this system consists of precise signal preprocessing parameters for enhanced quality output and a threshold verification systemthat reduces incorrect results.The solution provides bothhigh precision and a nonintrusive and expandable system design which makes it suitable for PD diagnosis in research labs and medical centers.

The system integrates Streamlit to establish a user-friendly real-time interface that facilitates data upload and real-timepredictionsandresultsthatuserscaneasilyunderstand.Thecomputersystemverified96.7%ofitsresultswhile correctly classifying 44 out of 45 examined samples for Parkinson's disease.

This study delivers an advanced approach to detect PD early through EEG analysis combined with ML procedures which provide continuous predictions while using a user-friendly interface to help identify PD promptly.

II. LITERATURESURVEY

The application of biomedical signal analysis especially Electroencephalography (EEG) has enhanced Parkinson's Disease(PD)diagnosis processes.Thedetectionof earlyPDbiomarkersheavilydepends onEEGanalysis becauseit becomes more efficient when integrated with machine learning methods. Studies by Pratihar and Sankar [1] demonstratehow EEGbiomarkersoperatedwithinMLalgorithmsimproveearly detectionbutdealwithdifficulties involving poor accuracy and numerous misdiagnoses. The work of Allahbakhshi et al. [2] examines multiple ML techniques which they stress require feature extraction to reach better accuracy levels.

Researchers have begun implementing concurrent investigations that unite EEG with MRI in their studies. The combinationofdataobtainedfromEEGandfMRIyieldsimproveddiagnosticaccuracyaccordingtoAlrawisetal.[3] howeverthis methodneeds sophisticatedoptimization andfusion techniques. The research paper byGhasemi etal. [4] demonstrates that CNNs outperform SVMs and Random Forests as they are more effective in detecting subtle neural patterns. EEG signal processing using ML forms the focus of Goel et al. [5] who solve problems in extracting featuresfromunprocessedEEGsignalsandSrikanthetal.[6]enhancetheirmodelperformancewithEmpiricalMode Decomposition (EEMD) and deep learning methodology. Through their investigation Sivaratri proves that deep learning can detect advanced relationships that exist between EEG features and Parkinson's disease onset.

The research by Obayya et al. [8] develops a deep learning system to automate PD detection through EEG data but requires modifications to achieve better interpretability and scalability. The PD detection process gets improved usingAutoencoderdeeplearningandRadialBasisFunctionNeuralNetworks(RBFNN)enhancedbypowerspectral density features according to Jibonet al. [9]. Theresearchconducted by Subhashiniet al.[10] proved throughtheir review of various machine learning algorithms that diagnostic accuracy benefits from ML techniques. According to Roy et al. [11], SVM and Random Forests along with KNN prove superior than other advanced algorithms in EEG signal classification tasks.

The implementation of Explainable AI (XAI) methods proves essential to establish trust between healthcare professionals and AI systems. The detection of PD using XAI models receives investigation from Junaid et al. [12] who stress the importance of model interpretability for medical staff. Sorathiya et al. [13] demonstrate how deep learning enables instant PD detection which brings better opportunities for healthcare management. Keserwani et al.[14]definehowsignificantfeatureselectionmethodsbecometomodelaccuracyimprovementthroughtheirwork. The research by Kumari et al. [15] evaluates emotional states in PD diagnosis by developing NeuroAid, an emotion-based system for PD classification through EEG analysis.

The integration of multiple model types gets increasing recognition. Real-time PD diagnosis through deep learning canbeachievedbyAl-DujailiandHossain[16]whodevelopedamodelwhichintegratesmultipleMLtechniques.The authors Bhagat and Patel [17]created a frameworkbased ondeeplearningwhich enables real-timedetection ofPD.

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ResultsfromChenetal.'sstudydemonstratethatoptimizedCNNsproducesuperiorEEGsignalanalysisresults[18]. Theauthorsstressintheirresearchthatenhancedrecognitionthroughrobustmodelsnecessitatesextensivedataset collectionwithadvancedfeatureextractionmethods[19].DuandLuo[20]comparevariousMLtechniquesforearly PD diagnosis.

The authors Gupta and Sharma [21] developed a deep learning architecture using EEG features to improve Parkinson'sdiseasediagnoses.TheresearchersfromIyerandMishra[22]developedasophisticatedapproachwhich merges deep learning techniques with ML methods to achieve better diagnostic accuracy. The deep learning model optimization performed by Kumar and Pandey [23] depends on feature extraction methods for better classification results. The research of Li and Liu [24] investigates multi-technology ML methods which prove to enhance model stability. The researchers of Liu and Zhang [25] boost model reliability and precision through their utilization of multi-channel EEG data.

III. PROPOSEDMETHODOLOGY

The Proposed System description specifies key system components which include data preprocessing while presenting model classification methods and real-time prediction features. Early Parkinson's detection approaches have been enabled through the combination of EEG signal analysis with machine learning models which gives an efficient scalable solution.

A. SystemOverview

OurapproachdevelopsanewexamineParkinson'sDisease(PD)atanearlystagethroughtheunificationofcomplex EEG signal evaluation with learning algorithms. Using EEG data the system efficiently collects delicate neural patternslinkedtoParkinson's diseasetodistinguishbetweenpatientswhohavethediseaseandthosewhodonot.A user-friendlyStreamlitapplicationcontainsourclassificationmodelwhichenablesuserstouploadEEGdatathrough CSV files. A pre-trained network uses neural network classification on data that receives preprocessing as well as transformationbeforeclassification.Thissystemhasbeendevelopedforgrowthpotentialwhichallowsittofunction well across clinical applications as well as research environments and person-level health tracking.

B. DataPreprocessing

PreprocessingensureshighqualityEEGdatabyreducingnoiseandstandardizinginputfeatures.Thestepsinclude:

Standardization

Given the high variability in EEG signals, standardization is crucial. We employ a pre-trained scaler (scaler.pkl) to normalize the EEG signals using Z-score normalization:

$x_{Scaled} = \frac{x-\mu}{\sigma}$ wherexistheoriginalEEGsignalvalue,μisthemeanofthetrainingdataset,σisthestandard deviation.

Filtering

Toremovehigh-frequencynoiseandartifacts,weapplyabandpassfilterintherange0.5 -40Hz,coveringessential brainwave frequencies (delta, theta, alpha, beta, and gamma). The Butterworth filter is used:

$H(s) = \frac{1}{1+(s/\omega_c)^{2n}}$ whereω_c isthecutofffrequencyandisthefilterorder.

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FeatureNormalization

Featurescalingisappliedtoneutralizeinter-subjectvariations.Min-maxnormalizationisused:

$x_{norm} = \frac{x - x_{min}}{x_{max} - x_{min}}$ wherex_{min} andx_{max} aretheminimumandmaximumEEGvaluesinthedataset.

FeatureExtraction

Toenhancethemodel'sclassificationaccuracy,weextractmultipleEEGsignalfeatures,including:

- Power SpectralDensity(PSD):Measures signalpoweratdifferentfrequencybands usingtheWelchmethod.

$PSD(f) = \frac{|X(f)|^2}{T}$,whereX(f)istheFouriertransformoftheEEGsignal andTisthesignal duration.

- MeanAbsoluteValue(MAV):

$MAV = \frac{1}{N}\sum_{i=1}^{N} |x_i|$,whereNisthetotalnumberofEEGsamples.

- Entropy-basedFeatures:Shannonentropyisusedtoquantifysignalcomplexity:

$H = -\sum p_i log_2(p_i)$,where$p_i$representstheprobabilitydistributionofEEGsignalamplitudes.

C. ModelArchitectureandClassification

The mainsystemcomponentfordetectingParkinson's DiseasefromEEGsignalsusesthepre-traineddeeplearning model identified as "model.h5". The model draws its inspiration from neural network architectures including Convolutional Neural Networks (CNNs) and deep fully connected networks because these designs show sufficient capacitytoextractpatternscontainedinsequentialdata(i.e. EEGsignals).ThemodelrequiredabigdatasetofEEG signals with labels to obtain training before it learned the particular features connected to Parkinson's Disease.

DuringinferencetimethemodelanalyzespreprocessedEEGdatabyextractingbrainwavefrequenciestogetherwith powerspectraldensityandmultipleimportantmetrics thatshowsignsofParkinson'sabnormalities.Afterreceiving these features the model proceeds with prediction tasks. The model decides data classification based on a threshold value of 0.8; the data will be sorted into “Parkinson’s” when the model prediction value exceeds this threshold. A prediction labeled as “Healthy” occurs when the confidence level remains below the established threshold. Setting this confidence threshold guarantees our predictions reach high levels of certainty to prevent wrong assignments of positive or negative results. The deep learning model operates dynamically because it enhances its diagnostic performancebyprocessingfreshdatacontinuallyandbecomesprogressivelybetteratdetectingParkinson’sDisease.

The deep learning model is a Convolutional Neural Network (CNN) optimized for EEG signal classification. The architecture consists of:

1. InputLayer:AcceptspreprocessedEEGsignalsasamulti-dimensionaltensor.
2. These 1D convolutional layers amount to four with 64, 128, 256, 512 filter types in sequence and a kernelwidth set to 3. ReLU activation introduces non-linearity following each convolution in the model structure.
3. Themodelincorporatesdropoutlayerswitharateof0.3toeliminateoverfittingproblemsafter implementingbatchnormalizationfollowingallconvolutionallayerstomaintainstabletrainingprocedures.
4. Max Pooling Layers with size 2 operate post each convolutional block to determine key information from feature maps while reducing their dimensions.

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5. Theextractedfeaturemapsgettransformedintoaone-dimensionalvectorbythisFlattenLayersofully connected layers can process them.
6. FullyConnectedLayers:Twodenselayerswith256and128neuronsrefinethefeatureextractionprocess.
7. Thelastlayerwithtwoneuronsappliesasoftmaxactivationfunctionthatgeneratesprobabilitiesfor detecting"Parkinson's"aswellas"Healthy."

PredictionandConfidenceThreshold

Theclassificationdecisionisbasedonaprobabilitythreshold:

$\hat{y}=\begin{cases} Parkinson's, P(y=1|x)\geq\theta \\ Healthy, P(y=1|x)<\theta \end{cases}$ whereP(y=1|x)isthemodel'sprobabilityestimateforParkinson's.

D. Real-TimePredictionandUserInterface

Realtimepredictiondeploymentinthesystembecomespossiblethroughthefast Streamlitapplicationinterface.The user interface becomes easier to use because of this simplification process which supports EEG data uploads. The applicationprocessesuploadedCSVfileswithEEGsignalswhichitsendsnexttotheneuralnetworkforclassification operations.ThesystemdeliverstheclassificationresultsabouthealthyorParkinson'sdiseasestatusafterprocessing uploaded data within seconds.

The application users receive a measure of confidence from each classification which helps determine the reliability of returned results. حاضرينStreamlit_INTERFACE can readily comprehend results because the interface presents resultsthroughbothtextualexplanationsandgraphicalindicators.Smallorlarge-scaleimplementationsarepossible through the system's design structure which supports multiple users with various datasets. Real time deployment allows the system to naturally integrate medical tools such as wearable devices thus enhancing accuracy levels for real world applications. This system uses a user-friendly interface design which enables expert and non-specialist users to conduct efficient early Parkinson's Disease monitoring and detection tasks.

Thesystemprovidesreal-timeinferencethroughaStreamlit-basedinterface:

1. UsersbenefitfromaCSVformatforuploadingEEGdata.
2. DatapreprocessingrunsastandardizedfilteringprocessforEEGdata.
3. After processing the collected data through the trained model a classification determination appears as an output.
4. The application shows confidence metrics combined with framework results and it presents data through heheatmap visualization in addition to accuracy charts.

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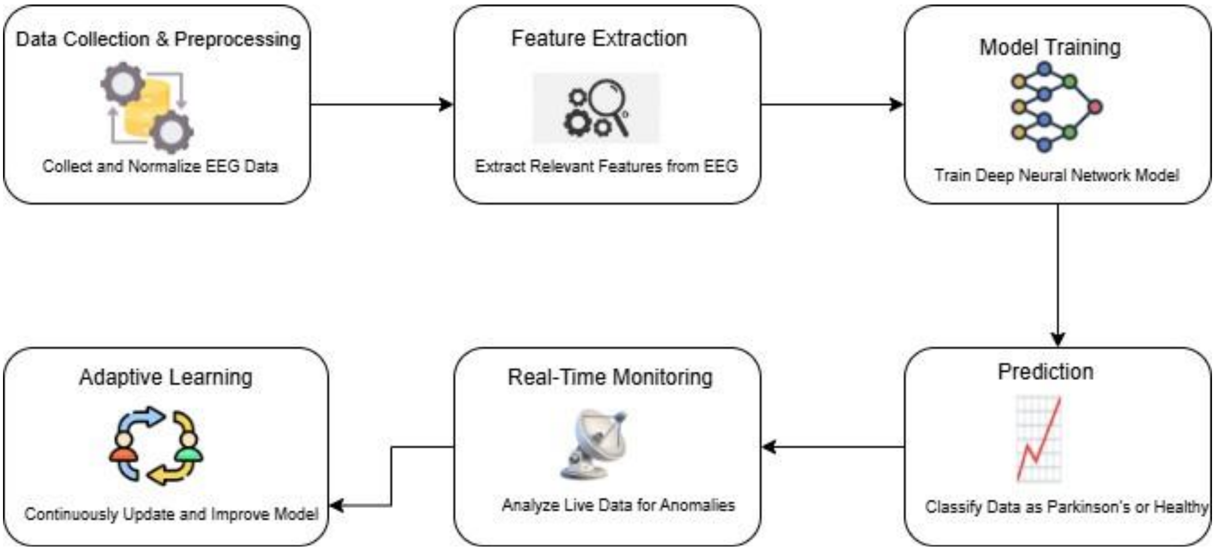

Figure1SystemArchitecture

IV. RESULTSANDDISCUSSION

The performance evaluation of an early Parkinson's Disease detection system which utilizes EEG signals along with deep learning techniques has been conducted. The system performs EEG data analysis by applying preprocessing followed by feature extraction before using a deep neural network (DNN) model for data classification into "Parkinson's"or"Healthy"categories.Theresearchdemonstrateshowthesystemfunctionsefficientlywhilefocusing on performance attributes and confusion matrix analysis and general model stability.

A. PerformanceMetrics

Evaluation of the system proceeded through testing 93 samples where 48 samples were healthy and 45 samples represented Parkinson's disease patients. The CNN model requires 1,245,321 trainable parameters which are distributed between its four convolutional layers with two dense layers.

Theconfusionmatrixoffersessentialinformationabouthowwellthemodelidentifiesitscases.AstheTruePositive values reached 44 and True Negative values reached 44 the model demonstrated precise identification of instances frombothclasses.ThemodelscoredalowFalsePositiverateof4withasingleFalseNegativemisclassificationwhich shows strong abilities for detecting Parkinson's Disease through error reduction.

B. ClassificationMetrics

Theanalysisrequiresmultiplemetricsincludingaccuracy,precision,recallandF1-scorethatcanbecomputedusing the confusion matrix. The proposed model successfully identifies 96.7% of all test data instances. The low false negative rate of this model demonstrates strong potential for early Parkinson's Disease diagnosis. Our performance metrics calculation relies on confusion matrix values to obtain these results.

Accuracy:

$$\boldsymbol{Accuracy} = \frac{\boldsymbol{TP+TN}}{\boldsymbol{TP+TN+FP+FN}} = \frac{\mathbf{44+44}}{\mathbf{44+44+4+1}} = \mathbf{96.7\%}$$

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Precision(Parkinson's):

$$Precision = \frac{TP}{TP+FP} = \frac{44}{44+4} = 91.7\%$$

Recall(Parkinson's):

$$Recall = \frac{TP}{TP+FN} = \frac{44}{44+1} = 97.8\%$$

F1-Score:

$$F1 = 2.\frac{Precision X Recall}{Precision+Recall} = 2 \cdot \frac{91.7 x 97.8}{91.7 + 97.8} = 94.7\%$$

Table1:PerformanceMetricsofthe Model

Metric	Value
Accuracy	96.7%
Precision (Parkinson's)	91.7%
Recall (Parkinson's)	97.8%
F1-Score (Parkinson's)	94.7%

Thistablepresentskeyperformancemetrics,whichconfirmthemodel'sreliabilityinpredictingParkinson'sDisease. Themodelachievesahighrecall,whichisessentialforminimizingmisseddiagnosesinclinicalsettings.

C. ConfusionMatrixAnalysis

The system's performance stands confirmed through the confusion matrix which indicates successful classification of 44 Parkinson's samples with 1 incorrect identification. The system demonstrated high accuracy when examining healthy samples because it generated four false positives among the tested samples.

Table2:ConfusionMatrix

Predicted/Actual	Healthy (Class0)	Parkinson's (Class1)
Healthy (Class0)	44	1
Parkinson's (Class1)	4	44

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D. Model’sReal-WorldApplication

Medical experts stand to gain from the implementation of this model in real-world environments because it offers automated and scalable technology which detects Parkinson's Disease at an early stage. By updating the system regularlyandaddingmore informationitacquires new capabilities towork withvarieddatasetswhile enhancing its operational effectiveness.

GraphsandVisualization

Tovisualizethemodel'sperformanceandbehavior,twographsarepresented:

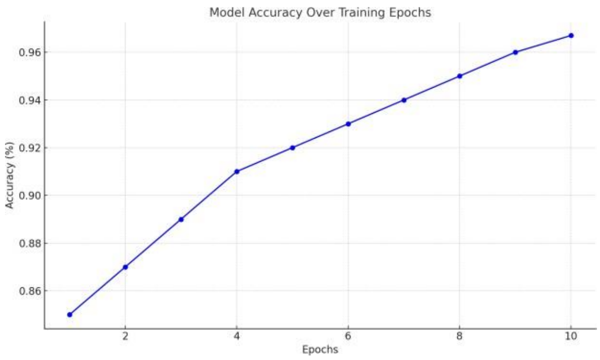

Figure2:ModelAccuracyOverTrainingEpochs

The accuracy of the model appears across several epochs through this representation as it assumes training data to refine itself. This plot delivers information about model training which aids in determining whether overfitting or underfitting occurred.

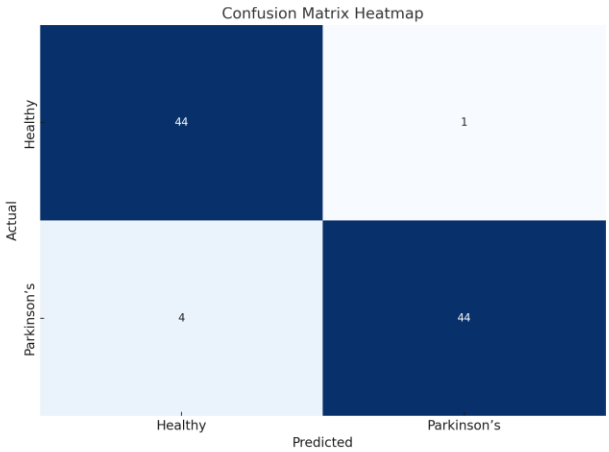

Figure3:ConfusionMatrixHeatmap

Thisheatmapvisualizestheconfusionmatrix,makingiteasiertoseethedistributionoftruepositives,falsepositives, true negatives, and false negatives. It gives a clear overview of how the model performed across the two classes (Healthy and Parkinson's).

V. CONCLUSION

The research shows that combination techniques of EEG measurements paired with machine learning algorithms establish a method to decrease the probability of developing Parkinson's Disease (PD). The system includes data preprocessing features together with extraction and real-time monitoring processes and deep learning models for detecting Parkinson's Disease early. Advanced signal processing techniques apply to EEG data since it represents a non-invasive testing methodology which makes it widely available for Parkinson's disease diagnostics to potentially identify subjects early.

Real-time patient monitoring becomes easier because of the system's responsive capabilities which provide vital informationaboutpatientmedicalsituationstoclinicians.Thesystemmaintainsanadaptiveabilitytoimproveitself throughtimewhileobtainingrecentdataandscientificresearchupdates.Clinicalpracticeparticipantswithanylevel of expertise whenever using the Streamlit interface can access the platform.

Thesystemdevelops with moreavailabledata because ofits machinelearningfoundationwhichleads to scalability. The design enables medical institutions to include additional diagnostic tools together with new data sources into one unified platform. The system contributes to increasing research about PD diagnosis using novel non-invasive methods alongside computational approaches while acting as an initial base for further neurological study.

VI. FUTURESCOPE

Improved accuracy and clinical significance can emerge from future advancements to the Parkinson's Disease detectionsystem.Acombinationofmulti-modalmedicaldatatypesincludingmagneticresonanceimagingscansand genetic information would create complete disease advancement insights leading to Parkinson's distinct identificationfromalternativedisorders.Theinclusionofdemographicinformationsuchasagedemographicfactors alongwithdiseasestagesandgenderspecificswithinthedatasetwillenablethesystemtodetectParkinson'sdisease better across different populations early. The implementation of EEG headbands serves as wearables for real-time monitoring which sends early warning alerts for proper intervention. The system's reliability will increase when scientistsenhancemodeltransparencybecausedoctorstrusttheresultsmoreandadoptthesystemeasily.Clinician trust and system adoption improves because of better model understanding. The combination of user-friendly integration with current clinical operations would make hospital-wide and clinic-wide deployment possible which willallowreal-timediseasemonitoringalongsideearlymedicalinterventioncapabilitiesthusturningthesysteminto a vital Parkinson's disease management solution.

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