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Digital Twins in Healthcare

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ABSTRACT

Digital twin (DT) technology, originally developed in industrial engineering to monitor and optimize physical assets, is emerging as a paradigm-shifting innovation in modern healthcare. A digital twin is a virtual replica of a physical entity, linked by a continuous, bi-directional flow of real-time data. In healthcare, a digital twin is an individualized, interconnected, interactive, informative, and impactful (the "5Is") virtual representation of a patient. It is a living, intelligent, and evolving virtual model of human organs, tissues, cells, or entire physiological systems that continuously updates via real-time patient data. Unlike static computational models, a true digital twin establishes a bidirectional, synchronized data loop with its physical counterpart. This paper examines the evolving role of digital twins in healthcare.

KEYWORDS: *digitalization, digital twin, healthcare, medicine.*

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INTRODUCTION

For decades, medicine has relied on a population-based, reactive paradigm to guide individual diagnostic and therapeutic decisions. While this evidence-based approach has established critical safety standards, it often fails to account for the unique genetic, physiological, environmental, and lifestyle variations of individual patients. The convergence of multi-omics, the Internet of things (IoT), and advanced artificial intelligence (AI) has catalyzed a paradigm shift in modern medicine. At the vanguard of this revolution is the digital human twin (DHT), which is a dynamic, virtual representation of a patient, organ, or physiological system that continuously synchronizes with its real-world counterpart. The physical twin (the patient) provides continuous or periodic streams of data—ranging from genomic sequencing and clinical laboratory results to real-time physiological metrics from wearable devices. A true digital twin in healthcare is distinguished by the "5Is" framework: it must be Individualized to a specific patient; Interconnected with continuous data streams; Interactive through virtual simulations; Informative by generating actionable clinical insights; and Impactful by directly improving clinical decisions and patient outcomes [1].

The digital twin (DT) concept is based on the idea of incorporating physical systems and their digital representations into the same functional structure. DT technology revolutionizes modern medicine with the creation of real-time virtual models of patients, organs, and healthcare systems; all of these improve diagnosis, treatment, and management. DT represents one form of digital transformation, as illustrated in Figure 1 [2]. It is regarded as the next generation of digitalization for decision making support. The current development of digital technologies has dramatically increased the adoption of digital twin (DT) systems into the healthcare sector, turning conventional medical practice into a smart and data-driven model. Figure 2 shows the conceptual model of a digital twin [3].

CONCEPT OF DIGITAL TWIN

The concept of the digital twin was introduced in 2002 by Michael Grieves of Florida Institute of Technology. He applied the concept in manufacturing and proposed the digital twin as the conceptual model underlying product lifecycle management (PLM). The concept was being practiced since the 1960s by NASA. The concept of digital twin consists of three distinct parts: the physical product, the digital/virtual product, and connections between the two products [4]. Figure 3 shows the historical evolution of DT technology [5].

A digital twin is much as it sounds: creating a digital duplicate of the physical entity.

It has two sides, one pertaining to a physical device and the other to a digital rendition of this device. DT is a real time digital replica of a physical device using 3D modeling and sensors. The DT is an emerging paradigm focusing on an enterprise asset such as a system, product or process. Its core goal is to virtually represent this asset as close to reality as possible. A digital twin may exist before its physical counterpart is made. Technologies enabling DT include AI, IoT, 5G, virtual reality, augmented reality, wearables, and cloud computing. Realizing the full potential of DTs requires a convergence of these technologies. Digital twins integrate AI, IoT, machine learning, and software analytics with spatial network graph to create living digital simulation models that change as their physical counterparts change.

The three main pillars of the digital twin technology are visualization, emulation, and simulation. The foundation of DT is the physical world, which may consist of devices/products, physical systems, process, or an organization. Service is an essential component of DT in view of the paradigm of everything-as-a-service. DT-related services include application service, resource service, knowledge service, and platform service. The process of implementing DT can be divided into four steps: digital representation, synchronous mapping, simulation and prediction, and virtual and physical fusion, as depicted in Figure 4 [6].

There are numerous requirements to describe "digital twin." To be considered a digital twin, the model must have some specific characteristics such as [7]:

1. Data is the carrier of information and the key driver of DT. Real-time data is important for knowing the status of the product. Data-driven digital twin can perceive, respond, and adapt to the changing environment.
2. Integration of the different nodes is essential for creating valuable data. Sensors communicate the data to the digital world through integration technology between the physical world and the digital world, and vice versa.
3. Scalability (ability to analyze different scales of information);
4. Interoperability (ability to convert, match and establish equivalence between representation models);
5. Expansibility (ability to integrate models);
6. Fidelity (ability to conform to the physical model); the core of any DT is a high-fidelity virtual model.
7. Connectivity that indicates the level of communication with its physical counterpart; connectivity by design through IoT which is a paradigm for ubiquitous connectivity. Connect the products/services to a central location with streaming, big data, in-memory, and analytic capabilities to capture sensor data and enrich it with business and contextual data.

These are the most frequent requirements of digital twins.

DIGITAL TWIN IN HEALTHCARE

Fundamentally, a healthcare digital twin is a real-time, continuously changing digital representation of a physical object, be it a patient, a given organ, or an entire healthcare facility. In healthcare, digital twins (DTs) consist of three basic and interconnected parts: the physical entity, the virtual model, and the real-time data link. Digital twin (DT) technology is catalyzing a profound paradigm shift in modern medicine, transitioning healthcare from a reactive, population-averaged model to a proactive, highly personalized, and continuous system of care.

The concept of a digital twin—a virtual replica of a physical entity, system, or process that is continuously updated with real-time data—originated in the aerospace and manufacturing industries. Over the past decade, rapid advancements in high-performance computing, cloud storage, biosensors, and artificial intelligence have enabled the translation of this engineering concept into the biomedical sciences, giving rise to the digital human twin (DHT). This virtual counterpart is continuously updated through bidirectional data streams from its physical twin, leveraging advanced computational modeling and artificial intelligence (AI) to simulate biological behaviors, predict health trajectories, and optimize therapeutic interventions [1]. Figure 5 shows a representation of DT in healthcare [8].

The underlying technology platform enabling DT is Internet of Medical Things (IoMT), which offers a way to link diverse collections of medical devices, equipment, sensors and wearable digital technologies in order to accept continuous delivery of valuable medical patient data. IoMT devices include wearable, implantable, remote monitoring, and connected medical devices to measure physiological and environmental data, which is increasingly being collected nonstop.

A digital twin for healthcare is a virtual representation of a person which allows dynamic simulation of potential treatment strategy, monitoring and prediction of health trajectory, and early intervention and prevention. The concept of digital twin for health holds great promise to revolutionize the entire healthcare system, including management and delivery, disease treatment and prevention, and health well-being maintenance, ultimately improving human life. Technologically, digital twins are built using two primary approaches: mechanistic (physics-based) models and data-driven models. Mechanistic models rely on established biophysical laws and differential equations to simulate physiological processes, such as hemodynamics in precision cardiology. Conversely, data-driven approaches leverage deep learning, neural networks, and transformer architectures to learn complex clinical trajectories from massive datasets of electronic health records (EHRs) and clinical trials. Figure 6 shows digital twin for health [9], while Figure 7 shows different types of digital twins in healthcare [5].

APPLICATIONS OF DIGITAL TWIN IN HEALTHCARE

Digital twin technology has emerged as a transformative force in healthcare, offering unprecedented opportunities for precision medicine, cancer care, medical training, personal well-being, personalized medicine, treatment optimization, hospital management, and disease prevention. The integration of digital twins into clinical workflows has transitioned from theoretical models to specialized applications, particularly in cardiology, oncology, and endocrinology. Figure 8 shows some applications of DTs in healthcare [10]. Common applications of digital twin in healthcare include the following [1,11]:

- *Precision Cardiology:* Cardiovascular medicine has emerged as one of the most mature fields for digital twin applications, driven by the highly structured physical and electrical laws governing cardiac function. Researchers have successfully constructed patient-specific cardiac digital twins (CDTs) by combining late gadolinium-enhanced magnetic resonance imaging with electrophysiological models. By simulating electrical wave propagation through the virtual fibrotic substrate, cardiologists can predict the exact locations of re-entrant drivers that perpetuate arrhythmia. This allows electrophysiologists to perform targeted in silico catheter ablations, identifying the optimal surgical strategy before entering the operating suite.

- *Personalized Oncology:* Digital twins have revolutionized cancer care across multiple dimensions. Oncology represents an incredibly complex frontier for digital twins due to the high biological heterogeneity and rapid evolutionary nature of malignant tumors. Cancer is highly heterogeneous and mutagenic; a drug that eradicates a tumor in one patient may be entirely ineffective in another. A cancer digital twin integrates multi-scale data—including genomic mutations, transcriptomic profiles, histopathological imaging, and real-time tumor microenvironment metrics—to create a virtual representation of a patient's malignancy. These models allow oncologists to simulate tumor responses across multiple therapeutic modalities, including chemotherapy, radiotherapy, immunotherapy, and targeted molecular therapies.

- *Chronic Disease Management:* Beyond acute interventions, digital twins are revolutionizing the daily management of chronic metabolic diseases, such as Type 2 diabetes and cardiovascular disease. Digital twins are uniquely suited for chronic care because they can leverage the massive influx of real-time data from wearable sensors and Internet of things (IoT) devices. Traditional diabetes care relies on static guidelines and periodic blood glucose measurements. In contrast, a metabolic digital twin continuously aggregates data from continuous glucose monitors, smartwatches, and dietary logs. By simulating each patient's unique postprandial glucose response (PPGR) and metabolic rate, the digital twin provided real-time, personalized dietary and behavioral "nudges."

- *Surgical Planning:* The application of digital twins in the perioperative space is transforming surgical precision, safety, and training. Historically, surgeons relied on 2D radiological slices and general anatomical knowledge to plan complex procedures, requiring significant intraoperative adaptation.

- *Drug Discovery*: The traditional drug development pipeline is notoriously slow, expensive, risky, and time-consuming, involving target identification, and validation followed by preclinical and clinical trials. Digital twins are revolutionizing this process across two major phases: drug discovery and clinical trial execution. At the molecular level, biotech platforms like DeepLife are constructing digital twins of human cells. By integrating single-cell

RNA sequencing, proteomics, and causal biological networks, these cellular twins allow researchers to perform high-throughput virtual screening of thousands of candidate drug molecules. Scientists can simulate how a compound affects specific cellular pathways, predicting efficacy and toxicity in silico long before initiating expensive in vitro or in vivo experiments.

- *Hospital Systems Optimization*: Beyond direct clinical care, digital twins are being deployed to model and optimize the complex operational ecosystems of healthcare facilities. Hospitals frequently suffer from systemic inefficiencies, including emergency department crowding, operating room scheduling bottlenecks, and staff burnout. During the winter surge of respiratory syncytial virus and influenza, the digital twin analyzed regional epidemiological data and hospital throughput patterns to predict the exact week of the winter surge with remarkable accuracy. This proactive insight allowed the hospital to pre-allocate beds, adjust elective surgery schedules, and optimize nursing staff levels, successfully avoiding capacity crises.
- *Pediatrics:* Clinical trials in pediatric and neonatal medicine face severe ethical and practical constraints. Because enrolling children and preterm infants in randomized controlled trials is challenging, many pediatric trials are discontinued early due to poor enrollment, leaving the pediatric community highly reliant on off-label drug usage extrapolated from adult data. The application of patient-specific digital twins offers a transformative solution to this systemic issue. For example, in neonatology, evaluating interventions for low-incidence, high-mortality conditions like necrotizing enterocolitis in extremely low-birth-weight infants requires massive, multi-center trials that are logistically and financially prohibitive.
- *Respiratory System:* Digital twins of the respiratory system integrate multiple scales of analysis, from alveolar mechanics to whole-organ function, enabling detailed simulation of lung biomechanics in both health and disease states. These models facilitate personalized treatment strategies and improved understanding of structure-function relationships.
- *Medical Education:* A DT application for critical care education has been developed to simulate patient conditions and responses during the crucial first six hours of critical illness. Patient-specific, three-dimensional mixed-reality anatomical models have been developed for surgical training and intraoperative guidance. These models, derived from CT or MRI data, enable surgeons to interact with highly accurate representations of anatomy, improving understanding of complex structures and spatial relationships. Mixed-reality anatomical models serve dual purposes in surgical education and training, enabling preoperative rehearsal and intraoperative guidance, while also facilitating remote teaching and collaboration through mixed-reality interfaces.
- *Biomanufacturing:* Biomanufacturing relies on naturally occurring processes and reactions that permit the consistent production or output of biological products at a commercial scale. Specifically, these products may include medicine and vaccine production, antibacterials, on-demand molecule production, and on-demand tissues and organs. In the virtual DT system, multi-scale mechanistic and data-driven models are combined to mathematically relate adjustable input conditions with output responses such as titer and yield and critical quality attributes.

BENEFITS

The deployment of medical digital twins promises to enhance clinical decision-making, improve patient outcomes, reduce systemic costs, and ultimately democratize high-quality healthcare. Beyond individual patient care, digital twin technology is driving significant operational and economic efficiencies within healthcare facilities and hospital systems. Other benefits of digital twin in healthcare include the following [1,11]:

- *Cost Reduction:* By enabling virtual testing and optimization, DTs can significantly reduce healthcare costs associated with trial-and-error approaches in treatment. DTs optimize resource utilization by predicting patient flow, equipment needs, and staffing requirements, thereby reducing operational inefficiencies. The long-term economic benefits extend to reduced disability costs, fewer complications, and shortened hospital stays, collectively contributing to more sustainable healthcare systems.
- *Personalized Medicine*: Every human body possesses unique anatomical variations, meaning that standard surgical templates are often insufficient for highly complex procedures. The primary benefit of medical digital twins lies in their ability to operationalize personalized medicine at an unprecedented scale. By synthesizing diverse data streams—including electronic health records (EHRs), high-throughput

genomic sequencing, real-time wearable sensor data, and advanced medical imaging—a medical digital twin (MDT) constructs a comprehensive, evolving "patient-in-silico." This dynamic model allows clinicians to move beyond static diagnostic snapshots and instead simulate how a specific patient will respond to various therapeutic interventions.

- *Disease Prediction:* Traditional diagnostic models excel at identifying disease once symptoms manifest. In contrast, MDTs leverage predictive analytics and machine learning to forecast disease progression and identify subtle physiological anomalies days or weeks before clinical symptoms appear. For instance, in chronic disease management, such as Type 1 and Type 2 diabetes, a digital twin can integrate continuous glucose monitoring data, nutritional intake, and physical activity levels to predict blood sugar fluctuations and glycated hemoglobin levels. This allows for preemptive insulin dosing recommendations and personalized lifestyle interventions, preventing dangerous hyper- or hypoglycemic events.
- *Risk-free Treatment*: In clinical practice, selecting the correct therapeutic regimen often involves a process of trial and error, which can carry significant risks for patients suffering from complex or multi-morbid conditions. MDTs provide a risk-free, virtual environment where physicians can "test-run" multiple treatment scenarios on the patient's virtual replica before administering them in the real world. In precision cardiology, patient-specific digital heart models have demonstrated remarkable clinical efficacy.
- *Clinical Trials:* In clinical applications, DTs facilitate personalized medicine by enabling the construction of patient-specific models. Digital twin technology is revolutionizing this landscape by introducing virtual patient cohorts and causal artificial intelligence to accelerate preclinical research and streamline clinical trials. In traditional randomized controlled trials (RCTs), half of the recruited patients are assigned to a control arm, receiving a placebo or standard-of-care treatment. By minimizing the need for physical control participants, digital twins make clinical trials safer, more accessible, and more appealing to diverse patient populations who are guaranteed to receive the active treatment.
- *Real-time Monitoring*: Digital twins provide continuous monitoring and analysis of patient health status, enabling early detection of potential health issues and timely interventions. Advanced DTs incorporate data from wearable sensors, implantable devices, and ambient monitoring systems to create dynamic models that evolve with the patient's condition. This continuous feedback loop allows for the detection of subtle physiological changes that might precede clinical manifestations of disease by days or weeks, creating opportunities for preemptive interventions.
- *Hospital Operations:* Hospitals are highly complex, dynamic systems where patient surges, staffing shortages, and resource constraints can severely compromise the quality of care. A hospital digital twin aggregates real-time data from bed management systems, staff schedules, and electronic health records to create a live, operational model of the facility. Administrators can use these models to run "what-if" scenarios, such as simulating the operational impact of a sudden influenza outbreak or evaluating the efficiency of a redesigned emergency department layout. This enables data-driven decisions regarding staff scheduling, capital investments, and patient throughput, reducing wait times and preventing hospital overcrowding.
- *Predictive Maintenance:* Medical imaging equipment, such as MRI scanners and CT detectors, represents a massive capital investment for healthcare systems. Unplanned equipment downtime not only disrupts clinical workflows and delays critical diagnoses but also results in substantial financial losses. By analyzing billions of operational data points using machine learning, their digital twins can predict component failures before they occur, allowing technicians to perform preventive maintenance during off-peak hours (e.g., overnight) and ensuring uninterrupted clinical workflows.
- *Transforming Medical Education*: In medical education, traditional physical mannequins and pre-scripted clinical scenarios often fail to capture the dynamic, unpredictable nature of real-life patient care. The integration of digital twins is reshaping how medical professionals are trained and how complex surgical procedures are executed. Traditionally, surgical training has relied on the "see one, do one, teach one" apprenticeship model, which introduces inherent variability and potential risks to patient safety. Digital twins offer a highly personalized, interactive, and risk-free alternative. An educational digital twin can dynamically adapt to the virtual interventions performed by a student.

Figure 9 shows some of the benefits of DT in healthcare [12].

CHALLENGES

Despite the immense promise of digital twins in healthcare, several formidable barriers must be overcome before they can be integrated into standard clinical practice. These challenges span legal, technical, ethical, and regulatory domains. Significant challenges regarding data privacy, data quality, standardization, digital divide, and clinical equity must be navigated. Other challenges of digital twin in healthcare include the following [1,11]:

- *Technical Challenges:* At the core of digital twin development is the mathematical and computational replication of human physiology. This task is hindered by the sheer scale of human biological complexity and the inherent limitations of current modeling paradigms. Building a high-fidelity digital twin requires the seamless integration of highly disparate, multi-modal data sources, including genomic sequences, clinical notes, continuous wearable telemetry, and radiological imaging. Currently, these data reside in highly fragmented, non-interoperable electronic health record systems and proprietary databases. A digital twin is sensitive to the quality, thoroughness, accuracy, and promptness of its underlying data and algorithms.
- *Regulatory Challenges*: Traditional regulatory pathways (such as FDA approvals) are designed for static medical devices or standardized chemical compounds. A digital twin, by definition, is a dynamic, continuously learning software system that behaves differently for every patient. Establishing standardized validation frameworks to prove the safety, clinical validity, and reproducibility of an adaptive in silico model is a major regulatory hurdle. Because digital twins are dynamic and continuously update their predictive algorithms based on new clinical inputs, they do not fit neatly into traditional, static regulatory frameworks.
- *Validation Challenges*: Establishing the validity and reliability of DT models in healthcare presents unique difficulties given the stakes involved in clinical decision-making. Traditional validation approaches often rely on historical data, which may not adequately represent future patient populations or novel clinical scenarios. Prospective validation studies are resource-intensive and time-consuming, particularly for chronic conditions requiring long-term follow-up. Validating DTs against gold standard measures can be problematic when such standards themselves have limitations or when the DT aims to provide insights beyond what conventional approaches can measure. The lack of standardized validation frameworks specific to healthcare DTs further complicates this challenge.
- *Ethical Concerns:* Beyond the technical and regulatory hurdles, the deployment of digital twins in healthcare introduces profound ethical and social challenges, particularly concerning equity, bias, and the conceptualization of the human self. Building digital twins for health presents a host of ethical considerations. Ethical considerations include but are not limited to obtaining informed consent from individuals for data collection and usage in digital twin development, addressing data ownership and control, providing patient autonomy, and identifying legal constraints. Other ethical issues include transparency, accountability, bias, fairness, and trust of clinicians in the AI outputs.
- *Privacy Concerns:* To operate effectively, digital twins require continuous access to highly sensitive personal health data, raising significant privacy concerns under frameworks like HIPAA and GDPR. In the private sector, there is a severe risk that health insurance companies will exploit digital twin data to conduct hyper-personalized risk assessments. Insurers could demand access to a patient's digital twin to monitor lifestyle compliance (e.g., diet, exercise, medication adherence) and dynamically adjust premiums or deny coverage based on predicted future health risks, leading to severe human rights violations and discrimination.
- *Cybersecurity Threat*: One of the most sensitive types of information in the healthcare sector is healthcare data in the digital world. The combination of digital twins with interconnected medical devices, cloud solutions, and IoMT ecosystems exposes healthcare systems to cybersecurity risks. These risks include unauthorized data access, theft, ransomware attacks, data manipulation, and system outages. Such incidents not only jeopardize patient privacy but may also pose a threat to life if digital twin-controlled clinical decisions are affected.
- *Data Quality:* Clinical data are notoriously noisy, incomplete, and inconsistent. A digital twin is only as reliable as the data that feeds it. Currently, health data is highly fragmented, siloed across incompatible EHR systems, proprietary wearable device APIs, and disparate clinical registries. Feeding such low-quality or incomplete data into a digital twin's predictive algorithms can result in highly inaccurate simulations—a classic manifestation of the “garbage in, garbage out”

principle. Achieving true digital twinning requires the establishment of universal data standards and robust interoperability protocols to enable seamless, real-time data flows.

- *Data Fragmentation:* To construct a comprehensive digital twin of a patient, developers must integrate highly heterogeneous data sources, including genomic sequences, high-resolution medical imaging, clinical laboratory results, continuous wearable sensor data, and unstructured physician notes. In reality, these data are highly fragmented and siloed across disparate electronic health record (EHR) systems, radiology departments, and third-party consumer health applications. This fragmentation prevents the seamless, real-time data aggregation required to maintain a synchronized virtual replica.
- *Data Ownership*: Questions regarding the ownership of a patient's digital twin, informed consent for virtual experimentation, and the potential for predictive models to be misused by insurance companies remain unresolved. Unlike traditional medical records, a digital twin represents a “living” virtual asset. This raises profound legal and ethical questions regarding data ownership. Until digital twin data ownership is clarified, patients risk losing control over their most sensitive personal information.
- *Data Protection:* The massive, continuous data collection required by digital twins directly clashes with core tenets of modern data protection laws, such as the European Union's General Data Protection Regulation (GDPR). Digital twins require maximum data richness and completeness across genomic, clinical, and environmental domains to generate high-fidelity simulations, directly violating the principle of collecting only strictly necessary data.
- *Algorithmic Bias*: AI models are trained on historical clinical data, which historically over-represents affluent, Western populations. If a digital twin is constructed using biased training sets, its predictive algorithms may perpetuate or amplify existing health disparities when applied to marginalized or underrepresented demographic groups. Scientists, clinicians, ethicists, and regulators must work in tandem to build interoperable data pipelines, eliminate algorithmic biases, secure patient privacy, and establish rigorous validation standards.
- *Digital Divide:* There is a critical risk of exacerbating healthcare disparities. Healthcare DT implementation raises significant concerns about digital equity and bias that must be proactively addressed. The high computational costs associated with building and maintaining digital twins risk exacerbating existing health disparities, potentially limiting access to affluent healthcare institutions and widening the digital divide. Without deliberate, policy-driven efforts to democratize access, digital twin technology could widen the health equity gap, providing hyper-personalized, preventative care to the wealthy while leaving marginalized populations further behind. If a digital twin is trained on data derived primarily from affluent, white, male populations, its predictive models will fail to capture critical differences.
- *Lack of Standardization:* While the manufacturing sector utilizes highly standardized data protocols, health informatics is plagued by a historical lack of standardization. For a digital twin to ingest and interpret data from various clinical systems and IoMT devices, it requires robust semantic interoperability—the ability of two or more systems to exchange information and accurately interpret its clinical meaning. Currently, healthcare systems utilize a fragmented patchwork of standards.
- *Surveillance:* The continuous, real-time monitoring required by digital twins creates an unprecedented infrastructure for surveillance. Public health applications of digital twins, while promising for epidemic tracking and resource allocation, raise significant concerns regarding state-sponsored surveillance and the erosion of individual liberty.
- *Liability:* When a clinician makes a diagnostic or therapeutic decision guided by a digital twin's simulation, and that decision leads to patient harm, establishing legal liability is extraordinarily complex. If the harm resulted from an inaccurate simulation, does the liability rest with the treating physician who trusted the model, the hospital that deployed the system, the software developers who designed the algorithm, or the medical device manufacturers who supplied the data-ingesting sensors? Because digital twins rely on complex interactions between hardware, software, and continuous data streams, isolating the root cause of a clinical failure is technically and legally challenging.

Figure 10 shows some of the challenges of DT in healthcare [12].

FUTURE OF DIGITAL TWINS IN HEALTHCARE

The future of digital twins in healthcare is not merely a story of incremental technological improvement; it is a profound philosophical shift in how humanity conceptualizes health, disease, and clinical intervention. The future points toward the convergence of multi-scale biology and generative artificial intelligence. Researchers envision the creation of a "biology foundation model"—a massive, multi-modal AI model trained on vast repositories of biological, medical, and clinical trial data. This foundation model will enable the seamless generation of digital twins that span from the microscopic (cellular signaling and gene expression) to the macroscopic (organ systems and whole-body physiology) [1].

The convergence of DTs with other emerging technologies presents exciting possibilities for healthcare innovation. Emerging opportunities in multimodal data integration, explainable AI, federated learning architectures, and human-computer interaction design that will shape next-generation digital twins. Looking forward, the ultimate vision for digital twins in healthcare is the creation of a lifelong digital twin. Ultimately, a digital twin may become a lifelong companion. Initiated at birth through genomic sequencing and early-life clinical data, this virtual counterpart would continuously evolve alongside the individual throughout their lifespan. By integrating lifestyle, environmental, and physiological data, the lifelong digital twin would serve as an intelligent, personalized health companion, shifting the global healthcare paradigm from treating established illnesses to preserving lifelong wellness.

CONCLUSION

Digital twin technology represents the logical zenith of precision medicine. It constitutes one of the most promising frontiers in modern medicine. It offers a visionary path toward truly personalized, predictive, and preventive medicine. By bridging the physical and digital realities through a dynamic, bi-directional flow of multi-modal data, digital twins offer unprecedented opportunities to personalize clinical care, optimize hospital operations, and accelerate drug discovery. While significant technical, ethical, and regulatory challenges remain, the remarkable successes achieved in precision cardiology, oncology, pediatric trials, and hospital operations demonstrate that this technology is not merely a futuristic concept, but an essential pillar of the future of global healthcare.

Digital twins have enormous potential to transform healthcare by enabling precise, data-driven treatments and optimized clinical operations. With continued innovation, collaboration, and thoughtful regulation, digital twins can dramatically enhance healthcare quality, safety, and efficiency across the globe. The integration of digital twins into healthcare systems offers exciting opportunities for more personalized, predictive, and responsive care, but it also brings to the surface a set of complex and interrelated challenges that must be addressed before these technologies can be used responsibly in clinical settings. More information about digital twin in healthcare can be found in the books in [13-20].

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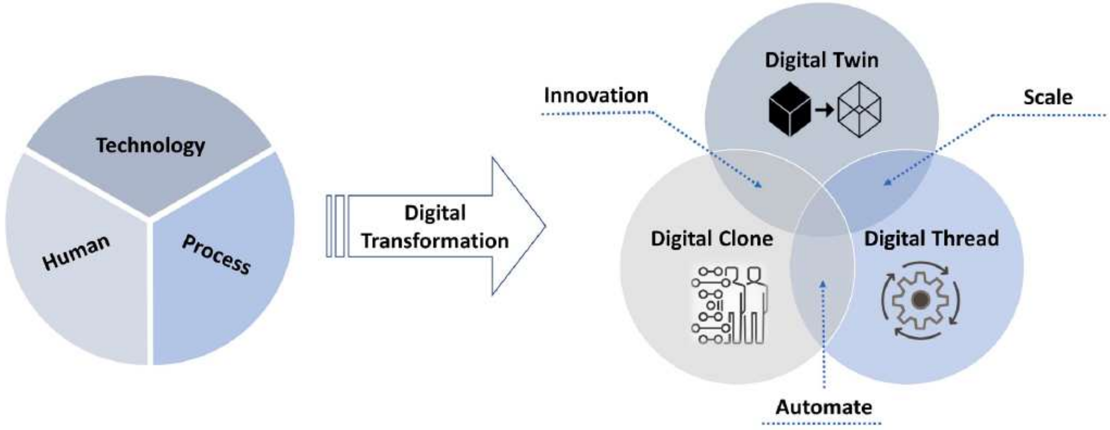

Figure 1 Digital twins as part of digital transformation [2].

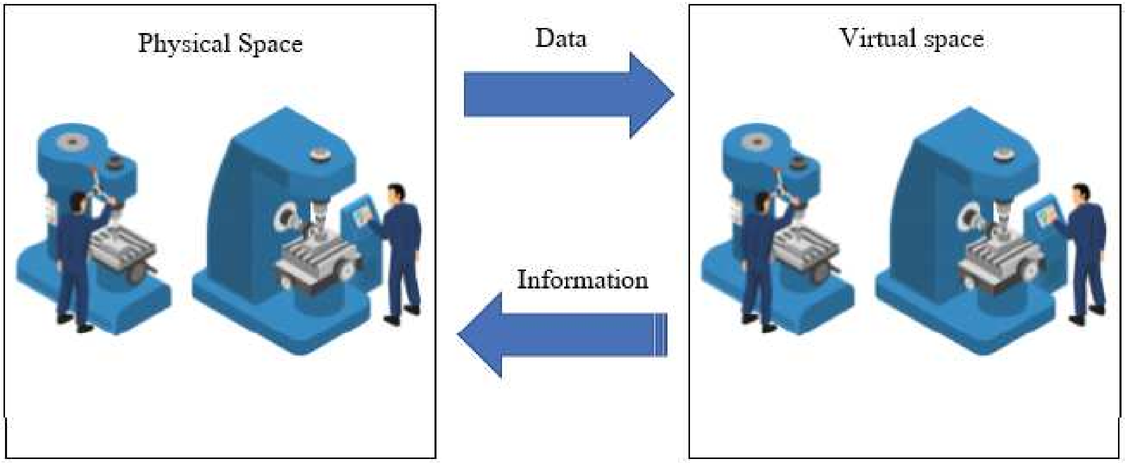

Figure 2 Conceptual model of a digital twin [3].

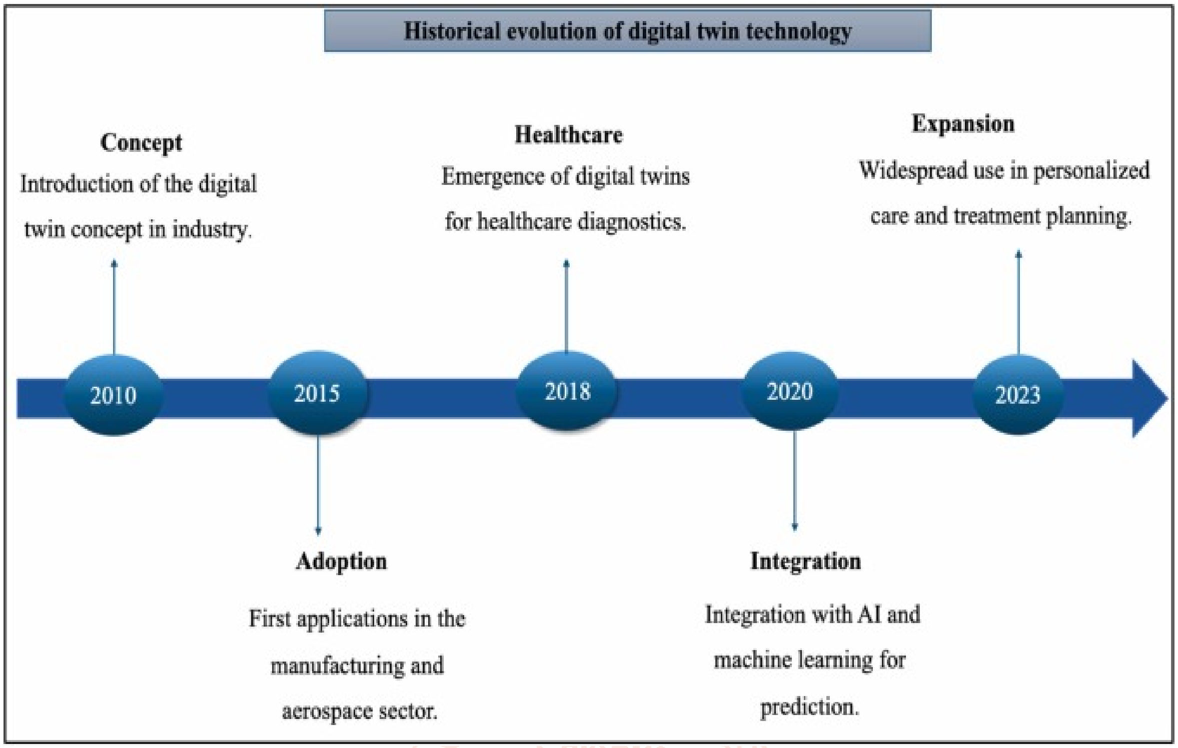

Figure 3 The historical evolution of DT technology [5].

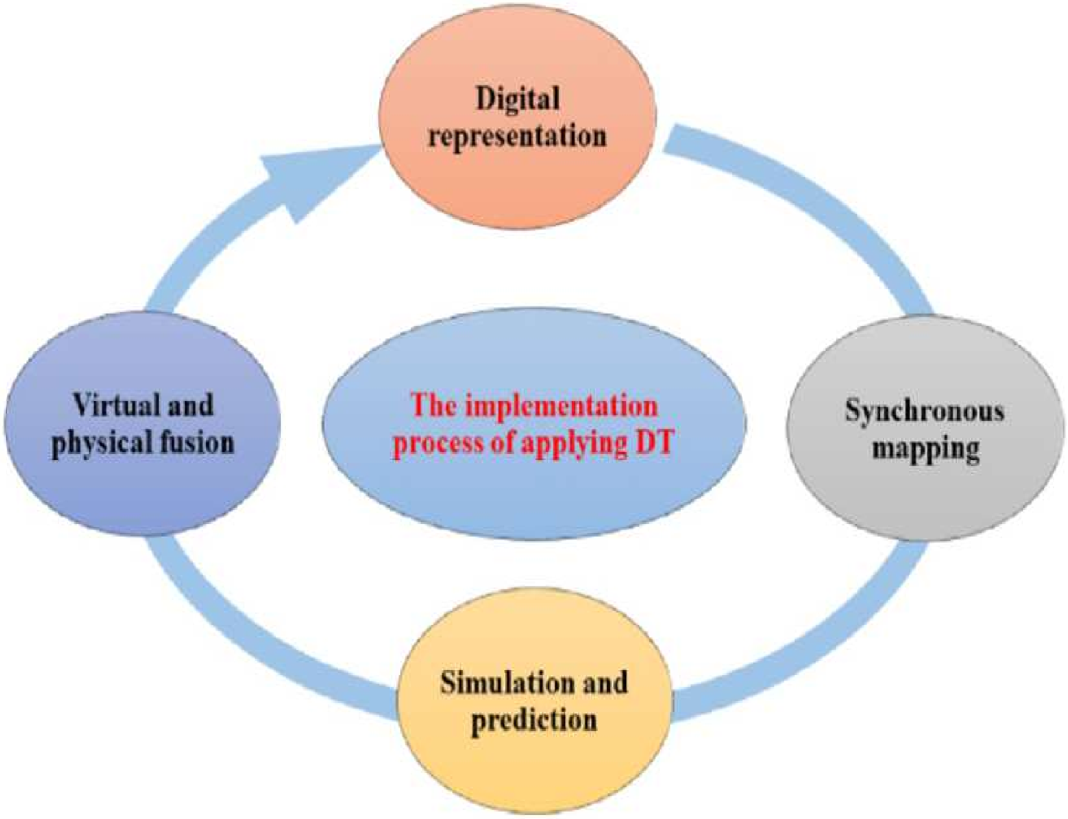

Figure 4 The implementation process of applying DT [6].

Figure 5 A representation of DT in healthcare [8].

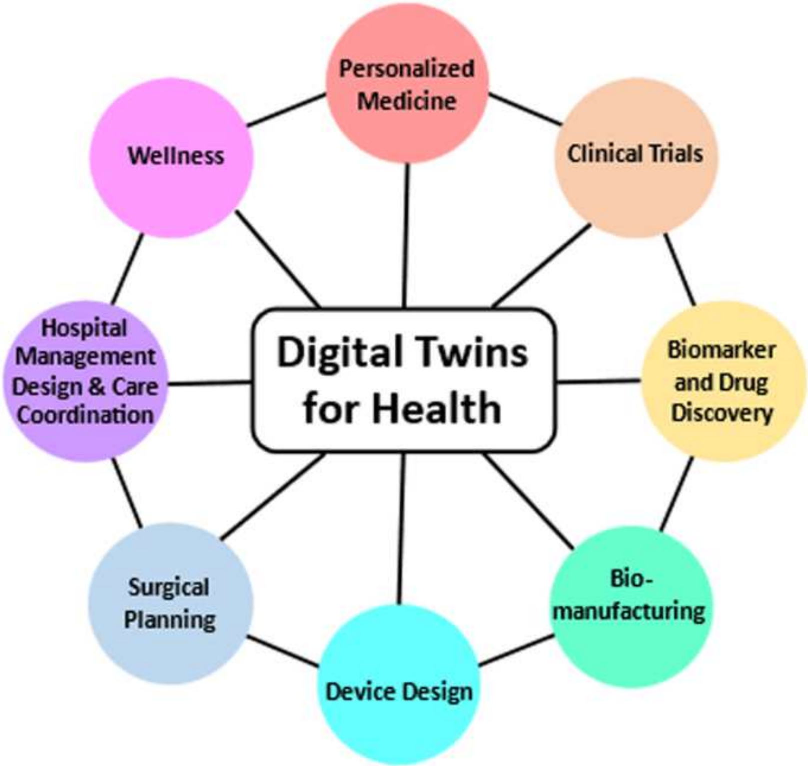

Figure 6 Digital twin for health [9].

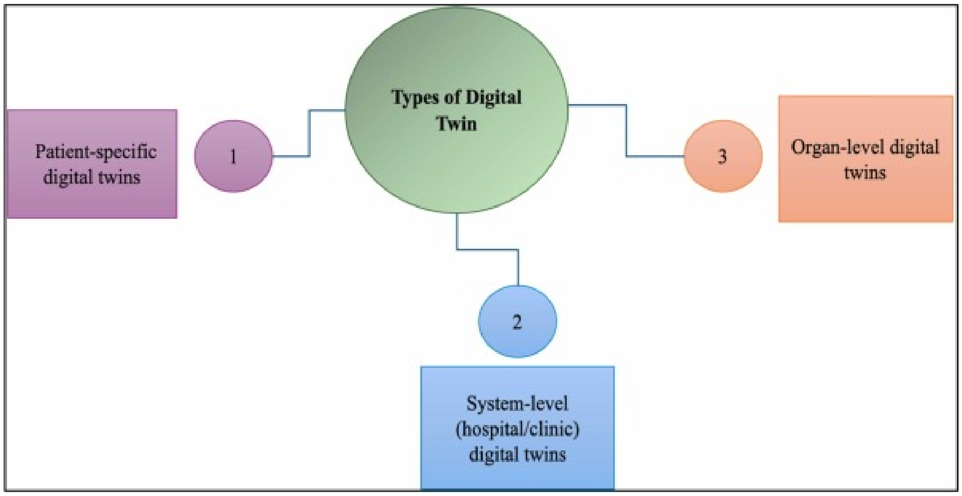

Figure 7 Different types of digital twins in healthcare [5].

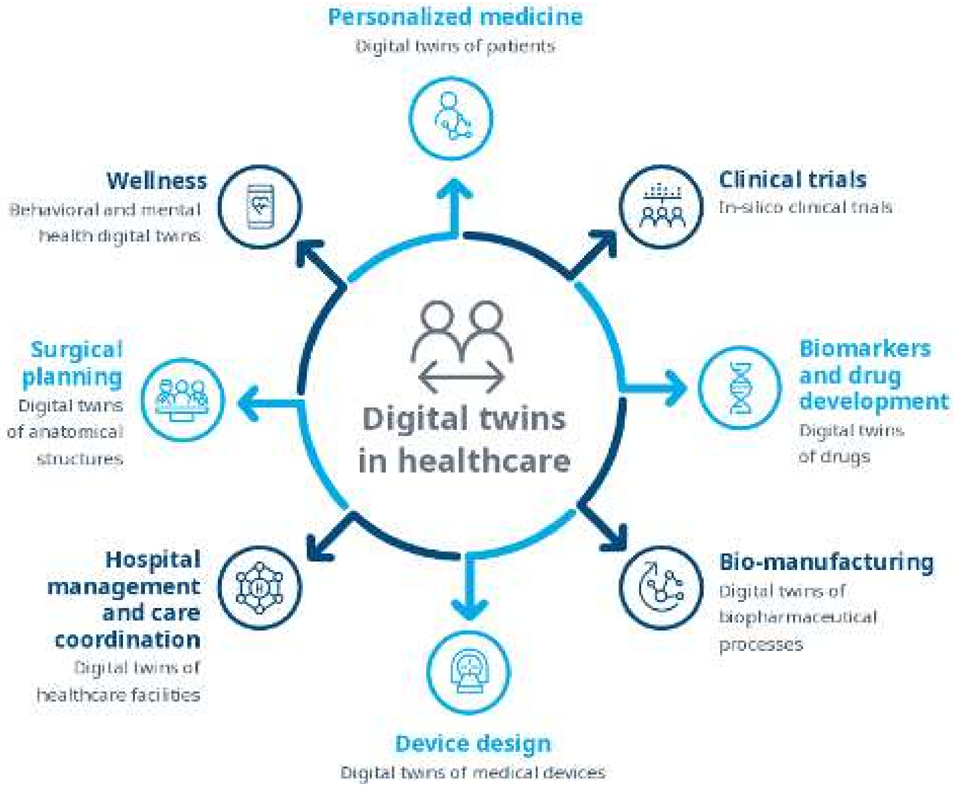

Figure 8 Some applications of DTs in healthcare [10].

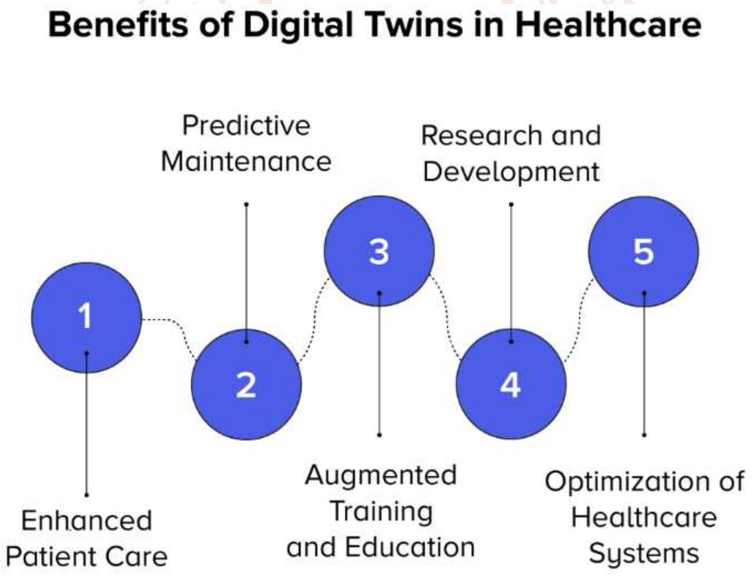

Figure 9 Some of the benefits of DT in healthcare [12].

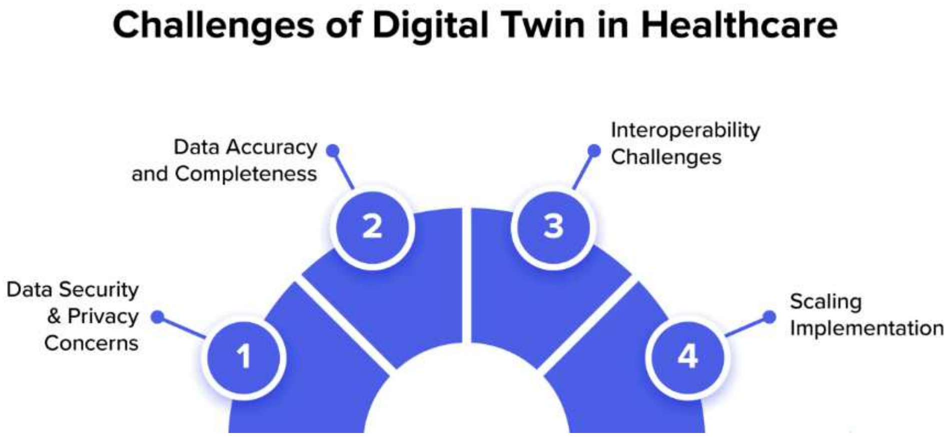

Figure 10 Some of the challenges of DT in healthcare [12].