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PATIENT DIGITAL TWINS AS THE FOUNDATION OF FUTURE MEDICINE: PERSONALIZED SIMULATION, PREDICTIVE MODELING, AND DATA-DRIVEN CLINICAL DECISION-MAKING

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ABSTRACT

Background: The growing availability of high-resolution imaging, biosensors, molecular profiling, and artificial intelligence has enabled the development of digital patient twins—computational models that reproduce individual physiological and pathological processes in silico. While digital twins have been widely proposed as tools for personalised medicine, their clinical and translational value across major disease domains has not yet been systematically synthesised.

Methods: A narrative review was conducted of full-text publications from 2020–2025 addressing digital patient twins in cardiology, oncology, chronic disease management, and rehabilitation. The analysed literature included translational and clinical studies, mechanistic modelling papers, and healthcare system implementations. Evidence was prioritised from studies reporting patient-specific simulations, comparisons with real clinical or imaging data, and therapy-support scenarios.

Results: In cardiology, electrophysiological and haemodynamic digital twins demonstrated high concordance with invasive mapping and imaging data and were associated with improved ablation planning, device optimisation, and reduced arrhythmia recurrence. In oncology, tumour digital twins integrating imaging and molecular data predicted tumour growth and treatment response with clinically meaningful accuracy, supporting personalised and adaptive cancer therapy. In chronic diseases, sensor-driven digital twins enabled early detection of physiological deterioration and supported proactive intervention, reducing exacerbations and hospitalisations. In rehabilitation, biomechanical and neurophysiological digital twins improved functional recovery by guiding personalised and robot-assisted therapy.

Conclusions: Digital patient twins are transitioning from experimental computational tools to clinically relevant systems capable of influencing diagnosis, therapy selection, monitoring, and patient outcomes. By enabling in silico testing of therapeutic strategies on a virtual representation of the patient, digital twins reduce uncertainty in clinical decision-making and support truly personalised care. Continued progress in data integration, model validation, and regulatory governance will be essential for their safe and widespread adoption in clinical practice.

KEYWORDS

Digital Twins, Patient Modelling, Predictive Medicine, Clinical Simulations, Personalised Therapy, Artificial Intelligence

CITATION

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1. Introduction

Modern medicine increasingly faces a fundamental limitation: while diagnostic technologies and molecular profiling have become extraordinarily detailed, therapeutic decisions are still largely guided by population-based evidence rather than by patient-specific predictions. Clinical guidelines, risk scores, and treatment algorithms are derived from cohorts that average across biological heterogeneity, yet patients with the same diagnosis frequently exhibit markedly different disease trajectories and treatment responses. This gap is particularly evident in complex disorders such as cardiac arrhythmias, heart failure, cancer, and chronic metabolic or neurological diseases, where small differences in anatomy, physiology, or molecular signalling can profoundly alter outcomes [2,6,12,16].

Digital patient twins have emerged as a response to this challenge. A digital twin is a computational model that represents an individual patient by integrating multi-scale data—including medical imaging, physiological signals, laboratory measurements, molecular profiles, and behavioural information—into a dynamic, continuously updatable virtual replica of the patient's biological system [2,8,16]. Unlike traditional clinical risk models, which estimate probabilities based on historical populations, digital twins aim to reproduce the mechanistic behaviour of a specific patient, allowing clinicians to explore how that individual is likely to respond to alternative diagnostic or therapeutic strategies.

The translational relevance of this paradigm is already evident in cardiology. Cardiac arrhythmias and heart failure are driven by patient-specific differences in myocardial structure, electrical conduction, and

haemodynamics that are not fully captured by standard imaging or electrocardiography. Digital twins of the heart integrate cardiac MRI or CT, electroanatomical mapping, and electrophysiological models to simulate the propagation of electrical impulses and mechanical contraction in individual patients. These models enable the virtual testing of ablation strategies, pacing configurations, and pharmacological interventions, allowing clinicians to predict which therapeutic approach is most likely to restore stable rhythm and improve haemodynamic performance before any invasive procedure is performed [1,2,10,14].

A similar need for patient-specific prediction exists in oncology. Tumours with the same histological diagnosis may differ substantially in growth kinetics, metastatic potential, immune interactions, and drug sensitivity. Digital tumour twins combine imaging, molecular tumour profiling, and mathematical models of cell proliferation, angiogenesis, and immune response to simulate tumour evolution and treatment response in individual patients. These models provide a framework for selecting and adapting therapies based not only on tumour type, but on predicted tumour behaviour in a given patient, potentially reducing exposure to ineffective treatments and limiting toxicity [3,5,11,13].

Beyond acute disease management, digital twins are also being applied to chronic disease monitoring and rehabilitation. In conditions such as heart failure, diabetes, chronic obstructive pulmonary disease, and neurodegenerative disorders, clinical deterioration often occurs gradually and is preceded by subtle physiological changes. Wearable sensors and home-monitoring devices now provide continuous streams of data on heart rate, activity, sleep, oxygen saturation, glucose levels, and other biomarkers. When integrated into digital twins, these data allow continuous updating of a patient's virtual model, enabling early detection of destabilisation and proactive adjustment of therapy before clinical decompensation occurs [6,12,15]. In rehabilitation and surgery, biomechanical and neurophysiological digital twins enable precise modelling of movement, load distribution, and neural recovery, supporting personalised planning of interventions and therapy regimens that maximise functional outcomes [16,19,20].

Despite this rapidly growing translational potential, the clinical adoption of digital twins remains uneven. While many modelling frameworks have demonstrated impressive physiological realism, their true value lies in their ability to support real clinical decisions and improve patient-relevant outcomes. Challenges related to data quality, model validation, interoperability, regulatory oversight, and ethical governance must be addressed before digital twins can become routine tools in patient care [4,6–8,12,15,18].

The aim of this narrative clinical review is therefore not simply to describe the architecture of digital twin systems, but to evaluate their evidence-based translational role in medicine. By synthesising current applications in cardiology, oncology, chronic disease management, and rehabilitation, this article examines how digital patient twins are being used to guide therapeutic decisions, what level of clinical validation they have achieved, and what they mean for the future of personalised, predictive healthcare.

2. Methods

This article was conducted as a narrative clinical and translational review, designed to integrate heterogeneous sources of evidence describing the clinical use of digital patient twins in medicine. Because digital twin technology spans multiple methodological domains—including physiological modelling, biomedical engineering, artificial intelligence, and clinical decision support—standard systematic meta-analysis was not feasible. Instead, a narrative framework was used to synthesise mechanistic, translational, and early clinical validation evidence into a coherent clinical perspective [6,8,15,18].

2.1 Literature identification and scope

Full-text peer-reviewed publications from 2020 to 2025 were analysed, reflecting the period in which digital twin technology transitioned from conceptual modelling into translational and clinical experimentation. The reviewed corpus included narrative and systematic reviews [3,6,12,17,18], conceptual and regulatory frameworks [4,8,15,16], and disease-specific translational and clinical studies in cardiology [1,2,10,14], oncology [3,5,11,13], rehabilitation and surgery [16,19,20], and chronic disease management using sensor-driven digital twins [6,12,15].

The inclusion strategy prioritised publications that reported one or more of the following:

- patient-specific digital twin construction,
- validation against clinical or imaging-based measurements,
- simulation of alternative therapeutic strategies,
- impact on clinical decision-making,
- integration of wearable or biosensor data into ongoing patient modelling.

Purely theoretical or engineering-only modelling studies without clinical relevance were used only to support methodological background [8,18].

2.2 Evidence weighting and translational relevance

Because large randomised controlled trials of digital twins remain rare, the analysed literature was weighted according to translational proximity to patient care rather than study design alone. Evidence was classified into three tiers:

1. Clinical–translational evidence
2. Studies reporting patient-specific digital twin simulations validated against invasive measurements, imaging, or observed clinical outcomes, including ablation planning, device optimisation, tumour response prediction, and rehabilitation guidance [1,2,10,11,13,14,16,19,20].
3. Mechanistic–clinical modelling evidence
4. Studies linking physiological or tumour models to patient-derived data such as MRI, CT, molecular profiling, or continuous biosignals, providing mechanistic explanations of disease behaviour and treatment response [2,3,5,8,12,14,16,18].
5. Conceptual, ethical, and systems-level frameworks
6. Publications addressing governance, interoperability, regulatory issues, and health-system integration of digital twins, used to contextualise clinical implementation [4,6,7,15,18].

This approach allowed integration of quantitative, mechanistic, and clinical information into a unified translational narrative.

2.3 Analytical framework

The literature was analysed using a disease-anchored clinical framework, structured around the following dimensions:

1. Disease context
2. Identification of clinical problems for which digital twins are being applied (e.g., arrhythmias, cancer, heart failure, neurological disability) [1–3,10–14,16].
3. Clinical decision point
4. Description of how the digital twin informs a specific therapeutic or diagnostic choice, such as ablation strategy, drug selection, radiation dosing, or rehabilitation planning [1,2,5,10,11,16,19].
5. Model–data integration
6. Assessment of how patient-specific data (imaging, biosignals, biomarkers, wearables) are incorporated into the digital twin and how uncertainty is managed [6–8,12,14–16,18].
7. Validation and outcome relevance
8. Evaluation of concordance between digital twin predictions and observed physiological, imaging, or clinical outcomes [1,2,10–14,16,19].
9. Clinical and ethical implications
10. Analysis of how digital twins affect patient safety, data governance, equity, and regulatory oversight [4,6,7,12,15,18].

2.4 Synthesis of findings

Findings from individual publications were integrated through qualitative synthesis rather than statistical pooling. Studies were compared to identify:

- common modelling strategies,
- consistency of validation approaches,
- recurring clinical use cases,
- and shared implementation barriers.

This allowed the development of a structured, evidence-based narrative describing where digital patient twins currently provide clinically meaningful support and where further validation is required [6,12,16].

3. Results

The reviewed literature demonstrates that digital patient twins are being actively translated into clinical and translational workflows across several major disease domains, with cardiology, oncology, chronic disease management, and rehabilitation representing the most mature and clinically relevant areas of application. Across these domains, digital twins are not used as abstract computational constructs but as patient-specific decision-support systems that integrate heterogeneous clinical data to guide diagnostic and therapeutic choices [2,6,12,16].

3.1 Digital Twins in Cardiology

Cardiology currently represents the most mature clinical domain for the application of digital patient twins, owing to the long-standing use of biophysical models of cardiac electrophysiology and haemodynamics combined with high-resolution imaging and continuous physiological monitoring. Contemporary cardiac digital twins integrate anatomical data from cardiac MRI or CT, intracardiac or surface electrocardiography, haemodynamic measurements, and wearable sensor data to generate patient-specific computational representations of cardiac structure and function [1,2,10,14].

These models are not limited to anatomical visualisation but aim to reproduce the biophysical mechanisms that generate cardiac rhythm, contraction, and blood flow. As a result, digital twins can simulate how an individual heart responds to pacing, ablation, pharmacotherapy, or mechanical loading, providing a virtual test environment for therapeutic decision-making prior to intervention [1,2,10,14].

3.1.1 Electrophysiological digital twins

The most advanced clinical implementations of cardiac digital twins are found in the field of cardiac electrophysiology. Patient-specific electrophysiological twins are constructed from MRI- or CT-derived chamber geometry, myocardial fibre orientation, ionic current kinetics, and regionally heterogeneous conduction properties reflecting fibrosis, infarction, or ischaemia [1,2,10]. These models reproduce the spatial and temporal propagation of action potentials through atrial and ventricular myocardium, enabling the simulation of arrhythmogenic mechanisms such as re-entry, conduction block, and wavefront fragmentation.

Crucially, electrophysiological digital twins have progressed beyond theoretical modelling into clinical validation studies. In cohorts of patients undergoing catheter ablation for atrial or ventricular arrhythmias, personalised *in silico* activation maps generated by digital twins demonstrated high spatial concordance with invasive electro-anatomical mapping, typically exceeding 80–90% overlap between simulated and recorded activation patterns [1,2,10]. These models have been used to virtually test alternative ablation lesion sets, allowing clinicians to identify critical conduction pathways and arrhythmia drivers prior to the procedure.

In translational studies, digital twin-guided ablation planning was associated with clinically meaningful improvements in procedural efficacy. Compared with conventional mapping-guided ablation, twin-informed strategies reduced post-procedural arrhythmia recurrence and improved acute termination rates in selected patient cohorts, demonstrating that patient-specific modelling can influence real clinical outcomes rather than merely reproducing physiological signals [1,2,10].

3.1.2 Haemodynamic and biomechanical digital twins

In parallel with electrophysiological modelling, cardiac digital twins increasingly incorporate biomechanical and haemodynamic components that simulate myocardial contraction, ventricular pressure–volume relationships, heart–vessel coupling, vascular compliance, and systemic resistance [2,10,14]. These models enable the assessment of both systolic and diastolic function under physiological conditions and in disease states such as heart failure, pulmonary hypertension, and coronary artery disease.

In patient-specific haemodynamic twins, predicted ventricular pressures, stroke volumes, and flow patterns have shown close agreement with measurements obtained from echocardiography, cardiac catheterisation, and MRI, typically within 5–15% error across clinically relevant ranges [2,10,14]. Such accuracy allows digital twins to be used for therapeutic scenario testing, including the evaluation of preload and afterload changes, the haemodynamic impact of pharmacological therapy, and the optimisation of device-based interventions.

In heart failure populations, haemodynamic digital twins have been used to stratify patients likely to respond to cardiac resynchronisation therapy (CRT) by simulating ventricular synchrony and mechanical efficiency under different pacing configurations. These models improve discrimination between responders and non-responders compared with imaging alone, supporting more precise selection of patients for device implantation and reducing the risk of ineffective therapy [2,10,14].

3.1.3 Integration of wearable and sensor data

The clinical relevance of cardiac digital twins is further enhanced by the integration of continuous physiological data from wearable and implantable sensors. Modern biosensors provide high-frequency measurements of heart rhythm, heart rate variability, oxygen saturation, physical activity, sleep patterns, and peripheral perfusion, enabling digital twins to be dynamically updated as a patient's physiological state evolves [10,14,15].

In longitudinal monitoring cohorts, wearable-enhanced digital twins have demonstrated the ability to detect subtle deviations from baseline physiology days to weeks before clinically overt deterioration. Early signatures of decompensated heart failure, atrial fibrillation recurrence, or myocardial ischaemia can be identified through model-based trend analysis, enabling earlier therapeutic intervention and potentially preventing hospitalisation or adverse cardiac events [10,14,15].

3.1.4 Clinical decision support

By integrating electrophysiological, haemodynamic, and continuous sensor data, cardiac digital twins provide a unified platform for patient-specific therapeutic decision-making. Clinically, these models have been applied to ablation planning, optimisation of implantable cardioverter-defibrillator (ICD) and cardiac resynchronisation therapy (CRT) settings, and the selection and dosing of cardiotropic pharmacotherapy [2,10,14].

In translational cardiology studies, digital twin-guided therapy planning has been associated with improved procedural outcomes, reduced arrhythmia recurrence, and better haemodynamic optimisation compared with standard-of-care strategies. By allowing multiple treatment scenarios to be tested virtually before clinical implementation, digital twins reduce uncertainty, support personalised therapy selection, and help align interventions with the unique physiological profile of each patient [2,10,14].

3.2 Digital Twins in Oncology

Oncology represents one of the most compelling application domains for digital patient twins due to the extreme biological heterogeneity of tumours and the resulting variability in therapeutic response. Patients with histologically similar cancers frequently exhibit markedly different growth kinetics, treatment sensitivities, and resistance mechanisms, making empirical therapy selection highly inefficient and clinically risky [3,5,11,13]. Digital tumour twins aim to address this challenge by integrating imaging, molecular profiling, and mathematical models of tumour-microenvironment interactions into patient-specific computational representations of cancer progression and treatment response.

Contemporary oncological digital twins combine radiological data from CT, MRI, or PET imaging with genomic, transcriptomic, and immunological tumour characteristics to generate dynamic models of tumour growth, vascularisation, and immune interaction [3,11,13]. These models move beyond static staging by providing patient-specific predictions of how a tumour is likely to evolve under different therapeutic conditions, creating a virtual testbed for precision oncology.

3.2.1 Modelling tumour dynamics

Digital tumour twins are designed to reproduce multiscale cancer dynamics by coupling cellular-level processes with tissue-level and systemic interactions. Current models incorporate tumour cell proliferation rates, invasive potential, angiogenesis, metabolic activity, immune cell infiltration, and molecular pathway activation, enabling reconstruction of tumour growth trajectories over time [3,11,13].

In translational oncology cohorts, digital twin-based predictions of tumour volume, growth rate, and spatial invasion patterns have demonstrated strong agreement with longitudinal imaging data. Reported correlations between simulated and observed tumour growth commonly range from $r = 0.70$ to 0.90 across different cancer types and imaging modalities, indicating that digital twins can reliably reproduce individual tumour dynamics [3,11,13]. This level of accuracy enables clinicians to forecast progression risk and evaluate how rapidly a tumour is likely to become clinically critical if left untreated or insufficiently treated.

3.2.2 Prediction of therapeutic response

Beyond modelling natural tumour evolution, digital twins have been developed to simulate response to major oncological therapies, including cytotoxic chemotherapy, targeted agents, radiotherapy, and immunotherapy. By integrating tumour-specific molecular signatures with drug-tumour interaction models and radiation sensitivity parameters, digital twins can predict how a given patient's tumour is likely to respond to different treatment regimens [3,5,11,13].

In translational and early clinical studies, tumour digital twins have been able to classify responders versus non-responders to specific therapies with clinically meaningful accuracy. Reported discrimination

performance for therapy response prediction typically falls in the AUC range of 0.70–0.85, depending on cancer type and treatment modality [3,11,13]. These predictions allow clinicians to compare alternative therapeutic strategies *in silico* before initiating treatment, reducing reliance on trial-and-error approaches that expose patients to ineffective or toxic therapies.

Importantly, simulation-guided therapy selection has been associated with improved tumour control probability and progression-free survival in pilot patient cohorts, indicating that digital twin–based decision support can influence real oncological outcomes rather than merely predicting imaging changes [5,11,13].

3.2.3 Uncertainty-aware and probabilistic modelling

Cancer biology is inherently stochastic, with substantial variability arising from genetic heterogeneity, microenvironmental influences, and measurement noise. Modern digital tumour twins therefore increasingly incorporate probabilistic and uncertainty-aware modelling frameworks that explicitly quantify confidence in predictions rather than producing single deterministic forecasts [3,8,18].

These models provide confidence intervals for tumour growth predictions, probabilities of alternative progression pathways, and estimated risks of treatment failure. By expressing uncertainty, digital twins allow clinicians to evaluate not only the most likely outcome but also the range of plausible scenarios, enabling more robust risk–benefit assessment when selecting therapies in high-risk or borderline clinical situations [3,8,18].

3.2.4 Adaptive digital twin–guided therapy

A defining advantage of oncological digital twins is their capacity for adaptive updating as new clinical data become available. Through the integration of serial imaging, circulating biomarkers, and treatment response measurements, tumour twins can be recalibrated over time to reflect evolving tumour biology [5,11,13].

This enables dynamic simulation of alternative treatment pathways as resistance emerges or disease behaviour changes. In practice, digital twin–guided adaptive therapy allows clinicians to adjust drug selection, dosing intensity, or radiotherapy schedules in response to model-predicted tumour trajectories, with the goal of maximising tumour control while minimising cumulative toxicity and delaying the development of resistance [5,11,13].

By linking real-time patient data with predictive modelling, adaptive digital twins move oncology from static protocol-based treatment toward continuous, model-guided personalisation of cancer therapy.

3.3 Digital Twins in Chronic Diseases

Chronic diseases such as heart failure, chronic obstructive pulmonary disease (COPD), diabetes mellitus, and neurodegenerative disorders are characterised by long-term progression, episodic exacerbations, and substantial inter-individual variability in disease trajectories and treatment response. Traditional episodic clinical monitoring often fails to detect early physiological deterioration, leading to delayed intervention, preventable hospitalisations, and accelerated disease progression [6,7,12]. Digital patient twins offer a fundamentally different paradigm by providing continuously updated, patient-specific models capable of forecasting deterioration before clinical decompensation becomes evident.

By integrating physiological measurements, behavioural data, treatment adherence, and historical clinical records, chronic-disease digital twins generate dynamic representations of a patient's health trajectory rather than static snapshots. These models allow clinicians to assess how disease processes evolve over time and how individual patients respond to therapy in their everyday environment rather than only during hospital visits [6,12,15].

3.3.1 Real-time physiological monitoring

The deployment of wearable sensors, home monitoring devices, and mobile health platforms enables continuous acquisition of clinically relevant physiological and behavioural parameters, including respiratory rate, oxygen saturation, blood glucose levels, heart rate variability, physical activity, sleep patterns, and pharmacological response [12,14,15]. These high-frequency data streams are assimilated into patient-specific digital twins, allowing real-time tracking of disease dynamics.

In longitudinal monitoring cohorts comprising hundreds to thousands of patients, digital twin-based models have demonstrated the ability to identify early deviations from baseline physiology that precede clinical exacerbations. In heart failure and COPD populations, early warning systems driven by digital twins achieved sensitivities in the range of 75–90% and specificities of 70–85% for predicting impending decompensation several days before hospital admission would otherwise be required [6,12,14,15]. This predictive capability enables proactive clinical intervention, such as medication adjustment or early outpatient review, rather than reactive emergency care.

3.3.2 Early detection of disease exacerbations

Digital twins excel in detecting subtle, multivariate physiological patterns that are invisible to conventional threshold-based monitoring. In chronic heart failure, small changes in heart rate variability, activity level, and peripheral perfusion can be integrated by the digital twin to predict fluid overload and haemodynamic instability. In COPD, combinations of respiratory rate, oxygen saturation, and sleep quality predict acute exacerbations, while in diabetes, glycaemic variability and behavioural patterns indicate metabolic destabilisation [6,12,14].

Across multiple chronic disease cohorts, digital twin-based early detection systems have been associated with reductions in emergency hospitalisation rates and shorter duration of exacerbation episodes, demonstrating that predictive modelling translates into clinically meaningful benefits rather than merely technical performance [6,12,14].

3.3.3 Long-term treatment optimisation

A central advantage of chronic-disease digital twins is their ability to simulate alternative management strategies over extended time horizons. By modelling how individual patients respond to medication dose changes, lifestyle interventions, rehabilitation programmes, or adherence patterns, digital twins enable clinicians to explore personalised treatment trajectories before implementing them in real life [12,15].

In real-world monitoring studies, digital twin-guided therapy optimisation has been associated with improved disease control, fewer acute exacerbations, and more stable physiological profiles compared with conventional guideline-driven management. This model-based approach supports a shift from static, population-based treatment algorithms toward continuously adaptive, patient-specific care pathways [12,15].

3.4 Digital Twins in Rehabilitation and Biomechanics

Rehabilitation medicine increasingly relies on precise, patient-specific modelling of musculoskeletal and neurophysiological function to optimise recovery after injury, stroke, surgery, and neurodegenerative disease. Traditional rehabilitation protocols are largely based on population averages and subjective functional assessment, leading to substantial variability in recovery rates and long-term outcomes [16,19,20]. Digital twins provide a quantitative framework for modelling movement, force generation, neural control, and adaptive motor learning, enabling personalised rehabilitation planning and outcome prediction.

By integrating imaging, motion capture, electromyography, force plate data, and neurophysiological signals, rehabilitation digital twins generate computational representations of how individual patients move, compensate, and adapt during recovery. These models allow clinicians to test alternative therapy strategies in silico and to predict how specific interventions will influence functional recovery over time [16,20].

3.4.1 Musculoskeletal digital twins

Musculoskeletal digital twins reconstruct individual bone and joint geometry, muscle-tendon dynamics, mechanical loading, and gait or limb movement patterns. Using imaging and motion analysis, these models quantify joint torques, muscle activation patterns, and load distribution across the musculoskeletal system [16,20].

In clinical and translational rehabilitation cohorts, musculoskeletal twins have demonstrated high agreement with experimental biomechanics, with errors in joint angle and force estimation typically below 10–15% compared with laboratory-based motion capture and force plate measurements [16,20]. This accuracy enables identification of compensatory movement strategies, abnormal joint loading, and biomechanical inefficiencies that contribute to pain, fatigue, and injury recurrence. Twin-guided therapy planning allows therapists to target specific muscles, adjust exercise intensity, and reduce pathological load patterns, supporting more efficient and safer rehabilitation.

3.4.2 Neurophysiological digital twins

In neurological rehabilitation, digital twins are used to model neural reorganisation and recovery following stroke, spinal cord injury, traumatic brain injury, or neurodegenerative disease. By integrating neuroimaging, electrophysiological signals, and functional performance data, these models estimate cortical plasticity, motor pathway integrity, and compensatory neural mechanisms [12,16].

In translational studies, neurophysiological digital twins have been shown to predict recovery potential and functional improvement trajectories with clinically useful accuracy, enabling stratification of patients likely to benefit from intensive therapy, robotic assistance, or neurostimulation. This supports personalised rehabilitation intensity and modality selection rather than uniform, one-size-fits-all protocols [12,16].

3.4.3 Integration with robotics and virtual reality

Digital twins form the computational backbone of advanced rehabilitation technologies, including exoskeletons, therapeutic robots, brain–computer interfaces, and virtual reality (VR) systems for motor re-education. By linking patient-specific biomechanical and neural models with robotic controllers and VR environments, digital twins enable real-time, adaptive therapy delivery tailored to the patient’s current functional state [16,20].

In clinical rehabilitation programmes, twin-driven robotic and VR-assisted therapies have been associated with faster functional recovery, improved motor scores, and higher patient engagement compared with conventional physiotherapy alone. This integration transforms rehabilitation from a subjective, therapist-driven process into a quantitative, model-guided system that continuously adapts to each patient’s progress [16,20].

4. Discussion

Digital patient twins have reached a critical point in their evolution from theoretical computational constructs to clinically relevant decision-support systems. The evidence synthesised in this review demonstrates that patient-specific digital twins can now reproduce key physiological and pathological processes with sufficient accuracy to influence real clinical decisions in cardiology, oncology, chronic disease management, and rehabilitation [1–20]. Importantly, these models are no longer evaluated solely against imaging or physiological measurements, but increasingly against clinical endpoints such as arrhythmia recurrence, tumour progression, disease exacerbation, and functional recovery.

Across multiple disease domains, digital twins have demonstrated the ability to improve the alignment between therapeutic decisions and individual patient biology. In cardiology, electrophysiological and haemodynamic twins support ablation planning and device optimisation, reducing arrhythmia recurrence and improving haemodynamic response [1,2,10,14]. In oncology, tumour digital twins predict growth dynamics and therapy response with clinically meaningful accuracy, supporting personalised treatment selection and adaptive therapy [3,5,11,13]. In chronic diseases, sensor-driven twins enable early detection of decompensation, reducing emergency hospitalisations and supporting proactive care [6,12,14,15]. In rehabilitation, biomechanical and neurophysiological twins improve functional recovery by enabling personalised, model-guided therapy [12,16,19,20].

These findings indicate that digital twins are beginning to function as clinical “decision amplifiers,” transforming large, heterogeneous patient data into actionable predictions that directly affect patient outcomes. Unlike conventional predictive models that rely primarily on statistical correlations, digital twins integrate mechanistic understanding with data-driven inference, allowing them to generalise across scenarios and remain clinically interpretable [2,6,8,16,18].

4.1 Clinical relevance and translational value

The central translational value of digital twins lies in their ability to connect individual patient data with treatment decisions and outcomes. In traditional clinical care, therapeutic strategies are often selected based on population averages derived from clinical trials, leaving clinicians to infer how an individual patient will respond. Digital twins invert this paradigm by enabling *in silico* testing of therapies on a virtual replica of the patient before intervention [2,6,12].

The results summarised in this review demonstrate that this paradigm is no longer hypothetical. In cardiology and oncology, digital twins already achieve prediction accuracies and outcome improvements that are clinically meaningful, supporting their use in therapy selection, risk stratification, and longitudinal disease management [1–5,10–14]. As these systems mature, they have the potential to reduce ineffective treatments, minimise adverse events, and shorten the time to optimal therapy for complex patients.

4.2 Data quality, uncertainty, and reliability

Despite these advances, the reliability of digital twins remains strongly dependent on the quality and completeness of the data used to construct and update them. Heterogeneous data sources—ranging from imaging and biosensors to electronic health records—introduce noise, bias, and missingness that propagate into model predictions [6–8,12,15,18]. Without appropriate uncertainty modelling, this variability risks misleading clinicians and patients.

The integration of probabilistic frameworks, as demonstrated in modern tumour and chronic disease twins, represents a critical step toward clinically safe deployment [3,8,18]. By explicitly quantifying

confidence intervals and risk distributions, digital twins allow clinicians to interpret predictions within a risk-aware decision-making framework rather than as deterministic forecasts.

4.3 Validation and clinical governance

A major challenge for the widespread adoption of digital twins lies in their validation and regulatory oversight. Unlike static medical devices, digital twins are adaptive systems that evolve as new data become available. This requires validation frameworks that go beyond one-time approval and instead support continuous performance monitoring and periodic re-certification [4,6,7,12,18].

The evidence reviewed here indicates that validation against both physiological data and clinical outcomes is feasible and increasingly common. However, standardised benchmarks, reporting guidelines, and quality metrics will be required to ensure that digital twins are safe, reliable, and comparable across healthcare systems.

4.4 Ethical and societal implications

The clinical power of digital twins also raises important ethical considerations. Because these models integrate genetic, behavioural, and physiological data into a unified patient representation, they create new risks related to privacy, ownership, and algorithmic bias [4,6,7,12,15,18]. Patients must retain meaningful control over their digital twins, and safeguards must be established to prevent misuse in insurance, employment, or discrimination.

Equally important is the risk of unequal access. If digital twin technologies are available only in well-resourced healthcare systems, they may widen existing health disparities rather than reduce them [6,7,12,13,15]. Addressing this challenge requires both technical and policy-level interventions.

4.5 Future clinical integration

Looking forward, digital twins are poised to become a central component of predictive, preventive, and personalised medicine. The integration of mechanistic models with artificial intelligence, high-resolution biosensors, and longitudinal patient data will further enhance their predictive accuracy and clinical utility [1,5,6,8,12,14,16].

As these systems become embedded in routine care, they have the potential to shift healthcare from reactive intervention toward proactive, model-guided disease management. In this paradigm, clinicians will no longer ask only “what is happening now?” but also “what will happen to this patient if we choose this therapy rather than another?”—a question that digital twins are uniquely equipped to answer.

5. Conclusions

Digital patient twins have evolved from experimental computational models into clinically relevant systems capable of supporting diagnosis, therapy selection, monitoring, and outcome prediction across multiple disease domains. The evidence synthesised in this review demonstrates that patient-specific digital twins can reproduce key physiological and pathological processes with sufficient accuracy to inform real clinical decisions in cardiology, oncology, chronic disease management, and rehabilitation [1–20].

In cardiology, electrophysiological and haemodynamic digital twins enable personalised ablation planning, device optimisation, and pharmacological strategy selection, contributing to improved arrhythmia control and haemodynamic outcomes [1,2,10,14]. In oncology, tumour digital twins integrate imaging and molecular data to predict growth dynamics and treatment sensitivity, supporting adaptive, precision-guided cancer therapy [3,5,11,13]. In chronic diseases, continuously updated twins allow early detection of physiological deterioration, enabling proactive intervention and reducing avoidable hospitalisations [6,12,14,15]. In rehabilitation, biomechanical and neurophysiological twins support personalised therapy planning and robotic assistance, improving functional recovery and long-term outcomes [12,16,19,20].

Together, these findings indicate that digital twins are beginning to move beyond technological demonstration toward measurable clinical impact. By enabling *in silico* testing of therapeutic strategies on a virtual representation of the patient, digital twins reduce uncertainty in clinical decision-making, shorten the time to optimal therapy, and increase the likelihood that each patient receives the treatment most compatible with their individual biology.

However, the safe and effective deployment of digital twins in routine care will require continued progress in data integration, uncertainty modelling, validation frameworks, and regulatory governance. Robust

standards for model performance, transparency, and ethical oversight are essential to ensure that digital twins are used responsibly and equitably across healthcare systems [4,6,7,12,15,18].

As high-resolution biosensors, advanced imaging, and artificial intelligence continue to mature, digital twins are poised to become a foundational component of predictive and preventive medicine. By shifting clinical care from reactive intervention toward continuous, model-guided personalisation, digital twins have the potential to fundamentally transform how diseases are detected, treated, and ultimately prevented.

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4. Julia Weronika Mieszkowska, Anna Kinga Tejchma – Data analysis; Visualization; Language editing
5. Paulina Jarząbek, Anna Kinga Tejchma – Investigation; Interpretation of results.
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