AI-Driven Early Identification of Parkinson's Disease Using Machine Learning and Mathematical Modelling

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Abstract

A progressive neurodegenerative disease, Parkinson's disease (PD) is often identified at an advanced stage when movement symptoms start to become noticeable. A higher quality of life and prompt care depend on early detection. In order to identify early indicators of Parkinson's disease, this research suggests an AI-driven framework that makes use of machine learning algorithms and mathematical modelling techniques. These biomarkers include speech signals, handwriting patterns, and neurophysiological data. To improve prediction accuracy, the framework combines supervised learning models like Support Vector Machines (SVM), Random Forests, and deep neural networks with sophisticated feature extraction techniques. Subtle motor and non-motor complaints are quantified and spatiotemporal signal fluctuations are analyzed using mathematical models. The effectiveness of the suggested method is shown by experimental validation using publically accessible datasets, which show that it can accurately and sensitively differentiate between healthy controls and early PD patients. This method not only facilitates early diagnosis but also establishes the groundwork for the development of individualized treatment plans in the medical field using predictive analytics.

Introduction

Parkinson's Disease (PD) is a chronic, progressive neurodegenerative disorder that primarily affects the central nervous system, leading to a gradual decline in motor and non-motor functions. It is caused by the degeneration of dopaminergic neurons in the substantia nigra region of the brain, resulting in a significant reduction in dopamine levels. Dopamine is a critical neurotransmitter responsible for regulating movement and coordination. The exact etiology of Parkinson's Disease remains unclear, but it is believed to be a complex interplay of genetic and environmental factors. The quality of life is greatly reduced by the motor symptoms of Parkinson's disease (PD), a progressive neurodegenerative illness marked by tremors, bradykinesia, stiffness, and postural instability. Delaying the course of Parkinson's disease (PD) and improving patient outcomes via prompt therapies depend heavily on early identification. Researchers have been creating intelligent systems that can identify early-stage Parkinson's disease (PD) using handwriting analysis, neuroimaging, and biosignal processing thanks to recent developments in artificial intelligence (AI) and computer vision. Analyzing both static and dynamic handwriting patterns is one method that shows promise. Fratello et al. [1] showed that PD patients may be successfully classified by integrating graph-based characteristics with handwriting signals. Likewise, Basnin et al. [2] suggested a static hand-drawing analysis technique that uses micrographic signals to identify early signs of Parkinson's disease. A continuous convolution network for offline handwriting identification was shown by Li et al. [3], who demonstrated exceptional performance in differentiating PD-affected samples without the use of preset templates. The accuracy of categorization has been significantly improved by including transformer designs and attention methods. A coordinating attention-enhanced Swin Transformer was created by Wang and al. [4] and shown strong performance in identifying handwriting abnormalities associated with Parkinson's disease. Using handwriting data, Dionela et al. [5] also investigated several machine learning algorithms for PD diagnosis, highlighting the potential of AI in creating non-invasive screening methods.

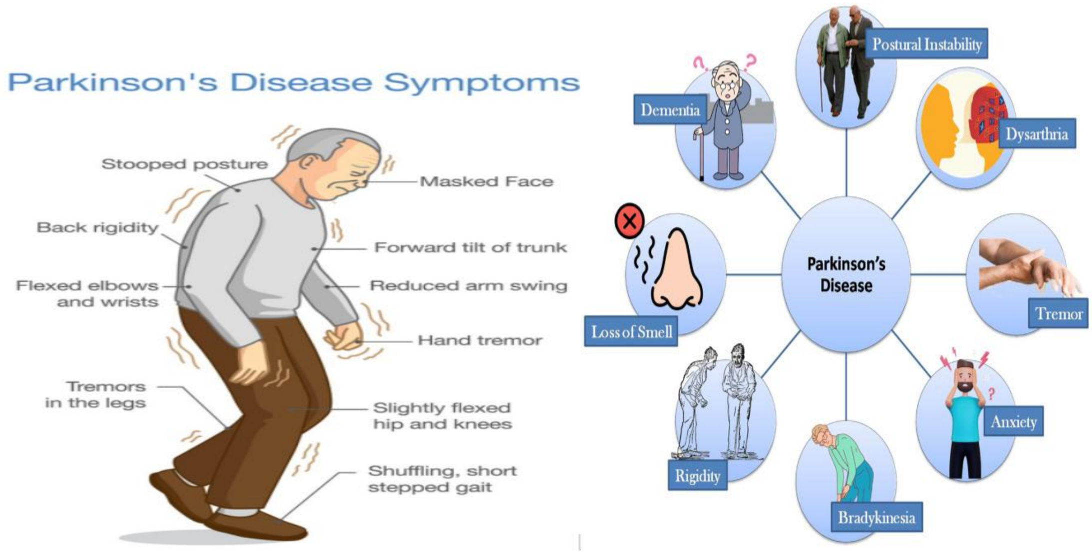

Figure 1: Symptoms of Parkinson's Disease

In addition to handwriting, picture analysis and EEG-based techniques are becoming more popular. While Afonso et al. [7] used transformers on EEG data and achieved notable accuracy using Stockwell Transform features, Ianculescu et al. [6] used deep learning to analyze medical photos in order to discover early PD signs. To further push the limits of precision medicine, Hussain et al. [8] suggested a fusion architecture that combines CNN and Swin Transformer for PD categorization based on MRI data. Furthermore, multimodal systems that integrate many data sources have become effective instruments. To improve diagnostic reliability, Zhou et al. [9] introduced a unique classifier that incorporates multimodal inputs. Kumar [10] gave a more comprehensive overview of AI-driven illness prediction, emphasizing its use in neurological conditions like Parkinson's disease. When taken as a whole, these research highlight how AI and computer vision are revolutionizing the development of intelligent Parkinson's disease diagnostic tools. In order to provide early and ongoing monitoring in both clinical and non-clinical settings, this work expands on these foundations by putting forward a real-time intelligent video surveillance system that can identify suspicious motor activity patterns suggestive of Parkinson's disease.

Parkinson's Disease (PD) affects approximately 1% of individuals over the age of 60, making it the second most common neurodegenerative disorder after Alzheimer's disease. It is characterized by a combination of motor symptoms such as resting tremors, bradykinesia (slowness of movement), muscular rigidity, and postural instability and non-motor symptoms, including sleep disturbances, depression, cognitive decline, and autonomic dysfunction. These symptoms progressively worsen over time, often resulting in severe disability and diminished quality of life. Early and accurate diagnosis of Parkinson's Disease is crucial, as timely therapeutic intervention can significantly improve patient outcomes and slow the progression of symptoms. However, current clinical diagnostic practices rely heavily on the subjective evaluation of motor symptoms by trained neurologists, which can lead to delayed or inaccurate diagnosis, especially in the early stages of the disease.

Related Work

Numerous investigations have examined the use of artificial intelligence (AI) and machine learning (ML) methods for the early diagnosis of Parkinson's disease (PD), with a focus on physiological signals, neuroimaging, and handwriting analysis. Fratello et al. [1] presented a classification-based screening method that separates PD patients from healthy people by combining graph theory with handwriting dynamics. Their method demonstrated the importance of motor signal variability as represented by both static and dynamic graph characteristics. By looking at tremor patterns and abnormalities in the drawings, Basnin et al. [2] also used supervised learning to assess micrographic static hand drawings and achieved promising early diagnosis accuracy. One method of PD identification that is still being researched extensively is handwriting. For offline hand drawings without established templates, Li et al. [3] suggested a Continuous Convolution Network, demonstrating the system's versatility across a range of handwriting styles. This region was further improved by Wang et al. [4] utilizing a Coordinate Attention-enhanced Swin Transformer, which greatly improved classification performance by extracting fine-grained spatial information from handwriting pictures. To further explore the efficacy of handwriting data, Dionela et al. [5] evaluated many machine learning algorithms, such as SVM and Random Forest, to assess how well they might detect early-stage Parkinson's disease using drawing data. Their results validated the use of basic sketching exercises in clinical screening procedures. AI-based picture analysis has shown promise in addition to handwriting. To encourage the use of computer vision in the diagnosis of neurodegenerative diseases, Ianculescu et al. [6] used AI models in conjunction with image processing methods to identify visual patterns associated with Parkinson's disease. Recent developments have also included the study of brain signals. Afonso et al. [7] created a deep learning system for EEG-based Parkinson's disease identification that makes use of Transformers and the Stockwell Transform. The spatiotemporal EEG patterns associated with early neurophysiological alterations in PD patients were successfully recorded by this method.

Table 1: Comparison Work for Different Models

Author	year	Dataset	Methodology	Accuracy
Fratello M.et.al [1]	2021	PaHaw Dataset	KNN	77.75%
Basnin N.et.al [2]	2021	HandPD Dataset	VGG-16	91.36%
Li Z.et.al [3]	2022	HandPD Dataset	CC-Net	89.3%
Wang N.et.al [4]	2023	HaPD and New HaPD	CAS Transformer	92.68%
Dionela.et.al [5]	2023	HaPD and NewHaPD Datset	MLP (Multi-layer Perceptron)	87.5%

Marilena Ianculescu.et.al[6]	2024	PaHaW Dataset	RF	95.24%

For MRI-based Parkinson's disease classification, Hussain et al. [8] suggested a hybrid model that combines Swin Transformer and Convolutional Neural Networks (CNNs). Their fusion model produced excellent diagnostic accuracy and resistance to image noise by using both local and global image characteristics. To enhance PD diagnosis, Zhou et al. [9] presented a unique integrative multimodal classifier that combines speech, handwriting, and imaging data. Combining diverse data sources may lead to more thorough and accurate disease modeling, as this method shows. Kumar [10] offered a more comprehensive viewpoint on the use of AI in early illness identification, including neurological diseases and cancer. Early intervention via predictive modelling is crucial, and the research highlighted the generalizability of deep learning across medical disciplines. Recent developments in deep learning, namely in the areas of vision transformers and attention processes, have greatly improved performance in challenging biomedical and picture classification tasks. The creation of handwriting and image analysis-based Parkinson's Disease (PD) detection tools has also been impacted by these advancements.

A lightweight but powerful attention module called ECA-Net (Efficient Channel Attention) was presented by Wang et al. [11] it improves convolutional neural networks (CNNs) by adaptively choosing informative features. Their approach has been very useful for jobs that call for modest feature classification, which makes it appropriate for biological applications where signal subtleties are important. The Chen et al. [12] presented CrossViT, which merged cross-attention processes with multi-scale vision transformers. In handwriting analysis and medical imaging, where spatial context is crucial, this design enables the network to record both global and local characteristics. CoAtNet, a hybrid architecture that combines convolutional processes with self-attention layers to achieve optimum generalization across data sizes, was introduced by Dai et al. [13]. This combination enables scalable PD detection algorithms that are capable of handling a wide range of handwriting resolutions and styles. In order to improve localization and classification tasks, Chu et al. [14] suggested Twins, a vision transformer design that reintroduces spatial attention in a more efficient form by improving feature interactions. The detection of fine motor abnormalities in PD handwriting samples is made possible by these spatial processes. Such deep learning techniques have been directly used to Parkinson's disease screening in a number of studies, going beyond architectural enhancements. To effectively distinguish PD patients from healthy people, Fratello et al. [15] created a classification system that makes use of both graph and handwriting signals. They were able to capture structural drawing patterns which are often distorted in PD patients through graph-based analysis. Similarly, Basnin et al. [16] looked for early indications of Parkinson's disease by analyzing static micrographic hand drawings. Their research used machine learning models on digital handwriting inputs to identify micrographic features that are indicative of early motor loss in Parkinson's disease (PD), such as uneven pen pressure and shorter stroke length. The combination of effective attention processes and domain-specific data modeling is shown by these research taken together. The development of AI-driven PD detection systems that combine cutting-edge neural network designs with actual patient data is firmly based on them.

PD Drawing Dataset:

The PD drawing dataset consists of two handwriting tasks: spiral drawings and wave drawings. Each type is systematically divided into training and testing sets. Furthermore, each set contains samples from two categories: healthy individuals and Parkinson's disease patients. This structured organization of the dataset enables the models to learn distinct handwriting characteristics associated with Parkinson's disease, allowing reliable model training, validation, and testing.

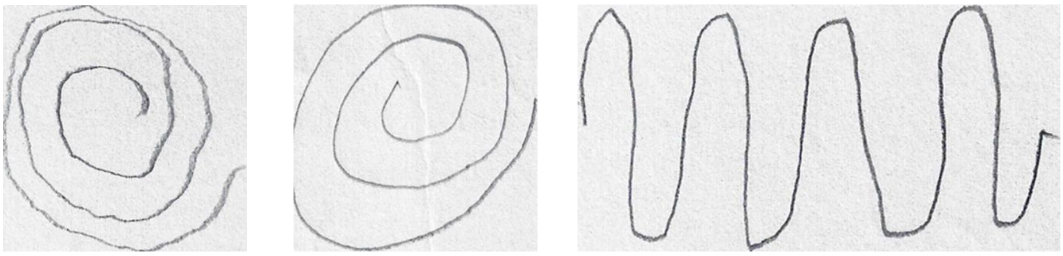

Figure 2: Spiral and Wave Images

Table: 1 Dataset Description

Component	Details
Data Type	Image dataset (.png)
Image Categories	Spiral drawings, Wave drawings
Classes	Healthy and Parkinson
Spiral drawing	The participant is asked to draw an Archimedean spiral (smooth continuous curve). Difficulties in drawing (shakiness, irregularity) indicate tremors or rigidity.
Wave drawing	Participant replicates a wave pattern. Used to assess micrographia and hand stability.

Proposed Work

The study focuses on handwriting-based Parkinson's disease detection using a carefully designed experimental setup. It leverages the PD drawing dataset, which includes two types of handwriting tasks: spiral drawings and wave drawings. The primary goal is to develop robust models capable of distinguishing between handwriting patterns of healthy individuals and Parkinson's disease (PD) patients Using hand-drawn spiral and wave graphics, this study offers a deep learning framework that is incredibly accurate in classifying Parkinson's disease (PD). A hybrid model that combines modified EfficientNet and Vision Transformer (ViT) is created to take advantage of both global contextual relationships and local spatial information. StarGAN-based augmentation is used to generate a variety of synthetic samples in order to address the issues of class imbalance and data scarcity. Standard performance indicators are used to train and assess the model.

The overall architecture of PD detection. This model contains three modules: StarGAN for data augmentation, a feature extraction module for handwriting feature extraction, and a classification decision module.

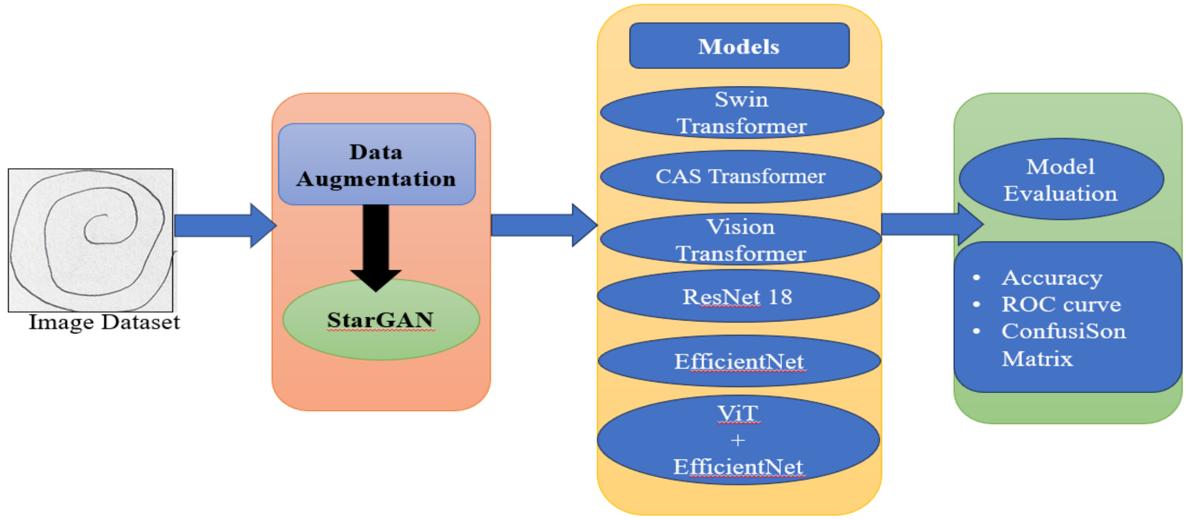

Figure 3: Overview of Proposed Models

Data Augmentation with StarGAN

To address the challenge of limited dataset size and enhance model generalization, StarGAN was employed for data augmentation. StarGAN, a multi-domain image-to-image translation framework, was used to generate synthetic handwriting samples for both healthy and Parkinson's classes. By introducing realistic variations into the dataset, the augmentation process enriched the training samples, helped reduce overfitting, and improved the models' ability to generalize to unseen data.

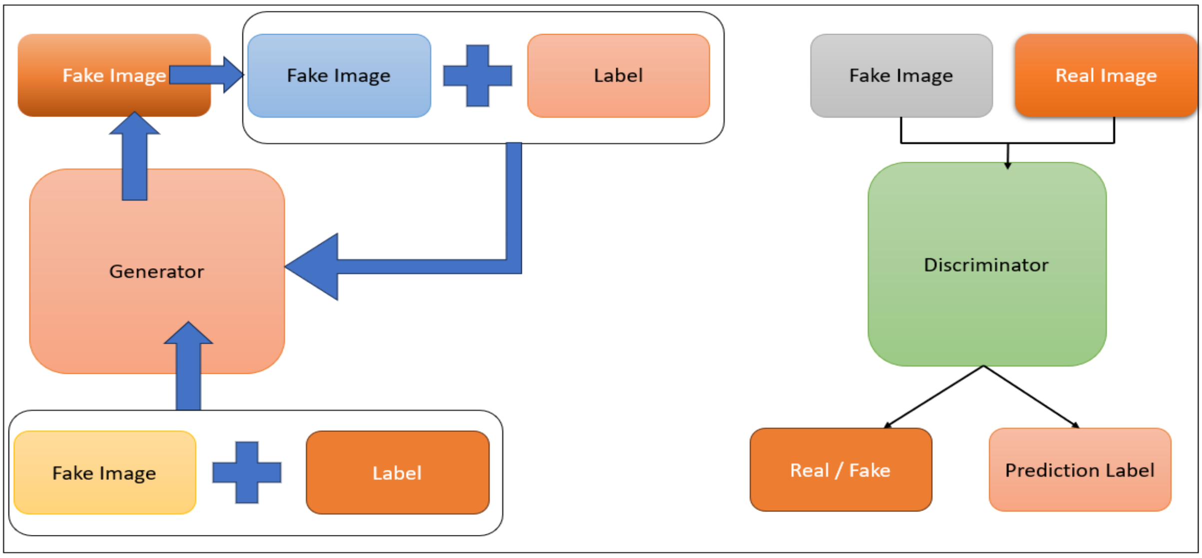

Figure 4: Working procedure for StarGAN

Experimental Result

The Modified ViT+EfficientNet model, which compares several deep learning architectures for handwriting-based Parkinson's disease (PD) detection, is the best performer in terms of classification accuracy. This hybrid method successfully extracts both local texture characteristics and global context from handwriting photographs by using the power of EfficientNet's optimized convolutional layers in conjunction with Vision Transformer (ViT) components. This model's higher performance emphasizes how crucial it is to combine transformer capabilities with traditional CNN efficiency, particularly when training on meticulously pre-processed and enhanced biological datasets. Competitive outcomes were also shown by other cutting-edge transformer-based topologies, including the CAS Transformer and Swin Transformer. By incorporating coordinate attention into the Swin Transformer structure, the CAS Transformer improves the machine's capacity to concentrate on certain areas of the handwriting picture while preserving contextual awareness across extended distances. Similar to this, Swin Transformer uses shifted windows to apply a hierarchical attention structure, enabling the model to interpret huge pictures effectively while preserving fine-grained spatial correlations. However, in this particular challenge, the Modified ViT+EfficientNet fared somewhat better than these models, despite their sophisticated architecture. PVT (Pyramid Vision Transformer), ResNet-18, and EfficientNet are other models that have been tried. ResNet-18 continues to be a solid baseline because of its residual learning capabilities and steady convergence, whereas PVT excels in multi-scale feature extraction via a pyramid architecture. EfficientNet, which is renowned for having a balanced depth, breadth, and resolution, did well on its own but shown improved performance when paired with ViT. Together, the findings imply that while attention-based models are strong, well-optimized CNNs especially when paired with transformers and trained on enriched datasets remain very successful for specific tasks such as the analysis of Parkinson's handwriting.

Challenges

Diagnosing Parkinson's disease (PD) is challenging, with a misdiagnosis rate of around 25%. Since confirmation is only possible after death, early and accurate diagnosis is difficult. Parkinson's disease detection studies face several challenges, including small and imbalanced datasets, which can lead to biased and inaccurate results. Many previous studies have shown low accuracy, indicating the need for better approaches. Additionally, collecting MRI data is expensive and difficult due to the need for patients to stay still. Handwriting abnormalities like micrographia further complicate diagnosis for clinicians. Parkinson's disease diagnosis is hindered by the lack of reliable biomarkers and the subjectivity of UPDRS assessments. Existing AI-based handwriting recognition systems often require specialized equipment, limiting their use at home. The study points out design flaws in current methods and emphasizes the need for simple, objective tools for early diagnosis.

Conclusion

When employing enhanced spiral and wave handwriting images to classify Parkinson's illness, the suggested modified ViT + EfficientNet hybrid model performs remarkably well. Additionally, the model's ROC AUC score of 1.0 indicates that it can discriminate between people who are healthy and those who have Parkinson's disease. The results demonstrate how well modified Vision Transformers and EfficientNet work together, utilizing both fine-grained characteristics and global context. With the use of data augmentation and strong assessment metrics, this hybrid architecture shows promise as a method for accurately and consistently diagnosing Parkinson's disease using handwriting analysis.

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