



(RESEARCH ARTICLE)



CardioTwinX: A digital replica of the human heart for pre-operative analysis

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Abstract

CardioTwinX is a web-based cardiac digital twin system designed to simulate patient-specific heart behavior for pre-operative analysis. The platform generates a virtual replica of the human heart using clinical parameters such as age, heart rate, blood pressure, cholesterol level, and existing cardiac conditions. A rule-based simulation engine models physiological changes including artery blockage and abnormal heart rate conditions. The system integrates a 3D visualization module, risk prediction engine, and analytical dashboard to evaluate surgical safety. By providing predictive insights before medical intervention, the proposed solution enhances decision-making, reduces potential complications, and supports medical education. CardioTwinX demonstrates the applicability of digital twin technology in personalized healthcare simulation through interactive and visual risk assessment.

Keywords: Digital Twin; Cardiac Simulation; Pre-Operative Analysis; Risk Prediction; Three js; Healthcare Analytics; Virtual Heart Model

1. Introduction

Cardiovascular diseases remain one of the leading causes of mortality worldwide. Pre-operative planning typically relies on static imaging techniques, physician expertise, and general population-based medical data. These conventional approaches lack patient-specific predictive simulation and dynamic visualization.

Digital twin technology enables the creation of virtual replicas of biological systems, allowing real-time simulation and predictive analysis. By modeling physiological behavior before medical intervention, clinicians can better understand risks and outcomes. CardioTwinX introduces a simplified cardiac digital twin system that integrates patient input, simulation logic, and 3D visualization. The proposed platform provides an interactive environment for predicting surgical risks and visualizing heart behavior, thereby enhancing decision support and educational applications.

2. Literature Survey

Mihai et al. (2022)

Mihai et al. (2022) presented a comprehensive survey on digital twin technologies across multiple domains. The study examined the integration of Internet of Things (IoT), artificial intelligence, machine learning, and cloud-edge computing in digital twin frameworks. The authors provided a cross-domain overview highlighting the architectural components and functional characteristics of digital twins. While the survey offered strong theoretical insights and taxonomy, it lacked experimental validation and healthcare-specific implementation. This work establishes foundational knowledge but does not address cardiac or patient-specific modeling.

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Newrzella et al. (2021)

Newrzella et al. (2021) proposed a conceptual classification model for digital twin systems based on a five-dimension framework. The study focused on defining structural elements and terminology to standardize digital twin development. The classification model improves understanding of system architecture, lifecycle integration, and data flow.

However, the research did not include healthcare-oriented case studies or practical clinical applications. Despite this limitation, the framework provides guidance for designing structured digital twin solutions in various domains, including potential healthcare applications.

Zhang et al. (2023)

Zhang et al. (2023) explored healthcare-focused digital twin systems using an architecture-based approach. The proposed model integrated IoT sensors, clinical data, and simulation techniques for patient monitoring and predictive analysis. The study demonstrated practical relevance for healthcare environments by emphasizing data-driven simulation. However, the implementation complexity and limited clinical validation were identified as challenges. This work highlights the importance of integrating patient data with simulation models for predictive healthcare systems.

Wang et al. (2025)

Wang et al. (2025) conducted a systematic review analyzing digital twin architectures, optimization methods, and performance evaluation metrics. The research identified trends in digital twin adoption and highlighted existing research gaps. The study emphasized scalability and performance improvements in digital twin frameworks. However, the review lacked cardiac-specific applications and did not focus on medical simulation. The findings provide general insights useful for designing efficient digital twin systems, including healthcare-oriented implementations.

Table 1 Comparison Table of Literature Survey

| S.No | Author(s) | Title | Methodolgy | Findings from the Reference Paper |
|------|-------------------------|-------------------------------------|---|---|
| 1. | Mihai et al.(2022) | Digital Twin - General Survey | Systematic survey of digital twin technologies using IoT, AI/ML, and cloud computing. | Digital twins improve prediction and monitoring, but healthcare-specific validation is limited. |
| 2. | Newrzella et al. (2021) | Digital Twin Classification | Five-dimension conceptual classification model for digital twin systems. | Provides standardized architecture; lacks practical healthcare implementation. |
| 3. | Zhang et al. (2023) | HealthCare Digital Twin Systems | Healthcare digital twin architecture integrating IoT sensors and clinical data. | Enables predictive patient monitoring; implementation complexity remains high. |
| 4. | Wang et al. (2025) | Patient - Specific Cardiac Modeling | Systematic review of digital twin architectures and optimization methods. | Identifies scalability trends; not focused on cardiac-specific applications. |

2.1. System Architecture

The CardioTwinX system follows a layered architecture designed to simulate patient-specific cardiac behavior and perform pre-operative risk analysis. The architecture consists of five major components: User Interface, Data Processing Layer, Digital Heart Model, Simulation Engine, and Risk Prediction Module. The User Interface Layer allows doctors or students to input patient parameters such as age, heart rate, blood pressure, cholesterol level, and existing cardiac conditions. It also provides interactive visualization of the 3D digital heart model and procedure selection options. This layer ensures user-friendly interaction and real-time control of simulations.

The Data Processing Layer validates and preprocesses the input parameters. It converts raw inputs into normalized values suitable for simulation. This layer also ensures that patient data is temporarily handled without permanent storage,

maintaining system safety. The Digital Heart Model represents a simplified virtual replica of the human heart. It includes chambers, valves, and blood flow pathways. The model dynamically adjusts heart rhythm, flow rate, and pressure values based on patient inputs and selected conditions. The Simulation Engine modifies the heart model to replicate specific cardiac scenarios such as artery blockage, valve stenosis, or abnormal heart rate. It performs logic-based calculations to adjust blood flow and pressure, visually reflecting the simulated condition in the 3D model.

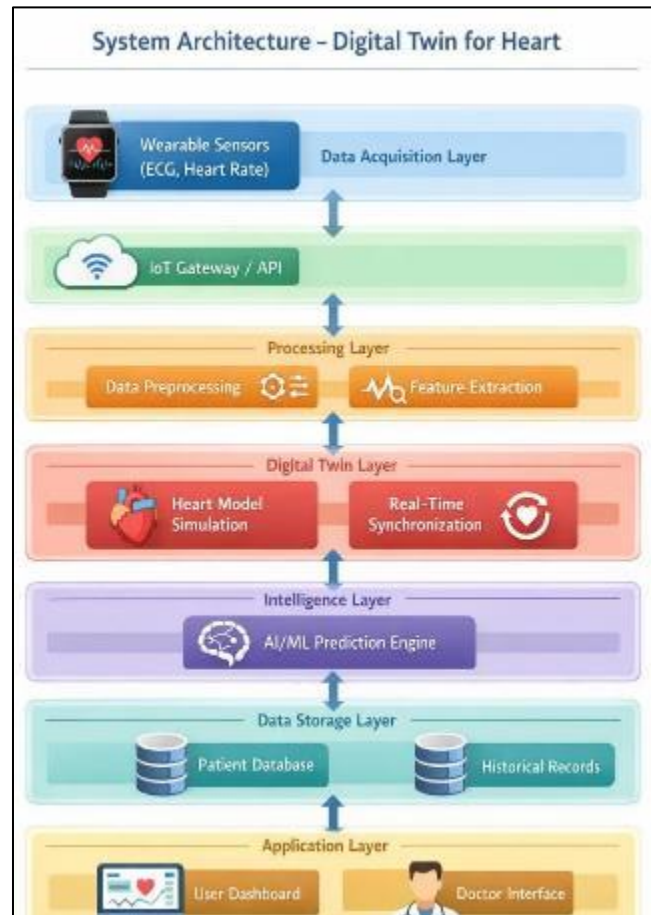


Figure 1 System Architecture

The Risk Prediction Module analyzes simulation outputs using rule-based decision logic. It evaluates parameters such as flow reduction, pressure variation, and heart rate abnormality to classify risk levels as Low, Medium, or High. It also generates possible complications and recommendations. Finally, the Results Dashboard presents the analyzed outcomes including risk level, blood flow status, predicted complications, and safety recommendations. It also displays before-and-after comparisons for improved clinical interpretation.

3. Proposed Methodology

3.1. Patient Data Collection

Patient data is collected through a user-friendly web interface designed to capture both basic and clinical parameters. These include demographic details such as age and gender, along with vital health indicators like heart rate, blood pressure (systolic and diastolic), cholesterol levels, and any pre-existing cardiac conditions (e.g., hypertension, coronary artery disease).

To ensure accuracy, input validation mechanisms are implemented to restrict unrealistic values. The collected data is securely stored and preprocessed before being forwarded to the simulation and analysis modules. This structured dataset acts as the primary input for generating a personalized digital twin of the patient's heart.

3.2. Digital Twin Simulation

The digital twin module creates a real-time virtual representation of the human heart using Three.js for 3D rendering. The model mimics cardiac structure and function, allowing dynamic interaction and visualization.

Based on the input parameters, the simulation engine alters heart behavior by applying predefined physiological rules. For example, conditions such as arterial blockage reduce blood flow, increase pressure in specific regions, and affect pumping efficiency.

The simulation operates in an iterative manner, continuously updating parameters to reflect realistic cardiac responses. This enables users to observe how different conditions or interventions might influence heart performance before actual medical procedures.

3.3. Risk Prediction

The risk prediction module uses a rule-based scoring algorithm to evaluate the patient's overall cardiac risk. Each input parameter is assigned a specific weight based on its clinical significance. For instance, high blood pressure and elevated cholesterol contribute more heavily to the risk score compared to minor factors.

The algorithm aggregates these weighted values to compute a cumulative risk score.

Additionally, the system can provide reasoning behind the classification by highlighting the most influential parameters, helping users understand the contributing factors to their risk level.

3.4. Visualization and Dashboard

The system presents results through an interactive visualization module combined with an analytical dashboard. The 3D heart model displays real-time simulation effects, where visual indicators such as color gradients (e.g., red for high stress regions) and motion changes represent physiological conditions.

The dashboard complements this by providing numerical outputs including heart efficiency, pressure levels, and calculated risk scores. Graphs and charts may be used to illustrate trends and comparisons.

Furthermore, the system generates basic recommendations or alerts based on the risk classification, assisting users and clinicians in making informed decisions.

3.5. Algorithmic Flow of a Duel Match

The CardioTwinX workflow follows the steps below:

- User enters patient clinical details through the web interface.
- System validates and preprocesses input parameters.
- Simulation engine processes the selected cardiac condition
- Blood flow reduction and pressure variations are calculated
- Risk score is computed using threshold-based logic
- Patient risk level is classified (Low, Moderate, High)
- 3D heart model updates to reflect simulation changes
- Results dashboard displays key insights and analysis
- Clinical recommendations are generated for decision support

3.6. Output Screens



Figure 2 Moderate Risk Prediction in Blood Vessels using CardioTwinX



Figure 3 Healthy Heart Condition Prediction using CardioTwinX

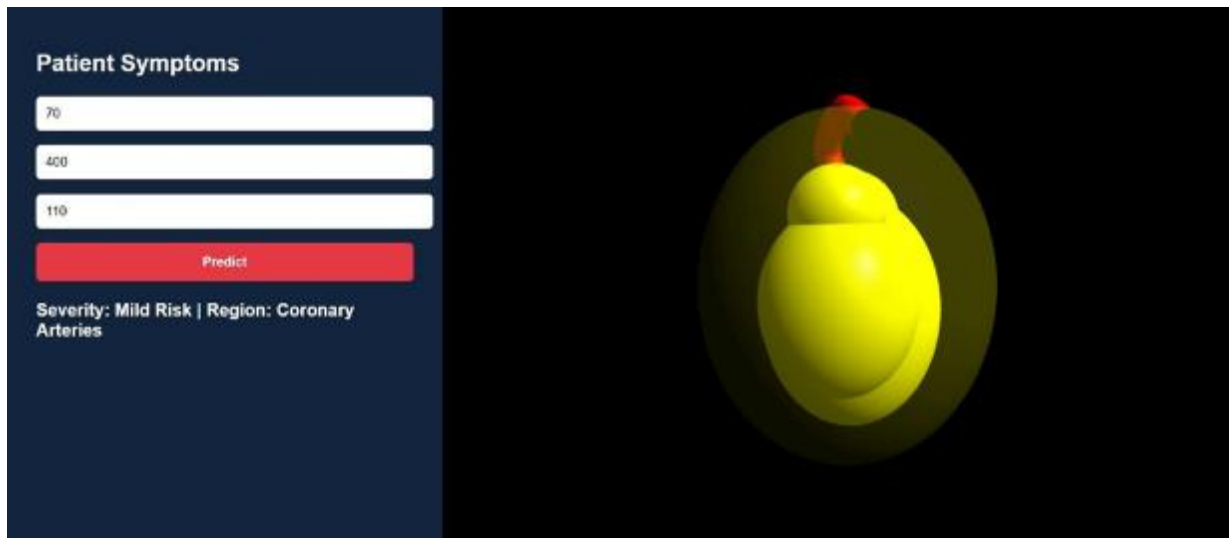


Figure 4 Mild Risk Detection in Coronary Arteries using CardioTwinX



Figure 5 Severe Risk Identification in Coronary Arteries using CardioTwinX

4. Conclusion

CardioTwinX presents a digital twin-based cardiac simulation system for pre-operative analysis. The platform integrates patient input, simulation logic, and visualization into a unified framework. By predicting risk levels and visualizing heart behavior, the system enhances decision support and educational applications. Although simplified, the proposed model demonstrates the potential of digital twin technology in personalized healthcare.

The system highlights how virtual simulations can reduce uncertainty in surgical planning and provide deeper insights into patient-specific conditions without invasive procedures. Its interactive design improves understanding for both clinicians and learners, bridging the gap between theoretical knowledge and practical application. CardioTwinX also emphasizes scalability, as the framework can be extended to include more complex physiological models and multi-parameter analysis.

Furthermore, the project establishes a foundation for integrating advanced technologies such as artificial intelligence, machine learning, and real-time IoT-based patient monitoring. These enhancements can significantly improve prediction accuracy, enable continuous health tracking, and support proactive medical interventions. With further development and clinical validation, CardioTwinX has the potential to evolve into a reliable and impactful tool in modern, data-driven healthcare systems.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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