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DETECTION OF PARKINSON'S DISEASE USING KEYSTROKE DATA AND MACHINE LEARNING ALGORITHMS

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Abstract

The human brain is still the most complex organ and still, not fully understood. The brain has ability to adapt, develop, learn, memorize, and perform daily tasks during our survival has inspired us to build artificial intelligent machines and apply machine learning in many fields. Not only does it control our thoughts, emotions, movements, or actions, but the human brain is also responsible for controlling our organs and any unintentional actions. Strong as it is, disorders related to the human brain may be severe and complex to heal or perhaps not curable. Even though we are living at the peak of our technology. However, we could not fully understand how our brain works as well as the reasons for many diseases. One of them is Parkinson's disease. A specific disorder related to dying neurons in our brain due to the unknown existence of proteins in a specific area. Every single corner of the brain is responsible for a specific task therefore any issue happening in the related area can cause a complex health disorder. When the area responsible for creating dopamine which is used for organizing our emotions as well as intentional movement is affected, a person might have Parkinson's disease. The purpose of this work is to analyze the disease and make predictions based on finger movement data that is related to the symptoms of the disease. In this research medical knowledge, medical data, and machine learning algorithms are used to build to model. The models are related one of the the main symptoms of the disease. In this research, different preprocessing techniques are used to increase the accuracy. The suggested models can give in a range of 76-95% accuracy based on medical data for Parkinson's disease.

Keywords: Machine Learning; Data Analysis; Parkinson's Disease; Feature Extraction; Ensemble Methods

1. Introduction

Parkinson's disease is a degenerative neurological disorder that is characterized by the onset of tremor, muscle rigidity, slowness in movement (bradykinesia), and stooped posture (postural instability). Parkinson's is the second-most common neurodegenerative disease after Alzheimer's disease. More than 10 million people worldwide are living with PD. The brain is responsible for many tasks and a combination of different brain regions can perform complex tasks such as movement from the Basal ganglia area. The basal ganglia have direct/indirect pathways to control our movement. When neurodegeneration which means loss of neuron cells occurs, the affected area causes disorders. In the system of basal ganglia, the substantia nigra is a small area responsible for creating dopamine. Dopamine is a neurotransmitter that enables neurotransmission (electrochemical communication between neurons) and affects our behavior with reward feelings as well as during movement. This means Parkinson's disease is a disease of basal ganglia related to dying neurons in the substantia nigra and depletion of dopamine. There are different symptoms of PD. Those are: Static tremor: or rhythmic shaking, usually begins in a limb, often hand or fingers. The shaking may decrease while performing tasks. Impaired posture: The posture of the patient may become stooped. Rigid muscles: Muscle stiffness may occur in any part of the body. The stiff muscles can be painful and limit the range of motion. Slowed movement (bradykinesia): Over time Parkinson's disease may slow the movement, making simple tasks more difficult to perform. The steps of the patient may become shorter while walking. Speech changes: The patient may speak quickly, softly, or be hesitant before talking. The speech may be more of a monotone rather than having the usual speech behavior. The suggested model analyses finger movements using a keyboard. In this research, after getting raw data, different methods for preprocessing were used, such as IQR for outliers, mean/ std /Variance, and time difference derivations. The ensemble learning methods performed well in this model. The purpose of dealing with different data is; that many models are using one or some of these methods to detect PD. However, in this research, a combination of models was used. Combined models' results will be evaluated by medical experts to make final decisions, hence the system will be able to detect the disease or possibility of the disease.

2. Literature Review

2.1 Human Brain

The brain is a collection of tissue in the head of the body. The brain integrates sensory information takes input generates output, and directs motor responses; it is also the center of learning. The human brain weighs approximately 1.4 kg (3 lb) and is made up of billions of cells called neurons [1]. The connections between neurons, known as synapses, allow the transmission of electrical and chemical messages from one neuron to another in the brain, a process that underlies basic sensory functions and is critical for learning, memory formation and thinking, and other cognitive activities. The transmission is done using electrochemical activities with the help of neurotransmitters.

Neurons communicate through the body and they communicate with one another to transmit signals. However, neurons are not simply connected physically. Each neuron's end is a small gap that is a synapse and to communicate with the next cell, the signal has to be able to cross the space. This process is known as neurotransmission. One of the most important neurotransmitters is dopamine as it is mostly responsible for feelings of reward pleasure and movement. Dopamine is critical for controlling the start and stop of voluntary and involuntary movements [2].

There are many regions in the human brain responsible for specific tasks such as the limbic system [3] which is responsible for emotions, also Basal ganglia, a group of nuclei (clusters of neurons) in the brain that are located deep beneath the cerebral cortex. The basal ganglia specialize in processing information on movement and in fine-tuning the activity of brain circuits that determine the best possible response in a given situation [4]. The basal ganglia also mitigate and control functions ranging from cognitive planning, emotions, and reward functions, and even cognition and learning. The contributions of the Basal Ganglia are still not understood.
One hypothesis (direct/indirect pathway model) suggests that the basal ganglia act to facilitate desired movements and inhibit unwanted and/or competing movements [5].

According to the direct/indirect pathway, when there is an intentional movement, a signal to initiate the movement is sent from the cortex to the basal ganglia, arriving at the caudate or putamen. Afterward, the signal follows a circuit in the basal ganglia known as the direct pathway, which leads to the silencing of neurons in the globus pallidus and substantia nigra [5]. This releases the thalamus from the inhibitory effects of the basal ganglia and allows movement to occur. There is also another circuit within the basal ganglia that is the indirect pathway, which involves the subthalamic nucleus and leads to the increased suppression of unwanted movements. It is believed that a balance between activity in these two pathways may facilitate smooth movement.

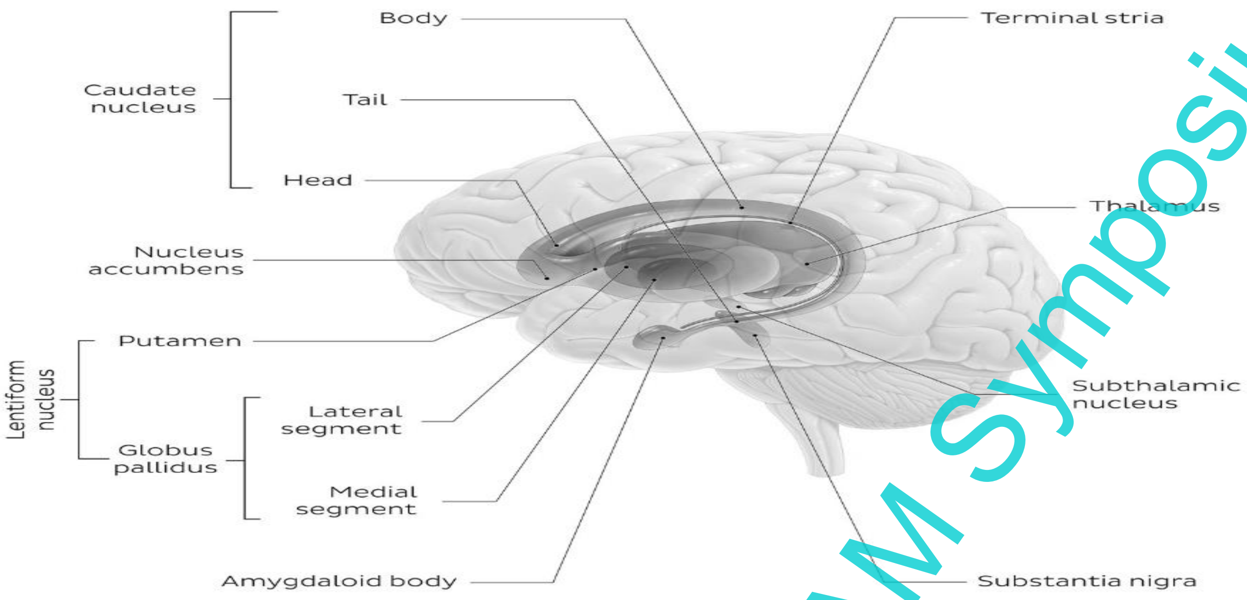

Fig. 1. group of nuclei (Basal Ganglia) and it's position in human brain

The substantia nigra (SN) is a midbrain dopaminergic nucleus that has a critical role in modulating motor movement and reward functions as part of the basal ganglia circuitry [6]. The substantia nigra is classically considered to be the primary input into the basal ganglia circuitry and a critical element to these functions [6]. When these subcortical nuclei are damaged such as during neurodegeneration or a stroke, neurological conditions may result, such as Parkinson's disease, schizophrenia, and Huntington's disease.

Dopamine is produced by neurons in the region at the base of the brain, and tyrosine (amino acid) is converted into another amino acid, named L-dopa. Afterward, L-dopa undergoes another change, as enzymes turn it into dopamine. It is known that low dopamine level causes stiff movements that are the hallmark of Parkinson's disease. Basal ganglia organize movements to occur or stop with the motor cortex therefore, decreased levels of dopamine due to neurodegeneration in the Substantia nigra area causes disorganization of the thalamus and basal ganglia causing Parkinson's disease.

2.2 Neuro Degeneration

Neurodegeneration is the progressive decline of neural tissue, it is a slow and progressive loss of neuronal cells in specified regions of the brain and is the main pathologic feature of Alzheimer's disease, Parkinson's disease, Amyotrophic lateral sclerosis, Huntington's Disease and Lewy Body Dementia. Each neurodegenerative disease of the brain is caused by the progressive accumulation of a specific protein inclusion (proteinopathy) [7]. Over time this accumulation becomes toxic to the brain leading to irreversible degeneration (death) of neurons and atrophy.

Fig. 2. Example diagram of normal and neurodegenerated brain

2.3 Parkinson's Disease

Parkinson's disease is a progressive disorder which affects the nervous system and the parts of the body controlled by the nerves. Symptoms of PD start slowly. The disease was first described in 1817 by British physician James Parkinson in his Essay on the Shaking Palsy [8]. The first symptom might be a tremor in the hand. Tremors are the common signature of the disease, however, it might also cause slowing of movement or stiffness. In the early stages of PD, the face of the patient may show little or no expression. arms may not swing while walking, the speech may become softer. PD symptoms worsen as the condition of the patient progresses over time. Parkinson's disease can't be cured and the reasons for the disease are still unknown.

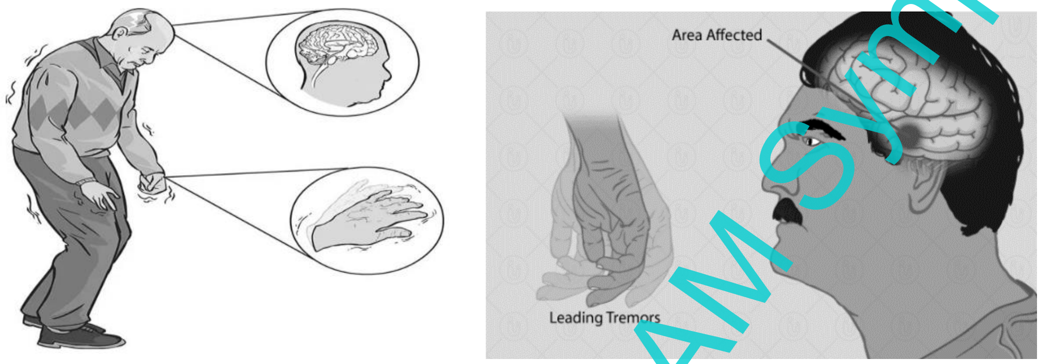

Fig. 3. Parkinson's disease disorder demonstration

Parkinson's is a disease of the basal ganglia. Classic clinical symptoms include bradykinesia (hands or fingers), resting tremors, postural instability, and shuffling gait (during walking). This disease is a result of neurodegeneration of the SNpc (substantia nigra pars compacta) dopaminergic neurons [8]. It is a degenerative neurologic disease marked by a constellation of movement and non-movement symptoms and associated with the presence of Lewy bodies in the brain. As dopamine starts to decrease, signs and symptoms of Parkinson's disease begin to appear [9].

2.4 Parkinson's and Finger movement

In Parkinson's disease, resting tremors most often occur in the hands by rotational movements of the fingers, especially the thumb and index finger. Even though we could observe a resting tremor, sometimes they could assume a pose suppressing the tremor. The finger-tapping test evaluates bradykinesia by focusing on decreasing frequency, amplitude, or both with repetitive actions. The vertical position of the hands during this task may also have clinical significance. Slowing down the speed, loss of amplitude, and pauses when tapping with fingers are consistent with "bradykinesia" — slowness of movement, which is one of the most important symptoms of Parkinson's disease [11]. Research has shown that subjects with Parkinson's disease tapped their fingers "slower and less rhythmically" compared to "healthy" subjects [11]. Based on this knowledge, the keyboard usage datasets were used. There are various kinds of research aiming at early detection of PD. In [10], focuses on vocal detection of Parkinson's disease while in [9] this research focuses on Gait data, and walking patterns during a walk. In [12], hand movements were analyzed, in our research, we analyzed the problem using 2 different datasets and made feature extraction based on outliers in data. Outliers in datasets might represent the moments when bradykinesia occurs.

3. Methods & Materials

3.1 Analysing with Finger movements using Tappy Keystoke Data

In this section, the Tappy keystroke dataset is a raw dataset for the detection of early Parkinson's Disease using multiple characteristics of finger movement while typing [13]. The dataset is created using keystroke logs collected from subjects with and without Parkinson's Disease. The purpose of this implementation is to analyze the routine interaction with computer keyboards can be used to detect changes in the characteristics of finger movement in the early stages of PD [14]. To apply feature extraction, we created additional features extraction as, Flight time and hold time can indicate meaningful information as Parkinson's Disease affects finger movements in early stages [15]. In this section subjects with tremors (mild, medium, or severe) were used for classification. The section aims to classify healthy controls and subjects that have the possibility or already have Parkinson's Disease.

Each collected data includes information about the typing time when the participants used their various computer applications (for example email, web browser, and so on). The keystroke logging software ("Tappy") was used to record the activities. The features of this section are below:

- Parkinson's: Whether they have Parkinson's Disease [True/False]
- Whether there is sidedness of movement [None /Left/Right]
- Impact: The Parkinson's disease severity or impact on their daily life [Mild/Medium/Severe] For each subject, a file that contains keystroke details was recorded.
- Hold time: Time between press and release for current key milliseconds
- Direction: Previous to current RL, RR, LL, LR (and S for a space key)
- Flight time: Time between the release of the previous key and the press of the current key in milliseconds

Below, mean (1), standard deviation (2), and variance (3) formulas are shown as they were used to extract new features.

$$\mu = \frac{\sum_{i=1}^{n} xi}{n} \quad (1)$$

$$\sigma = \sqrt{\frac{\sum_{i=0}^{n} (xi-\mu)^2}{n}} \quad (2)$$

$$\sigma^2 = \frac{\sum_{i=1}^{n} (xi-\bar{x})^2}{N} \quad (3)$$

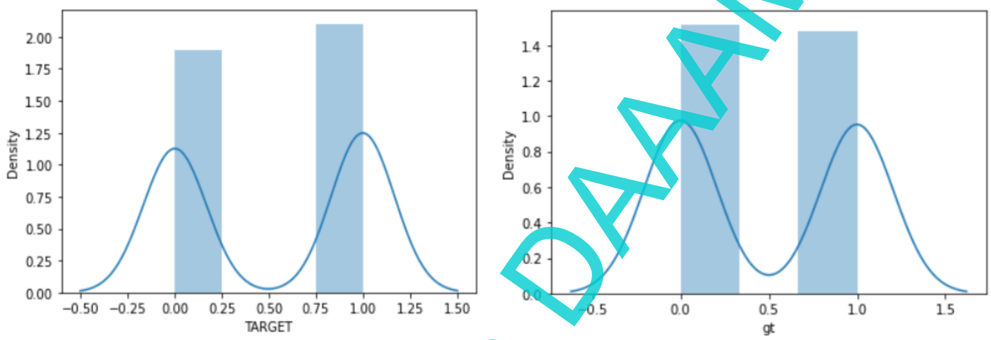

Fig. 4. Class distribution of Tappy keystroke and neuroQWERTY data respectively

Using the features related to hold time and flight time, new features were created to improve the work. Using hold time, hold time-mean and hold time-std were created. Flight time, mean of flight time Left to Right hand, and Right to left hand were also used. For each, several actions bigger than average are detected using the principle of; if the selected value is bigger than the mean value of the corresponding column. Outliers in this research were detected using the IQR method and manually (explained in the next section). Finally, the percentage of each value was calculated (4) using the formula below. To create the model ensemble learning methods were used.

$$\text{Percentage} = \frac{\text{Outlier}}{\text{length(flighttimeAction)}} * 100 \quad (4)$$

3.2 Analysing with Finger movements using NeuroQWERTY data

The MIT-CSXPD neuroQWERTY database contains keystroke logs collected from 85 subjects who are healthy or having Parkinson's disease (PD). Each collected data file includes time information collected during typing sessions using a standard Lenovo G50-70 i3-4005U word processor with 4 MB of memory and a 15-inch screen running Manjaro Linux [15]. The subjects were instructed to type as they would normally do at home [15]. Below are the default data columns without further feature extraction.

- pID – Subject ID
- gt – If they had or not they had PD
- updrs108 - Unified Parkinson’s Disease Rating Scale part
- afTap - Alternating finger-tapping result
- sTap - Single key-tapping result
- nqScore - neuroQWERTY index
- Typing speed
- file_n - The csv file(s) containing the subject's typing data

Each keystroke data csv file has four columns which give:

1. The key pressed.
2. The hold duration in seconds.
3. The key release time in seconds from time 0.
4. The key press time in seconds from time 0.

In this work, to increase the model accuracy, new features were extracted by detecting outliers that occur during the records. The hold duration in seconds, was used as a feature. Mean, standard deviation, and variance of hold time were added. Subtraction of key release time and Keypress time was added (5). The extracted features belong to each corresponding subject.

$$Subtracted = keyReleaseTime - keyPressTime \tag{5}$$

Parkinson's Disease affects finger movements as delays in hand movements occur [16]. The purpose of this section is to analyze the dataset to extract new columns that represent delays during the finger taps. To detect the outliers the IQR method was used. The quartiles (Q1, Q2, Q3) divide the dataset into four groups, each containing about 25% (or a quarter) of the data points. There are three quartiles: Q1, Q2, and Q3. Q1 (it is the first quartile) is the 25th percentile of the data. Q2 (second quartile) is the 50th percentile (medium part) of the data. Q3 (third or last quartile) is the 75th percentile of the data [17]. The Interquartile Range (IQR) is the distance between the first and third quartiles. Subtract the first quartile from the third quartile to find the interquartile range (6).

$$\mathrm{IQR} = \mathrm{Q3} - \mathrm{Q1} \tag{6}$$

Ensemble learning algorithms (The dataset with default features and the new dataset with extracted features were both used and compared) were applied. Updrs feature has a high correlation with the target column as Updrs is: the most widely applied rating instrument for Parkinson's disease [18]. Some sections of the UPDRS require multiple scores for each limb, with a possible maximum of 199 points. A score of 199 on the UPDRS scale corresponds to the worst level (complete disability), and a score of zero corresponds to no disability). In the dataset, the UPDRS column was removed to test the model behavior with the actual features. As UPDRS can be used to indicate PD directly.

3.3 Model Evaluation

In this research, Random Forest and Catboost supervised learning algorithms were used to build the model. To test and evaluate; Accuracy: It's the ratio of the correctly labeled subjects to the whole pool of subjects. Accuracy is the most intuitive one. Accuracy (7) answers the following question: How many subjects did we correctly label out of all the patients? (True Positive, True Negative, False Positive, True Negative)

$$\mathrm{Accuracy} = \frac{\mathrm{TP} + \mathrm{TN}}{\mathrm{TP} + \mathrm{FP} + \mathrm{FN} + \mathrm{TN}} \tag{7}$$

If it starts with True then the prediction was correct whether Parkinsonian or not, so a true positive is a PD person correctly predicted & a true negative is a healthy person correctly predicted. Oppositely, if it starts with False then the prediction was incorrect, so a false positive is a healthy person incorrectly predicted as PD & a false negative is a person with PD, incorrectly predicted as healthy.

4. Results

4.1 Analysing with Finger movements using Tappy Keystroke Data

The test results were obtained using feature extraction and machine learning algorithms. In the dataset, records were gathered by pressing, releasing, or pressing and holding a button afterward, measuring the timings between each interaction. Hold time in this case is an important feature. As it may represent stability or instability of the subject finger movement (rigidity, slowness, bradykinesia). PD affects motor functions thus, finger movements are also affected. Patients with Parkinson's disease have their motor activity deteriorate during a task to a greater extent with individual finger movements than with nonindividual finger movements. Thus, Parkinson's disease impairs individual finger movements to a greater extent than general hand movements. This difference reflects the more subtle cortical control required to stimulate and maintain this highly fractionated type of motor activity [20]. Just as during a cold day or when having arthritis can affect movement or cause stiffness, slowness of movement can make it difficult to move the hands and fingers [19]. Parkinson's disease can also cause unstable actions, in which the hand extends into an awkward position, making it difficult and sometimes painful to use.

The hold time and flight time are the main features of this work. To increase the features, mean, standard deviation, and variance of hold time were used. Also during the flight time (time between releasing a button and pressing the next button), maximum and minimum values were taken as well as their mean, standard deviation, and variance values. In this section and the next one, outliers are important to have because outliers may represent something unusual as slowness or any unstable action during finger movements. There are two approaches in this work, The first one is because of the possible slowness during movement.

The formulas above represent the from Left to Right and From Right to Left finger movement. The first formula takes values only higher than the mean value of all flight time columns, latter takes 100 values closer to the Maximum value. The final feature except for the target column (0 healthy, 1 subject with PD) is severity as mild, medium, and severe.

Ensemble methods offer several advantages over single models, such as improved accuracy and performance, especially for complex and noisy data. They can also reduce the risk of overfitting and underfitting by balancing the trade-off between bias and variance, and by using different subsets and features of the data. Combining multiple models provides overall best accuracies in this and other sections.

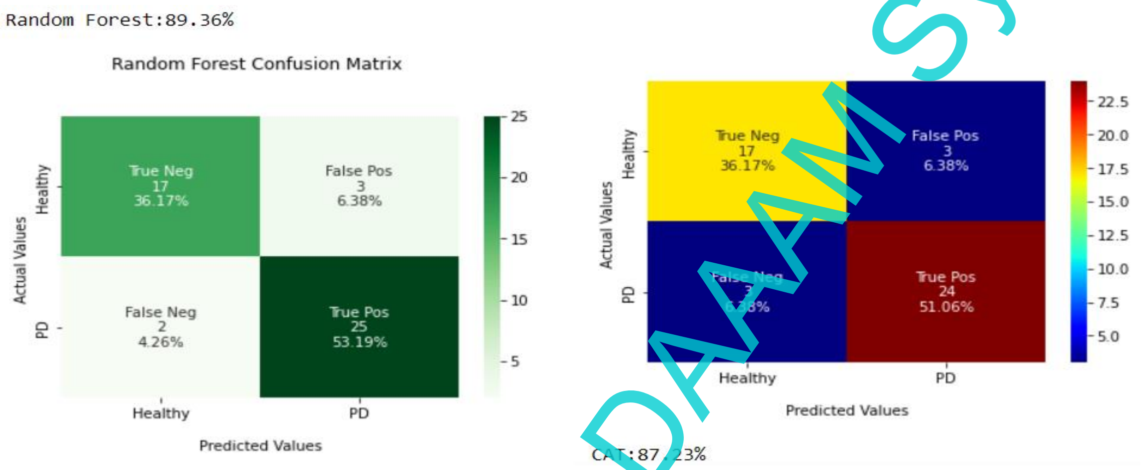

Fig. 5. Results of algorithms (test accuracies of ensemble learning methods)

4.2 Analysing with Finger movements using keyboard Part 2

In this section, the first implementation of NeuroQWERTY without feature extraction gave 76.47% accuracy whereas the final implementation dataset gave 94.12% accuracy. Both results are received using test data. The initial dataset contains similar features as afTap - alternating finger tapping result, nqScore, sTap - single key tapping result, and typing speed. The effects of feature extraction in medical data were experimented with and approved using different datasets and research [9] [21]. For each keystroke, there are .csv files where subject hold times and key press durations were recorded. In the second implementation that gives over 90 accuracies, the features are below:

1. Gt: Target column to predict
2. afTap (initial feature): alternating finger tapping result
3. sTap (initial feature): single key tapping result
4. nqScore (initial feature): motor index derived from computer-key-hold-time data using an ensemble regression algorithm [68].
5. typingSpeed (initial feature)
6. holdMean (new feature): mean value of hold time
7. holdStd (new feature): standard deviation of hold time
8. holdVar (new feature): variance of hold time
9. subtractionMean (new feature): mean of the difference between release and press time
10. subtractionStd (new feature): std of difference between release and press time
11. subtractionVar (new feature): variance of the difference between release and press time
12. outlierSubtraction (new feature): detected outliers of subtraction of release-press time

In PD, bradykinesia means slowness of movement and speed as movements are continued. Bradykinesia is considered one of the main symptoms of PD. Thus, lack of dopamine affects intentional movement making the subject hesitant and slow during the interaction and these movements are detectable using finger movements data. In this section, outliers were used to create new features as release time and press time of the button were subtracted for each subject, afterwards outliers of the calculation were detected using IQR statistical method. The latter model for PD analysis gave the highest results amongst others with 94.12% test accuracy.

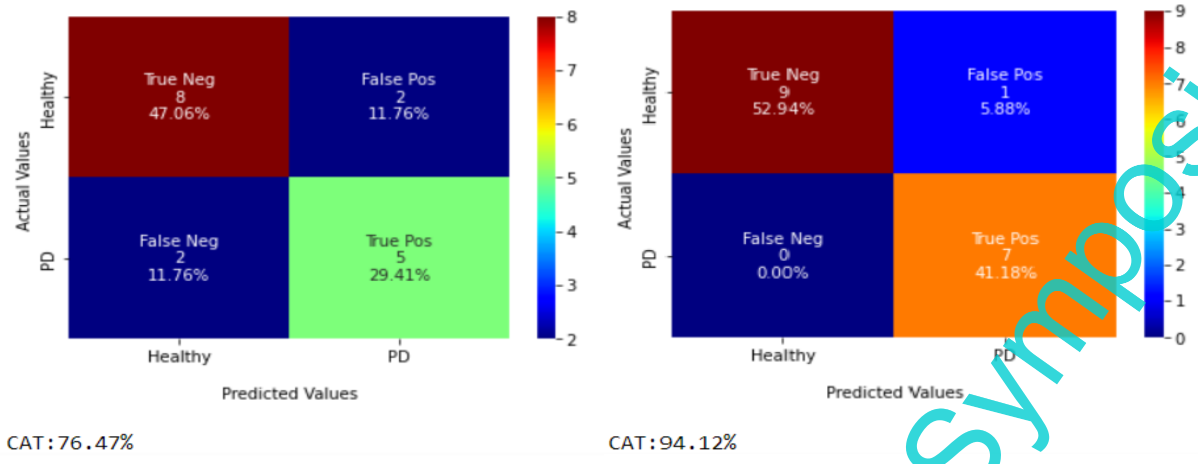

Fig. 6. Results of algorithms (test accuracies of ensemble learning methods) of second implementation

5. Discussion

Below is the chart, a full comparison between Random Forest and Catboost algorithms based on 2 different implementations and also after feature extraction for the second dataset (neuroqwerty2).

Fig. 7. Comparison chart of the results

Any effect coming from Basal Ganglia which is responsible for creating dopamine, can be detected in muscle movements in our body including finger movements. However, depletion of dopamine levels is a long and slow process therefore purpose is to detect the situation in earlier stages. Still, the reasons for Parkinson's Disease are unknown therefore another purpose of this research is to help understand why there is neurodegeneration occurs in the basal ganglia. PD disease is progressive which means in time it gets worse. Therefore it is crucial to detect this as early as possible. Dementia means that there is behavioral and/or cognitive impairment that significantly affects one's activities of daily living. However, it is an umbrella term that encompasses many different etiologies, including neurodegenerative, metabolic, vascular, and infectious diseases. A Lewy body is an abnormal aggregation or clumping of the protein alpha-synuclein.

There are two main reasons for using ensemble methods, rather than a single model, and these are: A set of learners can make better predictions and achieve better performance from a single contributing model.

An ensemble model reduces the spread or scattering of predictions and model performance. Ensemble learning is used to achieve better prediction performance than a single predictive model in an ML implementation. The way is, to add bias to reduce the variance component of the prediction error.

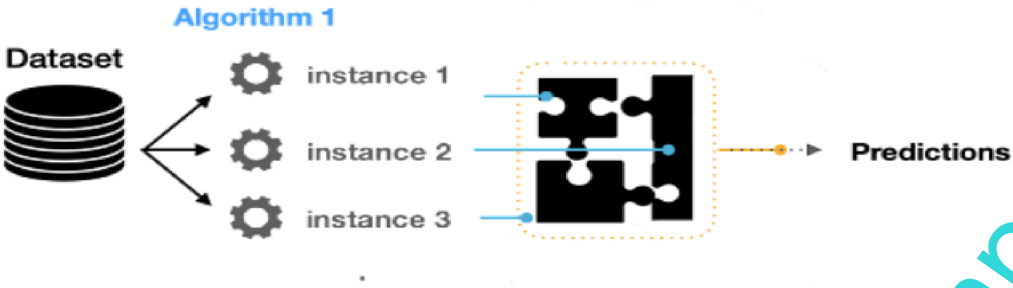

Fig. 8. Ensemble methods were applied in this research

The model can be used as an interpreter between a patient/subject and a medical expert. To test, the subject has to type using a keyboard With the help of collected data, the model can predict the possibility of having PD disease in the subject. Finally, medical experts can analyze the results. It is clear that neurodegeneration in substantia nigra occurs slowly thus it can start at earlier ages of the subject as well. Many people might not be aware of early signs that can, unfortunately, transform into PD disease in the later stages of their life. Providing an awareness and solutions model would help to increase the life quality of the subject as well as predict the disease.

6. Conclusion

The brain regions are responsible for different actions in the human body. Neurons are connected and they communicate with each other all the time during our life. Throughout our life, neurons die and the amount of the neurons decrease. However, when this process is severe and faster than usual, this causes neurodegeneration. The affected area of neurodegeneration causes specific disorders.

Ensemble learning algorithms gave the highest accuracies in this research, It is understood that instead of using one model, using multiple learners provides higher accuracies and more reliability (randomness, more realistic approach). One disadvantage of the model is, that the ensembling is less interpretable, and the output of the ensembled model is hard to explain similar to a black box.

The finger movement using the keyboard typing approach was successful with 94.12% accuracy. The initial data gave 76.47%, after using an outlier strategy to add more features, the model was able to perform much better. With the help of this approach, it is understood that PD has many symptoms, one of them being bradykinesia (slowness, hesitation) using outlier detection and creating features based on subtraction of outliers vs. mean/ std values was a successful implementation. The finger movement is also a movement recording data which means, the model is looking for hesitation or slowness during typing. In future work, EMG signals and sleep EEG signals will be added to the main model to make it stronger and more reliable. Even though models gave acceptable results, there is a possibility for False positives or False negatives.

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