Simulation of physiological parameters for homeostatic maintenance: The role of digital twin technology

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Abstract
Digital twin technology is an innovative approach to personalized health management by way of digital modeling of physiological parameters. This technology enables 24/7 monitoring of the basic life-sustaining functions of the organism, simulation of these functions, and early detection of deviations for timely intervention in preventive medicine. Digital twin applications provide a key component in maintaining homeostatic balance, preventing acute illnesses, and optimizing interventions. This review elucidates circuitously all the structural components of digital twins, their connections with physiological systems, applications in health and sports, and medical applications. We will discuss some of the major limiting factors, which include data security, costs, ethical issues, and legal regulations.

Keywords: *Digital Twin, Homeostasis, Personalized Medicine, Artificial Intelligence, Systems Biology, Health Technologies.*

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Homeostatik denge için fizyolojik parametrelerin simülasyonu: Dijital ikiz teknolojisinin rolü

Öz

Dijital ikiz teknolojisi, fizyolojik parametrelerin dijital modellemesi yoluyla kişiselleştirilmiş sağlık yönetimine yenilikçi bir yaklaşımdır. Bu teknoloji, organizmanın temel yaşam sürdürme fonksiyonlarının 7/24 izlenmesini, bu fonksiyonların simülasyonunu ve önleyici tıpta zamanında müdahale için sapmaların erken tespitini mümkün kılar. Dijital ikiz uygulamaları, homeostatik dengenin korunmasında, akut hastalıkların önlenmesinde ve müdahalelerin optimize edilmesinde önemli bir bileşen sağlar. Bu inceleme, dijital ikizlerin tüm yapısal bileşenlerini, fizyolojik sistemlerle bağlantılarını, sağlık ve spordaki uygulamalarını ve tıbbi uygulamalarını dolaylı olarak açıklamaktadır. Veri güvenliği, maliyetler, etik sorunlar ve yasal düzenlemeler gibi bazı önemli sınırlayıcı faktörleri tartışacağız.

Anahtar Kelimeler: *Dijital İkiz, Homeostaz, Kişiselleştirilmiş Tıp, Yapay Zekâ, Sistem Biyolojisi, Sağlık Teknolojileri.*

Introduction

Digital twin technology is one of the main foundations of the digital transformation process. Homeostatic balance is foundational and essential for ensuring survival and optimum functioning in living organisms. Homeostasis means steady internal physical and chemical conditions maintained by living systems. This includes core body temperatures, blood pH, glucose concentration, osmotic pressure, oxygen and carbon dioxide levels, as well as millions of hormone concentrations, all of which must remain within tightly regulated physiological ranges to ensure proper cellular activity, enzymatic function, and organ system performance (Cellina et al., 2023; Tao et al., 2018).

The human body achieves homeostasis through complex and highly integrated regulatory mechanisms within it. The central nervous system receives afferent signals continuously from peripheral sensory receptors. Cardiovascular System is Nutritional and fluids Exchange System. Endocrine System is Feedback to Central Nervous System on Metabolic Activity. Renal System-Electrolyte and Fluid Balance. Any of these homeostatics manipulates and alters by some factors, such as environmental stressors, pathogens, metabolic disturbances, or lifestyle factors, to possibly set off a pathogenic process or disease (Zhao et al., 2024; Hosseini et al., 2021).

This confluence during the past years between biomedical sciences and advanced computational technologies is now presenting new potentials for observing and intervening in the dynamic physiological systems. Digital health innovations- and shortly digital twin technology- made possible continuous high-resolution monitoring and analysis of a person's internal state. A digital twin is a virtual representation of a physical entity that is dynamically updated according to real-time data. Digital twin applications in health care may create a virtual model of an individual's physiological functions, integrated by a whole variety of data streams-from anatomical imaging and molecular biomarkers to treatment-metrics behaviors and environmental exposures (Krittanawong et al., 2020; Salvador et al., 2024). The individual digital representations will allow clinicians and researchers to visualize in a risk-free virtual environment how the body of a particular patient may respond to therapeutic interventions, stressors, or disease progression. Digital twins can also predict a deviation from homeostasis before any clinic symptoms are visible, which opens up proactive, personalized medical strategies against the direct approach to prevent reactive medicine shifting from reactive to preventive medicine. This not only assures better outcomes for the patient but also enhances healthcare systems in terms of efficiency and sustainability (Vallée,2023; Haleem et al., 2023; Ríos et al., 2020). Accordingly, digital twin technology is one among the new transforming frontiers in precision health and dynamic homeostatic control (Tao et al., 2018; Björnsson, et al., 2019).

The building blocks of digital twin technology

Data collection

Digital twin technologies succeed with systematic and incessant acquisition of data, imparting multimodal real-time information into its virtual model. Foremost, wearable-sensor devices—the likes of smartwatches, fitness bands, skin patches, biosensor-embedded textiles, and implantable monitor-having devices—hold a place of prominence in the flywheel of capturing real-time physiological signals. These devices detect critical health parameters, including heart rate, respiratory rate, arterial oxygen saturation (SpO_2), blood pressure, electrocardiogram (ECG) patterns, glucose levels, skin temperature, and the galvanic skin response (Salvador et al., 2024; Cheng et al., 2020; Zhou et al., 2020).

With the inclusion of these biosensors, biometric systems track facial expressions, voice modulations, and body postures to ascertain inferences about stress, mood, and cognitive load. M-health applications provide user-reported data on medication adherence, dietary intake, fluid consumption, and exercise routines. EHRs afford clinical data retrospective of diagnostic imaging, laboratory values, prescriptions, surgical histories, allergies, or even chronic disease registries (Hossani et al., 2022).

The biological fidelity of the digital twin further benefits from genomics, proteomics, metabolomics, and microbiome profiling, integrating high-dimensional omics datasets. Epigenetic signatures and gene-environment interplay allow for some dynamic personalization of the model. Environmental data—air quality, ambient temperature, noise pollution, UV exposure, etc.—may also be streamed from geolocation-based databases or external sensors to encompass extrinsic factors acting on health (Zhang et al., 2020).

Probing truthfulness, completeness, and frequency of acquisition of data, these are of paramount importance to sustain high resolution and contextual awareness of the digital twin. Synchronizing across devices and timestamping all stakeholders' heterogeneous data streams cohesively aligns the streams. Reliable and lossless transfer of data preferably through encrypted cloud platforms or edge-computing nodes is important to maintain the two pillars of reliability and privacy. Integrity of data, minimum latency, and compliance with standards of protecting health data—for example, HIPAA, GDPR—are set-in-stone features of the architecture of digital twin data collection (Cellına et al., 2023; Hassani et al., 2022)

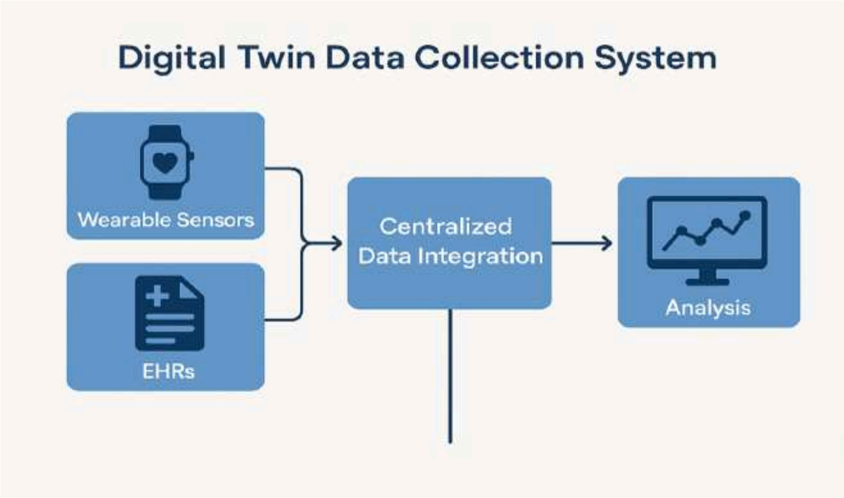

Figure 1. Flowchart of digital twin data collection system: From wearable sensors and EHRs to centralized data integration and analysis.

Modeling and simulation

First, the data collected undergo the process of mathematical modeling and artificial intelligence methodologies to realize a dynamic digital avatar of the individual, which accurately and continuously simulates one or more organs of the individual. The digital twin, thus modeled, represents real-time, or very close, simulation of physiological responses, metabolic activity of one's body, and organ systems, as well as all biological processes being simulated broadly but in real-time.

Modeling methods span to and across a disciplinary spectrum to capture the complexity and dynamics that these biological systems have inherently (Tao et al., 2018; Hosseini et al., 2021):

Systems Biology Approaches: This is by bringing into the mathematical framework cellular and molecular networks, for example, profiles of gene expression via pathways of metabolism and cascades of signaling, to represent complex biological interactions and their effects on the function of the whole organism.

Dynamic Systems Theory: Based on differential equations, dynamic models describe mechanisms to act into homeostasis and environmental perturbations (Cheng et al., 2020). Thus making it possible to analyze system behavior over time concerning stability and responses to perturbation.

Differential Equation-Based States: These states track organ and metabolic activities over continuous time with differential equations describing evolving states of biological parameters. Such models, for instance, can be used for simulating hemodynamic variables in the cardiovascular system or pharmacokinetic/pharmacodynamic (PK/PD) profiles of specific drugs. This modeling can be done at the individual cell, molecular, or organ systems level, which is then treated as an autonomous agent acting in a specified environment and interacting with other agents. This modeling can then be used to achieve heterogenous yet complex biological systems connecting micro-levels with corresponding macro-level outcomes of interest.

Machine Learning and Artificial Intelligence Algorithms: Data-driven techniques learn from massive datasets of physiologic responses and health records in predicting future states, as well as pathological changes, using various techniques like deep learning, support vector machines, and random forests. (Sun at al., 2022).

The organism will be able to predict how the organism would respond to different endogenous and exogenous stimuli, such as stressors or those coming from pharmacological interventions with environmental change or further disease progression, when simulating the modeling. It is likely for possible adverse effects, which drugs may have, early signals of metabolic dysfunction or risk to cardiovascular health, before clinical presentation. (Sun at al., 2022)

Definitely, along with these advancements in simulation for the prognostic, a method for the early identification of high-risk populations would in form to introduce personalized preventive strategies. With the convenience of digital twin simulations for therapeutic planning optimization and better patient outcomes, these can shift into clinical decision support systems.

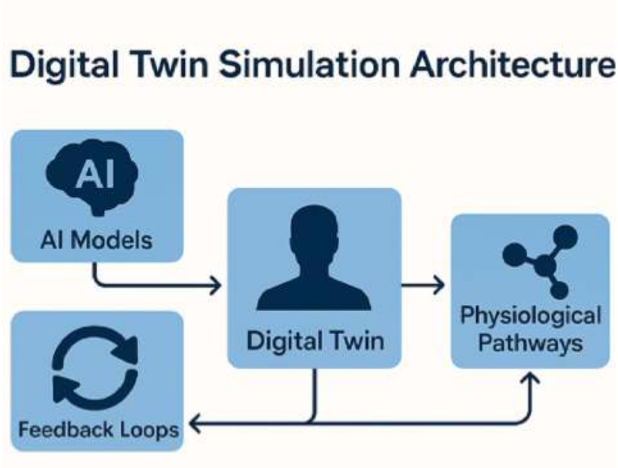

Figure 2. *Digital twin simulation architecture: Integration of AI models, physiological pathways, and feedback loops.*

Real-Time predictions and feedback

Digital twins continuously analyze the individual's physiological status in real time, feed-in, and process the incoming data from various sources; these include physiological status as presented by wearable sensors, mobile health applications, and electronic health records (Salvador et al., 2024; Zhao et al., 2024). Such a system performs real-time monitoring to track subtle deviations and emerging imbalances in homeostasis before any clinical symptoms occur.

Upon identifying any possible risk or critical alteration, such as impending hypoglycemic episodes through declining glucose levels too rapidly, the digital twin generates real-time early warning messages (Chu et al., 2023). Such messages may be incorporated directly as an application on the user's or healthcare provider's mobile phones, as an SMS alert, or as part of the already integrated healthcare communication framework (Gonzalez-Rıvaz et al., 2025).

Most importantly, such alerts are accompanied by informed recommendations in individual cases that may vary from advice on medication dose adjustments to dietary or lifestyle adjustment suggestions and advice to seek clinical evaluation. This feedback loop engages dynamic management of the health condition, thus minimizing adverse events and yielding more favorable outcome measures in patients (Zhou et al., 2020).

Digital twins thus go beyond the conventional passive monitoring system and enter the domain of intelligent decision-support tools. These are equipped to offer substantive realistic guidance to both users and practitioners in making appropriate, data- informed decisions in real-time to achieve more effective health care delivery tailored to the individual.

Clinical applications

Management of diabetes

Digital twinning has offered a boost for personalized management in a novel way; type 1 and type 2 diabetes mellitus have become a new example of the transformation processes brought about by digital twins to allow continuous, dynamic, and integrative monitoring of metabolic parameters and other physiological quantifiable performances (Chu et al., 2023; Ríos et al., 2020). Digital twins construct truly individualized metabolic profiles via the collection and the processing of real-time information such as glucose levels in blood, conditions of administering insulin, consumption of carbohydrates, physical activity, and many other lifestyle factors.(González-Rivas et al., 2025; Niarakis et al., 2024).

The most basic feature of digital twins in diabetes care, at its very essence, is that of continuously monitoring glycemic variability. By capturing the changes in blood glucose levels thrice daily and developing the patterns of glycemic indices, these models can identify those patterns that predict at which time hypoglycemic or hyperglycemic episodes are about to occur. The use of this predictive knowledge enables early intervention to correct the direction of glucose levels and minimize acute complications. Using such integration with CGM and insulin pumps allows setting up of automated insulin dosing algorithms which react to the real-time physiological need of the patient to improve their glycemic control in an easy way to the patients (Kamel Baulas and Zhang ., 2021; González-Rivas et al., 2025).

In addition to the above, digital twins are also able to trace the early indications of diabetes complications in the long run, such as diabetic retinopathy, nephropathy, and neuropathy. Such models identify minute physiological changes occurring before symptoms start to manifest by mounting longitudinal data on clinical domains, laboratory findings, and biomarker profiles that can lead to early stratification of risk and preventive healthcare (Vallée, 2023; González-Rivas et al., 2025).

The information from dietary habits, physical activity patterns, and personal preferences further enriches personalized lifestyle interventions embodied in digital twins. Predictive analytics use these digital twins to assess how different diets and physical activity affect metabolism and tailor individualized diet and activity plans optimizing metabolic health. Importantly, this personalization is dynamically updated according to new incoming data, allowing adaptation in time to changes in health or effectiveness of treatment (Haleem et al., 2023).

Overall, digital twin technology makes diabetic management extensive and patient-centered by promoting ongoing monitoring, predictive modeling, and personalized intervention. The approach optimizes short-term and long-term benefits through improved glycemic control and reduced risk for acute as well as chronic complications, while empowering patients through real-time feedback and clinical decision support, ultimately improving quality of life and long-term outcomes (González-Rivas et al., 2025).

Cardiovascular disease

Digital boys/digital doubles or twins basically played a major role in almost all critical cardiovascular diseases such as an increasingly progressive spectrum, including hypertension, coronary artery disease, and heart failure. Analyzing the dramatically growing multidimensional physiological data continues. Heart rate variability, blood pressure fluctuation, electrocardiogram (ECG) patterns, and the relevant levels of biomarkers such as troponins and natriuretic peptides form essential parameters that are combined into the digital model that develops a comprehensive profile (Krittanawong et al., 2020; Siemens Healthineers, 2021).

Through advanced analytics and predictive modeling, such digital twins would be able to identify minute deviations pointing toward cardiovascular events- myocardial infarction, arrhythmias, or acute decompensated heart failure- much before clinical signs could appear. Examples may include variations in heart rate variability or changes of ECG morphology that might indicate autonomic malfunction or might show ischemic aspects preceding an infarction as well as trends on blood pressure or biomarker fluctuations indicating such events as early stages of an increase in heart failure exacerbation.(Coorey et al., 2022;Salvador et al., 2024).

The early detection makes the groundwork for very personalized and timely interventions, which could be medication changes, lifestyle changes, or emergency clinical evaluation to avail of the greatest benefits from significantly decreased risks of severe or fatal results (Coorey et al., 2022; Cellına et al., 2023). Furthermore, digital twins can simulate or open avenues for investigating individual therapeutic approaches, such that medical practitioners optimize therapeutic plans for the individual's specific cardiovascular Dynamics (Salvador et al.,2024).

All in all, digital twin technology renders proactive risk assessment, constant monitoring, and optimized treatment for the individual patient, ultimately improving that patient's prognosis and quality of life, i.e. digitally augmented disease management in a cardiovascular patient.

Electrolyte balance and renal function

With digital twins, one can perform a continuous holistic monitoring and predictive management of electrolyte balance and renal function in patients of chronic kidney disease (CKD) or subjects undergoing therapy with heavy diuretic influence upon fluid and electrolyte homeostasis. The technology builds a dynamic individual model of renal and systemic homeostasis based on multidimensional physiological data.

Real-time monitoring of important electrolyte disturbances in sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}) is monitored. These electrolytes may trigger extreme clinical end-organ-complications: hyperkalemia and hypokalemia may give rise to cardiac arrhythmias, alterations in calcium and magnesium cause neuromuscular irritability, while acid-base imbalances affect the metabolic set-up. Digital twins permit continuous monitoring for perturbations in serum electrolyte concentrations, correlating these with other physiological parameters, and highlight potential early signs of dysregulation that would precede clinical symptoms.

In tandem, digital twins synthesize and analyze the bits and pieces of information regarding renal function: glomerular filtration rate (GFR), blood urea nitrogen (BUN), and serum creatinine concentration (Hosseini et al., 2021; Tao et al., 2018). By longitudinally assessing trends and short-term changes in these parameters, the model can detect the initial stages towards renal incapacity or acute kidney injury (AKI) and further allow time intervention. The model of the digital twin will also consider comorbidity and treatment issues as well hemodynamic status in the context of renal pathology.

Fluid management also occupies distinguishingly important space in digital twins. Patient hydration status can be predicted with great confidence complete with comprehensive data on fluid intake, urine output, electrolyte excretion, and hemodynamic measurements fed into the system. In this way, the digital twins cater to personalized recommendations slated toward modifying fluid therapy to eliminate complications associated with volume overload, for illustration, by worsening hypertension and heart failure or dehydration that works against renal perfusion and function (Balasubramanyam, et al., 2024).

Digital twins can use predictive analytics and simulation to assess the renal and systemic impact of therapeutic interventions such as changes in diuretic dosing or starting nephrotoxic agents. This enables the customizing of treatment for individuals, balancing risk and benefit.

Thus, the management of electrolyte disturbance and renal function utilizing digital twin technology begins once an imbalance is detected through continuous monitoring. Dynamic fluid management can then proceed with projection of treatment outcome under all those considerations. All in all, integration of this approach greatly enhances patient safety by optimizing clinical decision-making and prognosis in renal impairment or electrolyte disturbance patients.

Health and performance in sports

Digital twin technology is an inevitable event in enhancing performance and wellness management by professional sports people and hobbyists alike. The broad spectrum of physiological and biomechanical parameters- such as musculoskeletal load, energy expenditure, thresholds of lactate, and sleep and recovery patterns-in terms of continuous analysis will create integrated and personalized profiles of an athlete's current physical state and performance capacity.

Musculoskeletal load monitoring is a good technique to quantify the stress placed on the muscles, joints, and connective tissues by training and competing so that training intensity and volume can be adjusted accurately to reduce the likelihood of injury occurrence. Energy expenditure has also been useful when combined with metabolic markers such as lactate threshold to improve conditioning programs relative to aerobic or anaerobic power.

Sleep quality and recovery were also used to generate personalized recovery protocols from the wearable sensors and self-reports that interpreted the data regarding how much strain the body holds. The artificial brain detects signs of very early on overtraining syndrome or excessive fatigue and allows timely adjustment in training for performance decline prevention and injuries.

Moreover, such systems recreate various training and recovery approaches to steer the precompetition buildup scientifically, developing endurance, strength, and overall performance of an athlete. Digital twins have reduced recovery times and optimized training loads, thereby improving the potential of sustaining performance at its peak while stretching the athletic longevity.

To sum up, digital twin technology incorporates complex, multi-dimensional flows of data, while delivering tailored information for training and recovery, and the prevention as well as enhancement of performance, and generally an improved athlete's well-being.

Medical research and clinical trials

Digital Twins have brought in virtual test subjects for the Imaginary research conducted in silico, thus opening a most advanced simulation in the medical field for quite a change in the medical research and drug development process (Ríos et al., 2020). Digital twinning can simulate pharmacokinetic (PK) and pharmacodynamic (PD) personalized processes for an individual, accurately modeling absorption, distribution, metabolism and excretion of the drug as a function for the patient's unique biological profile (Kamel Baulos and Zhang et al., 2021). The accurate prediction of therapeutic action and likely drug-drug interactions and toxicity avant la lettre is breathtakingly precise and happens before clinical applications.

Digital twins can stratify participants into clinical trials according to different genetic, phenotypic, and environmental factors (Tao et al., 2018; Zhao et al., 2024). Stratification thus improves trial design, as it allows the specification of subpopulations that may respond differently to the given intervention, thus increasing the precision, reproducibility, and ethical relevance of study results. Second, digital twins run trial outcomes as if in a virtual world for optimizing dose regimens and reducing sample sizes for predicting adverse events, leading to the optimization of clinical research for efficiency and economy at the same time (Cheng et al., 2020).

Hypothesis testing and discovery with biomarkers take place there in quite a fast track, with computerized simulations that can run indefinitely, under any condition, without any ethical complication and practical consequences of human experimentation. It boosts personalized medicine, facilitating therapy decisions by predicting the response of the individual. This, then, states that there is consideration now to the new concept of a digital twin in medical research and clinical trials, speaking of promissory changes that would much develop in quick time the power to predict, develop personalized models and optimize study designs that in turn will improve patient safety and therapeutic efficacy.

Challenges encountered

Data security and privacy

Healthcare data become regarded as one of the most sensitive forms of personal information when it is articulated in its component form that an individual might possess knowledge of intimate details as pertaining to an individual's physical and mental health state. Digital twins continuously accumulate, transmit, and store such petrifying amounts of data, which subsequently make them soft targets for unauthorized access and cyber attacks. Hence, security and patient privacy enshrining are among fundamental objectives (Vallée, 2023).

That is in addition to the application of solid protection measures, of which some should include industrial-grade encryption techniques for data at rest and in transit, which will then back encryption against interception or tampering. For instance, other technologies like blockchain have decentralized, immutable ledgers that will ensure integrity and traceability of health records which add to fraud and data manipulations reduction risks-in a way. Anonymity and pseudonymization techniques will help safeguard a patient from being identifiable during sharing of data with related purposes of research application. Last but not least, multifactor authentication systems serve a reinforced access control by demanding more than one verification before granting access to repositories of sensitive data.

On the other hand, privacy is also ensured by the risk incessant assessment and compliance to data-protection laws such as GDPR or HIPAA, and by building a culture of safety in each health provider and the patient.

Cost and accessibility

Many aspects of digital twin systems require funding: purchasing sensor hardware, developing or licensing AI and machine learning modules, and integrating with existing healthcare information infrastructure (Cellına et al., 2023; Hassani et al., 2022). Where costs may pose further enormous barriers in some particular situations, like that of a resource-limited condition, especially in low- and middle-income countries, they may become exacerbated existing inequities regarding accessibility and quality of healthcare. (Vallée, 2023).

While money will certainly be an issue, ease of accessibility will depend more on the techno-literacy of the patient and the healthcare professional themselves. If intermediate interfaces with regular requirement for device calibration and challenges in data interpretation are created, them there would be a big limitation in usability, especially in older adults' populations or in those lacking any digital experience (Zhang et al., 2020). Hence, to overcome this digital divide, investments need to be made not just in technology, but also in education systems, user-centric designs, and support systems that allow all users to interact with digital twin platforms efficiently (Vallée,2023)

Cost containment based on continuity with scalable cloud computing, open-source software, and modular hardware components along with the policy measures for equitable distribution of technology to make sure that the benefits emerging from digital twin applications in healthcare become democratized (Ríos et al., 2020; Siemens Healthineers, 2021).

Standardization and legal regulations

The creation of international standards is critical for digital twin technologies to be integrated safely and effectively in clinical practice and medical decision-making. Integration, and hence a broader usage, become impossible if heterogeneous data formats, variable quality standards, and completely irregular interoperability frameworks exist (Ríos et al., 2020; Hosseini et al., 2021).

New legal and ethical concerns arise with respect to data sharing, ownership, and cross-border transfer of health information. In such cases, the developers of technology, the providers of care, and the users should clearly define their responsibilities and liabilities with respect to failures of the system and erroneous outputs (Cellına et al., 2023). For informed consent, new complexities arise, where patients are expected to understand how their data are used for not only their own care but also potentially for training algorithms and other broader research (Zhao et al., 2024; Balasubramanyam, et al., 2024).

These regulatory bodies' comprehensive frameworks to deal with these issues must harmonize standards across jurisdictions to allow innovation while safeguarding patient rights (Ríos et al., 2020). Clarity between clinicians, technologists, ethicists, and policymakers is essential for the ethical and legally sound application of digital twins in practice (Siemens Healthineers, 2021; Tao et al., 2018).

Conclusion

By offering the possibility for monitoring, modeling, and maintaining an individual body's homeostasis, digital twin technology stands for a radical advance in personalized medicine, the tools of which might only be dreamt of before (Tao et al., 2018; Cellína et al., 2023). Digital twins are transformed from a reactive modality toward a proactive, prevention-predictive-patient treatment model because real-time data streams are all connected into predictive algorithms. Transformational dimensions are already visible in chronic disease management, improved sports performance, public health surveillance, and biomedical research, deeply embedding digital twins into the core future intelligent healthcare systems (Björnsson et al., 2019; Haleem et al., 2023).

Fast evolution and increasing application of digital twins are seen in recent studies from 2020 to 2025. Salvador et al. (2024) showed that digital twin technology, through simulation modeling of cardiac electrophysiology with respect to congenital heart disease, will produce individualized therapy plans. Á GEénRivas et al. (2025) mentioned that digital twin technology changed the parameters describing diabetes care by employing AI to offer real-time glycemic monitoring and dynamic modifications of lifestyle. As such, evidence supporting the ability of digital twins to integrate areas of clinical involvement with individualized therapy becomes undeniable.

Yet many challenges remain before digital health can go mainstream. Data security and privacy remain major issues which need to be solved by means of encryption technology or blockchain technology in compliance with rights established in acts such as GDPR and HIPAA (Vallée, 2023; Zhang et al., 2020). Even under such resources-poor environments, accessibility and affordability pose sometimes significant constraints to the utilization of such tools, warranting some equity distribution of these technologies (Ríos et al., 2020; Balasubramanyam et al., 2024). Moreover, a lack of common standards in data integration and interoperability raises a call for global cooperation to strengthen establishment of international guidelines (Hosseini et al., 2021; Zhao et al., 2024).

The interaction of this technology produces an ethical and legal dilemma. Specifically, issues related to ownership of data, securing informed consent, and attribution of liability in case of erring systems need regulatory frameworks that will safeguard patients' rights and win their trust (Cellína et al., 2023; Siemens Healthineers, 2021). The solution to the above barriers requires a coalition of actors in one multidisciplinary endeavor for responsible innovation: health care providers, engineers, policymakers, and ethicists.

Digital twin technology may thus revolutionize health delivery systems by molding precision medicine into a scalable method for improving health outcomes for larger populations. Addressing current limitations and encouraging global collaboration could guide digital twins toward making the future of healthcare more powerful, intelligent, adaptive, equitable, and patient-centered. Research and advancement of technology will integrate digital twins into the next generation of healthcare systems.

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