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Human Digital Twin Technology Using IoT in Field of Personalised Healthcare

Mr. Anmol Kumar

Student, Computer Application, Babu Banarasi Das University

Abstract

IoT-integrated HDT represents a revolutionary methodology for personalized medicine, allowing for real-time, data-driven simulations of patient physiology, behavior, and treatment responses. This research was necessary because proactive, individual care is increasingly required in the face of growing chronic diseases and healthcare inefficiencies-a motivation intensified by the gaps in conventional systems and the promising role of IoT-empowered HDTs in strengthening predictive analytics and ensuring better patient outcomes.

The study conducted a review of 40 peer-reviewed papers from reputed sources like IEEE, Springer, and Elsevier on the applications of HDT-IoT in healthcare during 2023-2025, following a structured multi-phase methodology. The different phases included the collection and selection of the literature, mapping 8 high-severity challenges - cybersecurity, scalability, and ML accuracy among others - comparative mapping with severity scores and sector tags, specializing in 10 papers regarding personalized healthcare, and framework development. Key findings included commonly identified IoT use cases, such as wearables-based vitals monitoring and predictive analytics for chronic diseases, and AI/ML-driven personalization, while mapping challenges that clearly indicated deployment bottlenecks such as data privacy and interoperability.

It has also advocated for a challenge-centric framework, with a modular architecture of HDT (IoT Data Layer → Semantic Engine → ML Personalization → Dashboard Interface) to reduce barriers and drive ethical and scalable solutions. Deliverables will include comparison tables, academic presentations, and wireframes that can be used practically.

This work contributes a diagnostic tool to the HDT-IoT implementations that advance personalized healthcare and reduce health disparities and policymaking. Testing through empirical pilots to validate the framework is recommended for future research.

INTRODUCTION

Human Digital Twins (HDTs) represent a transformative leap in healthcare, adapting engineering's digital twin concept to create dynamic, real-time virtual models of individuals that integrate physiological data, behaviours, and environmental interactions through IoT devices, enabling personalized medicine by shifting from reactive care to proactive, precision approaches that account for genetic, lifestyle, and environmental factors; at their core, HDTs are advanced digital replicas continuously updated via biometric streams from wearables like smartwatches (monitoring heart rate, sleep, activity), glucose monitors, cardiac devices, and smart implants, processed on cloud platforms using AI and machine learning for predictive diagnostics and tailored treatments, as seen in oncology simulations of tumor drug responses or preventive detection of Parkinson's through gait analysis and mental health via EEG and app

data; real-world applications are advancing with companies like Philips and Siemens developing platforms for post-surgery cardiovascular monitoring and Medtronic optimizing diabetes management with IoT insulin pumps, potentially slashing hospitalizations and costs amid Gartner's forecast of 25 billion IoT healthcare devices by 2025; technologically, HDTs leverage AI for modeling, blockchain for secure data sharing under GDPR and HIPAA, cloud and edge computing for scalability and low-latency updates, advanced biocompatible sensors (including ingestible ones), and 5G connectivity, with institutions like MIT and Stanford pioneering "living" twins incorporating microbiome and social data; however, ethical hurdles include privacy risks from breaches enabling discrimination or identity theft, equity disparities favoring affluent access, AI biases from non-diverse training data, and dilemmas over HDT autonomy versus physician judgment, raising liability issues; looking ahead, by 2030, HDTs could standardize clinical practice, bolstering telemedicine, remote monitoring, augmented reality visualizations, and AI-driven drug discovery, but realizing this potential requires interdisciplinary collaboration to mitigate challenges and ensure equitable benefits, justifying their revolutionary role in modern healthcare through proven integrations, predictive capabilities, and scalable technologies that promise to enhance outcomes while addressing evolving ethical and societal needs.

MOTIVATION

Laying the scientific foundation for HDTs promises to open a new frontier in personalized healthcare, wherein real-time data from IoT devices can simulate, monitor, and predict human health with unprecedented precision. At the same time, HDT systems are still largely experimental and fragmented, particularly within the healthcare domain.

The existing literature has great use cases, from Parkinson’s detection to robot-assisted telerehabilitation, but most such deployments face several critical deployment barriers. Some of these include:

- Technical limitations in real-time data synchronization and ML model accuracy
  What's missing is a unified framework that dosen't just celebrate the HDT capabilities but systematically identifies and scores the challenges that prevent real-world adoption.
- Shift the focus from “what HDT can do” to “what’s stopping HDT from working”
- Enable the design of HDT systems to be ethical, scalable, and deployment-ready.

This work, a comparative framework for guiding future HDT–Healthcare innovations from academic research to techfest demonstrations and clinical dashboards, involves an analysis of 40 papers and their mapping across 8 high-severity challenges.

LITERATURE REVIEW AND SYNTHESIS

The literature on Human Digital Twin technology, especially in integrating IoT for personalized healthcare, represents a field at the intersection of digital health, data science, and medical innovation that is maturing at a rapid pace. From over 40 peer-reviewed publications ranging from 2018 to 2023 in flagship journals such as IEEE Transactions on Biomedical Engineering, Journal of Medical Internet Research, and Nature Digital Medicine, HDTs can be referred to as dynamic computational models that mirror an individual's physiological, behavioural, and cognitive states in real time. These models evolve from simple monitoring tools toward sophisticated decision support systems powered by IoT-enabled data streams interpreted by semantic engines into actionable health narratives. Examples involve wearables, telerehabilitation, neurological monitoring, and predictive analytics enabled by IoT infrastructure, which provides for multi-modal data fusion and remote, non-invasive care. AI and ML techniques, including

federated learning for privacy, context-aware algorithms, and ontology-driven semantic modeling, further personalize HDTs, adapting them to individual health trajectories and behavioural patterns. Despite this progress, persistent challenges identified in the literature include data privacy, real-time synchronization, interoperability, ML accuracy, and scalability. Many of these gaps are interconnected, emphasizing the need for both regulatory innovation and technological solutions such as blockchain and open standards. In general, HDT technology has transformative potential for shifting healthcare from a reactive to a proactive footing; however, its full realization will require interdisciplinary collaboration and empirical validation to overcome deployment barriers with a view to ensuring ethical, scalable, and personalized care.

Although there is growing interest in HDT technology to enable personalized healthcare, most of the existing research in the literature focuses either on use-case demonstration or technical architecture without systematically addressing the deployment challenges inhibiting real-world adoptions. Clearly, HDTs depend on continuous data from IoT devices, semantic modeling, and AI-driven personalization. Their implementation across health care systems has remained fragmented, ethically complex, and technically fragile.

PROBLEMS-FACED

- This research identifies eight recurring high-severity challenges that cut across HDT–Healthcare applications through a review of 40 peer-reviewed papers.
- User Intrusiveness: Continuous monitoring raises ethical concerns around privacy, consent, and psychological impact.
- Real-time data synchronization: IoT devices, each with multiple modalities of data streams, are hard to align and process in real time.
- ML Model Accuracy: Predictive models lack personalization, leading to overfitting or misdiagnosis.
- Cybersecurity: Sensitive health data are more prone to breaches and require robust encryption with access control.
- Interoperability: Different devices and platforms do not have standardized protocols to enable their interworking.
- Scalability & Cost: Most of the HDT systems are prototypes and are not designed for population-level deployment.
- Class imbalance: Unique conditions and edge cases are underrepresented, which impacts model generalization.
- Sensor Noise & Reliability: The environmental factors and limitations of devices introduce inaccuracies in the capture of data.

These challenges exist and compound upon one another, building on and complicating the others to make it difficult to scale HDT systems ethically and effectively. Current literature lacks a comparative framework that would analyse, score, and prioritize these barriers across sectors.

OBJECTIVES

The main focus of this study is to create a challenge-oriented, comparative framework that will allow for the systematic, in-depth comparison of HDT systems proposed or implemented in the domain of personalized healthcare that have been integrated with IoT technologies. It will change the mind-set from

illustrating the opportunities presented by HDTs toward the identification and mitigation of obstacles in their implementation processes.

Certain objectives:

- Analyze 40 peer-reviewed papers across the domains of HDT–Healthcare to extract recurring challenges and technological patterns.
- Define and classify 8 high-severity challenges for HDT deployment: User Intrusiveness | Real-Time Sync | ML Accuracy | Cybersecurity | Interoperability | Scalability | Data Imbalance | Sensor Noise.
- Score and map each paper for challenge density and severity to understand high-risk sectors and maturity levels.
- Specialize the framework for personalized healthcare, focusing on several use cases related to Parkinson's detection, telerehabilitation, and COVID-19 monitoring.
- Propose a modular architecture for the HDT incorporating IoT data pipelines, semantic modeling, and AI-driven personalization. Support future research, teaching, and deployment by providing a scalable, ethical, and actionable roadmap for the design of HDT systems.

METHODOLOGY

This research adopts a structured, multi-phase methodology for the development of a challenge-centric framework in the form of HDT systems for personalized healthcare using IoT. Systematic literature analysis, thematic challenge extraction, comparative scoring, and framework synthesis have been combined to identify deployment barriers and guide future HDT design.

1. Selection of Literature and Scope of Study

Timeframe: 2023–2025

Sources: IEEE Xplore, Nature Digital Medicine, Journal of Medical Internet Research, ACM Digital Library

Selection Criteria:

- Papers focusing on HDT or Digital Twin applications in healthcare
- Integration of IoT, AI, ML, or semantic modeling
- Relevance to personalization, monitoring, prediction, or rehabilitation
- Final Dataset: 40 peer-reviewed papers ranging across diverse healthcare domains

2. Identification and categorization of challenges

Objective: Extract recurring barriers to HDT deployment

Method: Thematic analysis of selected papers

Identified Challenges: 8 categories

- User Intrusiveness
- Real-time data synchronization
- ML Model Accuracy
- Cybersecurity
- Interoperability
- Scalability and Cost
- Data Imbalance
- Noise and Reliability of Sensors

3. Comparative Mapping and Scoring

Process:

Each paper was mapped against the 8 challenge categories.

Severity scores assigned:

🔴 High

🟡 Medium

🟢 Low

The implementation of standard secondary physical education programs is challenged by the integration of adapted activities into the curriculum. A comparative table showing challenge density per paper. Sectoral challenge profiles, for example, Parkinson's detection, telerehab, and COVID-19 monitoring

4. Specialization in Healthcare HDT

Focused Subset: 10 papers directly relevant to personalized healthcare

Analysis Dimensions:

- IoT device types and data modalities
- ML personalization techniques, including federated learning and context-aware models
- Semantic modelling and use of ontology

Outcome: Identification of healthcare as the most challenge-dense HDT domain.

5. Framework Building

Design: A modular HDT architecture that integrates:

- IoT Data Layer
- Semantic Interpretation Engine
- ML Personalization Module
- Ethical and Scalable Deployment Interface

Purpose: This should help guide future HDT system design, teaching, and deployment.

6. Output and Application

Deliverables:

- Challenge-centric comparative table
- Sector-wise challenge density map

Academic PPT and visual layout Poster-ready summary and dashboard wireframe for future scope Use Cases: Research planning Techfest presentations Teaching modules Ethical design audits.

Future Outcomes

Based on a challenge-centric framework developed through the review of 40 HDT–Healthcare papers from 2023 to 2025, this research also opens several pathways toward future innovation, deployment, and interdisciplinary collaboration. Accordingly, the following outputs are expected:

1. **Scalable HDT Architectures Development**

- The proposed modular framework can be used for designing HDT systems that are scalable across clinics, hospitals, and home-care setups.
- Future prototypes may integrate edge computing, federated learning, and semantic engines to ensure real-time, privacy-preserving personalization.

2. **Creation of a Sector-Wise HDT Deployment Dashboard**

- From the challenge-density scores, a visual dashboard could be developed to assist stakeholders in

identifying high-risk sectors by prioritizing interventions and monitoring HDT readiness.

- This dashboard could be used by healthcare administrators, researchers, and policymakers to guide ethical and cost-effective deployment.

3. Gamified Teaching Modules & Techfest Demonstrators

- The framework can be transformed into interactive teaching tools, including Hinglish-based modules, quizzes, and visual posters for workshops and techfests.
- These modules will help students and educators grasp HDT concepts by using analogies, simulations, and challenge-based learning.

4. Ethical Design Audits for HDT Systems

- These categories of challenges may be used as an ethical audit checklist to make sure that HDT systems meet the threshold tests in privacy, interoperability, and inclusivity.
- This can support regulatory bodies and developers in aligning HDT systems with frameworks like GDPR and HIPAA.

5. Collaborations in Cross-Disciplinary Research

- The framework encourages collaboration among data scientists, clinicians, IoT engineers, and ethicists to co-design HDT systems that are technically robust and socially responsible.
- Future studies may involve real-world pilot deployments, with a special emphasis on chronic care, mental health, and remote rehabilitation.

6. Publication and Standardization Roadmap

- The comparative framework can be extended into a standardized benchmarking tool for HDT research publications.
- It may contribute to white papers, IEEE standards, or digital health policy briefs that define best practices for HDT-IoT integration.

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