# Virtual Human Twin in Healthcare: Ethics, Opportunity, and Implementation Pathways

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*The virtual Human Twin is an Artificial Intelligence based model that digitally represents the anatomy and disease condition of an individual using clinical and synthetic data.it predicts disease progression and supports personalized treatment planning. This paper examines the ethical and operational challenges in implementing such systems, including data privacy, consent and validation and accuracy. Hospitals must create oversight frameworks to manage model safety and data security. When properly governed, Virtual Human Twin technology supports collaboration, improves predictive care, and represents a responsible balance between innovation and ethical accountability.*

**Keywords:** Virtual Twin, Predictive Healthcare, Ethics, Artificial Intelligence Governance

## 1. Introduction

In 1994, computer assisted medical decision making was considered a distant possibility. That year, a seminal paper by Berner and colleagues in the New England Journal of Medicine evaluated the leading automatic decision support systems of the time, with generally poor results that led many to doubt their usefulness for clinical practice. The following two decades saw major changes in healthcare data management, including the widespread introduction of electronic health record and mobile health applications.

By the 2010s, new types of artificial intelligence algorithms particularly deep learning models transformed computing capabilities. In 2017, Sebastian Thrun and colleagues demonstrated that computers could perform on par with dermatologists in distinguishing images of malignant and benign skin lesions using convolutional neural networks trained on hundreds of thousands of images. In parallel, advances in natural language processing (NLP) allowed machines to interpret complex textual information such as medical reports and discharge summaries.

Transformer based systems introduced in 2017 became capable of reasoning over large corpora of text, and by 2023 generative pre-trained transformers could answer medical licencing exam questions at the level of a human graduate. Computers had moved from data processing to medical reasoning, paving the way for the Digital Twin concept and its future manifestation as the Virtual Human Twin.

## 2. Background and Evolution of Digital Twins

The Digital concept was first adopted by NASA during 1960s space programme to stimulate spacecraft performance and troubleshoot flight issues in real time. During the Apollo 13 mission, this approach proved life-saving as engineers reproduced spacecraft conditions virtually to guide astronauts safely home.

Overtime, Digital Twin technology expanded beyond engineering into industrial systems through the integration of loT devices, sensor networks, and high performance computing. . These advances made real time data synchronisation feasible, setting the foundation for applications in medicine. In 2024, the *National Academies of Sciences, Engineering and Medicine (NASEM*) defined a Digital Twin as a virtual construct that mimics the structure, context, and behaviour of a natural or engineered system, is continuously updated with data from its physical counterpart, possesses predictive capability, and informs decision-making.

NASEM emphasised three criteria for a true Digital Twin: personalisation to the individual system, dynamic data updates, and predictive utility for decision support. Models that lack any of these features should be classified as digital shadows or general digital models rather than authentic Digital Twins.

## 3. Foundations of Digital Twin Technology

Digital Twin technology is built on simulations of biological processes operating cellular, organ, and systematic levels. In medicine, a Digital Twin represents a complete in-silico replica of a patient, capable of simulating future physiological states and detecting deviations from health before they manifest clinically.

To archive this, the digital Twin continuously receives data from its physical counterpart through connected sensors, imaging, laboratory data, and electronic records. This live information stream enables health forecasting and facilitates preventive intervention. Research groups have developed virtual microbial cells, human cellular process simulations, and

complex multicellular structures. Others have recreated organ-level functions, such as the beating heart, to test drugs and devices virtually.

While this technological foundation offers remarkable precision, it also introduces ethical considerations .concerns about data ownership, misuse, and over-reliance on machine interpretation are widely discussed. Patients and healthcare consumers have expressed interest in participating in these digital ecosystems while retaining autonomy. Surveys reveal that individuals value the benefits of personalised prediction but want freedom to decline participation without disadvantage.

The digital Twin also challenges traditional concepts of human learning an experience. When algorithms continuously optimise human behaviour, there is a risk that individuals lose their capacity for trial and error which is the fundamental process by which human development occurs. The broader social effects of this optimisation-driven paradigm remain uncertain.

## 4. Human Digital Twin and Model Classification

According to the national Academics of sciences, Engineering, and medicine, a digital Twin in healthcare must be personalized, dynamically updated, and predictive. It must support clinical decision-making rather than merely mirror data.

Digital Twins emerged from engineering but have diversified into several distinct biomedical model types. These range from detailed mechanistic organ simulations to generalised predictive algorithms. The term is sometimes misapplied to systems that lack the defining properties of bidirectional feedback or continuous updates.

To address this ambiguity, NASEM's 2024 report "*Foundational Research Gaps and Future Directions for Digital Twins"* standardised terminology. It defines a Digital Twin as a virtual information construct that mirrors a natural or engineered system, updates dynamically with real world data, predicts future states, and informs real world decisions. The key principle is bidirectional interaction that is both the physical and virtual entities influence each other.

The report emphasised the importance of verification, validation, and uncertainty quantification (VVUQ) to assess model trustworthiness. VVUQ ensures the predictive quality of computational models through systematic evaluation. The American Society of Mechanical Engineers (ASME) has previously formalised these standards, providing an established framework adaptable to healthcare.

NASEM also categorised the existing biomedical models meeting Digital Twin criteria. Among them, metabolic and cardiac systems dominate due to the high availability of structured data and clear physiological markers. Metabolic Digital Twins are used for diabetes and obesity research, while cardiac twins model blood flow and perfusion. Musculoskeletal systems follow, as skeletal imaging enables straightforward reconstruction.

Certain areas such as neurological or reproductive health still remain under presented due to limited high quality data. However, wearable EEG headsets, brain-computer interfaces, hormone sensors, and implantable monitors may soon enable continuous data capture for these systems.

In practice, the creation of a Human Digital Twin requires three essential steps:

1. Developing a mathematical model of the human system.
2. Dynamically updating this model with data that reflect changing biological states.
3. Enabling the model to predict outcomes that guide real-world interventions.

Some Digital Twins directly influence their physical counterparts. For example, Lai et al. described a cardiac twin integrated with an implantable cardioverter-defibrillator (ICD) that detects arrhythmias and automatically restores rhythm. Other models, such as Twin Health's Twin Precision Nutrition program, operate in a "*human-in-the-loop*" mode which collects multi-sensor data to tailor nutrition and lifestyle interventions under human supervision.

Models that reflect the physical body without influencing it are known as digital shadows. . Others, such as personalised one-time models used for surgical planning, serve as decision-support tools. For instance, O'Hara et al. created a digital clone of a patient's heart using MRI data to map arrhythmogenic circuits and plan ablation therapy. After successful treatment, the model was retired.

Virtual patient cohorts simulate groups of patients for research purposes. Joslyn et al. used such a cohort to study T-cell therapy responses, enabling mechanistic insights without human trial risk. NASEM's classification highlights that while all these tools serve valuable functions; only those fulfilling continuous feedback, personalisation, and predictive requirements qualify as true Digital Twins.

## 5. Validation and Verification Framework

Verification and validation are central to building trust in Digital Twins. ASME's computational modelling and simulation standards provide structure for evaluating accuracy, consistency, and uncertainty.

VVUQ involves confirming that the mathematical representation of a biological system is correctly implemented (verification), that it reliably predicts real world outcomes (validation), and that any uncertainty is quantified and documented.

O'Hara's cardiac model exemplifies the power of rigorous validation, linking model predictions to measured electrophysiological outcomes. Joslyn's immune-cell cohort, by replicating patient kinetics, also demonstrated model reproducibility and scalability.

These examples underscore the principle that Digital Twins must be "fit for purpose." The level of complexity must match the clinical objective. Overly intricate models may reduce interpretability without adding accuracy, while simplified but validated models can provide actionable insight.

VVUQ frameworks adapted from ASME allow developers to specify assumptions, boundary conditions, and error margins. This ensures transparency and builds confidence among clinicians and regulators alike.

## 6. Applications in Healthcare and Industry

### 6.1 Healthcare Operations

Digital Twins have found increasing application in hospital management and operations Twins simulated patient flow and resource consumption. GE Healthcare's Care Command Center in Oregon used real time hospital data to forecast bed occupancy and ventilator use, preventing shortages. Siemens Healthineers and the Medical University of South Carolina used workflow simulations to identify inefficiencies and improve system performance.

These systems demonstrate how the Digital Twin extends beyond patient physiology to institutional optimisation becoming a mirror of the healthcare ecosystem itself.

Smartphone-based tools such as DTCoach provided remote behavioural guidance during isolation periods, while AI-assisted tele-rehabilitation systems enabled patient–clinician interaction through bidirectional control. These operational twins integrate infrastructure, human behaviour, and digital communication, marking the early evolution of cyber-physical hospitals.

### 6.2 Medical Device Design

Digital Twin technology has also accelerated medical device innovation. Dassault Systems and the U.S. Food and Drug Administration launched the SIMULIA Living Heart Project in 2014 to crowd source a virtual replica of the human heart. The Living Heart Twin, validated across global studies, now supports cardiac device design and preclinical testing.

Companies such as Philips and Siemens Healthineers have incorporated this platform into device development pipelines. The FEops HEART guide extends this technology into clinical practice, using AI-driven simulation to plan and optimise procedures like trans-catheter aortic valve implantation (TAVI) and left atrial appendage occlusion (LAAO).

During the COVID-19 pandemic, On Scale's Project BreathEasy developed a Digital Twin of the lung to improve ventilator management and resource allocation. Meanwhile, the Living Brain Project applied similar methods to study neurodegenerative disease progression.

The long term goal of these initiatives is to create a comprehensive human body digital twin, a continuously learning system that integrates organ level models into a unified, adaptive representation of human health.

### 6.3 Biomarker and Drug Discovery

Digital Twins have become powerful tools for accelerating biomarker identification and drug discovery. Traditional computer-aided drug design (CADD) techniques, such as structure-based and ligand-based modelling, are now integrated with machine learning to enhance predictive accuracy. Digital Twin modelling shortens the pharmaceutical process by simulating realistic biochemical reactions, thereby enabling faster, more targeted research.

Numerous drugs developed through in-silico techniques have already reached the market, including antiviral therapies for HIV (atazanavir, saquinavir, indinavir, and ritonavir), anticancer agents such as raltitrexed, and antibiotics like norfloxacin. Digital Twins further refine these workflows by identifying drug targets most likely to succeed in clinical trials.

Collaborations such as the Atos–Siemens partnership have applied Digital Twins to optimise pharmaceutical laboratory processes, enabling real time feedback and control in drug manufacturing. Takeda Pharmaceuticals has adopted Digital Twin technology in production to accelerate the launch of new therapies. By virtually modelling the biochemical interactions between compounds and target proteins, these systems can reduce the drug development cycle dramatically.

### 6.4 Bio Manufacturing

Digital Twins are increasingly being used in bio manufacturing to improve efficiency and predict process outcomes. Silico Biotechnology AG and Teva Pharmaceuticals partnered to apply Digital Twin models for predictive control of biopharmaceutical production. These systems combine mechanistic and data-driven models to relate adjustable parameters such as pH, temperature, and oxygen concentration to critical performance metrics like yield, titer, and product quality.

The integration of Internet of Things (IoT) sensors, Artificial Intelligence (AI), and cloud computing allows continuous monitoring of production environments. These tools enable process optimisation and early detection of deviations that could affect product quality. Such systems represent the beginning of a future in which fully virtualized production chains can self-correct based on model feedback, improving both safety and cost efficiency.

### 6.5 Surgical Planning

Digital Twins are revolutionising surgical planning by providing highly accurate, patient-specific anatomical models. They allow surgeons to simulate procedures virtually before operating on the patient.

In cardiology, the Heart Navigator platform enables physicians to perform simulated trans-catheter aortic valve replacement (TAVR) procedures using patient imaging data. Virtual simulations of prosthesis selection and implant depth

reduce the risk of complications. Orthopaedic surgery has adopted similar techniques, with Digital Twins of bone and joint structures used to select implants and plan stabilisation strategies.

Deep Convolutional Generative Adversarial Networks have been employed to model trabecular bone, supporting virtual vertebroplasty planning and assessment of fracture risks. In oncology, Digital Twins help predict vertebral fracture risk in patients with spinal metastases following stereotactic body radiotherapy (SBRT), assisting clinicians in designing safer treatment plans.

These models increase surgical precision, reduce intraoperative uncertainty, and improve patient specific outcomes.

### 6.6 In-Silico Trials and Clinical Research

Digital Twins are transforming clinical research by supporting *in-silico* trials that reduce the need for extensive physical testing. Less than ten percent of adult cancer patients participate in traditional clinical trials, and oncology continues to face high attrition rates in drug approval.

By using computational twins, researchers can simulate control and treatment arms virtually. The VICTRE (Virtual Imaging Clinical Trial for Regulatory Evaluation) study exemplified this innovation by creating synthetic mammography images of nearly 3,000 virtual patients. It compared digital breast tomosynthesis with standard mammography and found results consistent with those of a real-world trial of 400 women.

Regulatory agencies such as the U.S. FDA and European Medicines Agency (EMA) now acknowledge the use of *in-silico* methods for device and drug evaluation. Synthetic control arms have already informed drug approvals for therapies such as alectinib, palbociclib, and blinatumomab.

The DIGIPREDICT consortium is developing Digital Twins to predict disease progression and intervention needs in infectious and cardiovascular diseases. The PRIMAGE project in Europe applies AI-enabled Digital Twins to paediatric cancers, integrating imaging, molecular, and clinical data for prognosis and treatment planning.

Platforms like Medical Augmented Intelligence (MAI) can convert standard MRI or CT scans into interactive 3D models within seconds. The Digital Twin Consortium and Digital Twins for Health (DT4H.org) have created global collaborations that span oncology, sepsis, diabetes, mental health, and cardiovascular disease research.

## 7. Ethical, Technical, and Social Challenges

Despite the promise of digital Twin technology, several ethical and operational challenges remain unresolved.

### 7.1 Data Acquisition and Integration

The creation of accurate Digital Twins requires the integration of vast datasets from multiple sources, physiological, genetic, biochemical, and environmental. Currently, there is a lack of standardisation and interoperability among systems. Uniform data formats and exchange protocols are essential for creating coherent models that can be shared between institutions and countries.

### 7.2 Data Privacy and Security

Digital Twins depend on access to sensitive, personal health data. Protecting this information against breaches or misuse is paramount. Compliance with regulations such as the Health Insurance Portability and Accountability Act (HIPAA) and the General Data Protection Regulation (GDPR) is essential. Systems must employ encryption, anonymisation, and secure audit trails to safeguard patient data and prevent unauthorised access.

### 7.3 Data Quality and Accuracy

Health data are inherently noisy and prone to bias. Sensor inaccuracies, incomplete records, and population-level imbalances can distort model predictions. Continuous data validation and recalibration are necessary to ensure reliable outputs. Longitudinal data collection improves accuracy by reflecting individual physiological evolution over time.

### 7.4 Data Bias and Fairness

Algorithmic bias presents a critical challenge. If training data underrepresent certain populations, model recommendations may perpetuate inequalities. Ensuring that datasets are diverse and models undergo fairness audits is crucial. Digital Twin systems must be transparent about their decision-making criteria and subject to external validation.

### 7.5 Ethical Considerations

Ethical challenges extend to questions of consent, ownership, and equity. Informed consent processes must explicitly address how patient data will be used, stored, and updated. Individuals must have the right to withdraw participation without penalty.
Healthcare equity must be prioritised to ensure that advanced technologies do not widen the digital divide between resource rich and resource poor populations. Ethical frameworks must be codified into the government policies to ensure patient autonomy and social justice.

### 7.6 Modelling Complexity and Societal Impacts

The complexity of human physiology poses significant modelling challenges. Human behaviour and environmental interactions cannot yet be fully captured in computational models. Moreover, if predictive systems over-optimise behaviour,

they could diminish human agency by reducing opportunities for experimentation and adaptation. The social and philosophical consequences of this shift warrant continuous examination.

### 7.7 Computing Infrastructure and Business Models

High performance computing (HPC), fifth-generation (5G) connectivity, and cloud-based data architectures are required for real-time Digital Twin operation. Future advancements in augmented reality (AR) and virtual reality (VR) could enhance clinician twin interaction. Block chain and distributed ledger technologies (DLT) can provide decentralised, secure data management.

Financial sustainability is another challenge. Developing Digital Twins requires significant investment in infrastructure and expertise. Initially, adoption will likely be led by government or defence sectors, as was the case for NASA. Over time, scalable public–private models will be essential to democratise access.

## 8. The Virtual Human Twin: European and Indian Context

The European Commission's Virtual Human Twin (VHT) Initiative, part of the Digital Europe Programme, marks a milestone in global digital health. The initiative connects over seventy five organisations and invests more than eighty million euros in developing multi-scale models of human physiology under strict ethical and governance frameworks.

The European approach emphasises interoperability, transparency, and equitable data usage. Its long term vision is to create a digital ecosystem where individual twins can contribute anonymously to population-level models, improving collective health understanding. Public institutions, rather than private corporations, are designated as custodians of twin data, reinforcing public trust.

For India, the European model provides a blueprint for responsible adoption. The Ayushman Bharat Digital Mission offers a ready-made infrastructure for digital health integration, with secure data exchange mechanisms. Integrating Virtual Human Twin frameworks within this platform could enable personalised, predictive healthcare for millions.

The Bagchi–Parthasarathy Hospital at the Indian Institute of Science exemplifies a potential pilot site for VHT implementation. Combining clinical expertise with computational and ethical oversight, such institutions can create locally validated Digital Twins reflective of India's genetic, environmental, and sociocultural diversity.

Developing country-specific validation protocols, ensuring equitable access, and embedding ethical review mechanisms will be critical to sustainable success. India's strength in digital public goods provides a unique advantage for for pioneering inclusive, affordable twin-based healthcare.

## 9. Discussion and Implementation Outlook

Implementing Virtual Human Twin (VHT) technology in clinical environments requires coordinated development across science, policy, and ethics. Hospitals will need multidisciplinary teams consisting of clinicians, data scientists, biomedical engineers, ethicists, and information security experts. Together they will define operational standards for building, validating, and maintaining twins.

Institutional Twin Oversight Boards should be embedded within hospital ethics committees to ensure that every twin model follows approved consent protocols, bias-monitoring procedures, and security requirements. These bodies can also evaluate algorithmic explainability so that clinical staff understands why a model recommends a given action.

Government policy must promote open yet protected data sharing. National regulatory frameworks should mandate anonymisation and audit trails for all clinical data used in twin creation. Collaboration between public institutions, private developers, and academia will foster balanced innovation. Funding mechanisms similar to biomedical research grants can help smaller hospitals access computational resources.

Education and workforce training will be essential. Clinicians must learn how to interpret model predictions responsibly, and engineers must understand medical ethics and patient safety. Curricular inclusion of artificial-intelligence literacy in medical and nursing schools can bridge the current skill gap.

From a technical standpoint, implementation will likely begin with tertiary-care centres equipped with robust digital infrastructure. Over time, regional hospitals and public-health programmes can adopt simplified versions for chronic-disease management. Integration with electronic-medical-record systems will allow seamless feedback loops between the physical patient and the digital representation.

Ultimately, Virtual Human Twins should serve as decision-support companions rather than replacements for physicians. Their success will depend on transparency, human oversight, and measurable improvements in patient outcomes.

## 10. Conclusion

The Digital Twin originated in engineering as a means to preserve and monitor machines. Its evolution into the Virtual Human Twin transforms it into a moral, medical, and societal framework for preserving life. Across research, diagnostics, treatment, and policy, the twin has become a mirror reflecting both the power and the responsibility of intelligent systems.

For the Virtual Human Twin to realise its full potential, it must learn continuously while acting transparently and remaining accountable to human judgment. It must be scientifically rigorous, ethically grounded, and socially inclusive.

When properly governed, the Virtual Human Twin can shift healthcare from reactive crisis management to proactive, predictive, and preventive medicine. It will enable collaboration among clinicians, researchers, and patients building a healthcare ecosystem that anticipates disease rather than merely responds to it.

The Virtual Human Twin is not intended to replace physicians but to extend their insights. It is then next step in humanity's attempt to understand itself, blending data and empathy into a single system that both measure and respects life.

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**Author Contributions**

- Mrs.. Meenakshi Achalia conceptualised the study and supervised manuscript development.
- Dr. Sriram Menon Koottala prepared the primary literature synthesis, compiled the data, and structured the operational analysis.
- Ms. Gopika K contributed to the review of ethical frameworks and clinical-data integration.
- Ms. Maria Martin contributed to editing, formatting, and reference coordination.

**Conflict of Interest**

The authors declare that there are no conflicts of interest associated with this work.