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(Review Article)

Unlocking the power of digital twins in personalized healthcare

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Abstract

Digital twins (DTs) emerge as a transformative force within the realm of healthcare, heralding a new era characterized by personalized treatment modalities and enhanced therapeutic efficacy. This review delves into the profound advancements witnessed in DT applications, varying from customization of treatment plans for complex ailments like heart disease and cancer, to optimization of drug discovery processes and rehabilitation protocols.

The advent of DTs represents healthcare innovation, offering virtual replicas of patients and anatomical structures that empower clinicians with unprecedented insights and capabilities. These virtual models enable the tailoring of treatment strategies to individual patient profiles, facilitating precise interventions that maximize therapeutic outcomes while minimizing adverse effects.

Nevertheless, amidst the promise of DTs lie certain limitations and challenges that warrant meticulous attention. Chief among these, is the imperative for interdisciplinary collaboration across medical, technological, and ethical domains to ensure seamless integration and ethical deployment of DTs in healthcare settings. Robust measures must be instituted to safeguard patient data privacy and uphold ethical principles such as fairness, autonomy, and transparency.

Despite these challenges, the transformative potential of DTs in healthcare remains unparalleled. Through virtual organ simulations, personalized medicine initiatives, and the optimization of clinical trials, DTs offer a glimpse into a future, where interventions are truly tailored to the needs of patients. Realizing this potential necessitates concerted efforts to address the identified challenges and pave the way for a future characterized by improved patient outcomes, enhanced decision-making processes, and the realization of personalized medicine.

Keywords: Digital Twins; Healthcare; In Silico; Virtual Representation; Personalized Medicine

1. Introduction

In 2010, NASA defined a Digital Twin (DT) as an “integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system using the best available physical models, sensor updates, fleet history, etc., to replicate the life of its flying counterpart”. While initially focused on aeronautics, this definition underscores how digital twins naturally extend the realms of simulation and optimization (Wu et al., 2022). Since then, digital twins have evolved to incorporate quantitative sensing techniques capable of capturing large datasets. These techniques combined with realistic mathematical models enable the characterization of the spatial and temporal dynamics of various phenomena. As a result, digital twins have transitioned beyond their original purpose of replicating physical devices and, now are utilized to test components, diagnose issues, and optimize operations across a wide range of fields including manufacturing, aeronautics, public utilities, and notably, oncology (Chang et al., 2023). This transformation has elevated digital twins from a concept associated with science fiction to a practical tool with tangible real-world applications. A digital twin

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embodies a mathematical model or a suite of models that offers a virtual representation of a specific physical entity, enabling the prediction of its future behavior. This predictive capability facilitates a customized decision-making process, allowing targeted actions to optimize the entity's behaviours or outcomes from an intervention. The overarching framework for constructing a digital twin can be abstracted into six key components: Physical state- The parameterized state of the physical entity, Observational data- Available information describing the entity's state, Control inputs- Actions or decisions influencing the entity, Digital state- Parameters and model inputs defining the computational mod-els comprising the digital twin, Quantities of interest- Model outputs or estimated quantities describing the entity, Rewards-Quantification of the overall performance of the entity-twin system.

These components serve as the foundation for establishing a dynamic decision network. Initially, experiments are conducted on the target physical entity to obtain observational data, representing its physical state (Laubenbacher et al., 2024). Subsequently, the digital state is developed by leveraging these data to calibrate or assign the model parameters and define the digital twin geometry. The model comprising the digital twin can take the form of statistical, mechanism-based, or hybrid models, with "mechanism-based", indicating that each term or parameter in the model represents a specific biological or physical mechanism. The model is specified in generating predictions of the entity's behaviours, i.e., the quantities of interest. Finally, the predicted outcomes are evaluated and quantified as rewards. For instance, oncology rewards may encompass overall survival, drug toxicity, and quality of life. Guided decisions are made regarding adjustments in applying to the physical entity, and additional experiments are conducted to monitor changes in the physical state. As additional data is required, the digital state can be updated alongside its outputs. This iterative process persists over time to optimize the behaviors of the physical entity.

Digital twin technology offers a promising and practical approach to achieving precision care tailored to individual patients in the field of oncology, for example (Yankeelov et al., 2023). A particularly effective method involves integrating clinically available imaging techniques into mechanism-based digital twins. These digital twins combine quantitative data obtained from imaging with mathematical models based on biological mechanisms to understand and predict tumour growth dynamics and responses to treatment. By doing so, they have the potential to enhance the accuracy of diagnosis and prognosis and provide opportunities for personalized treatment optimization. To fully realize the potential of digital twins in oncology several advancements are needed. This includes developing more realistic mechanism-based mathematical models, improved experimental techniques to observe tumor dynamics across multiple scales with higher spatial and temporal resolution, and refining numerical techniques for rapid and accurate model calibration, selection, and uncertainty quantification (Wu et al., 2022).

Creating the development of patient-specific digital twins is an undertaking that necessitates the coordination of various professionals, including experimentalists, medical practitioners, and mathematical modelers. A crucial component of a digital organ, system, or entire body model is a dynamic equation that transforms a virtual representation into a digital twin after incorporating an imaging representation, such as CT, MRI, or US, of the actual organism (Boulos & Zhang, 2021). By tuning and modifying the initial phantom results a digital representation of a specific patient can be created. Some digital twin models, which have been approved by the FDA, hold great promise for integrating various computational approaches, which have been developed, by the international scientific community. Most recent advancements include web-based or cloud-based platforms that can be utilized across different hardware or learning curve configurations. It is essential to improve data capture accuracy and speed, to support the development and implementation of digital twins, as they play a key role in accelerating the delivery of personalized care. The pharmaceutical industry's experience could also lead to in-silico clinical trials before conducting diverse experiments on animals or humans, ultimately reducing the time required for important research in emerging fields.

2. Methods

This study aimed to explore digital twins, their potential uses and prospects, and the challenges faced in digital healthcare. The research utilized academic databases like PubMed, Web of Science, Google Scholar, Scopus, and related sources. The search focused on terms such as DT, medicine, and digital health. Previous studies have laid the groundwork for DT, including concepts like the virtual physiological human. However, DTs represent an expansion and enhancement of past research, due to their integration of diverse technologies. Thus, the study selected and presented applications of DT in medicine, followed by a discussion of their advantages and limitations. It commenced with an overview of DT technology across major databases, proceeded with an examination of models aligning with medical characteristics, and explored applications of DT in medicine. Finally, the review concluded by addressing current constraints and proposing future directions for research.

3. Results

Health Digital Twins (HDT) represent a breakthrough in personalized medicine by combining cutting-edge research with individual patient data (Johnson et al., 2023). Examples like Living Heart and Living Brain showcase the initial applications of HDT, with plans to expand into diverse areas such as cell models and patient cohorts. HDT is expected to transform medical practices, enabling precision medicine and surgery while empowering patients with greater autonomy over their healthcare. Ultimately, HDT promises to enhance health outcomes for all by covering all medical disciplines and the entire patient journey. Improving human health necessitates a deeper understanding of the human body, leveraging insights from global research efforts. Drawing from the digital revolution's legacy, pioneered by Dassault Systèmes in the 1980s and 1990s, which transformed product development through digital mock-ups, we are now witnessing a similar paradigm shift in the organic realm. By integrating real-world knowledge with multidisciplinary, multiscale modelling and simulation technology, unprecedented insights into the human body can be attained. This entails harnessing data from various sources, including medical records and diverse expertise, to prevent diseases and expedite healing. Secure, cloud-based platforms are essential for storing and accessing this data, facilitating the creation of virtual twins of the human body. These virtual models enable visualization, testing, and prediction of various scenarios, from drug effects to surgical outcomes, tailored to individual patients. Just as companies have used virtual innovation to enhance real-world products, the healthcare sector can harness this approach to revolutionize medical practices, precision medicine, and personalized care. It is imperative to seize this opportunity, to advance healthcare toward a future of tailored, informed, and effective treatments.

3.1. Digital Twins in Healthcare

Several studies are concluding in the fact that digital twins can support incorporating clinical decision support to advance precision medicine and patient-centred care (Grob et al., 2023; Vallée, 2023). The transformative potential of digital twin technology is revolutionizing healthcare systems, through real-time data integration, advanced analytics, and virtual simulations, which can enhance patient care, predictive analytics, clinical operations, and innovation. Moreover, significant is the ability of digital twins to provide personalized treatment plans, enable predictive analytics for early detection of health risks, and optimize resource allocation. However, the implementation of digital twins faces challenges such as data privacy, interoperability, ethics, and scalability. Furthermore, developing general frameworks to address identified gaps, utilizing questions, critiques, reviews, and analogies with real-life applications should be established (Machado & Berssaneti, 2023). Successful integration requires addressing these challenges and fostering collaborative decision-making between patients and healthcare providers.

Laubenbacher et al. (2024) present the development and potential applications of medical digital twins (MDTs) in personalized medicine, highlighting the need for computational models that can be personalized to individual patients and dynamically re-calibrated over time. Integrating biological mechanisms into these models and utilizing different types of data to create personalized digital twins for various health conditions, is pointed out. However, there are limitations such as the lack of discussion on important issues due to time constraints and expertise among participants, the early stage of development of the described projects, and specific technical challenges within individual projects. Despite these limitations, it is important to continue the efforts to deepen our understanding of human biology, collect relevant data, and develop algorithms necessary to personalize computational models for practical implementation in healthcare settings.

In more detail, Masison et al. (2021) introduced a hub-and-spokes design for internal digital twin architecture in medicine, focusing on modular software design to implement precision medicine with computational modelling technology. The modular approach separates dynamic biological processes into individual modules within the digital twin architecture, facilitating easier modification and extension of the model without breaking dependencies. Nevertheless, limitations include the requirement that all component models be written in Python, acknowledged shortcomings of the current platform, and concerns about performance efficiency due to software abstraction overhead. While parallelizing model simulations is essential for complex medical digital twins, the modular structure neither aids nor hinders parallel computation. Despite that, distributed computation is feasible due to the stochastic nature of biomedical models, allowing simultaneous simulations on separate computers or processors for efficient analysis using aggregate statistics. Another advantage of DTs is that they save resources and reduce financial costs (Milne-Ives et al., 2022). Future directions include developing remote monitoring systems, integrating individual and population data, improving digital twins, and training them with intervention data for personalized recommendations. Challenges such as data linkage issues and quality concerns can be addressed through expertise, machine learning, and novel data collection systems. However, there is limited knowledge about humans and sparse data in the medical field, necessitating reverse-engineering human biology and encoding it into models. Challenges also arise with connecting data and models across scales, as well as implementation issues surrounding data privacy in DTs (National Academies of Sciences, Engineering, and Medicine, 2023).

According to a study that analysed 94 high-quality papers on Digital Twin applications in healthcare, focusing on technology development and application scenarios influenced by various factors, it concluded by highlighting the encouraging evolution of DT in healthcare, the importance of addressing challenges, and the role of emerging technologies like 5G, IoT, and AI, particularly in addressing future healthcare challenges such epidemics as COVID-19 (Sheng et al., 2023). However, proactive government policies to promote DT development, while ensuring data security and privacy are needed. Addressing the predictive power of digital twin approaches involves examining underlying structures and economies, with ethical considerations needing integration into technological development to shape its trajectory responsibly (Braun, 2021). Moreover, the potential of Digital Twins in healthcare to facilitate more precise and personalized treatments, demonstrated through a proof-of-concept using synthetic data is being researched (Wickramasinghe et al., 2024). Findings include the identification of potential applications of DTs in various healthcare areas such as genomics, aged care, dementia, and cancer care. Nevertheless, assumptions about data availability, the rarity of complete numerical data in real clinical practice, and common occurrences of missing and incomplete data in healthcare should be considered. Thus, the need for significant data pre-processing in real-world applications and discusses challenges in overcoming these issues to enable the use of DTs in healthcare, arises.

3.2. Advancements in digital twins

From 2011 to 2022, significant medical advancements have transformed various domains of healthcare, as described in a study by Sun et al. (2023). These advancements span diagnostics, treatment planning, pharmaceutical processes, and personalized medicine, integrating cutting-edge technologies such as artificial intelligence, digital twins, computational modeling, and cloud computing. One of the earliest breakthroughs was by Niederer et al. (2011), who employed mechanical models to predict patient responses to cardiac resynchronization therapy (CRT), leading to novel patient selection criteria. In 2017, the Cone Health team introduced HeartFlow Analysis, a non-invasive diagnostic test combining CT imaging, AI, cloud computing, and computational physiology to assess the impact of blockages on coronary blood flow. Prakosa et al. (2018) further refined DT technology by enhancing ablation guidance for infarct-related ventricular tachycardia through patient-specific target identification. The same year, Philips launched HeartNavigator, a real-time 3D visualization tool that optimizes device positioning during cardiac procedures.

Advancements continued with Chakshu et al. (2019), who developed a DT model integrating blood flow dynamics and head vibrations to assess carotid stenosis severity via video analysis. Similarly, Mazumder et al. (2019) constructed a DT of the human body capable of generating detailed data on blood pressure and circulatory changes. In 2020, Suzuki et al. devised a rupture risk model for aneurysms using multivariate logistic regression applied to CT images, while Mussomeli et al. (2020) showcased Takeda Pharmaceuticals' adoption of DT technology to streamline pharmaceutical processes. Concurrently, Erol et al. (2020), in collaboration with Atos and Siemens, improved pharmaceutical manufacturing through IoT and AI-driven DT models, while Grosman et al. (2020) introduced a personalized insulin pump therapy using DTs. Other 2020 advancements included Croatti et al.'s integration of agent-based DTs with multi-agent systems for personalized trauma management and Subramanian et al.'s development of a DT combining scientific and clinical information to optimize drug research and clinical trials.

In subsequent years, the application of DT technology expanded. Golse et al. (2021) designed a DT model of blood circulation to predict post-operative portal hypertension, while He et al. (2021) constructed a DT of the lumbar spine to analyze biomechanical properties. Zohdi (2021) leveraged machine learning to optimize ventilation systems, and Pilati et al. (2021) implemented a DT-based vaccine process simulation to improve production efficiency. Aubert et al. (2021) utilized 3D X-ray imaging to simulate bone healing and assess fracture risk. More recently, Hernigou et al. (2022) refined DT models for subtalar joint orientation using AI-enhanced CT analysis. Laubenbacher et al. (2022) proposed a roadmap for developing a DT of the immune system to accelerate biomedical research. Additional innovations in 2022 include Cydar's application of cloud GPU computing, computer vision, and machine learning to enhance surgical visualization and decision-making, FEops' use of AI-enabled DTs for cardiac anatomical analysis, and Corify Care's introduction of a mapping system for cardiac activity analysis using advanced imaging and signal processing. Collectively, these advancements demonstrate the growing integration of AI, DTs, and computational modeling in modern healthcare. Despite challenges such as data availability and interoperability, these innovations have revolutionized diagnostics, treatment planning, and pharmaceutical development, ultimately improving patient outcomes.

3.3. Limitations of digital twins

The predominant focus of current Human Digital Twin (HDT) research lies within the healthcare and medical domains, where applications include managing athletes' fitness, monitoring patients' health, and modelling organs for medical purposes (He et al., 2024). Such applications of HDT exhibit a significant association with human biology and physiology. In contrast, there is a noticeable scarcity of studies exploring HDT applications in the manufacturing industry. However, existing HDT studies briefly touch upon frameworks and concepts related to this field. Significant challenges must be overcome for successful implementation. Collaboration across diverse disciplines such as brain science, psychology, and biomechanics is essential for developing accurate and comprehensive human models within the HDT framework. Privacy concerns, regarding utilizing various data sources in HDT, necessitate measures such as user consent and secure data processing through techniques, like edge computing and federated learning. Effective fusion of data from multiple sensors and devices is crucial for enhancing the usability and variety of HDT applications. Ensuring the interpretability of machine learning and deep learning models within HDT, possibly through explainable Artificial Intelligence (XAI), is vital for building user trust and enabling practical applications. Balancing the autonomy of the cyber twin in HDT with user control requires careful consideration to ensure informed decision-making and collaboration. Additionally, strict regulatory mechanisms and ethical guidelines are necessary to address privacy and data regulatory issues associated with HDT, particularly in sensitive domains like medical treatments. By addressing these challenges through collaborative efforts and regulatory frameworks, HDT has the potential to drive positive impacts on individuals and society while mitigating associated risks.

Digital twins hold immense potential for revolutionizing various aspects of the healthcare sector, with applications ranging from virtual organs and genomic medicine to personalized health information and drug treatment customization. By creating realistic digital replicas of organs, healthcare professionals can conduct intricate simulations for diagnostic purposes, treatment planning, and understanding the impact of various conditions on organ function. Furthermore, digital twins enable advanced insights into an individual's genetic makeup, facilitating personalized healthcare interventions based on genetic markers. They also play a crucial role in providing personalized health information by aggregating and analyzing diverse datasets related to an individual's health, thereby offering tailored recommendations for preventive care and lifestyle modifications. In addition, digital twins facilitate the customization of medications based on an individual's unique physiology, optimizing dosage and minimizing side effects. They also aid in scanning the entire body for early disease detection and planning surgeries by providing surgeons with advanced simulations and insights. Nonetheless, implementing digital twins in healthcare faces challenges such as data privacy and security concerns, interoperability issues, ethical considerations, complexity of healthcare systems, and resource constraints. Overcoming these challenges will be essential for unlocking the transformative potential of digital twins in healthcare, ultimately contributing to personalized medicine, improved patient outcomes, and enhanced healthcare decision-making.

4. Conclusion

In summary, digital twins offer groundbreaking advancements in healthcare by enabling precise diagnostics, personalized treatments, and enhanced surgical planning through sophisticated simulations and real-time data analysis. By integrating diverse health data, these virtual replicas facilitate early disease detection, optimize medication dosages, and provide tailored preventive care strategies. However, challenges such as data security, interoperability, ethical concerns, and the complexity of healthcare systems must be addressed to ensure seamless implementation. Overcoming these barriers will pave the way for a more efficient, patient-centric healthcare model, ultimately improving patient outcomes and transforming medical decision-making. Embracing digital twin technology will not only enhance healthcare delivery but also contribute to a future where precision medicine is accessible to all, driving better health and well-being for society.

Compliance with ethical standards

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