RADemics

ML and IoT Approaches for Early Diagnosis and Prediction of Alzheimer's Disease

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Abstract

Alzheimer's disease (AD) was a progressive neurodegenerative disorder with profound cognitive and functional impairments, posing significant challenges for early diagnosis and effective management. Traditional diagnostic methods, including neuroimaging, cerebrospinal fluid analysis, and cognitive assessments, often detect the disease at advanced stages, limiting the efficacy of therapeutic interventions. Recent advances in machine learning (ML) and Internet of Things (IoT) technologies have enabled the development of innovative frameworks for early detection, continuous monitoring, and personalized prediction of AD. ML algorithms, encompassing supervised, unsupervised, and deep learning models, facilitate multi-modal data analysis, extracting complex patterns from neuroimaging, genetic, cognitive, and behavioral datasets. Concurrently, IoT-enabled wearable devices and ambient sensors capture longitudinal physiological and behavioral signals, supporting real-time monitoring and adaptive predictive modeling. The integration of ML and IoT provides hybrid frameworks capable of dynamic risk assessment, early detection of prodromal symptoms, and data-driven clinical decision support. This chapter systematically reviews state-of-the-art ML and IoT methodologies, evaluates benchmark metrics for predictive accuracy, and highlights case studies demonstrating their clinical applicability. Regulatory, ethical, and interpretability considerations are also discussed to ensure safe and equitable deployment of these technologies. By addressing existing challenges and identifying future directions, hybrid ML-IoT frameworks represent a transformative approach for enhancing early diagnosis, personalized intervention, and precision healthcare in Alzheimer's disease.

Keywords: Alzheimer's disease, machine learning, Internet of Things, early diagnosis, predictive modeling, hybrid frameworks

Introduction

Alzheimer's disease (AD) was a debilitating neurodegenerative disorder that manifests through progressive cognitive decline, memory impairment, and deterioration of functional abilities, representing one of the foremost challenges in global public health [1]. The prevalence of AD was expected to rise sharply with aging populations, imposing significant social, economic, and healthcare burdens [2]. Early detection remains critical because interventions applied during the initial stages can significantly slow disease progression, enhance quality of life, and reduce long-term care costs [3]. Traditional diagnostic modalities, including neuroimaging techniques such as magnetic resonance imaging (MRI) and positron emission tomography (PET), cerebrospinal fluid (CSF) biomarker analysis, and standardized neuropsychological assessments, often detect the disease only after considerable neuronal damage has occurred [4]. These approaches are limited by high costs, procedural invasiveness, and reliance on specialized clinical expertise, which restrict timely intervention. The inherent complexity and heterogeneity of AD necessitate advanced strategies that can process diverse datasets, identify subtle patterns, and predict disease trajectories with high precision. Computational approaches, particularly those leveraging machine learning (ML) and the Internet of Things (IoT), provide a promising avenue to overcome these limitations by integrating high-dimensional datasets and enabling predictive, personalized, and adaptive healthcare solutions for early-stage Alzheimer's detection [5].

Machine learning methodologies have emerged as pivotal tools in the early detection of Alzheimer's disease due to their ability to manage large-scale, heterogeneous, and multi-modal datasets [6]. Supervised learning techniques, including support vector machines, random forests, and gradient boosting algorithms, have demonstrated effectiveness in classifying disease stages and predicting conversion from mild cognitive impairment to Alzheimer's [7]. Deep learning architectures, such as convolutional neural networks (CNNs) and recurrent neural networks (RNNs), further enhance predictive capabilities by extracting hierarchical spatial and temporal features from raw neuroimaging and longitudinal patient data [8]. Unsupervised and semi-supervised learning models are increasingly employed to identify latent structures within multi-dimensional datasets, uncovering previously unrecognized patterns associated with early cognitive decline. Integration of these algorithms with feature selection and dimensionality reduction techniques ensures efficient processing while preserving critical clinical information [9]. Multi-modal data fusion, combining neuroimaging, genetic, and cognitive variables, enhances model robustness and generalizability, allowing the identification of subtle prodromal changes that often precede clinical diagnosis. These ML-based computational strategies form the foundation for predictive frameworks capable of supporting evidence-based, precision-oriented intervention strategies in Alzheimer's disease management [10].

The advent of Internet of Things technologies has introduced a new dimension to early Alzheimer's detection through continuous and real-time patient monitoring [11]. IoT-enabled devices, including wearable sensors, ambient monitoring systems, and mobile health applications, facilitate longitudinal tracking of physiological and behavioral parameters such as heart rate variability, sleep quality, gait dynamics, speech patterns, and daily activity routines [12]. The real-time collection of high-resolution data allows for the detection of minute deviations from normative behaviors, serving as early indicators of cognitive decline [13]. When combined with machine learning algorithms, these IoT-derived datasets enable hybrid predictive frameworks that continuously adapt to evolving patient data, offering dynamic risk assessment and personalized recommendations [14]. IoT-driven monitoring extends healthcare beyond episodic clinical visits, providing insights into real-world, naturalistic environments and capturing variations in patient behavior that traditional assessments might overlook. Such integration supports the development of proactive intervention strategies, enhances patient engagement, and contributes to individualized care pathways in the management of Alzheimer's disease [15].