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Review

The State of the Art of Digital Twins in Health—A Quick Review of the Literature

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Abstract: A digital twin can be understood as a representation of a real asset, in other words, a virtual replica of a physical object, process or even a system. Virtual models can integrate with all the latest technologies, such as the Internet of Things (IoT), cloud computing, and artificial intelligence (AI). Digital twins have applications in a wide range of sectors, from manufacturing and engineering to healthcare. They have been used in managing healthcare facilities, streamlining care processes, personalizing treatments, and enhancing patient recovery. By analysing data from sensors and other sources, healthcare professionals can develop virtual models of patients, organs, and human systems, experimenting with various strategies to identify the most effective approach. This approach can lead to more targeted and efficient therapies while reducing the risk of collateral effects. Digital twin technology can also be used to generate a virtual replica of a hospital to review operational strategies, capabilities, personnel, and care models to identify areas for improvement, predict future challenges, and optimize organizational strategies. The potential impact of this tool on our society and its well-being is quite significant. This article explores how digital twins are being used in healthcare. This article also introduces some discussions on the impact of this use and future research and technology development projections for the use of digital twins in the healthcare sector.

Keywords: digital twins; health 4.0; digital health; healthcare; simulation

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1. Introduction

The incorporation of digital models as an indispensable part of the process of studying and developing physical objects is an established practice. The virtual prototyping approach combines the power of digital technology with the principles of engineering and design, allowing physical products and systems to be created and improved more efficiently and accurately. The ability to virtually simulate and analyse objects and systems prior to their physical production has proven to be an invaluable tool in a wide variety of sectors, including manufacturing, engineering, architecture, and medicine, among others, providing benefits such as time savings, cost reductions and the possibility of optimizing the performance and functionality of products [1–3].

The advent of the fourth industrial revolution, known as Industry 4.0, characterized by the fusion of physical and digital technologies and the creation of intelligent and interconnected systems, has resulted in a reinvention of the concept of simulation, giving rise to what is defined as digital twins [2,4,5]. The continuous growth and evolution of technologies such as the Internet of Things (IoT), artificial intelligence (AI), machine learning and big data has made it possible to collect, process and store large amounts of data in real time. These technologies are essential for the creation and operation of what we now know as the digital twin (DT), providing the basis for capturing data from the physical world and transforming it into accurate virtual replicas, allowing us to analyse various aspects of an object, equipment, a process or even an industrial plant in its entirety, testing scenarios and possibilities before implementing them in their physical copy, making decision-making faster, more efficient and less expensive [2,6].

A digital twin is, conceptually, defined as a digital replica or virtual representation of an object, process, or system. However, its definition can be even broader, considering it as a virtual model (data plus algorithms) with special characteristics not found in traditional models and simulations, which dynamically combines the physical and digital worlds, taking advantage of new technologies, such as intelligent sensing, analysis of large volumes of data and artificial intelligence (AI), to detect and prevent failures, improve performance and prospect opportunities for innovation in the entity studied [7,8]. In this way, its potential goes beyond virtual prototyping, being able to provide information and subsidies to anticipate situations before they occur, allowing scenarios to be planned, reducing costs, minimizing losses and failures, and mitigating risks and damages that compromise the activity [9].

The increasing use of digital twin technology across industries highlights its potential to revolutionize the way we create, manage, and operate even the most complex systems. The health field is characterized by a complex ecosystem that requires effective and efficient operations, optimizations, management, and control to offer reliable, economical, and quality healthcare actions and services. The main challenge is to provide the best possible healthcare services to patients using limited healthcare resources. The use of digital twins for predictive analysis, process improvement, supply capacity planning, risk management, assertiveness in diagnosis, and increased clinical safety, among others, will allow managerial and clinical decisions to improve the quality of health care offered in the future [10–12].

The aim of this work is to compile the state of the art in the use of digital twins in healthcare, by reviewing the scientific literature on the subject, thus making it possible to assess the trends and challenges of this technology for the coming years. This work expects to explore the various applications of digital twins in healthcare, their potential for further development, and the challenges they present. By doing so, we hope to provide valuable insights for this growing technology and its potential to revolutionize the planning, production, and management of healthcare structures and processes.

In addition to this introduction, this article contains five other sections. Section 2 describes the bibliographic research carried out on digital twins, digital health, and healthcare. Section 3 lists the methodology used for the rapid literature review. Section 4 presents the results. Section 5 discusses the results. Finally, Section 6 presents the conclusion and the limitations of the work.

2. Literature Review

This section presents the theoretical basis used to support the discussion of the use of digital twins in healthcare. To this end, we sought to contextualize the topic, seeking to understand the process of digital transformation in the health sector and its relationship with innovative forms of service provision, especially in health care.

2.1. Digital Twins

A digital twin can be understood as technology capable of mapping the real world to the digital world through interaction between the two in real time. By reflecting the composition and structure of the entities studied, the relationship between them and the external environment and their behaviour in the digital world, this technology makes it possible to appropriate the current state of these entities, predict subsequent changes and provide guidance in their operation. Digital twins can be used to simulate a variety of entities with increasing levels of complexity, from everyday consumer objects to complex systems such as transportation, cities, ecosystems and even the human body [13–15].

Although the concept was mentioned as early as the 1990s in David Gelernter's book *Mirror Worlds*, it was Michael Grieves, at a conference for industry at the University of Michigan in 2002, who proposed an architecture for digital twins. The model mentioned both the concepts of real and virtual space and the flow of data between them. Although it had an initial idea of dealing with reality and virtual existence in the context of digital twins, the model did not explain exactly how these two elements would interact, nor did it indicate which technology could be used for this interaction [7,16]. It was not until 2010 that the concept of digital twins was formally introduced by John Vickers in a NASA strategy report, marking the official starting point for the development of the idea of digital twins. The United States Space Agency began using the term "digital twins" in its technological strategy in 2012, signalling its commitment to exploring and improving this innovation.

Advances in computer processing capacity, storage and data transmission speed have triggered the emergence of innovative technologies, which include machine learning, connectivity (4G and 5G) and the management of large volumes of data (big data), cloud computing and the Internet of Things (IoT). These technologies represented a significant transformation in the industrial landscape, being the main drivers of the so-called Fourth Industrial Revolution, also known as Industry 4.0. Machine learning empowers systems to learn and adapt from data, driving automation and intelligent decision-making. Connectivity, in turn, allows devices, machines and systems to communicate in real time, enabling more effective coordination and better process integration. Big Data deals with the ability to collect, store and analyse significant volumes of data, providing valuable insights to improve processes and make decisions with more confidence. Cloud computing enables access to scalable and flexible computing resources, reducing costs and improving efficiency. IoT, in turn, involves the interconnection of physical devices on the network, allowing remote monitoring and control. Together, these technologies are redefining the industry, promoting greater efficiency, personalization, automation, and the creation of new business models. In this context, digital twin technology has recently been developed [7,9,17–20].

The concept of digital twins appears intrinsically related to this perspective of technological innovation, aiming to create a detailed and as faithful as possible digital representation of a real-world entity. This digital representation makes it possible to experiment with scenarios and possibilities even before they are implemented in the physical world, resulting in more agile, effective, and economically advantageous decision-making. Through digital twins, it is possible to accurately model objects, systems, and processes in a virtual environment. This digital replica mirrors not only the physical characteristics but also the dynamics and behaviour of the real world. Thus, it is possible to carry out more detailed simulations and test different approaches without incurring the costs associated with manipulating objects or modifying physical systems. The ability to virtually test scenarios and changes makes decision-making more informed, as the impact of choices can be assessed before implementing them. Furthermore, this approach contributes to the early identification of problems, allowing for more economical and efficient corrections [3,15,21].

In practice, a digital twin uses data, such as physical models, sensor updates and operation histories, and integrates several simulation processes from different perspectives. This allows one to map the object or system in virtual space, reflecting its entire life cycle or execution time. Digital replicas offer two major advantages: on the one hand, they help to create hypotheses and scenarios to anticipate any type of error or adverse event, and on the other hand, they contribute to optimizing the functioning of different types of processes and operations.

A digital twin is composed of three main parts: (1) the physical product in real space, (2) the virtual product in virtual space and (3) the data and information link that connects the real and virtual spaces. The virtual part not only stores the history of the physical part but can also provide optimization and prediction for it so that convergence between the parts is always sought [5,6]. They are characterized by three functions: (1) data fusion of various characteristics of physical objects and high-fidelity mapping of physical objects in real time; (2) coexistence and evolution throughout the life cycle of physical objects; and (3) description, optimization, and control of physical objects.

Healthcare is a field in which digital twins are being explored and applied. Digital twins are highly relevant for the development and consequent advancement of digital health. There is a growing demand from key players in the health sector for new digital health solutions, which are technologically viable and capable of actively and intelligently using patient data. These replicas can be used for a variety of purposes, including analysing existing situations, and predicting the results of interventions. The use of digital twins (DTs) in healthcare can help individuals understand and diagnose different pathologies, simulate therapies or medical treatments, and predict their results. Such predictions can be made for a specific individual or for an entire population.

To date, most studies [10,12,21–32] in the industry have focused on the virtualization of individual assets, considering the point of view of a specific application, such as body parts, organs or body systems, aiming to personalize care or in the reproduction of health equipment and facilities such as hospitals. However, in the real world, these assets are often interconnected and play roles in common processes and ecosystems. Certainly, the greatest potential for its future use is to virtualize contexts and situations that involve several interrelated strategic assets of a macro healthcare organization. This results in the creation of digital twin ecosystems based on a "digital twin as a service" perspective. The future of healthcare is inextricably linked to our ability to effectively improve healthcare delivery and the patient experience through well-informed and consistent new technologies, and digital twins can play this role.

2.2. Digital Health

According to the World Health Organization, digital health encompasses the field of knowledge and practice related to the development and use of digital technologies to support health. Digital health generally encompasses a broader spectrum of technologies and applications, while "e-Health" or "eHealth" often focuses on the digital delivery and consumption of healthcare services. This definition expands upon the original concept of e-Health to include the latest technological advances, such as the Internet of Things, artificial intelligence, big data, and robotics [33].

Digital health would then comprise the use of information and communication technology (ICT) resources to produce and make reliable information about health status available to citizens, health professionals and public managers [34]. This represents a revolution in healthcare, taking advantage of technological advances to improve the access, efficiency, and quality of healthcare services. It is a rapidly growing field that encompasses a wide range of technologies and applications, all aimed at improving the well-being of patients and simplifying the work process for healthcare professionals. The accelerated incorporation of technology has profoundly changed the way medical care is being provided, as well as the management of health care.

The evolution of the concept of digital health and its interconnection with digital transformation demonstrate the profound influence of technology on the provision of medical care. Digital health interventions are increasingly being integrated into healthcare workflows with the aim of improving the efficiency and effectiveness of patient care. As a result, continued patient engagement with these digital interventions can maximize benefits in terms of health outcomes. However, the journey is a long way from completion, and the next decades promise a continuous redefinition in the way healthcare services are provided, making them more patient-focused, accessible, and effective.

Although digital health has extraordinary potential, it faces significant challenges and risks. One such notable challenge is the 'Digital Health Paradox'. While this technology has the potential to increase access to healthcare, it can also be perceived as a "form of barrier" where people who benefit most often face more difficulties accessing it due to a lack of resources or digital skills. This makes them more susceptible to the "infodemic", misinformation and the risk of having their personal data exploited [35–37]. To achieve digital equity, it would be essential to identify three conditions to ensure that people can enjoy the benefits of digital transformation: (i) access to infrastructure and connectivity, (ii) competence in digital literacy, and (iii) encouraging the use of digital technologies [38].

The incorporation of digital health into day-to-day healthcare services is essential for an accessible, patient-centred healthcare system. Its widespread adoption can meet individual and collective health needs and can also offer a harmonious therapeutic relationship through unique therapeutic projects and the reconfiguration of the bond between patients and health equipment [39].

The ability to collect, analyse and share data effectively is enabling unprecedented personalization in healthcare, improving the assertiveness of treatments, reducing costs, and putting patients in control of their own health [40,41]. This digital revolution is shaping the future of healthcare and promises to bring even more disruptive changes in the years to come. However, for this to become a reality, it is necessary to bring together efforts in initiatives that boost the analytical intelligence of healthcare organizations to enable the integration, mining and interoperability of data that enable the prescription, prediction, and personalization of patient-centred and value-based care.

2.3. Healthcare

The health sector has made historic advances in basic sanitation, the development of vaccines and medicines, the rapid incorporation of medical technologies for diagnosis and treatment, and the improvement and expansion of health care, among others. However, social and demographic factors such as intense urban mobility, accelerated population growth with increased life expectancy, and high health costs have increased the level of difficulty in providing health responses for national health systems. In addition, the emergence of new diseases with a global reach dramatically encourages the health sector to be better prepared in the coming decades.

Providing quality healthcare means guaranteeing and respecting the dignity of each citizen who forms part of and builds a given society. There has been much discussion about the best way to manage health in countries. The World Health Organization (WHO) defines a health system as a set of activities whose primary purpose is to promote, restore and maintain the health of a population, to achieve an optimal level of health in an equitable manner and with adequate risk protection, the provision of safe and effective services, the humanized reception of citizens and the provision of efficient services. Health care systems constitute social responses organized to respond to the needs (and preferences) of societies [42].

Among the current and future challenges for global health, we highlight the greater use of health systems resulting from the demographic and epidemiological transitions of the world population, the increasing incorporation of new technologies and the expansion of self-care managed by individuals, the increase in individuals' expectations mainly due to the association with other consumption patterns, and the inability of supply/wealth to grow in the same proportion as needs due to the inelastic behaviour of demand, unlike the needs for health care, which tend to infinity [43]. Although the amounts spent on health, as a proportion of the gross domestic product (GDP), are becoming increasingly greater, discrepancies continue between countries and continents when considering per capita spending. Therefore, health underfunding has also been repeatedly identified as one of the main causes of precarious health services in many countries [44].

However, perhaps the greatest challenge of all is the shift in the focus of the workforce in the health sector, which is no longer centred on acting essentially on the disease and becomes centred on the person, involving and committing individuals to their own health. In the disease-centred model, the main purpose is treatment and, if possible, curing the disease. Its emphasis is on identifying the signs and symptoms necessary to reach a diagnosis and then beginning the most appropriate treatment for that pathology. It is worth noting that in this model, the health professional is the one who defines the object of the work, with the patient playing just a supporting role. In the person-centred care model, the purpose goes beyond the disease because, no matter how assertive the treatment is, the main objective is to promote the individual's autonomy and their participation as a protagonist of their health status. In this new paradigm of health care, the provision of services would necessarily occur in a way that respects autonomy, responding to the needs, preferences and values of the person assisted, with the guarantee that such values guide all clinical decisions, thus resulting in strong engagement of the individual with their health status. Person-centred care helps users develop the knowledge, skills, and confidence they need to manage and make informed decisions about their own health and healthcare more effectively [36,45,46].

Established as a global priority in 2005 by the World Health Organization (*WHO—World Health Organization*) [33], the digital transition has significantly impacted the health domain by creating the conditions for redefining the care model in the sense of becoming more integrated, participatory, and personalized.

Currently, the delivery of healthcare services continues to occur in a fragmented and timely manner for most patients. It becomes extremely difficult for healthcare professionals and patients to monitor all important events, correlations and exposures that negatively affect the provision of healthcare, both in terms of cost and quality. In this context, digital twins offer remarkable potential to significantly improve healthcare delivery.

The correlation between healthcare and digital twins becomes intricate and complex. For example, digital twins have the potential to improve medical diagnosis [40]. Healthcare professionals can use these virtual representations to simulate medical conditions, test different treatment approaches, and evaluate results before applying them to real patients. This can lead to more accurate diagnoses and more effective treatments. Additionally, digital twins can improve communication and collaboration within healthcare teams. By enabling healthcare professionals to access centralized, up-to-date patient information, care coordination becomes more efficient. Doctors can share insights and treatment decisions based on hard data. The potential of digital twins in telemedicine is also notable. Patients can have a digital "avatar" that represents their health status, allowing doctors to monitor health remotely. This is especially valuable in chronic care situations or in places where access to medical care is limited [47].

The combination of healthcare and digital twins opens the door to a revolution in healthcare delivery. With the potential to improve diagnoses, treatments, care coordination and remote monitoring, this correlation promises to offer significant benefits for patients, doctors, and the entire healthcare system. The journey towards more effective and personalized healthcare begins with the amalgamation of digital innovation and healthcare delivery, resulting in unique, highly customized therapeutic projects.

3. Methodology

The objective of this research was to analyse scientific publications with the purpose of investigating the use of digital twins in healthcare and the trends and challenges in their use, providing insight into the possible paths of healthcare. This research sought to answer two guiding questions: "How are digital twins being used in the healthcare sector?" and "What are the challenges and perspectives of using digital twins in the healthcare sector?" The PICO strategy (acronym for P: population/patients; I: intervention; C: control; O: outcome) is used to help to define what the research question should in fact specify for this paper. Figure 1 presents the four components of the PICO strategy.

The Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) was a great help for authors to prepare transparent accounts of their reviews, providing syntheses of the state of knowledge in a field, from which future research priorities can be identified. For this paper, a literature search was conducted in digital libraries of six academic databases: IEEE Xplore, Dimensions, Scopus, Web of Science, PubMed, and ACM. The six databases were chosen with the aim of covering the Engineering and Health research areas. IEEE Xplore and ACM serve the purpose of containing the Engineering/Technology area, whereas the PubMed database is focused on the health area. Scopus, Web of Science and Dimensions incorporate many fields of knowledge and were included to identify any other records relevant to this study that were not in the specific databases. We tried to restrict the search by using specific keywords to find publications of interest.

The search strategy was based on three main terms: *digital twins*, *digital health*, *and healthcare*. Another filter applied in the search strategy was publications within a time range of up to 5 years (2018 to 2023). The resulting search query is shown below in Table 1.

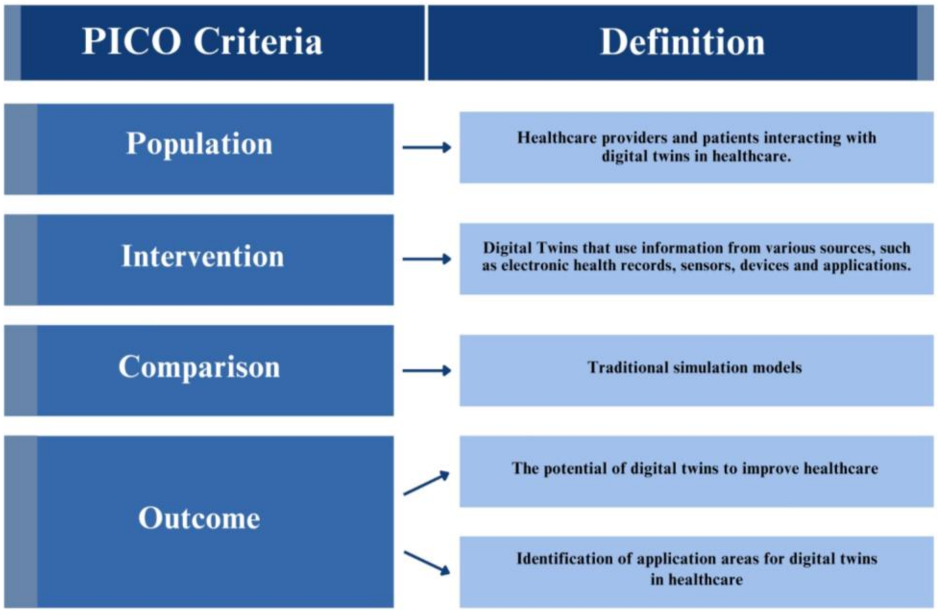

Figure 1. PICO Strategy.

Table 1. Search Strings.

Search String	Data Base	Results
("All Metadata": "Digital twins") AND ("All Metadata": "digital Health") AND ("All Metadata": "Healthcare")	IEEE Xplore	6
[Full Text: "digital twins"] AND [Full Text: "digital Health"] AND [Full Text: Healthcare]	ACM digital library	25
"Digital twins" [All Fields] AND "digital Health" [All Fields] AND ("delivery of health care" [MeSH Terms] OR ("delivery" [All Fields] AND "health" [All Fields] AND "care" [All Fields]) OR "delivery of health care" [All Fields] OR "healthcare" [All Fields] OR "healthcare's" [All Fields] OR "healthcares" [All Fields])	PubMed	5
(TITLE-ABS-KEY ("digital twins") AND TITLE-ABS-KEY ("digital Health") AND TITLE-ABS-KEY (healthcare))	SCOPUS	19
"Digital twins" (topic) and "digital Health" (topic) and "Healthcare" (topic) and 2019n0r 2020 or 2021 0r 2022 or 2023 (years of publication)	Web of Science	7
("Digital twins") AND ("digital Health") AND ("Healthcare")	Dimensions	24

At the end of applying the search strings, a total of 86 results were reported. After analysing possible duplicate references in the Zotero library, 28 duplicate results were excluded. At this point, a total of 58 publications was reached. This last material then went through a data survey, collection, and analysis process, divided into three stages:

- Pre-analysis evaluating title, abstract and keywords;
- Exploration of the selected material;
- Treatment of results and interpretations.

The exclusion criteria included studies in languages other than English and articles unavailable or only partially available for download in the chosen databases. Furthermore, all articles that did not explicitly mention the use of digital twins in health, as well as items selected in the search which were books or book chapters, were also excluded from the discussion.

The only inclusion criterion was confluent studies that dealt with topics related to digital twins, digital health, and health care.

Following the pre-analysis stage, 31 results were excluded. Subsequently, during the exploration of the remaining articles, an additional 14 were excluded due to a lack of explicit focus on the application of digital twins in healthcare. Figure 2 illustrates the entire process.

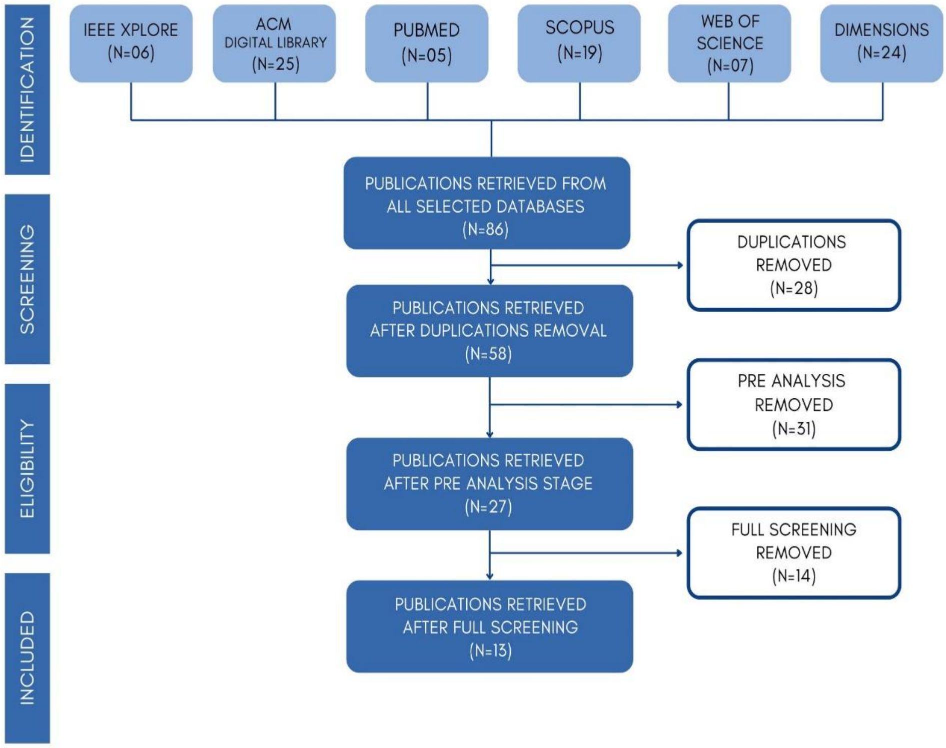

Figure 2. PRISMA flow diagram of the selection process.

At the end of the methodology, 13 articles were obtained that met the eligibility criteria proposed for discussion.

4. Results

The studies included for discussion can be categorized according to the application of digital twins in the health sector into two groups: the clinical applications group, with seven records, and the operational applications group, with six records. The full spectrum of the articles is detailed below in Table 2.

When carrying out the content analysis of the articles, we can also verify a subdivision within the groups. In the clinical applications group, we have five articles that are focused on the theme of personalized care/precision medicine, signalling the development of digital technologies based on real-time patient data for the management of specific diseases or conditions, one article addressing the reproduction of biological structures creating avatars of organs or even the human body, and another that focuses on ethical issues related to using DTs in healthcare. In the operational applications group, we have a subgroup with 5 articles that discuss the application of digital twins supporting the optimization of operational processes by using real-time data integration, advanced analytics, and virtual simulations to improve patient care, and another subgroup with one article that relies on the construction of virtual structures such as hospitals.

In summary, in the sample of selected articles, the main benefits of using digital twin technology for healthcare predominantly included increased personalization of care, improved quality of care with the increasingly consistent use of precision medicine, and gains in the operational efficiency of health facilities, equipment and services.

However, some of the included studies also highlighted key challenges related to DTs in healthcare, such as interoperability, the processing of large volumes of data, patient confidentiality and data security, and listed them as the greatest obstacles at present for the large-scale implementation of this technology.

Table 2. Findings and results.

Application and Type of DT	Key Findings
Healthcare management (Personalized care)	
Wickramasinghe et al. (2022) [47]	Application of digital twins to support healthcare in the context of personalized treatment for uterine cancer.
Gabrielli et al. (2023) [28]	Proposition of a digital therapeutic methodology for mental health with digital twins associated with virtual coaching solutions to carry out more effective, AI-based digital health interventions.
Rivera, Luis F., et al. (2019) [10]	The use of DT to support precision medicine techniques in the context of continuous monitoring and personalized data-driven medical treatments with example in the management of chronic conditions.
Schwartz et al. (2020) [19]	Discussion on the impacts of using technologies in health care management, especially DTs, which, by incorporating biological (genomic), behavioral, psychological and digital health data, will make users themselves evaluate the relationships between their own health patterns response to treatments and the contingencies that impact them, modifying the standard of health self-management.
Ricci et al. (2021) [41]	The use of digital twins to support healthcare in the context of precision medicine in trauma management.
Healthcare management (Ethics)	
Huang et al. (2022) [36]	Identification and analysis of the main ethical risks associated with the use of digital twins in personalized healthcare.
Healthcare management (Virtualization of Biological Structures)	
Viceconti et al. (2023) [32]	Discussion on the creation of the Virtual Human Twin with technical, political and social considerations.
Operational control (Process Optimization)	
Aluvalu, et al. (2023) [22]	The use of digital Twins in the treatment of patients in emergency services, making service more agile and assertive, with reduced length of stay through patients' facial recognition.
Chaudhari et al. (2021) [24]	The use of Digital Twin in the healthcare sector associated with other technologies such as IoT and Artificial Intelligence for monitoring health conditions and evaluating responses to medical therapies and the use of certain medications health management for elderly patients.
Safa and Asan (2023) [26]	Review of the main jobs for DTs in Healthcare and analysis of their potential to improve healthcare management and its challenges.
Sun T, He X, Li Z. (2023) [12]	Review of DT technology in medicine and discussion of its potential applications, mainly in diagnosis and treatment, as well as its challenges in the field of digital health.
Vallée (2023) [30]	Using digital twins to optimize clinical operations (workflow analysis and resource allocation) and improve patient safety.
Operational control (Virtualization of physical units)	
Cheng et al. (2022) [25]	Creating smart twin hospitals by integrating technologies powered by IoT, AI, cloud computing and 5G applications with monitoring and assessment of healthcare scenarios.

5. Discussion

Digital twins, at their core, represent highly detailed and interactive replicas of objects, processes, dynamic structures, and even human entities. They operate synchronously and synergistically in combination with their real-world counterparts. This concept has deep roots in engineering, especially in the practice of prototyping. However, with the increasing advancement of technology, digital twins have become a promising tool by opening space for innovation and the development of solutions in various areas.

They have become viable thanks to developments in sensing, notably the Internet of Things (IoT) and artificial intelligence. These technologies can capture information from the physical world and transmit it to a virtual environment. The key to the functionality of a digital twin is constant synchronization with the real world, a task carried out through communications via the internet, 4G, Wi-Fi and, mainly, 5G, making this possible in real time.

Creating a digital twin allows you to anticipate future scenarios or review past events, all without the need to experience these situations. This saves costs and minimizes risks. Digital twins have been used in healthcare to build digital representations from large volumes of health data, such as hospital environments, test results, human physiology, lines of care, etc., through computational models. To build virtual twins, several categories of data are used that cover individuals, populations, and even environmental characteristics.

Healthcare has transitioned from a singular focus on illness to a broader emphasis on primary care and health promotion, recognizing the complexity of the healthcare ecosystem. Among the most notable advancements are the contributions of digital twinning to precision medicine, which enables personalized treatment and diagnosis for patients. Although the use of digital twins to develop new, customized healthcare management approaches commenced in 2018, it is still an emerging and evolving concept.

Considering the results found in the selected literature, four main axes of the application of digital twins in health are presented at Figure 3:

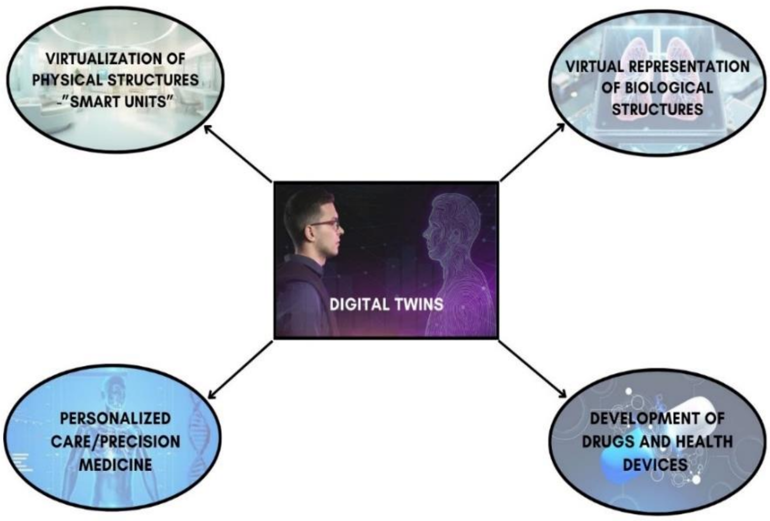

Figure 3. Main axes.

5.1. Axis 1: Use of Digital Twins for Virtual Representation of Biological Structures

The use of digital twins in the virtual representation of biological structures has enabled a new approach in medical education and clinical practice. The evolution of imaging technologies, such as magnetic resonance imaging and computed tomography, has allowed the creation of extremely precise 3D models of organs and tissues. These models provide an interactive representation that not only increases the understanding of anatomy but also improves knowledge retention for medical students. The ability to "navigate" organs and systems in a virtual environment has a lasting impact on the training of future doctors, providing an immersive learning experience that can be difficult to achieve with traditional methods.

The application of digital twins to simulate medical procedures is another exciting facet of this axis. These models allow healthcare professionals to practice surgical interventions and medical procedures in a virtual environment that accurately replicates the human body. This not only reduces the risk to patients during actual procedures but also improves the skill and confidence of healthcare professionals. Furthermore, three-dimensional visualization of organs and pathological structures in digital twins aids in understanding complex clinical cases and making informed clinical decisions.

The creation of a fully developed digital health twin (DHT) is still a goal for the future. However, several companies and research institutes are exploring the development of digital replicas of body parts or physiological systems for specific purposes. For example, in the field of orthopaedics, these digital twins can be used to create virtual models of a patient's musculoskeletal system, including skin, bones, joints, and muscles. These digital twins can be employed to simulate surgical procedures, test various implants prior to surgery, and predict how a patient will respond to treatment.

This exploration facilitates the transition towards personalized medicine, enhancing the customization of therapeutic strategies, forecasting the future health requirements of individuals and populations, and assisting in the planning of public health policies and interventions.

Building a DT for this purpose demands access to extensive healthcare data repositories, which include genetic information, medical records, imaging, histopathology, and other pertinent sources. These data must be of high quality, accurate, and comprehensive. For Viceconti et al. [32], the discussion on the creation of the Virtual Human needs technical, political, and social considerations, such as the challenge of providing fair and transparent use of data.

Perhaps the greatest change is in the path that health treatments will follow, moving from being organized by a standard to being based on the genetic, phenotypic, structural, physical, and psychosocial characteristics of the individual, being referred to as precision medicine or even more broadly as personalized care. Essentially, patients are treated as individuals and not according to some norm or standard of care (providing the right treatment at the right time to the right person).

5.2. Axis 2: Use of Digital Twins to Improve Healthcare Processes (Personalized Care)

Digital twins are software-based replicas that simulate the dynamic functions and potential failures of engineered products and processes. In healthcare, patient-specific digital twins integrate established knowledge of human physiology and immunology with real-time, patient-specific clinical data. This integration enables predictive computer simulations across various types of diseases and conditions. These medical digital twins could prove invaluable in healthcare management, leveraging mechanistic insights, observational data, medical histories, and the capabilities of artificial intelligence (AI) to optimize treatment strategies and improve patient outcomes.

In the context of personal digital twins, prevention emerges as a pivotal focus, accompanied by the empowerment of patients. Central to this approach is ensuring that patients comprehend their health status and take responsibility for it. Currently, the strategy involves comparing patients with a comprehensive database to identify similarities and differences. However, the aim is to advance beyond this by gathering historical health data from earlier stages when the patient was healthy. These data can then be utilized to assess current health status, estimate risks, and devise a tailored prevention plan. This approach empowers patients to adjust their behaviours proactively and detect potential diseases early, leveraging straightforward information that can be extracted without direct patient involvement, according to the work of Schwartz et al. [19].

The application of digital twins to improve healthcare processes is driving significant advances in several areas. In oncology, for example, digital twins play a fundamental role in modelling tumours and simulating treatments. This approach allows physicians and oncologists to adjust treatment strategies based on the progression of a patient's disease, resulting in more personalized and less invasive interventions. Furthermore, continuous monitoring of tumours in digital twins enables a more agile response to changes in the clinical picture, providing better results for patients. In the work of Wickramasinghe et al. [47], DTs can support personalized treatment for uterine cancer. Similarly, in women's health, digital twins are used to monitor gynaecological conditions such as endometriosis and fibroids and to manage pregnancy more effectively. The ability to simulate scenarios and monitor the progress of pregnancy in a virtual environment offers patients more personalized and safer care. This also makes it possible to identify complications early, which is essential to ensure maternal and foetal health.

In the area of geriatric care, digital twins enable the creation of care plans adapted to the complex needs of older adults. With the aging of the population, this personalization becomes crucial for guaranteeing the quality of life of elderly people. Digital twins can model a patient's health conditions, considering comorbidities and risk factors associated with advanced age. This results in more comprehensive and effective care that improves seniors' quality of life and reduces unplanned hospital admissions. Rivera et al. [10] explained that the use of DTs to support precision medicine techniques in the context of continuous monitoring and personalized data-driven medical treatments could facilitate the management of chronic conditions. Digital twins can also improve the management of trauma and fractures, especially in the elderly population as explained by Ricci et al. [41] as well as in mental health, when used in association with virtual coaching solutions according to Gabrielli et al. [28].

A crucial point in the use of digital twins in personal care concerns the ethical and moral risks associated with use without any type of reflection. This has been well explored by Huang et al. [36].

5.3. Axis 3: Use of Digital Twins to Depict Healthcare Structures and Improve Operational Efficiency

The use of the digital twin in the healthcare sector has stood out as a powerful tool to improve the management of healthcare units and, consequently, the system in which they are inserted. This technology allows the creation of a virtual copy of the unit and even the system, providing a detailed analysis of operations, capabilities, human resources, and service models. This makes it possible to identify areas for improvement, anticipate future challenges, and improve organizational strategies.

A digital twin allows healthcare managers to monitor operational processes under various performance conditions and address potential issues before they arise. This capability shifts healthcare management from a reactive approach to a predictive approach. Furthermore, DTs transform existing resources into tools that optimize processes, reduce costs, and accelerate innovation in healthcare management.

Operational efficiency in healthcare is a constant concern, and digital twins play a crucial role in optimizing healthcare systems. One of the main benefits is the improvement in resource allocation in hospitals and other healthcare units. Digital twins allow a detailed analysis of the use of beds, personnel, and equipment, enabling more efficient and effective planning. This not only reduces patient waiting times but also improves assertiveness in the provision of care, resulting in a more successful patient journey and a more positive experience for everyone involved in the care process. This topic was addressed both in the works of Safa and Asan [26] and Cheng et al. [25].

Taking a hospital as an example, by using historical and real-time data from operations, as well as information from the surrounding environment, such as cases of notifiable diseases and traffic accidents, the digital twin allows the hospital unit manager to make informed decisions, identify a lack of beds, optimize team schedules, and manage room occupancy more effectively. This approach not only increases resource efficiency but also improves hospital and staff performance while reducing costs. In the works of Aluvalu et al. [22], Sun and Li [12], and Chaudhari et al. [24], digital twins were seen as a potentially important technology in improving the patient's journey by seeking to streamline operational and care processes. By building a digital twin of the patient's journey, the healthcare unit can predict patient activity and plan operational capacity according to demand, resulting in significant improvement in services delivered to the patient, in addition to increased safety, increased volume and a better patient experience.

Modelling and forecasting the demand for healthcare services are also areas where digital twins offer great potential. By analysing real-time data and simulating scenarios, healthcare systems can make more informed decisions about resource distribution and staffing, ensuring that care is available where and when it is needed. These capabilities are critical for improving operational efficiency and ensuring that the healthcare system is prepared for future challenges.

5.4. Axis 4: Use of Digital Twins for the Development of Medicines and Health Devices

In relation to drug development, digital twins enable detailed simulation of molecules, pharmacological interactions, and virtual clinical trials. Throughout the drug development process, extensive amounts of data are generated and managed, which digital twins harness to create models. Consequently, DTs can expedite clinical trials in drug research, enabling faster trials with reduced patient enrolment. This approach saves time and resources by accelerating the identification of promising drug candidates. Furthermore, digital twins enable the development of personalized medicines adapted to the individual needs of patients, which is a major advance in precision medicine. The digital twin has applications in the analysis of data related to the use of medications and their effects. By integrating information from patients, healthcare professionals and other sources, the digital twin enables a comprehensive and dynamic view of a medicine's safety profile. Moreover, DTs will be pivotal in vaccine development by assisting scientists in selecting optimal antigens and facilitating virtual development processes.

The increasing use of personal health monitoring devices, such as mobile apps and integrated sensors, enables active surveillance of the user's key health parameters, such as electrocardiogram (ECG), blood pressure, heart rate and glucose level, minimizing potential inaccuracies in data recording. Such devices can collect and transmit information anonymously to the cloud, where it can be compared with disease symptom histories or even alert competent healthcare professionals when necessary. Digital twins are proving to be important for the design and testing of new products. They allow detailed simulations of the functioning of devices such as prosthetics, monitoring devices and medical equipment. This helps identify design issues and ensure that devices are safe and effective before they are manufactured and deployed. Furthermore, digital twins are useful for training healthcare professionals in the use of new devices, improving the safety and quality of treatments.

Finally, the bibliography presented by the research also exposes some of the main challenges in the use of digital twins in healthcare and its future, which we highlight:

- Data Integration: Healthcare management involves a vast amount of information and clinical data. One of the main challenges is the efficient integration of these data into digital twins, ensuring that all relevant information is available in one place. This can be complicated by the diversity of health record systems and data standards.
- Privacy and Security: Maintaining the privacy and security of health data is a critical concern. Digital twins contain highly sensitive information, and it is essential to ensure that they are protected from unauthorized access and data breaches.
- Interoperability: Healthcare systems often use different technologies and standards. For digital twins to be effective, they need to be interoperable, i.e., able to communicate and share information effectively between different systems.

Overall, DTs have significant potential to positively impact these processes, if concerns about privacy, accuracy, and user involvement are properly addressed. As previously stated, digital twins (DTs) offer two key benefits: real-time health information and predictions, and interactive capabilities that allow communication between DTs, decision-makers, and, depending on the model, the individuals themselves. To address the ethical concerns surrounding DTs, it is important to clarify the conditions and requirements for using them to simulate a person's health.

At first, each digital twin (DT) must correspond to a real person and be assigned a unique identifier. This identifier will allow logging into one's virtual representation, setting health parameters to monitor, and controlling who can view this information. Ensuring the DT is accurately created, and the data validated is crucial, with an authorized institution overseeing this process. To protect privacy, technologies like passwords, biometrics, and blockchain encryption should be used to prevent data tampering. Medical professionals may need access to modify or review this information as necessary. Continuous data exchange between sensors, wearables, and the DT is required to ensure the DT accurately reflects changes in the person's health status. Future solutions, like blockchain technologies, might be necessary to maintain accuracy and reliability even if data flow is disrupted. It is important to specify the scope and purpose of the DTs, including the types of data they will handle, such as text (diagnosis records), numbers (weight, blood pressure), or images (ECGs), and how these data will be processed. Clearly defining the interfaces for data input and transfer is crucial. Additionally, it must be determined what kind of feedback the DT should provide. This feedback could be directed to the person being simulated, their doctor, or a designated decision-maker. The feedback, which might include predictions, suggestions, alerts, or treatment plans, should help the person and their healthcare providers make informed decisions about their health, such as improving lifestyle habits or seeking further treatment. Privacy and security must be prioritized, especially in decision-making processes, to balance detailed health information with privacy concerns. Many of these technical requirements remain unresolved, especially concerning the processing and modelling of large data sets. However, advancements in quantum computing and AI indicate that solutions to these challenges could become available soon.

Finally, digital twins have the potential to offer significant societal benefits, such as enhancing precision in public health interventions. However, their application in personalized medicine may not be equally accessible to all individuals or communities, which could exacerbate existing disparities. Additionally, identifying patterns within a population of digital twins might lead to problematic segmentation and discrimination. Therefore, it is essential to establish governance mechanisms that protect individual rights, ensure the privacy and security of personal biological data, and promote transparency and fairness in both the use of data and the distribution of its benefits at both individual and societal levels.

Primary health care (PHC) can be understood as the level of care that represents the entrance door to the health system. PHC services provide care to people over time, dealing with the most common problems of the community through health promotion, prevention, treatment, and rehabilitation. It should be noted that despite the health sector's rising costs, increased demand for services and the already established role of primary health care in improving a population's health levels, no study was found in the selected literature on the specific use of digital twins. The closest study was the one that signalled the use of digital twins to monitor elderly people and chronic diseases; however, it did not mention that digital twins were a line of care in primary health care. Studies on the use of DTs in hospital environments have been increasingly common, both in terms of building "smart hospitals" and trying to improve patients' journeys at the hospital level, although there are still few studies in the literature.

As it is the main axis of changes in health systems to improve health levels, it is extremely necessary that primary health care receive due attention from the scientific community and the industrial complex as a promising field for the use of digital twin technology in healthcare and in the operation of its units. As its main attributes include first contact/access, longitudinality of care, comprehensiveness, and coordination, PHC is, by far, the most promising area in health to leverage the use of digital twins in the sector. In addition, because PHC works in a territorialized way and with a recognizable population, it has the possibility of using digital twins to consolidate and infer scenarios through predictive analyses in relation to the health status of its population.

6. Conclusions

In this paper, we provide a literature review on the use of digital twins in health and their possible trends based on the content analysis of articles on the subject selected through a specific search of the IEEE Xplore, Dimensions, Scopus, Web of Science, PubMed, and ACM databases.

This work was able to contribute to broadening discussions about the future of healthcare from the perspective of incorporating new technologies, notably digital twins. The two guiding questions, "How are digital twins being used in the health sector?" and "What are the challenges and perspectives of using digital twins in the health sector?", were answered to some extent.

The use of digital twins, especially in healthcare management, presents major challenges related to data integration, privacy, and interoperability. However, trends indicate great potential in treatment personalization, predictive capacity for unwanted events, remote monitoring, accuracy of procedures and treatments, and data-driven decision-making, which could result in significant improvements in quality and efficiency for the healthcare sector. As technologies and practices evolve, digital twins can increasingly play a leading role.

It is important to highlight the complexity of the various clinical, technical, organizational, ethical, and legal issues that, due to their incipience, still make it difficult to fully realize the benefits associated with the adoption of digital twins in healthcare, which, therefore, can limit their large-scale implementation. The growing relevance of using digital technologies is aligned with investment in strategies to promote health and well-being, as well as interventions that help people self-manage their biopsychosocial condition. In this context, the use of digital twins has great potential to transform healthcare by establishing a communicative and informative connection between two worlds, virtual and real, making it challenging to manage in the coming years. As these actions are closely related to the scope and breadth of primary health care, it is crucial that the application of digital twin technology can be directed as a common effort to leverage this level of care in favour of increasingly effective health responses.

More in-depth future studies should be carried out to explore the possible consolidation of the use of digital twins in health, especially in processes linked to healthcare and primary health care, or even clarify which initiatives should be implemented or even strengthened to sustain the advances made thus far.

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