NeuroFuzzXAI: A Hybrid Artificial Intelligence Framework for Epileptic Seizure Detection

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Abstract

Background and Aim: Detecting epileptic seizures from electroencephalogram (EEG) recordings is crucial for accurate diagnosis and treatment. While deep learning models achieve strong predictive performance, their black-box nature limits clinical applicability. This study proposes a hybrid framework that combines explainable artificial intelligence (XAI) with fuzzy logic to improve both accuracy and interpretability in seizure classification. The objective is to enhance transparency in decision-making by identifying key EEG features and providing an interpretable risk assessment. *Materials and Methods:* This study utilizes the publicly available Epileptic Seizure Recognition dataset [i], which consists of EEG recordings from 500 subjects, segmented into 11,500 one-second windows, each described by 178 features. The dataset is balanced, comprising five equally distributed classes that capture a diverse range of brain activity patterns, including pathological conditions as well as natural variations in EEG signals. The classification labels were manually assigned by neurologists, serving as the gold standard diagnostic for seizure detection and ensuring that predictions align with clinically validated seizure patterns. A deep learning model was implemented in PyTorch, trained with cross-entropy loss and optimized using Adam. Instead of using all 178 features, SHapley Additive exPlanations (SHAP) identified the three most influential EEG features, which were then processed through a fuzzy inference system that assigns seizure risk as Low, Medium, or High. This hybrid approach enhances interpretability while maintaining predictive accuracy, reducing computational complexity, and mitigating overfitting. *Results:* Compared to a standard deep learning model utilizing all features, our hybrid approach improved classification performance by 12%. The deep learning component alone achieved a high classification accuracy, but integrating fuzzy logic refined decision boundaries and enhanced interpretability. SHAP analysis highlighted key EEG features contributing to predictions, increasing model transparency. The fuzzy inference system generated clinically meaningful risk assessments that closely aligned with deep learning outputs, providing an intuitive representation of seizure likelihood. *Conclusion:* The proposed hybrid framework successfully integrates deep learning with explainable fuzzy logic, addressing both performance and interpretability challenges in seizure detection. By bridging artificial intelligence-based classification with human-intuitive decision-making, this approach holds promise for clinical applications. Future work will focus on real-time deployment in healthcare settings to support epilepsy diagnosis and monitoring.

Keywords: Epileptic Seizure Detection; Explainable Artificial Intelligence (XAI); Fuzzy Logic System; Electroencephalogram (EEG) Analysis; Hybrid Deep Learning Model.

[i] Dataset source: https://www.kaggle.com/datasets/harunshimanto/epileptic-seizure-recognition