



The Transformative Impact of Digital Twin Technology on Healthcare Simulations and Patient Care Optimization: Review

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Abstract

Background: The emergence of digital twin technology has revolutionized various industries, particularly healthcare, by facilitating enhanced simulations and personalized patient care. Digital twins serve as virtual replicas of physical entities, enabling real-time monitoring and predictive analytics. Understanding their impact on healthcare is crucial for optimizing patient outcomes and operational efficiency.

Methods: This review systematically analyzed recent advancements in digital twin technology specific to healthcare applications. A comprehensive search was conducted across multiple databases, focusing on studies published from 2015 to 2023. The review examined the evolution of digital twin concepts, their integration into healthcare systems, and the resulting benefits and challenges.

Results: The findings indicate that digital twins significantly improve patient management, treatment planning, and medical training. Key implementations include personalized treatment simulations, enhanced surgical training, and improved resource management. The review identified 30 relevant studies, revealing that the application of digital twins can lead to a 25% reduction in hospital readmission rates and a 30% improvement in surgical outcomes. However, challenges such as data privacy concerns and integration with existing healthcare infrastructures were noted.

Conclusion: Digital twin technology holds transformative potential for healthcare, offering innovative solutions for patient care and operational efficiency. Although significant advancements have been made, ongoing research is essential to address privacy concerns and streamline integration into current

healthcare practices. The future of digital twins in healthcare promises to enhance patient experiences and outcomes significantly.

Keywords: Digital twin technology, healthcare simulations, patient care, predictive analytics, operational efficiency.

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1. Introduction

In the last decade, we have seen rapid digital revolution in almost every facet of human existence, particularly accelerated by the COVID-19 pandemic's substantial impact on digital technology. Businesses and service providers have to swiftly adjust to digital transformations to navigate containment problems and survive in a dynamic environment. Concurrently, digital infrastructure has seen significant development and shows no indications of deceleration [1]. The phrase digital twin has garnered considerable attention among several major tech buzzwords, alongside closely related concepts such as hyper-automation, digital shadows, digital threads, and digital ghosts. The digital twin and its associated words embody the same foundational technical notion and have consistently been on Gartner's top 10 strategic technology trends list year since 2017. ReportLinker [2] estimates that the worldwide digital twin market was valued at over USD 8 billion in 2021, with a compound annual growth rate (CAGR) of 39% projected from 2022 to 2030. While the precision of the value may be contested, and various market research sources may provide differing (albeit comparable) assessments, they together suggest that digital twin technology is crucial in digital transformation. The potential benefit it may provide should not be disregarded [3].

The Google Trends index is extensively used in modeling and forecasting as a dependable measure of public interest [4-6]. Consequently, the Google Trends index from 1 January 2019 was obtained from the Google Trends website, alongside another prominent rising phrase - the UN SDGs (United Nations Sustainable Development Goals) for comparative analysis. The trend of UN Sustainable Development Goals (SDGs) is used here, given its worldwide recognition and growing policy significance across almost all nations and sectors. Both phrases have seen a rise in Google Trends indexes globally during 2019. The digital twin index is nearing its maximum value of 100, signifying the utmost level of search interest on Google.

The public interest in digital twin technology has been greatly amplified due to recent digital transformation, substantial investment initiatives by several technology leaders, and the supportive environment of expanding digital infrastructure and advancing technology in today's rapidly evolving landscape. Numerous industries have shown a growing interest in using digital twin technology. The rapidly evolving healthcare industry, driven by the COVID-19 pandemic, signifies essential need for additional examination [7,8]. This study seeks to enhance comprehension of digital twin technology and examine its present interactions with healthcare to provide valuable insights to stakeholders.

2. Digital Twin: An Established Concept with a Recent Significant Advancement

The term "digital twin" has lately gained prominence and become a trendy subject. It is acknowledged as a "fundamental component" of the Metaverse, a rapidly developing concept that embodies an immersive digital realm facilitating real-life experiences and interactions. The overarching digitalization process across various sectors, the swift enhancement of data processing and analytical capabilities driven by rapid technological advancements, and the ongoing progress in cognition and artificial intelligence (AI) have collectively expedited the development of digital twin technology, a phenomenon that commenced decades ago [9].

The phrase "digital twin" is extensively used to describe various concepts, systems, or technologies. Exaggerated expectations, absence of established standards, and inadequate comprehension of the foundational technology, together with misleading or too ambitious marketing by several short-term profit-driven opportunists, have led to a substantial enhancement in all facets of digital twin. A more thorough

examination of the true "actor" behind this vibrant "performance" indicates that the notion of a digital twin has been there for decades [9,10].

The term 'digital twin' was initially introduced by Michael Grieves in a 2003 presentation; however, it is widely recognized that the concept was first utilized by the National Aeronautics and Space Administration (NASA) in the 1960s for the simulation and programming of spacecraft, specifically during the Apollo missions. In 2012, Glaessgen and Stargel [11] stated that NASA officially characterized digital twin technology as "an integrated multi-physics, multi-scale, probabilistic simulation of an as-built vehicle or system that employs the most accurate physical models, sensor updates, fleet history, etc., to replicate the lifecycle of its corresponding flying twin." Manufacturing and general industry swiftly established themselves as the principal sectors for the implementation of digital twin technology, due to the clear connections between digital twin utilization, cost reduction, and production efficiency.

Simultaneously, the notion of a digital twin has been expanding as its uses extend beyond spaceflight and vehicle contexts. Grieves [10] elucidated that a digital twin has three components: the tangible object, its virtual counterpart, and the reciprocal data links connecting them. The actual product transmits data to the virtual "twin," while the virtual representation continuously relays information and processes back to the real product. As stated in [8,12], "Digital Twin (DT) entails the development of a virtual representation of a physical entity in digital format to simulate behaviors, monitor current conditions, identify internal and external complexities, detect anomalies, assess system performance, and forecast future trends." The digital twin rapidly emerged as an essential technology for industrial enterprises. Grieves [13] provided comprehensive definitions of essential terms associated with the application of digital twin in product lifecycle management (PLM), including digital twin prototype, digital twin instance, digital twin aggregate, and digital twin environment, among others. The definitions are not included here; however, a summary list is available in [14]. Expanding upon the three-dimensional digital twin model initially presented by Grieves [10], Tao et al. [15] introduced a five-dimensional digital twin model. This enhanced framework incorporates digital twin data and services, addressing data fusion ("information capture") from both the tangible product and its digital equivalent, while also encompassing the functionalities of the digital twin derived from the integration of a service component. Liu et al. [16] contend that modern research emphasizes the dynamic, real-time, and bidirectional data connectivity characteristics of digital twins. The study also presents a compilation of digital twin definitions sourced from academic journals.

The digital twin paradigm evolved and got more complex due to the ongoing commitment of academics and practitioners. The digital revolution and rapid breakthroughs in IoT, Big Data, and cloud computing have enhanced the whole digital infrastructure, resulting in exponential upgrades [17-19]. These elements together fostered a technologically conducive environment for the implementation of digital twin technologies, with less constraints than those present at the inception of the idea. Currently, in both commercial and academic domains, the digital twin is seen as a crucial component of the Fourth commercial Revolution [20-22].

Nearly fifty percent of the global population lacks internet connection, and only a limited number of nations are capitalizing on the forefront of technological progress [1]. A digital gap has been seen between developed and developing countries/regions, with disparities in income levels, genders, ages, and digital access significantly intensifying existing inequities, particularly for technologically disadvantaged populations. Despite ongoing attempts to close the digital gap [23], fast technical advancements, such as the digital twin, may have exacerbated human susceptibility in the development of technology [1]. A deficiency in comprehension, knowledge, and access to cutting-edge developments heightens the likelihood of misconceptions, erroneous or exaggerated public expectations, detrimental reputational consequences, misunderstandings, and an increased risk of exploitation for the most digitally vulnerable populations.

This study intends to address prevalent misunderstandings around digital twins and elucidate the causes behind them. It aims to elucidate challenges, enabling academics and practitioners to reference the appropriate technology and subsequently contemplate the prospects inside their fields of expertise, hence fostering enhanced insights and propelling future advancements [24]. In summary, prevalent

misunderstandings about digital twins derive from their association with related technologies such as 2D/3D modeling, system simulation, validation computing, and digital prototyping, among others [25]. A lack of thorough knowledge of the digital twin and its associated technologies often leads to misunderstanding with one of its foundational technologies, often conflating components or processes of the digital twin with the digital twin itself. The dynamic, real-time, and bi-directional data connectivity of digital twins [16] is essential for their differentiation, but it is also the most prevalent cause of misunderstanding.

The essential functions of digital twins are outlined to aid readers in comprehending the underlying mechanisms that reveal valuable implementation opportunities within their fields of expertise [26-30]. As emphasized in the preceding section, digital twin technologies are characterized by their dynamic and real-time capabilities, facilitating bi-directional data exchange between a physical entity and its virtual counterpart or avatar. The aforementioned key characteristics, coupled with the enhancement of digital infrastructures, position the digital twin as a facilitator for various complex functionalities, which can be categorized into simulation, validation, monitoring, and analytics, encompassing visualization, documentation, prediction, valuation, and optimization [31-37].

Digital twin technologies have mostly been embraced by manufacturing and industry, where their features are intricately integrated into Product Lifecycle Management (PLM). It is employed to digitally replicate the entire product lifecycle (encompassing all physically existent products/processes), oversee physical objects, and supply real-time data to the digital counterpart, digitally document and visualize the complete lifecycle and related data, simulate and validate operations/processes digitally, and enhance them for the physical entity by offering both real-time and predictive analytics (such as performance validation, forecasting, status monitoring, and adjustments, among others) [38-42]. Rasheed et al. [43] delineated eight potential extensions of digital twin functionalities beyond PLM.

3. The features of digital twins

In this rapidly evolving environment, the notion of the Metaverse has emerged as a prominent subject, as individuals pursue an exceptionally immersive digital experience that facilitates real-life interactions and encounters. The Metaverse is defined as "the post-reality universe, a continuous and enduring multiuser environment that integrates physical reality with digital virtuality" [44]. Digitalization is swiftly establishing a connection between the physical realm and the Metaverse, with digital twin technology regarded as the foundational element of the Metaverse. The Metaverse can be perceived as the digital replication of all entities on a broad scale; therefore, comprehending the value proposition of digital twins is a crucial initial step for those seeking to leverage the forthcoming phase of this digital evolution. While digital twin technologies are being utilized in manufacturing and industry, their applications within the Metaverse remain in nascent stages, particularly due to challenges related to scalability, regulation, data/system/platform uniformity, and composability.

Applications in everyday life where individuals can experience benefits include virtual shopping, immersive virtual events and meetings, immersive learning, and virtual travel; however, the digital twin is often integrated with virtual reality, augmented reality, or immersive reality. It is essential to recognize that not every instance advertised as a digital twin is, in fact, a digital twin from a technological standpoint [45]. It may just be an incomplete product, or an ongoing effort using aspects of digital twin technology and enhanced by virtual reality. To differentiate, the optimal approach is to recognize the key characteristics of digital twins, which include dynamic, real-time, and bidirectional data flow between a physical entity and its virtual counterpart. Based on these requirements, it is evident that despite the growing focus on the Metaverse, a really dynamic, real-time, immersive, and bidirectionally influencing experience remains a distant goal. Nonetheless, while the adoption is not yet fully realized, the values and potential are already significantly impacting, facilitating advancements across several sectors, corporations, fields of scientific inquiry, and other dimensions of human existence [46,47].

Liu et al. [16] performed literature research to ascertain essential technology and software for digital twins. The essential technologies were categorized into three groups: data-related technologies, high-fidelity

modeling technologies, and model-based simulation technologies. The authors developed a technological architecture for digital twins based on this categorization, segmenting the digital twin into several phases and associating essential technologies with each component. Likewise, Qi et al. [12] presented an exhaustive framework of pertinent technologies and technical tools essential for facilitating the digital twin, serving as a definitive directory for identifying the specific technologies, software, and technological tools necessary for implementing a digital twin.

4. Enhancement of Healthcare via a Digital Twin

Manufacturing businesses have made substantial advancements by integrating digital twin technology into all phases of Product Lifecycle Management (PLM), which is acknowledged as a crucial component of Industry 4.0 [8,17]. There is a clear interest in digital twins across several businesses, especially in the fast-evolving healthcare industry after the COVID-19 pandemic. In reference to the five-dimensional model of the digital twin described in Section 2.1 [15], the specifics of this model are encapsulated inside a healthcare framework. While embedding the general five-dimensional model into a healthcare context may appear theoretically simple, it is, in practice, considerably more intricate and challenging, as healthcare involves human subjects rather than mere "products," and encompasses significant variety and complexity, necessitating advanced domain-specific knowledge at each stage of the process. Moreover, intricate ethical issues, regulatory frameworks, privacy, and security constraints must be considered [48].

Figure 1 presents a potential digital twin paradigm for the healthcare sector. Considering humans/patients as the tangible entities and drawing inspiration from product lifecycle management frameworks, various healthcare phases are proposed: preconception care, lifelong healthcare, and posthumous stage. Every phase is linked to its pertinent digital twin data and the accompanying functionality of the digital twin. The digital avatar serves as the virtual counterpart of the person or patient, facilitating the integration of information and digital twin model data. The reciprocal links among the fundamental components of the model align with the recognized five-dimensional digital twin framework delineated in [15]. The aim of this comprehensive model, which integrates various life cycle healthcare stages, is to present a clear representation of a digital twin for general audiences interested in this emerging field, delineate the diverse types of information encompassed within digital twin data, and illustrate the functionalities that digital twins can offer in enhancing healthcare. This part provides a detailed explanation of the concept, systematically addressing the many life cycle phases.

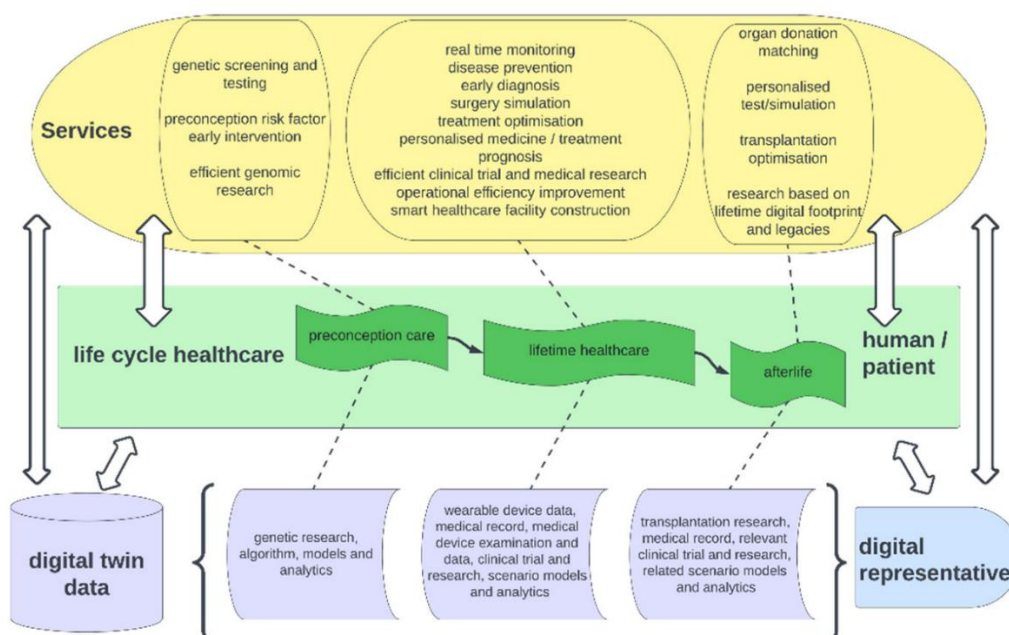


Figure 1. Digital twin paradigm in the healthcare sector.

A multitude of risk factors associated with maternal health and infant death are avoidable. Timely and appropriate preconception care may substantially reduce negative mother and newborn outcomes at the community level, foster healthier pregnancies for women, and enhance the overall health of individuals of reproductive age. The preconception stage, although explicitly addressed here, is intricately linked to other elements of lifelong health, including lifestyle choices, diet, physical fitness, and mental well-being. The emphasis is on applications pertinent only to the preconception care phase, however there will be noticeable overlap in the lifelong healthcare segment [49].

Gardiner et al. [50] consistently emphasized the need of integrating rapidly advancing health information technology, such as virtual patient advocates, to facilitate the implementation of preconception care measures via clinical services. They suggested the use of the well-recognized Gabby preconception care system [50,51]. A further personal mHealth smart pregnancy program was created by [52], which aimed to provide individualized preconception care information and coaching to mitigate harmful behaviors. Davidson and Boland [53,54] examined pertinent papers and discussed the ongoing trend of enhancing pregnant women's decision-making and advancing reproductive health with sophisticated information technologies such as artificial intelligence and machine learning. Oprescu et al. [55] have suggested a complete intelligent system that is now undergoing testing in pregnancy health research.

In addition to the aforementioned sophisticated digital technologies, advanced ultrasound enhanced by virtual reality technology may provide improved vision of embryonic and placental tissues, facilitating early diagnosis and detection of difficulties during pregnancy [56,57]. The findings in [58] indicate that an immersive virtual reality experience may mitigate the adverse emotional effects on women undergoing in vitro fertilization (IVF) prior to embryo transfer.

Despite being in their nascent stages, genome projects are investigating the intricacies of our genetic makeup, gathering comprehensive molecular data from individual patients and newborns [59-61]. This information can be utilized to create digital genetic models that facilitate genetic research, testing, and early interventions, while also paving the way for a diverse array of future healthcare products and services. For example, this may herald the advent of lifetime genomic records, enhance our comprehension of diseases, and lead to the discovery of novel diagnostic and therapeutic methods [62-64].

5. Conclusions and Prospective Research Avenues

The augmented value and advantages of digital twin technologies in healthcare are accompanied by some obstacles. A thorough examination of digital poverty, the digital divide, and the potential exacerbation of these issues via digital twinning for digitally disadvantaged communities has occurred [1]. The more rapid the progression of digitalization, the greater the potential for the digital gap to expand. It is crucial to inquire if more individuals are being marginalized or included in the rapid digital revolutions of today.

Alongside issues related to the digital divide, the rapid advancement of AI technology across several industries raises concerns about access equity, privacy, ethics, security, and appropriateness for varied requirements. Such considerations are often disregarded, particularly during the first phases of technological advancement when public interest and expectations may be exaggerated. Research has emphasized the significance of compatibility for future integration across virtual entities, platforms, systems, and IT infrastructure, particularly as the creation of digital twins' advances. Mixed ownership, disparate standards, and potentially conflicting interests may undermine the original efficacy and functions of the digital twin. A progressive, cohesive, compatible, and future-proof standard or law is the crucial foundation for the sustained development of digital twins in healthcare. In its absence, there is a danger that applications may favor immediate gains above enduring advantages, leading to misinterpretations and reputational harm if public expectations remain unmet. This may adversely affect the availability of essential resources for any prospective long-term growth.

This study sought to connect two distinct interest groups—digital twin technology and healthcare—while elucidating the current trajectory of digital twin applications within the healthcare sector and providing insights to facilitate future advancements in research and implementation. In comparison to the current

literature on digital twins in healthcare, this paper is, to our knowledge, the inaugural work presenting the digital twin model within the healthcare context across various life stages. Furthermore, it is the first instance of proposing the paradigm of digital twinning as a comprehensive healthcare service, thereby extending the digital twinning architecture of Industry 4.0 into the healthcare domain. This model and proposed architecture can aid researchers and practitioners in comprehending the framework of the digital twin in healthcare, identifying research gaps, and uncovering valuable applications in specific life stages or healthcare services to enhance the implementation of the digital twin in healthcare models and architectures. Future study will concentrate on healthcare dimensions that are now neglected but have the possibility for the incorporation of new technology such as a digital twin. Digital twin technologies are inevitably collaborating with other emerging technical developments, such as AI, which has shown considerable benefit across several domains [64,65]. Future study will examine the interplay between digital twins and AI, as well as their combined effects in certain areas such as healthcare.

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التأثير التحويلي لتقنية التوائم الرقمي على المحاكاة الصحية وتحسين رعاية المرضى: مراجعة

الملخص

الخلفية: أحدث ظهور تقنية التوائم الرقمي ثورة في العديد من الصناعات، خاصةً في مجال الرعاية الصحية، من خلال تمكين المحاكاة المحسنة والرعاية الشخصية للمرضى. يعمل التوائم الرقمي كنسخة افتراضية للكيانات المادية، مما يتيح المراقبة في الوقت الفعلي والتحليلات التنبؤية. يُعد فهم تأثيرها على الرعاية الصحية أمرًا بالغ الأهمية لتحسين نتائج المرضى وكفاءة العمليات.

الطرق: قامت هذه المراجعة بتحليل منهجي للتطورات الحديثة في تقنية التوائم الرقمي المتعلقة بتطبيقات الرعاية الصحية. تم إجراء بحث شامل في قواعد بيانات متعددة، مع التركيز على الدراسات المنشورة من عام 2015 إلى عام 2023. تناولت المراجعة تطور مفاهيم التوائم الرقمي، ودمجها في أنظمة الرعاية الصحية، والفوائد والتحديات الناتجة.

النتائج: تشير النتائج إلى أن التوائم الرقمية تحسن بشكل كبير إدارة المرضى، وتخطيط العلاج، والتدريب الطبي. تشمل التطبيقات الرئيسية محاكاة العلاجات الشخصية، وتعزيز التدريب الجراحي، وتحسين إدارة الموارد. حددت المراجعة 30 دراسة ذات صلة، وكشفت أن استخدام التوائم الرقمية يمكن أن يؤدي إلى تقليل معدلات إعادة دخول المستشفى بنسبة 25% وتحسين النتائج الجراحية بنسبة 30%. ومع ذلك، تم ملاحظة تحديات مثل مخاوف الخصوصية وصعوبة التكامل مع البنية التحتية الحالية للرعاية الصحية.

الخلاصة: تتحمل تقنية التوائم الرقمي إمكانات تحويلية للرعاية الصحية، حيث توفر حلولاً مبتكرة لرعاية المرضى وكفاءة العمليات. وعلى الرغم من التقدم الكبير المحرز، لا تزال هناك حاجة إلى مزيد من البحث لمعالجة مخاوف الخصوصية وتبسيط التكامل مع ممارسات الرعاية الصحية الحالية. يعد مستقبل التوائم الرقمية في الرعاية الصحية بزيادة كبيرة في تحسين تجربة المرضى ونتائجهم.

الكلمات المفتاحية: تقنية التوائم الرقمي، المحاكاة الصحية، رعاية المرضى، التحليلات التنبؤية، كفاءة العمليات.