

NEUROTWIN AI

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Abstract- *NeuroTwin AI is an intelligent healthcare system designed to build a personalized digital twin of the human brain. At present, treatment planning for brain-related diseases such as epilepsy, Alzheimer's, and Parkinson's relies heavily on trial-and-error methods, where doctors prescribe medications or suggest procedures without being able to simulate outcomes in advance. This uncertainty often leads to ineffective treatments, risks to patient safety, and increased healthcare costs. NeuroTwin AI addresses this challenge by creating a virtual brain model using MRI, fMRI, EEG, and clinical data, allowing doctors to simulate therapies such as medications, Deep Brain Stimulation (DBS), Transcranial Magnetic Stimulation (TMS), and surgical procedures in a safe digital environment.*

The system also employs Explainable Artificial Intelligence (XAI) techniques like SHAP, LIME, and Grad-CAM, ensuring that every prediction and recommendation is accompanied by clear reasoning, thereby improving doctor trust and transparency. The development of this system follows a structured methodology involving communication with clinicians, planning of modules, data modeling, and deployment of AI-based simulations. It is built using advanced algorithms such as Convolutional Neural Networks (CNN), Graph Neural Networks (GNN), State-Space Models, and Reinforcement Learning, supported by federated learning to ensure patient privacy. Testing is carried out through validation against real patient data and clinician feedback. The result of this project is a prototype of NeuroTwin AI, which enables doctors to explore treatment outcomes virtually, reduce risks, improve decision-making, and save time and resources. This system has the potential to transform the way neurological treatments are planned and delivered, offering safer, more effective, and personalized healthcare.

I. INTRODUCTION

In today's healthcare environment, providing efficient, reliable, and personalized treatment for neurological disorders is critical for improving patient outcomes and quality of life. Brain-related diseases such as **epilepsy, Alzheimer's disease, Parkinson's disease, and stroke** are highly complex, involving dynamic neural interactions, diverse patient responses, and the risk of severe side effects from trial-and-error treatment methods. Traditional approaches to treatment planning, often based on generalized

medical guidelines and non-adaptive prediction models, lead to **inefficiencies, uncertainties, and increased risks for patients.**

The prevalence of neurological disorders is increasing worldwide, with millions of patients depending on accurate treatment strategies. Currently, diagnosis and treatment decisions rely on **MRI, fMRI, EEG, and clinical evaluation.** However, these methods provide only static information and do not allow doctors to predict how a patient's brain will respond to different therapies. In addition, existing AI-based systems often act as **black-box models**, making predictions without providing clear reasoning. This lack of **explainability** reduces trust among doctors and limits their use in critical decision-making. Patients and clinicians face challenges such as uncertainty about treatment outcomes, the need for repeated hospital visits, and the risk of side effects from unsuitable medications or invasive procedures.

The limitations of current systems create the need for a **personalized, transparent, and safe digital healthcare platform** that allows doctors to test treatment options before applying them to real patients. Advances in **Artificial Intelligence (AI), Machine Learning (ML), and Explainable AI (XAI)** provide an opportunity to revolutionize neurological healthcare by creating **digital twins of the human brain.** A digital twin is a virtual model of a patient's brain built using multimodal data (MRI, fMRI, EEG, and medical history). This twin can simulate brain dynamics and allow doctors to explore "what-if" scenarios for different treatments such as drug therapy, Deep Brain Stimulation (DBS), Transcranial Magnetic Stimulation (TMS), or surgical interventions.

To address these challenges, researchers propose **NeuroTwin AI**, an innovative system that integrates **Convolutional Neural Networks (CNNs), Graph Neural Networks (GNNs), State-Space Models (SSM), and Reinforcement Learning (RL)** to build a patient-specific brain twin. The system employs **XAI methods such as SHAP, LIME, and Grad-CAM** to provide visual and textual explanations for predictions, ensuring transparency and trust. **Federated learning techniques** are applied to train models across hospitals without sharing raw patient data, maintaining compliance with **GDPR and HIPAA** regulations.

The methodology used in the development of NeuroTwin AI follows a structured approach similar to **Design Thinking and AI system engineering**, including communication with neurologists, requirement analysis, data modeling, prototype development, and testing. Validation is carried out through clinician feedback and comparison with real-world patient outcomes.

II. LITERATURE REVIEW

“Sanz Leon, P., Knock, S., Woodman, M., Domide, L., Mersmann, J., McIntosh, A. R., & Jirsa, V. K., *The Virtual Brain: A simulator of primate brain network dynamics*, **Frontiers in Neuroinformatics**, 2013.”

This paper introduces *The Virtual Brain (TVB)*, a platform that simulates large-scale brain networks using structural connectivity data. It demonstrates how mathematical models of brain regions connected through realistic networks can reproduce activity patterns similar to fMRI, EEG, and MEG signals. This research laid the foundation for the concept of **digital brain twins**, proving that computational brain models can generate clinically relevant dynamics. NeuroTwin AI builds upon this by personalizing simulations for individual patients using multimodal data, enabling real-time treatment testing and decision support.

“Jirsa, V. K., Stacey, W. C., Quilichini, P. P., Ivanov, A. I., & Bernard, C., *On the nature of seizure dynamics in the human brain*, **Brain**, Oxford University Press, 2014.”

The authors present the *Epileptor model*, a neural-mass model that captures seizure onset, evolution, and termination. The study shows how a compact five-state model can reproduce diverse seizure dynamics. This work highlights the power of computational models in explaining epilepsy. NeuroTwin AI integrates this principle by embedding seizure models into its **treatment simulation module**, allowing doctors to evaluate anti-epileptic therapies virtually before applying them to real patients.

“Jirsa, V. K., Proix, T., Perdakis, D., et al., *Individualized whole-brain models of epilepsy spread*, **NeuroImage**, 2017.”

This study demonstrates how large-scale brain networks can be personalized with the Epileptor model at each node to simulate how seizures spread in individual patients. The results matched invasive EEG recordings and postsurgical outcomes, proving the feasibility of **patient-specific brain simulations**. NeuroTwin AI adopts this approach by constructing personalized brain twins that support treatment planning and surgery optimization, offering a more reliable prediction of outcomes.

“Proix, T., Bartolomei, F., Guye, M., & Jirsa, V. K., *Individual brain structure predicts seizure propagation*, **Brain**, 2017.”

This research emphasizes that seizure propagation is strongly dependent on each patient’s structural brain network. Personalized simulations predicted seizure spread patterns in 15 patients, demonstrating the importance of **individualized structural data**. NeuroTwin AI applies this finding by using MRI and fMRI connectivity as critical inputs to build patient-specific models, improving the accuracy and reliability of treatment simulations.

“Proix, T., et al., *Spatiotemporal diversity of seizures: A mechanistic explanation*, **Nature Communications**, 2018.”

The study investigates why seizure propagation differs not only across patients but also between episodes in the same patient. Using computational models, the authors explain that seizure variability arises from dynamic brain network mechanisms. NeuroTwin AI extends this principle to simulate diverse treatment responses, helping clinicians anticipate different patient outcomes for medications or stimulation therapies.

“Van Essen, D. C., Smith, S. M., Barch, D. M., et al., *The WU-Minn Human Connectome Project: An overview*, **NeuroImage**, 2013.”

This project provides a comprehensive high-resolution map of human brain connectivity through multimodal imaging data. It has become a reference dataset for large-scale neuroscience research and modeling. NeuroTwin AI leverages the Human Connectome Project’s insights and methods to validate its models, ensuring both **population-level reliability** and **patient-level personalization**.

“Wilson, H. R., & Cowan, J. D., *Excitatory and inhibitory interactions in localized populations of model neurons*, **Biophysical Journal**, 1972.”

One of the earliest and most influential mathematical models of neural populations, this work describes excitatory-inhibitory interactions and their role in shaping brain dynamics. The Wilson-Cowan model provided the theoretical basis for many modern neural-mass and seizure models. NeuroTwin AI incorporates these principles into its **state-space modeling framework**, simulating dynamic changes in brain states during treatment to predict risks and side effects.