A Hybrid AI Framework for Sensor-Based Personal Health Monitoring towards Precision Health

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Abstract

Non-communicable diseases are on the rise globally, resulting in accelerated efforts to develop personal health monitoring systems for early detection, prediction, and prevention of diseases. This is part of the vision of precision health, an emerging paradigm that focuses on preventing disease before it strikes by encouraging people to actively monitor and work towards improving their health. A key facilitator of this is the use of wearable sensors that can collect and measure physiological data. Although many sensor-based health monitoring systems have been proposed, interoperability of health data and processes, prediction of future health states, and uncertainty management remain open challenges. This research aims to alleviate these challenges through the development of a reusable framework integrating both data-driven and knowledge-driven AI within a hybrid AI architecture.

Introduction

Non-communicable diseases are collectively responsible for 74% of all deaths worldwide[1], and continue to increase in prevalence and incidence. In response to this, the field of precision health has emerged, which incorporates health monitoring into people's daily lives outside clinical settings, thereby empowering them to actively participate in their health (Gambhir et al. 2021). This can be facilitated by wearable sensors, which capture various physiological signals and have become ubiquitous and relatively affordable.

However, sensor data cannot be used in isolation, since non-communicable diseases are influenced by lifestyle factors, health history, and comorbidities. This supplementary health data can be derived from health records, questionnaires, and interviews, and its interpretation requires expert medical knowledge. In a systematic mapping study of the state of the art in sensor-based health monitoring systems (Nzomo and Moodley 2023), we identified several key challenges among such systems: interoperability, situation analysis (the detection and prediction of health situations), decision support, context awareness, and uncertainty handling. We critically evaluated the extent to which these challenges have been addressed in current systems and found notable deficiencies in existing work, particularly in the areas of interoperability, situation analysis, and uncertainty handling.

A key aspect of interoperability that is poorly explored in existing work is process and clinical interoperability, which entails a shared understanding of healthcare processes and the seamless transfer of care between different clinical teams (Benson and Grieve 2021). AI-driven health monitoring systems have the potential to elevate this, supporting clinicians in providing seamless and consistent care outside clinical settings that is grounded in established clinical guidelines and workflows. With regard to situation analysis, several systems are capable of detecting abnormalities in sensor observations or classifying individuals into predefined health states. However, most are unable to predict the risk of adverse outcomes in the future. Finally, many systems do not take uncertainty into consideration in the situation analysis or decision support processes. Given the probabilistic nature of health situations and outcomes, uncertainty is implicit in the health domain and must be managed for effective health monitoring.

Aim and Objectives

My research aims to address these outstanding challenges through the design and evaluation of a hybrid AI framework for sensor-based personal health monitoring. To achieve this aim, I have outlined three objectives:

1. *To design a hybrid AI architecture that integrates both data-driven and knowledge-driven AI techniques.*

   This is related to neuro-symbolic AI, which combines data-driven methods such as artificial neural networks (neuro) with knowledge-driven methods (symbolic) combining the strengths of each to achieve the best of both worlds (Sarker et al. 2021). I explore an agent-based approach, taking advantage of the Beliefs-Desires-Intentions framework (Rao and Georgeff 1995), which models the agent's beliefs about its environment, desires that it would like to accomplish, and intentions that it is currently working towards. Agent-based computing provides a useful paradigm through which these different techniques can be integrated, and has been applied extensively in the health domain (Isern and Moreno 2016).
2. *To iteratively develop and evaluate the components of the architecture.*

[1]https://www.who.int/news-room/fact-sheets/detail/noncommunicable-diseases, accessed 06 Dec 2023

These components include machine learning models, ontologies and knowledge graphs, and Bayesian networks. While machine learning can extract meaningful patterns from sensor data and forecast physiological signals, it is limited in explainability. This can be enhanced by ontologies and knowledge graphs, which are useful not only for formally representing heterogeneous health data, but also encoding the expert knowledge that can be used to interpret it, thereby enabling reasoning and inference. Bayesian networks are effective for probabilistic reasoning under uncertainty and can also represent causal relationships in data.

3. *To evaluate and demonstrate the functional adequacy of the proposed framework using two application use cases.* The research is divided into two phases, which each phase corresponding to one of the use cases. The first phase focuses on health risk detection and prediction through the use case of atrial fibrillation (AF), while the second phase focuses on wellness promotion through the use case of stress monitoring.

Current Progress: Health Risk Detection and Prediction

For the first phase of the research, I have developed an abstract hybrid AI architecture capable of health risk detection and prediction as well as subsequent decision support. The architecture is demonstrated and evaluated through the use case of AF, which is not only the most common type of arrhythmia but is also associated with serious health risks including stroke and major bleeding (Hindricks et al. 2021; Brieger et al. 2018).

I developed machine learning models to detect AF and distinguish it from other arrhythmias from an electrocardiogram signal. Further, together with my research group, we demonstrated the efficacy of using a Bayesian network to enhance the explainability of the machine learning outputs, and validated the approach of combining machine learning and Bayesian networks within an agent architecture (Wanyana et al. 2022, 2023). I have also developed an application AF monitoring ontology to represent sensors and sensor observations, personal information, and expert medical knowledge for the AF use case. Using machine learning, rule-based reasoning, and fuzzy inference, the architecture is able to detect and predict health situations and offer appropriate decision support, while incorporating human participation as well as established health workflows and clinical guidelines.

Future Work: Wellness Promotion and Ethical Implications

The second phase of the research focuses on stress monitoring for wellness promotion, which plays an important role in holistic healthcare. I will develop machine learning models and extend the ontology for stress detection and prediction using electrocardiogram and electroencephalogram data. I will also develop a dynamic Bayesian decision network to model general sequential decision making based on the detected and predicted stress states.

As part my research, I also intend to analyse the ethical implications of AI-based personal health monitoring. Although it has emerged as a promising solution to the increasing prevalence of non-communicable diseases, it is not without its risks. For instance, false positives may cause undue anxiety and psychological harm to the monitored person and result in costly and/or invasive diagnostic procedures as part of the cascade of care (Mandrola and Morgan 2019). These potential harms must be carefully considered before the adoption of personal health monitoring systems.

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