# Digital Twins in Healthcare: Creating a Framework for Ethical Use

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***Abstract*—Digital twins are rapidly emerging within the healthcare industry. A digital twin is essentially a virtual, data-driven version of something real, designed to reflect changes as they happen through continuous data updates. Utilitarianism, duty ethics, and virtue ethics are applied to evaluate the ethical use of digital twins in healthcare. This idea emerged from aerospace engineering concepts from the 1960s to 2010, such as NASA's Apollo 13 mission, where simulated environments were used to test solutions after an oxygen tank explosion. The concept later shifted from manufacturing to healthcare with projects like the Stanford Living Heart, where a digital model of a heart was created to test compounds. In healthcare, digital twins can represent a patient, organ, or care process by combining data from records, imaging, labs, and wearable devices while providing real-time insights and predictive analysis through simulation and machine learning [1]. Due to the rapid rise of these new forms of healthcare informatics, ethical questions arise, such as how patient data is being used within digital twin systems and how bias plays a role in medical decisions. Additionally, there are many privacy and data concerns regarding patient care. Many patients are unaware of how exactly the personal health data from a digital twin is being used to make a decision that could potentially alter their lifespan. The ethical use of digital twin systems must protect patient's privacy and offer ethical, individualized care. Preliminary findings indicate that digital twins can be successful in individualizing patient care and implementing proactive care, but create a new range of data and responsible use concerns. [2] This research establishes a standardized ethical framework for the use of digital twins including a grading system to ensure ethical compliance. The results demonstrate that integrating ethical frameworks with technical standards improves transparency and reduces bias in digital twin systems. Ultimately, this approach supports more responsible use of digital twins in decision-making.***

***Keywords—Digital Twins, Privacy, Healthcare, Replica, Personalized, Health***

## I. Introduction

Digital twins are virtual replicas of physical systems that are updated on a regular basis and have become an innovative tool in the healthcare industry. These models were originally used in engineering and manufacturing operations but are now used to optimize treatment plans, predict disease progression, model patient physiology, and more [1]. Nonetheless, this heavily data driven model relies on sensitive information and raises concerns around ethical regulations for privacy, bias, consent, and decision making authority.

Digital twins are used in hospitals and other care systems across the globe. However, despite the promising results these systems have provided in the healthcare industry, there is a lack of comprehensive framework that ethically ensures the digital twins are being developed and implemented responsibly. Prominent issues include the transparency of algorithmic decision making, how patient data is collected and protected, and the reliance of simulated predictions for medical decisions [2]. While recent studies highlight the potential of digital twins, most of the literature focuses on technical development and clinical applications, with limited research on ethical implications [3]. This ultimately establishes a gap between engineers, clinicians, and policymakers to assess risk and ensure ethical compliance within a universal and regulated standard across diverse applications.

The aim of this study is to examine the ethical challenges and existing frameworks associated with the rapidly emerging use of digital twins in various healthcare applications. This study also aims to create an ethical framework so that the use of digital twins has both responsible and fair use.

This study seeks to analyze the applications of digital twins in healthcare. It also aims to identify the ethical concerns associated with digital twins. This study will also identify the key differences in other subject frameworks based on digital twin usage – highlighting the engineering, medical, and data/software frameworks. The study presents an ethical framework for assessing the ethics of digital twin use in healthcare. It will include recommendations for training models to ensure responsible and fair use of digital twins in the medical industry.

This study is important because digital twins have an increasingly important role in the medical industry. While development is increasing, there is no clear ethical framework designed specifically for digital twins.

By comparing these different frameworks, this research identifies each limitation of the framework and uses that understanding to create a more complete ethical framework. This new framework is designed to better protect patient privacy and provide more responsible, fair patient care than the current digital twin technology used currently.

This study argues that existing deontological, utilitarian, and virtue ethical frameworks are not adequate on their own to describe what is needed for fair and responsible usage of digital twins. By combining their strengths and addressing their limitations, a new ethical framework can be developed. This new ethical framework will allow for less bias, more data privacy, and overall responsible use of digital twin technology.

## II. Motivation

### A. *Motivation for the Development of Digital Twins*

The motivation for developing digital twins originated from the need for them in healthcare. Essentially, over time, systems like the human body have become harder to understand as further insights have been gained into their complexity. Methods of examining the human body, such as MRI or CT scans, only allow for viewing one condition in the human body at a given point in time [4]. They do not allow for continuous updates of disease progression or modeling of a patient over time. Digital twins changed that. With them, one can measure the change over time in disease progression, which allows for a more accurate prognosis in a patient.

The motivation for the development of digital twin systems also stemmed from the emergence of new cures and medicines that require future modeling. With it, solutions can be tested safely without risking real patients [5]. With more demand for personalized care, it is helpful to have methods of modeling that can be used to test solutions on patients without any direct impact on the patients themselves. Growing demand for more personalized and individualized care.

### B. *Beginning Trials*

In the first stages of digital twin usage, early digital twin models were first tested and introduced in engineering and aerospace systems. These were used in simulated environments that tested solutions to problems that the engineering or aerospace systems could go through. These simulated environments were used to test solutions without affecting real systems. Initial trials focused on monitoring system performance and predicting failures [6]. By using virtual models, engineers were able to analyze different scenarios and make adjustments before applying them to systems in the real world. These early uses allowed for more informed decisions in various aerospace and engineering systems.

In the healthcare field, early healthcare trials used digital models of organs, such as the heart, to test treatments. These models combined data from imaging and previously found medical records to create digital models of the patient. These representations allowed doctors to see how treatments might affect the organ without affecting the actual patient. [4]. Early trials focused on improving treatment planning and understanding disease progression. These uses showed that digital twins could help support more personalized patient care.

### C. *Lessons from Early Digital Twin Trials*

After numerous trials, it was discovered that digital twins can enhance the understanding of complex systems, such as the human body. They are very helpful in testing treatments and solutions for a patient [7]. What makes digital twin usage different from other types of solutions is that it can be used without harm to the patient themselves. All solutions are digital and are based on health records and imaging.

Digital twins support better decision-making and treatment planning. With them, a patient has even more options than what a healthcare team can provide [7]. They can test all options of a medical issue and find the best solution for the longest prognosis of a disease.

Digital twins are an emerging leading technology in personalized healthcare. They are based solely on patient data, including imaging and medical records [8]. This is data that is only personalized to one patient. Everyone has different data and, thus, a slightly different digital twin. Digital twin systems also enable more proactive care before a disease progresses. In current times, imaging is used, and plans are made based on a single image, rather than continuously taking patient data and images. With a digital twin, this changes. More continuous patient data can be taken, and with that, the digital twin molds to the patient data. It is easier to identify the disease progression, and thus easier to cure the patient's condition [9].

However, early digital twin trials showed that these systems are not always perfect. Only complete data – past health history and genetic data is sufficient for reliable results. This data has to be taken accurately, whether it is imaging or patient records taken by a doctor. Limitations in data can affect the accuracy of the model [1]. Ethical concerns, such as privacy and how the data taken from the patient is used, became more noticeable with digital twin usage because it is solely data-driven. The need for clear guidelines and frameworks became evident.

These initial trials underscored both the promise and the risks of digital twin models.

### D. *Future Possibilities*

Digital twins can be used for patient-specific heart or organ models to test drugs or surgeries safely. Digital twin platforms that work with hospitals can monitor patients in real time, while a wearable device such as an Apple Watch or FitBit can move data into these models from their users to keep the Digital Twin model updated with what information it can get. Information like heart rate and sleep schedule, which these wearable devices usually provide, is fundamental for many early onset diseases [5]. Predictive maintenance systems can also help ensure medical equipment works properly for patient care.

Virtual training simulators can let doctors practice on patient-specific models before real procedures. These could be improved more to be even more accurate as to what the patient may experience. Smart hospital management systems use digital twins to manage equipment efficiently. Whole-body digital twin systems can combine multiple organ models to understand how treatments affect the entire body. Online health platforms, such as Minute-Clinic Online services, enhanced with digital twin visualizations allow for a better diagnosis given patient data.

Emergency response simulations can use hospital or city-scale digital twins to plan for natural disasters or outbreaks, such as COVID=19 [7]. Overall, many healthcare products show how digital twins can improve patient care.

## III. METHEDOLOGY

### A. *Data Collection*

One of the first steps to digital twin usage is collecting data. This occurs through finding different sources of medical records, such as imaging. Imaging can consist of scans such as Magnetic Resonance Imaging (MRI), or Computed Tomography (CT) scans [7]. Medical records can also come from wearable devices. Devices on the market currently include, but are not limited to: Apple Watches, Oura Rings, and the FreeStyle Libre system.

During the process of data collection, both data tracked from the past and current data taken in a healthcare facility are used. Data must be taken accurately and correctly. Data taken for a patient often falls into two categories: historical data, and real time data. Historical data is defined as past diagnoses that doctors may find. This can be defined as past family history and diagnoses, treatments, and outcomes of those treatments. Past family history and diagnoses, according to the NIH, is defined as “contrast records information about the patient's medical, personal and family history” [1]. Treatments are defined as the management or care of a person when dealing with intervention for illnesses. Outcomes can range from not being inflicted with the disease or functional ability without further medical intervention.

Real time data is defined as statistics such as heart rate, activity levels, and test results taken from a licensed health practitioner. When real time data is taken, it must be taken with precision and accuracy. If data is not taken with precision, the digital twin will not work as needed. It will use the wrong data to model the patient.

After data is collected, it is put into a single system. This system is online and uses real time data [1]. Systems such as HeartFlow and Siemens Healthineers are prime examples of digital twin systems which data can be uploaded into. These systems create digital twins – such as HeartFlow specializing in blood flow and blockages in coronary arteries.

Following the placing of data in a system, the data is cleaned. Cleaning is defined as removing errors and duplicates within the historical data taken. This step also checks for missing or incorrect values and makes sure the data is consistent. Clean data is important because it helps the system work correctly and produce more accurate results [5].

Data is then standardized. Standardization occurs by making sure all historical data is consistent. This historical data can be taken from many different places, so it is important that all of the data matches. This includes using the same units and naming across the dataset. Standardization helps the system compare and combine data correctly, leading to more reliable results [4]. Cleaning and standardizing helps to ensure that the model is built using reliable and organized information.

### B. *Digital Twin Model Creation*

A virtual model of the patient (or a specific organ) is created using the processed data. This data has been collected, cleaned, and standardized. The digital twin is then made using computer software [4]. This computer software turns the data into a virtual model (often 3D) of the patient or organ. Examples of computer software used are Materialise Mimics or 3D Slicer. These can turn patient data into personalized 3D models.

The model is personalized. It represents the DNA and the physicality of the patient it models. Advanced technologies such as artificial intelligence are often used to build and refine the model. This allows the digital twin to reflect changes in the patient’s condition over time. As a result, the model can be used to support more accurate and personalized treatment decisions.

The result is a personalized digital representation that is unique to each patient [7]. It is based on the patient’s own data, such as medical records and images. It can be used to test different treatments. This helps doctors make better decisions. The model can also be updated over time.

### C. *Continuous Monitoring and Updating*

The digital twin is updated as new data becomes available. This means as new prognoses or treatments become available, they are put into the system [10]. This helps keep the model accurate and up to date. It also allows doctors to adjust treatments based on the latest information.

Real-time data from wearable devices or hospital monitoring systems is added to keep the model current. This allows for the digital twin to be kept up to date and current as to what is going on in the patient’s body. It helps to track changes in health as they happen. This makes it easier to detect problems early before the problem becomes something that can’t be responded to in time. It also allows for the healthcare team to respond quickly with treatment that is more personalized to the patient. Though the treatment may not always be correct because of the differences in a digital system versus a human – it is more suited for what the patient needs, because it is all personalized. Continuous updates make the model more accurate. Updates are also useful in long term care, where more assistance is needed in long term or recurrent diseases.

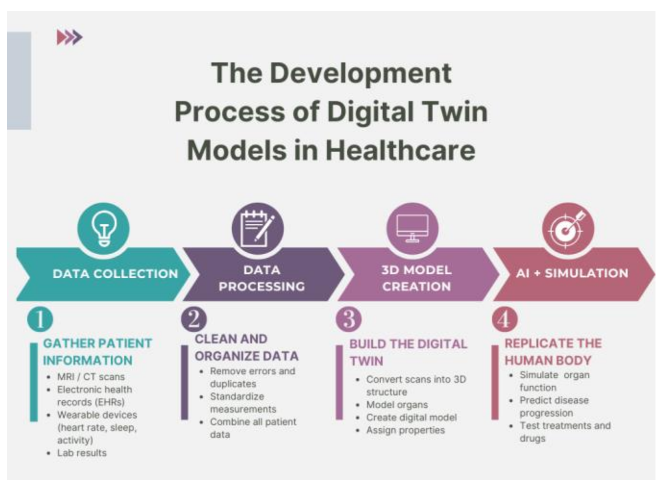

Fig. 1. *Steps for creating a healthcare digital twin from inputting patient data to simulation and prediction.*

## IV. Proposed Ethical Framework

This framework must only be used in cases where there is a continuous connection of the data between the human subject and virtual representation. This framework aims to bridge the gap between the key stakeholders in digital health twins. A universal regulated standard in the usage of digital health twins allows engineers, clinicians, and policymakers to use this tool both cohesively and ethically. This framework is based on the ethical lenses of deontological, virtue ethics, and utilitarianism. From the deontological lens there is a moral duty to give patients the right to privacy and ensure transparency in algorithms used. From the lens of virtue ethics in order for clinicians to use this technology effectively, they must maintain moral character and use digital twins as a tool to help in decision making but not as the ultimate decision. Virtue ethics also applies to developers because responsible use of digital twins must be considered during the design phase of digital twins. Utilitarianism is applied in order to ensure that this technology is beneficial for the collective good in order to accomplish this training on diverse datasets must occur. Protocols must be established in order to maintain ethical data handling. The data streamline from electronic health records, medical imagery, laboratory results, and wearable devices must be integrated. To ensure transparent usage of digital health twins, clinicians must provide an explanation of how their health data is processed in order to influence medical decisions through documentation to patients [7]. Clinicians and Engineers using digital health twins must invest in secure systems in order to protect health data information that is used in these data-driven models.

### A. Data privacy and security

From a deontological lens, data privacy and security is a duty of developers and clinicians to provide. Protocols must be established in order to maintain ethical data handling. The data streamline from electronic health records, medical imagery, laboratory results, and wearable devices must be integrated. To ensure transparent usage of digital health twins, clinicians must provide an explanation of how their health data is processed in order to influence medical decisions through documentation to patients. Clinicians and Engineers using digital health twins must invest in secure systems in order to protect health data information that is used in these data-driven models.

### B. Accountability and Ethical Implementation

In order to reduce algorithmic bias as a result of training, engineers developing digital health twins developers must demonstrate that models are trained on diverse datasets. This will ensure that outcomes are consistent across diverse patients. The implementation of a standardized grading mechanism that scores digital twin systems on transparency and logic behind the algorithm, reliability, and the ability for the patient to give proper consent. Protocols must be established to ensure that predictive healthcare models are not the only tool used in making clinical decisions, and that provider input is weighed as well. Software, medical, and engineering ethics must all be combined in order to effectively implement this technology while considering current ethical frameworks.

## V. Related Research

Research on digital twins in healthcare is about making dynamic, virtual models of patients or organs so that personalized medicine can be used, treatment outcomes can be simulated, and clinical operations can be improved. Some of the most important areas include cardiovascular simulation, planning cancer treatment, practicing surgery, and managing chronic diseases through real-time data monitoring [11].

### A. Simulations

A key feature is real-time, two-way data exchange between the object and its virtual replica, which helps make sure that the simulated conditions match those in the real world. Companies can also connect more than one digital twin to model more complicated systems as part of a bigger digital transformation or Industry 4.0 plan [12]. Simulation packages might include data processors, synchronization services, sensor kits, analytics platforms, and visualization dashboards.

These models integrate multi-omics data, clinical parameters, and lifestyle factors to create comprehensive patient profiles that guide precision therapeutics and interventions. Digital Twins regularly maintain monitoring and analyzing a patient's health status all the time. This lets doctors find health problems early on and take action quickly. Advanced DTs use data from wearable sensors, implantable devices, and systems that monitor the environment to make dynamic models that change as the patient's condition changes. This ongoing feedback loop makes it possible to find small changes in the body that could happen days or weeks before the disease shows up in a clinical setting. This opens up the possibility of preemptive interventions [13]. Through protocol simulation, it is easier to plan specific treatments for specialized patients.

## VI. Alternatives

While digital twins are transforming healthcare with their ability to create real-time, data-driven replicas of patients, emerging technologies are offering powerful alternatives that deliver similar benefits with fewer demands on cost and complexity. Innovations such as wearable sensor networks, along with dynamic multicellular disease models, provide more accessible pathways to personalized care and predictive insights without requiring the extensive data integration and computational intensity of full digital twin systems. These advancements are shaping a more efficient and scalable future for healthcare, where precision and practicality can coexist.

### A. Wireless Sensor Networks

Wireless Sensor Networks (WSNs) are an essential component of the Internet of Things (IoT). They provide a practical and cost-effective way to monitor health in real time by using interconnected sensor nodes that can sense, process, and send data about physical and environmental conditions. These networks can organize themselves and work in both structured and unstructured architectures [16]. This makes them very flexible for uses like environmental tracking, surveillance, and healthcare monitoring. In healthcare, WSNs let you keep track of vital signs and patient conditions all the time, just like digital twins do when they collect data.

But WSNs don't need complicated, high-quality simulations or continuous bidirectional modeling like digital twins do, so they are much less computationally intensive and easier to use. Even though there are still problems like secure data transmission, new lightweight encryption and authentication methods have made WSNs more efficient and safer. WSNs are still a good option because they can be expanded and provide useful, real-time information without the high costs of full digital twin systems.

### B. *Dynamic Multicellular Disease Models*

Dynamic Multicellular Disease Models (MCDMs) are a new and very specialized way to personalize medicine by simulating complex interactions at the cellular level. These models, which are often called "cellular digital twins," try to predict how diseases will progress and how patients will respond to certain treatments with a level of accuracy that goes beyond traditional whole-organ modeling. MCDMs have a lot of promise for improving targeted therapies and drug development, but theyare still mostly in the research phase and have not yet been widely used in clinical settings.

One of the biggest differences in MCDMs is whether they are in silico or in vitro. In silico MCDMs are computer simulations that use mathematical algorithms to predict cellular behavior, molecular pathways, and tissue-level responses to treatments [17].These models use computer methods like agent-based modeling, partial differential equations, and machine learning to mimic how cells work, how chemicals move, and how diseases spread. In silico models are fast, scalable, and cost-effective because they work entirely through simulation. This makes them useful for predicting how drugs will work, running virtual clinical trials, and studying how diseases work. However, their accuracy is limited by what we already know about biology and the assumptions that are built into the algorithms.

In contrast, in vitro MCDMs are real laboratory systems that use cutting-edge techniques like tissue engineering and microfluidics to recreate human tissue environments. These models use organoids, 3D cell structures, and organ-on-a-chip platforms to closely mimic real biological conditions. This allows researchers to monitor how cells behave and interact in a controlled setting. In vitro models give more realistic and observable data, but they are usually slower, more expensive, and not as easy to scale up as in silico models. These two methods work well together because experimental data from in vitro systems can make in silico models more accurate, which makes the research process more effective and efficient [17].

## VII. Future Work

The future work in digital twins within the healthcare field targets advancing multi-scale and ethically regulated systems that can mimic the complex human physiology. While creating real-time data-driven models that can help make decisions in clinical environments. Thus, future research involves developing fully integrated, multi-organ, and whole-body digital twins in comparison to single-organ models. For example, DTs have transformed cardiac care through applications ranging from molecular-level drug interaction studies to organ-level hemodynamic simulations [5]. In neurology, DTs have enabled unprecedented insights into disease progression and treatment planning [5]. DTs 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 [5]. With the optimization of the digital twins systems, it will have the ability to capture interactions across molecular, cellular, and physiological levels, which is a current issue due to the data heterogeneity and computational complexity.

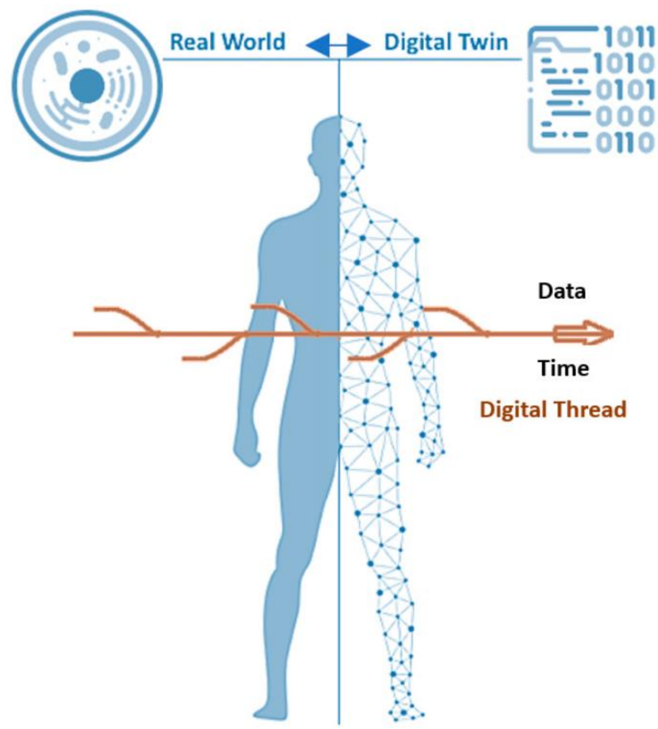


Fig. 2. *Image provides a comprehensive overview of the DT applications in the human body [13].*

## VIII. Conclusion

Digital twins have the potential to revolutionize healthcare systems by creating personalized, proactive care through real time data time data predictive modeling. While early research shows promising improved decision-making, their use in healthcare environments raises important regulatory and ethical concerns.

The main issues include the privacy of patients, informed consent, data ownership, and algorithmic bias. Enforcing the emphasis on rights ethics to ensure these systems are being used responsibly for the greater good of society. The transparency between the systems and patients is complex and can be misinterpreted, enabling biased datasets to lead to unequal healthcare. Ultimately, establishing a correlation to duty ethics by reinforcing moral obligations to ensure they are using the digital twins systems with the utmost safety regulations.

To address this issue the systems must ensure they are prioritizing data protection and transparency while upholding human oversight in clinical decision making. Essentially, a standardized ethical framework fostered by diverse data training and technical system evaluation is vital to enable the responsible utilization of digital twin systems.

In conclusion, digital twins have the potential to make a major difference in healthcare by improving how doctors understand and treat patients. By using real-time data and predictive models, they can help detect problems earlier and allow for more personalized care. This can lead to better health outcomes, fewer complications, and more efficient use of medical resources. As the technology continues to develop, it may become an important part of everyday healthcare systems.

At the same time, it is important to carefully manage the risks that come with using digital twins. Protecting patient privacy and ensuring data is secure should always be a top priority. There must also be efforts to reduce bias in the data and make sure the systems are fair for all patients. If these issues are not addressed, it could lead to unequal treatment or a loss of trust in the healthcare system.

Overall, digital twins should be used in a responsible and ethical way. This means having clear rules, maintaining human oversight, and ensuring transparency between patients and healthcare providers. By balancing innovation with strong ethical standards, digital twins can be used to improve healthcare while still protecting patient rights, safety, and trust in the long term.

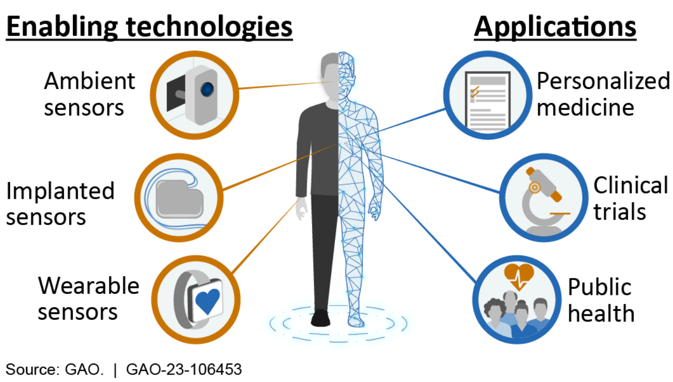


Fig. 2. *Image provides a comprehensive overview of the Digital twin applications and enabling technologies in the human body [18].*

## References

[1] E. Katsoulakis et al., "Digital twins for health: a scoping review," npj Digit. Med., vol. 7, no. 1, Art. no. 77, pp. 1–14, Mar. 2024, doi: 10.1038/s41746-024-01073-0.

[2] Y. Zhang, K. Shi, and B. Li, "A Brief History of Digital Twin Technology," PET Clinics, Oct. 2025, doi: https://doi.org/10.1016/j.cpet.2025.09.006

[3] .T. Li, Y. Shen, Y. Li, Y. Zhang, and S. Wu, "The status quo and future prospects of digital twins for healthcare," EngMedicine, vol. 1, no. 3, p. 100042, Nov. 2024.

[4] Institute of Electrical and Electronics Engineers, IEEE Code of Ethics, IEEE, 2024. [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html

[5] E. O. Popa et al., "The use of digital twins in healthcare: socio-ethical benefits and socio-ethical risks," Life Sci. Soc. Policy, vol. 17, no. 1, 2021.

[6] H. K. Rudsari et al., "Digital twins in healthcare: a comprehensive review and future directions," Frontiers in Digital Health, vol. 7, Nov. 2025.

[7] S. I. Gore et al., "Ethical and Legal Implications of Digital Twin Deployment," IGI Global, 2025.

[8] Konstantinos Papachristou et al., "Digital Twins' Advancements and Applications in Healthcare," Journal of Personalized Medicine, 2024.

[9] K. Bruynseels et al., "Digital Twins in Health Care: Ethical Implications," Front. Genet., 2018.

[10] T. Winter and M. H. Chico, "Realising the digital twin," AI & Soc., 2025.

[11] M. M. Armstrong, "Digital twin," IBM, 2020.

[12] NIH, "Medical Definitions and Records," https://www.ncbi.nlm.nih.gov/medgen/628444

[13] M. N. K. Boulos and P. Zhang, "Digital twins: from personalised medicine to precision public health," Journal of Personalized Medicine, vol. 11, no. 8, p. 745, Aug. 2021.

[14] Oxmaint, "Digital Twins in Surgery & Treatment Planning," Mar. 12, 2026.

[15] S. Rani and V. Hasanpuri, "Data Security and Ethical Considerations," CRC Press, 2025.

[16] T. Jabeen, I. Jabeen, H. Ashraf, N. Z. Jhanjhi, A. Yassine, and M. S. Hossain, "An Intelligent Healthcare System Using IoT in Wireless Sensor Network," *Sensors*, vol. 23, no. 11, p. 5055, Jan. 2023, doi: https://doi.org/10.3390/s23115055

[17] A. Danchin, "In vivo , in vitro and in silico : an open space for the development of microbe-based applications of synthetic biology," *Microbial Biotechnology*, Sep. 2021, doi: https://doi.org/10.1111/1751-7915.13937.

[18] U.S. Government Accountability Office, "Science & Tech Spotlight: Digital Twins—Virtual Models of People and Objects," GAO-23-106453, Washington, D.C., Feb. 2023.

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