Learning Latent Sleep Dynamics from Multimodal Polysomnography for Mild Cognitive Impairment Prediction: A Fractal Analysis-Based Method

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Aims: Sleep is a fundamental biological process closely linked to cognitive function, yet its relationship with cognitive decline remains incompletely understood. This study aims to investigate multimodal polysomnography (PSG) using fractal-based feature extraction to characterize signal complexity, self-similarity, and latent sleep dynamics for predicting mild cognitive impairment (MCI).

Methods: Data from the Human Sleep Project, including **demographic variables, multimodal PSG signals, sleep staging annotations, and respiratory, movement, arousal events** from five U.S. institutions, were analyzed. Physiological features were extracted from EEG, EOG, EMG, respiratory, and cardiovascular signals using standard deviation, mean absolute value, root mean square, zero-crossing rate, and Hjorth parameters. **Nonlinear signal complexity was quantified using Higuchi and Petrosian fractal dimensions (HFD, PFD)** computed on full-night and stage-specific EEG segments. Sleep staging dynamics were further characterized by applying fractal analysis to sleep staging sequences. To capture **temporal sleep structure**, **sleep staging annotations were encoded as multivariate time series** and projected into a low-dimensional space via incremental principal component analysis (PCA), from which **latent trajectory features, including variance and fractal dimensions**, were derived. All features were integrated along with demographic variables, and classified using a **class-balanced Random Forest model.**

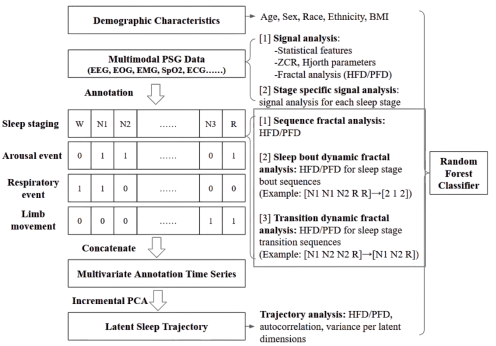

Fig 1. Proposed framework for predicting MCI from PSG.

Results: The proposed model achieved a 5-fold cross validation AUROC of 0.664 ± 0.069. Performance on test dataset revealed AUROC of 0.694.

Conclusion: The proposed framework captures multi-scale sleep complexity and latent temporal dynamics, providing a promising approach for PSG-based cognitive assessment.