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THE ARCHITECTURE AND PRINCIPLES OF BUILDING DIGITAL TWINS FOR PREDICTIVE DIAGNOSTICS IN PERSONALISED MEDICINE

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Анотація

У роботі розглянуто архітектуру та принципи побудови цифрових двійників (динамічна віртуальна модель пацієнта, що постійно оновлюється завдяки даним [1]) для предиктивної діагностики в персоналізованій медицині. Цифровий двійник визначається як модель, що інтегрує інформацію з електронних медичних карт, геномних досліджень та IoT-пристроїв (мережа сенсорів і пристроїв, які збирають та передають дані [2]). Показано, що такі моделі здатні враховувати індивідуальні особливості пацієнта, працювати на різних рівнях – від молекулярного до організмового, а також забезпечувати проведення in-silico *експериментів (комп'ютерні моделювання для перевірки сценаріїв лікування чи впливу факторів [3]), виявлення аномалій та підтримку клінічних рішень. Окремо акцентовано увагу на викликах кібербезпеки та етичних аспектах використання чутливих біометричних даних. Результати дослідження демонструють потенціал цифрових двійників у трансформації сучасної медицини від реактивної до превентивної та перспективи їх інтеграції у державну систему охорони здоров'я.*

Ключові слова: цифровий двійник, предиктивна діагностика, персоналізована медицина, IoT-пристрої, *in-silico* експерименти

Abstract

This paper examines the architecture and principles underlying the creation of digital twins (a dynamic virtual model of a patient that is constantly updated using data [1]) for predictive diagnostics in personalised medicine. A digital twin is defined as a model that integrates information from electronic health records, genomic studies and IoT devices (Internet of Things – a network of sensors and devices that collect and transmit data [2]). It has been shown that such models are capable of taking into account a patient's individual characteristics, operating at various levels – from the molecular to the organismal – as well as facilitating in silico experiments (computer simulations to test treatment scenarios or the impact of factors [3]), the detection of anomalies, and the support of clinical decisions. Particular attention is drawn to cybersecurity challenges and the ethical aspects of using sensitive biometric data. The study's findings demonstrate the potential of digital twins to transform modern medicine from reactive to preventive and the prospects for their integration into the national healthcare system.

Keywords: digital twin, predictive diagnostics, personalised medicine, IoT devices, in silico experiments

Introduction

This paper examines current approaches to the use of digital twins [1] in the fields of predictive diagnostics and personalised medicine. Such models combine information from electronic health records, genomic studies and IoT devices [2], creating a foundation for continuous health monitoring.

The potential for using digital twins to conduct in silico experiments [3], predict risks and support clinical decision-making is analysed. The importance of ethical considerations and cybersecurity issues arising from the handling of sensitive biometric data is highlighted. This approach demonstrates the potential for medicine to transition from a reactive to a preventive model and opens up new opportunities for integrating digital twins into the healthcare system.

Research results

This paper examines the potential applications of digital twins in the fields of predictive diagnostics and personalised medicine. A digital twin [1] acts as an integration platform that brings together various sources of information: electronic health records, genomic studies, laboratory test results and data from IoT devices [2]. As a result, the digital twin is not a static model but functions as a data stream reflecting the patient's current state of health. This enables the doctor to obtain a more accurate picture of physiological processes and predict potential deviations even before clinical symptoms appear.

An important aspect is the multi-level nature of the digital twin, which spans various scales – from the molecular and cellular levels to the level of the organism as a whole. This multi-scale approach enables the analysis of both local biochemical processes and systemic changes in the patient's physiology. For example, changes in cellular metabolism can be correlated with the risk of developing cardiovascular diseases, enabling more accurate predictions. Furthermore, the customisation of the model – tailoring parameters to the patient's specific physiological constants – makes the digital twin a unique tool for personalised medicine.

Particular attention has been paid to the possibility of conducting in silico experiments [3]. This means that a doctor can test various treatment options or exercise regimens in a virtual environment without exposing the patient to any risk. For example, it is possible to simulate the body's response to a new drug or assess the effects of physical exercise on a patient with heart disease. As shown in Figure 1, a digital twin combines a person's real face with a virtual model in the form of a three-dimensional mesh, symbolising the ability to transfer physiological processes into a computer environment for analysis and prediction. This approach opens up new horizons for preventive medicine, where decisions are made based on predictions rather than only after symptoms appear.

Figure 1 – Visualisation of the digital twin concept: a comparison of a person's real face and its digital model in the form of a three-dimensional mesh.

The study also showed that digital twins are capable of detecting anomalies in physiological data long before critical conditions develop. Artificial intelligence algorithms analyse large datasets in real time, enabling the detection of pre-syncope conditions or the risk of a heart attack several hours or even days before the event. This creates the conditions for timely intervention and reduces the likelihood of complications developing.

Particular emphasis is placed on the aspects of interaction between the digital twin and the doctor. It is important that the results of the modelling are presented in a clear graphical form, which is facilitated by the human-computer interface [4] (user interaction with the computer system via a clear and user-friendly interface). Data visualisation allows the doctor to quickly assess the patient's condition, understand the logic behind the prognosis, and make an informed clinical decision. This is particularly relevant in cases where artificial intelligence algorithms operate as 'black boxes', and the doctor needs to have interpreted results in order to trust the system.

At the same time, the study highlights challenges relating to cybersecurity and ethical considerations. As digital twins handle sensitive biometric data, the question arises of how to protect them from unauthorised access. Furthermore, it is important to ensure the transparency of artificial intelligence algorithms so that doctors can understand the logic behind the predictions and make decisions based on reliable information.

Thus, the study's findings confirm that digital twins are a promising tool for transforming medicine from reactive to preventive. They enable continuous health monitoring, the conduct of in silico experiments, the detection of anomalies, and the support of clinical decisions. The prospects for implementing this technology within the public healthcare system open up new opportunities for improving the quality of medical services and reducing risks for patients.

Conclusion

This paper analyses the architecture and principles underlying the development of digital twins for predictive diagnostics in personalised medicine. It is shown that a digital twin [1] is a dynamic model of a patient that integrates data from electronic health records, genomic studies and IoT devices [2], ensuring continuous monitoring of health status.

The research findings confirm the effectiveness of in-silico experiments [3] for predicting the body's reactions and assessing risks without direct intervention in the patient's physiology. The use of a human-computer interface [4] is also important, as it allows the doctor to receive interpreted modelling results in a clear graphical format.

Thus, digital twins open up new opportunities for the transition of medicine from a reactive to a preventive model, facilitate the personalisation of treatment and create prospects for integration into the national healthcare system.

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