

Digital Twin in Healthcare: A Review of Technologies, Applications and Challenges

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ABSTRACT: A digital twin is a virtual replica of a physical entity that is continuously updated with real-world data and can be used to analyse, predict and test outcomes without risk to the original. Originally developed for aerospace and manufacturing, the concept is now being adapted to healthcare, where the twin may represent a single organ, an entire patient or a hospital. Conventional care relies on population averages, periodic check-ups and trial-and-error treatment, which leaves gaps in personalisation, early detection and safety. This paper reviews the concept of the healthcare digital twin, its enabling technologies (wearable sensors, artificial intelligence, cloud computing, medical imaging and health records, and 5G networks), a generic working architecture, and major application areas including personalised medicine, surgical planning, chronic disease management, drug development and hospital operations. It further discusses live patient monitoring, benefits, data privacy and regulatory considerations (HIPAA, GDPR and India's DPDP Act 2023), and open challenges of cost, interoperability, workforce readiness and biological complexity. The review concludes that digital twins can make healthcare more predictive, personalised and safer, provided that privacy, standardisation and affordability are addressed.

KEYWORDS: Digital Twin, Healthcare, Personalised Medicine, Wearable Sensors, Artificial Intelligence, Remote Patient Monitoring, Data Privacy.

I. INTRODUCTION

Modern medicine still depends heavily on evidence drawn from groups of patients. A drug dose that works well for the average patient may be ineffective or harmful for a particular individual because of differences in genetics, age, lifestyle and existing conditions. At the same time, most patients are observed only during scheduled visits, so deterioration between visits can go unnoticed. Finally, new treatments and complex surgeries carry inherent risk because they cannot be rehearsed on the patient beforehand.

The digital twin offers a way to address all three problems. A digital twin is a virtual copy of a real object or system that is kept synchronised with its physical counterpart through a stream of real data: when the real entity changes, the twin changes as well. The idea first gained traction in engineering, where aircraft engines, machinery and factories were mirrored digitally so that faults could be predicted before they occurred. In healthcare, the same principle is applied to a patient, a body part such as the heart or lungs, or even an entire hospital.

The overall aim of a healthcare digital twin is twofold: to detect health problems early and to select the treatment best suited to each individual. This paper presents a structured overview of the topic. Section II gives background and related work. Section III describes the enabling technologies. Section IV explains the working principle and architecture. Sections V and VI cover applications and live monitoring. Sections VII to IX discuss benefits, security and challenges, and Sections X and XI outline future scope and conclude the paper.

II. LITERATURE REVIEW

A. From Industrial to Medical Twins

The digital twin concept originated in product lifecycle management and was popularised in aerospace, where physical assets are monitored by sensors and mirrored by simulation models. Its success in predicting failures and optimising maintenance motivated researchers to explore the human body as an analogous, though far more complex, system.

B. Types of Healthcare Digital Twins

- **Organ twins:** a virtual heart reconstructed from a patient's scans, used to study function and the likely effect of therapy.
- **Patient twins:** models that integrate physiological signals, imaging, laboratory results and history for one person.
- **Hospital twins:** models of the flow of patients, beds, staff and equipment used to improve operations.

C. Existing Studies

Recent systematic reviews have mapped current applications, frameworks and future directions of digital twins in healthcare [1], [2], and others have focused on hospital operations such as resource allocation, infection control and workflow optimisation [3]. In cardiology, Corral-Acero et al. set out a vision of precision cardiology enabled by the digital twin, in which patient-specific heart models support diagnosis and therapy planning [4]. In elderly care, Liu et al. proposed a cloud-based framework that uses digital twin technology to deliver healthcare services to older adults [5].

D. Research Gap

Together, these works show a field that is expanding quickly but is still maturing in terms of clinical validation, standardisation, affordability and data sharing between institutions. These gaps motivate the discussion of challenges and future scope in Sections IX and X.

III. ENABLING TECHNOLOGIES

A healthcare digital twin is not a single technology but a combination of several that work together, as summarised in Table I.

Table I. Enabling Technologies of A Healthcare Digital Twin

Technology	Role in the digital twin
Sensors wearables	Smartwatches and body patches measure heart rate, sleep, oxygen and other signals and transmit them continuously.
Artificial intelligence	Analyses data, finds patterns and predicts health problems before they become serious.
Cloud computing	Stores large volumes of data and supplies the computing power for simulations.
Scans and records	X-ray, MRI, CT and past reports are used to build the patient-specific model.
5G networks	Transfer data with low delay so clinicians see the patient state almost live.

A. Sensors and Wearables

Wearable devices are the main source of real-time data. They allow the twin to reflect the patient’s present condition rather than a snapshot from the last clinic visit.

B. Artificial Intelligence

Machine learning and related methods turn raw data into insight. They learn each patient’s normal ranges, detect deviations and forecast risks. As more data is received, the models can become more accurate.

C. Cloud Computing and Networks

Building and running a twin requires storage and computation beyond what a single device or clinic can offer. Cloud platforms supply this capacity, while high-speed networks such as 5G ensure that data from the patient reaches the model, and results reach the doctor, without noticeable delay.

D. Imaging and Health Records

Anatomical detail comes from imaging, and clinical context comes from electronic records. Combining them allows the model to be personalised to one individual’s body and history.

IV. WORKING PRINCIPLE AND ARCHITECTURE

A. Workflow of the Digital Twin

The operation of a healthcare digital twin can be summarised in four steps:

1. Data collection: data are gathered from wearables, scans, laboratory tests and records.
2. Model building: a computational model of the patient or organ is constructed from this data.

3. “What-if” testing: different drugs, doses or surgical options are simulated and their outcomes compared.
4. Clinical application: the best option is applied to the real patient and the results are fed back.

A defining property is the two-way link between the patient and the twin. Patient data continuously update the twin, and the twin’s predictions assist the doctor’s decision. This feedback loop distinguishes a digital twin from a static simulation, which does not update itself after it has been built.

B. Conceptual Model

Conceptually, the state of the twin at time t can be expressed as an update of its previous state using the latest sensor measurements:

$$\hat{x}(t) = f(\hat{x}(t-1), y(t)) \quad (1)$$

where $\hat{x}(t)$ is the estimated health state of the patient, $y(t)$ is the vector of newly measured signals (for example heart rate and oxygen level), and f is the update function implemented by the underlying physiological or AI model. An alert is raised when $\hat{x}(t)$ departs from the patient’s own baseline by more than a clinically defined threshold.

C. Layered Architecture

A typical layered view consists of (i) a data acquisition layer (sensors, scans and records), (ii) a communication layer (5G and internet), (iii) a data and computation layer (cloud storage and analytics), (iv) a modelling and AI layer, and (v) an application layer where clinicians view alerts, dashboards and treatment simulations. An example is a virtual heart built from a patient’s scans and used to check how a cardiac drug is likely to act before it is prescribed.

D. Key Features

- **Live updates:** the twin reflects the patient’s current health.
- **Personalised care:** treatment is planned from the individual’s own body and history.
- **Early warning:** problems may be flagged before symptoms are felt.
- **Safe testing:** drugs and surgeries are tried virtually first.
- **Continuous learning:** accuracy improves as more data arrive.

V. APPLICATIONS IN HEALTHCARE

A. Personalised Medicine

By simulating how a specific patient is likely to respond, a twin can help select the right drug and dose and reduce side effects, replacing one-size-fits-all prescribing.

B. Surgical Planning

Surgeons can rehearse a difficult operation on a virtual organ reconstructed from the patient’s scans, anticipating difficulties and choosing the safest approach before operating.

C. Chronic Disease Management

Conditions such as diabetes and heart disease require longterm follow-up. A twin tracks the condition daily rather than only at check-ups, enabling timely adjustments to treatment.

D. Drug Discovery and Clinical Trials

Virtual testing of candidate drugs can save time and cost and can reduce reliance on animal experiments. Faster, more targeted trials are an important research benefit.

E. Hospital Operations

Hospital-level twins support the management of beds, staff and equipment, which helps shorten waiting times. Systematic reviews also highlight infection control and workflow optimisation as promising uses [3].

VI. LIVE PATIENT MONITORING

Remote monitoring is one of the most practical near-term uses of the technology. Wearables transmit parameters such as heart rate, blood pressure, oxygen level and blood glucose around the clock. The twin compares incoming readings with the patient's own baseline instead of a generic population range. When it detects a worrying pattern, for example a steadily rising heart rate, it alerts the doctor immediately. This approach lets clinicians support patients from a distance. It is especially valuable for people in villages and remote regions, for the elderly and for home-care settings, where frequent hospital visits are difficult. The cloud-based elderly care framework in [5] is an example of this direction.

VII. BENEFITS

- **Better outcomes:** early detection allows treatment to start sooner and work better.
- **Improved safety:** errors occur on the computer model rather than on the patient.
- **Lower cost:** fewer repeated tests, fewer failed treatments and shorter hospital stays.
- **Patient engagement:** individuals can visualise and better understand their own health.
- **Faster research and training:** trials and clinical education can be accelerated using virtual models.

VIII. DATA SECURITY, PRIVACY AND REGULATION

A digital twin holds highly sensitive information, including medical history and test results, so security is central to its acceptance. The main safeguards are:

- **Authentication:** passwords, biometrics such as fingerprints, or one-time passwords ensure that only authorised persons can access the data.
- **Encryption:** data should be protected both when stored and when transmitted.
- **Legal compliance:** applicable regulations must be followed, including HIPAA in the United States, GDPR in the European Union and the Digital Personal Data Protection (DPDP) Act, 2023 in India.
- **Patient consent:** data should be collected and used only with the patient's permission.

Because the twin continuously streams data between devices, cloud services and clinical systems, the number of potential attack points is large. Security must therefore be built into the design rather than added afterwards.

IX. CHALLENGES AND LIMITATIONS

- **High set-up cost:** sensors, computing infrastructure and software are expensive, which can limit adoption in smaller hospitals.
- **Interoperability:** hospital information systems often do not exchange data smoothly, making it hard to assemble a complete picture of the patient.
- **Workforce training:** clinicians and technical staff need new skills to use and trust these tools.
- **Biological complexity:** the human body is extraordinarily complex, so building an exact and fully validated replica is difficult, and model predictions carry uncertainty.
- **Privacy and ethics:** consent, data ownership and misuse of personal data must be carefully managed.

X. FUTURE SCOPE

Future research and development are expected to focus on full-body twins that integrate multiple organ systems, more advanced and more reliable AI models, and lower-cost solutions that make digital twins available to hospitals and patients of all sizes. Standardised data formats, rigorous clinical validation and clear ethical and regulatory frameworks will be needed to move from research prototypes to routine clinical use.

XI. CONCLUSION

A digital twin in healthcare is a live computer copy of a patient, organ or hospital that is constantly updated with real data. By combining wearables, AI, cloud computing, medical imaging and fast networks, it enables early problem detection, safe testing of treatments and care tailored to the individual. Remote monitoring extends these benefits to people who are far from hospitals. However, cost, privacy and data sharing between institutions remain obstacles. If these are overcome, digital twins have the potential to make healthcare safer, more affordable and more accessible.

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