Designing the Future of Healthcare: The Role of Design Research in Shaping Digital Twin Technologies

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Digital twins, which are virtual representations of physical objects or systems, are set to revolutionise healthcare. This position paper argues that design research practices will play a crucial role in shaping the responsible development and adoption of digital human twins in healthcare. While digital twins offer immense potential for personalised medicine, predictive healthcare, and improved patient outcomes, they also present significant technical, operational, and ethical challenges. The paper explores these challenges and opportunities based on review of the literature and a thought leadership workshop. Challenges include data governance, privacy concerns, and the need for cross-disciplinary collaboration. It highlights opportunities, such as accelerated medical training, expanded access to care, and enhanced decision-making processes. The authors emphasise the importance of design research methods, including speculative design and participatory approaches, in addressing complex healthcare issues and fostering responsible innovation. By engaging diverse stakeholders and employing human-centred design principles, researchers can navigate the ethical implications of digital twins while harnessing their transformative potential. The paper concludes with recommendations for researchers, emphasising the need for holistic perspectives, diverse design contributions, and integration of digital twins throughout the healthcare journey.

Keywords: digital twins, healthcare, design, speculative design, responsible innovation

Introduction

Digital twins are virtual representations of physical objects or systems that are linked to their real-world counterparts through continuous data exchange. Often generated through 3D modelling and simulation, digital twins allow detailed analysis and monitoring of the physical twin (Tao et al., 2018). While initially used in manufacturing and robotics, digital twin technology is now expanding into sectors like healthcare that deal with complex living systems (Lauer-Schmaltz et al. 2024; He et al. 2024).

Digital twin technologies offer immense potential to transform healthcare through personalized virtual models that can predict disease, test treatments, and optimize care pathways (Park et al. 2019; Katsoulakis et al. 2024). However, realizing this future requires overcoming significant technical, operational, and ethical challenges around data governance, mitigating bias, managing risks like privacy violations, and bridging gaps in regulation and clinical workflows.

At the same time, digital twins present powerful opportunities to accelerate medical training, expand access to underserved populations, rethink disease prevention, reduce diagnostic blind spots, and enhance shared decision-making between providers and patients. But harnessing these opportunities responsibly hinges on unprecedented cross-disciplinary collaboration and public trust-building.

This paper argues that design research practices will play a crucial role in shaping the responsible development and adoption of digital human twins in healthcare. Designers, working closely with clinicians, patients and ethicists, can help ensure these emerging technologies are transparent, accessible and focused on improving health outcomes for all.

The Development of Digital Twins

Michael Grieves coined the digital twin (DT) term in 2002, and this was used by Jonathan Vickers, NASA, in 2010. The principle follows that a high-level virtual replica of a component object or real-world system allows near real-time monitoring, analytics, maintenance, simulation and prediction for optimization and efficiency. However, digital twin definitions across sectors are highly debated, and there is no working consensus, competing maturity models, and emergent standards (Katsoulakis et al.

2024). Various national government definitions are emergent, such as the UK's Department of Science, Information and Technology (DSIT):

"A digital twin is a virtual model of an object, a system, or a process. It is connected to its real-world counterpart by a 2-way flow of right-time data, meaning it mimics it in all aspects. This helps us test decisions before we make them and understand how different actions might affect the real world. However, it is essential that at all times, the real-world counterpart is able to continue to operate safely and securely without its digital twin." (DSIT 2024)

For healthcare, digital twin approaches have embryonic possibilities in individual scale replication, such as diagnostic and monitoring equipment (medical robotics) and strategic healthcare at scale for publics using geographic information systems (Health GIS) for resource management and health geo-demographics. The origins of DTs fail to mention the already established range of technologies and simulations that effectively form a longer project for embedding computation, modelling and robotics in healthcare. This longer project cannot be separated from ethical and socio-technical relationships as well as from a political choice, making the DT space a critical problem space for experimentation on the future we want and those we do not. The embryonic technology and the problem space described are areas in which design research adds critical value in working across disciplines.

For example, the release of the computer game SimHealth (Thinking Tools, 1994) sought to simulate and 'game' American healthcare during the Clinton healthcare plan reforms (1993), juxtaposing the simulation with real-world health politics. The Markle Foundation commissioned Maxis Business Solutions to create SimHealth in order to provide a game experience of complex policy and health care. The game was released on Capitol Hill, and copies were provided to lobbyists and the White House

(Salvador, 2020). This simulation demonstrated how computational models can influence real-world policy decisions by allowing stakeholders to explore different scenarios and their potential consequences. Much like SimHealth's role in healthcare policy formation, modern digital twins serve as sophisticated decision-support tools that enable stakeholders to test and evaluate different approaches before implementation. This parallel highlights how virtual representations can bridge the gap between theoretical planning and practical implementation in healthcare systems.

Methodology

This paper's findings are based on a comprehensive literature review and insights from a thought leadership workshop held in March 2024 at Lancaster University. The literature review examined current research on digital twins in healthcare, focusing on technical developments, challenges, opportunities, and ethical considerations.

The literature review was conducted using systematic search strategies across major academic databases including Web of Science, Scopus, and PubMed. Key search terms included combinations of "digital twin*" AND ("healthcare" OR "health" OR "medical"), as well as related terms such as "virtual patient", "patient simulation", and "medical digital twin". Additional searches included "design research" AND "digital twin*" to capture design-specific literature. The review focused on papers published between 2018-2024, encompassing both theoretical frameworks and practical applications.

The workshop, titled "Designing the Future of Digital Twins in Healthcare," brought together 22 experts from diverse fields including medicine, engineering, computer science, design, and ethics. Participants represented institutions such as

Lancaster University, Durham University, Sheffield Hallam University, and the National Physical Laboratory.

The workshop format included presentations on the current digital twin landscape in healthcare, breakout sessions exploring challenges and opportunities for design in digital healthcare twins, and a session on speculative design approaches. Key activities included mapping stakeholders and identifying potential collaborators for future research.

This mixed-method approach, combining literature analysis with expert insights from the workshop, allowed for an exploration of the role of design in shaping the responsible development and adoption of digital human twins in healthcare. It provided a platform for cross-disciplinary dialogue and helped identify key areas where design research and speculative design can inform patient-centric digital twin solutions.

Challenges, Opportunities and Stakeholders

There are a significant and potentially endless number of challenges, opportunities and stakeholders related to the development and implementation of digital human twins in healthcare some of which were revealed in the workshop and listed in Table 1. These are discussed in relation to relevant literature below.

Table 1: Key challenges, opportunities and stakeholders discussed in the workshop

Challenges	**Opportunities**	**Key Stakeholders**
Technical:	***Medical Training:***	***Industry:***
- Need for longitudinal patient data	- Risk-free simulation environments	- Consumer tech tracking companies
	- Surgery practice	- Medical device manufacturers
- Keeping pace with AI and sensor advancements	- Rare disease response rehearsal	- Sensor hardware companies

		- Simulation platform providers
Operational:	***Research:***	- Pharmaceutical companies
- Traditional funding models lack agility	- Virtual trials for vulnerable populations	- Cybersecurity firms
- Immature imaging and sensing technologies	- Expanded care access for underserved communities	
- User acceptance hurdles	- Accelerated R&D pipelines	***Academia:***
		- Medicine
Ethical:	***Patient Care:***	- Bioengineering
- Prioritizing life-saving vs care improvement	- Comprehensive disease visualization	- Computer science
- Risk of eroding personalized care	- Shift towards preventative, holistic care- Health economics	- Health economics
- Potential exacerbation of health inequalities	- Optimization of medication regimes	- Ethics
		- Design
Data-related:	***Innovation:***	-Sociology
- Ensuring representative datasets	- Incorporation of consumer self-tracking data	
- Upholding data privacy and consent standards	- Data storytelling	***Other:***
- Addressing historic biases in medical research	- Policy impact simulation	Healthcare providers (Doctors, Care managers, Patient advocates)
		Policymakers and Regulators (Government healthcare agencies, Ethics Review Boards, Standards bodies)

		Third sector (NGOs, Media, Charities)
		Public

Challenges:

Realizing the full potential of digital twins in healthcare faces significant challenges across technical, operational, and ethical dimensions. On the technical front, longitudinal patient data spanning long time periods is required to create comprehensive digital twin models that can accurately simulate disease progression and treatment responses (Saracco, 2019). Integrating these data-hungry technologies with existing NHS systems and data infrastructures pose obstacles (Alazab et al. 2022; Vallée, 2023). Moreover, the breakneck pace of AI and sensor advancements is outpacing the ability of regulations, data governance frameworks, and ethical guidelines to adapt (Mathews et al. 2020). This raises concerns around unintended consequences of flawed models, misuse of personalized digital twins, and perpetuating biases baked into training data (Rajkomar et al. 2018; Topol, 2019).

Operational barriers loom large as well. Traditional funding models and research paradigms lack the agility to keep up with the iterative, multi-disciplinary nature of digital twin development (Delgado and Oyedele, 2021). Key imaging and sensing technologies underpinning digital twins, like whole-body scanners, remain immature (Pesapane et al, 2022) and expensive. User acceptance hurdles exist, with scepticism around autonomous AI systems making life-critical medical decisions (Topol, 2019). Healthcare workers will require extensive training on using and interpreting digital twin outputs. Fundamentally, the complexity and computational intensity of modelling entire

human bodies over decades strains current technical capabilities (Saracco, 2019; Lauer-Schmaltz et al. 2024).

Ethical minefields must be carefully navigated, including how to prioritize using digital twins to save lives versus improving care, mitigating risks of eroding personalized care and over-reliance on in silico clinical trials, and preventing exacerbation of health inequalities (Bruynseels et al. 2018; Huang et al. 2022). Data-related quandaries loom large - like ensuring representative datasets that capture diversity, upholding data privacy and consent standards, and determining acceptable testbeds given historic biases in medical research (Popa 2021; Noroni et al. 2021).

Opportunities:

In spite of the formidable challenges, digital twins present a multitude of promising opportunities across the healthcare landscape. They might enable relatively risk-free simulation environments for medical training, from surgery practice to rehearsing rare disease response (Alazab et al. 2022; Valee, 2023; Katsoulakis et al. 2024). Entirely new avenues for ethical research open up, like virtual trials for vulnerable populations where conventional studies are unviable. Underserved communities could potentially see care access expand through personalized virtual care pathways. By partnering with industry and leveraging AI, digital twins could accelerate healthcare R&D pipelines through several mechanisms: enabling rapid virtual testing of drug candidates before clinical trials, simulating patient responses to new treatments across diverse populations, and identifying potential complications earlier in the development process. This approach could potentially reduce development timelines and costs while improving safety testing protocols.

The rich longitudinal patient datasets accumulating in the NHS are fertile ground for model training. Digital twins could empower clinicians and patients to visualize disease comprehensively, challenge ingrained treatment conventions, and shift focus towards preventative, holistic care approaches incorporating environmental and lifestyle factors - a paradigm shift from reactive symptom management (Sun et al. 2023, Armeni et al. 2022). Largely untapped domains like mental health and well-being represent greenfield opportunities. Digital twins could potentially map mental health through multiple data streams, including behavioural patterns from mobile devices, voice analysis for emotional states, sleep patterns, social interaction metrics, and physiological stress indicators. These emotional and behavioural digital twins could integrate both quantitative bio signals (heart rate variability, cortisol levels) and qualitative data (mood journals, therapeutic interactions) to create holistic models of mental well-being. Such approaches could help identify early warning signs of mental health challenges and personalize interventions while maintaining patient privacy and agency.

Incorporating consumer self-tracking data, qualitative observations, and other contextual signals could forge digital twins that holistically capture lived health experiences beyond clinical measures (Haleem et al. 2023). Public health researchers could harness models to simulate policy impacts. New frontiers in user interaction and data storytelling could enhance shared decision-making between providers and patients. With diverse stakeholder involvement, blind spots around underrepresented subgroups like women could diminish. Digital twins may optimize medication regimes, or run virtual trials too risky for sensitive groups like pregnant women.

Key Stakeholders:

Responsibly unlocking digital twins' transformative potential requires bridging diverse stakeholder groups. In industry, partners are needed from cybersecurity, sensor hardware, simulation platforms, pharma, medical devices, and consumer tech tracking domains. Academia must integrate interdisciplinary know-how - medicine, bioengineering, computer science, health economics, ethics, design, sociology and more. Policymakers, regulators, standards bodies, government healthcare agencies and ethics review boards all have critical governance roles.

On healthcare's front lines, providers from doctors to care managers along with patient advocates are essential voices. Managers stewarding resource allocation and operational leadership at hospitals and health systems are key enablers. Third sector groups spanning media, charities, NGOs and community health organizations must be part of the conversation, raising marginalized perspectives and shaping public discourse. And ultimately, earning the public's trust as both data contributors and recipients of digital twin-guided care is paramount. Only with sustained collaboration across this ecosystem can digital twins be developed responsibly and equitably (Craglia et al. 2021; He et al. 2024).

The Role of Design

Design research methods offer opportunities for a multi-stakeholder approach that can consider the complexities of implementing digital twins in the present and future. Design is well suited to consider so-called ‘Wicked problems’ which do not have definitive formulations or ‘correct’ answers. (Rittel and Webber 1973). Design also has a particularly important role to play in the responsible research and innovation process (RRI) which asks innovators to take actions such as Anticipating, Reflecting, Including

and Responding to implications of their work (Stilgoe et al. 2013). This is because a key role of designers is to anticipate complex requirements of users and shape products and processes accordingly.

The need to engage with societal desirability, ethical acceptability and sustainability has seen the development of approaches to these questions 'by design' whereby these responsible innovation elements become design requirements rather than subject to retrospective mitigation of any consequences. These can thus be led by human-centred design processes, to support privacy, security and ethics. New approaches also extend beyond human-centred design to give more nuanced approaches (He et al. 2024); for example Design Justice as an approach which centres communities and focuses on inclusion to design based on principles that support people who are traditionally marginalized (Costanza-Chock, 2020), and More-Than-Human Design which looks beyond human actors to consider impact on other objects, organisms and ecosystems. (Wakkary, 2021). An important aspect of this is including diversity within design teams to help mitigate bias, and give broader perspectives. This may be combined with participatory design processes which involve the community to which it is relevant at all stages of the research process. The application of these principles may offer important new avenues for responsible development of digital twins that will empower rather than disempower, for example giving people meaningful ownership of their own health data.

Equally, we can consider how the newly emerging field of Design for Policy can be applied in the context of digital twins. Policy, regulation and standards development has a key role in ensuring responsible use and development of digital twins. For example, digital twins may be used in decision making processes and potentially as part of autonomous or semi-autonomous systems that act on behalf of individuals or

communities. If this is the case, accountability and transparency are critical. Bellotti and Edwards (2004) argue that if a context-aware system is acting on behalf of users in any capacity, the system must also be intelligible - able to represent to users what the system knows, how it knows it, and what it is doing about it. The development of standards such as IEEE7001 enable accessible and transparent design (Winfield et al. 2021), and such approaches must also be taken for digital twins in healthcare, to support trust and adoption. Design for Policy applies design research approaches and methods to support policy making (Braga et al. 2024), and can bring a user-centred and community-centred lens to creating policy and standards.

The Role of Speculative Design:

Speculative design is an approach to design that uses provocative scenarios, artifacts, and narratives to explore the implications of emerging technologies and imagine alternative futures (Dunne and Raby, 2013).

Given the scale of challenges and opportunities surrounding digital twins in healthcare, speculative design can play a crucial role in responsibly guiding the development of these exponential technologies. Speculative design utilizes provocative scenarios, artifacts, and narratives to spark discourse and surface implications around emerging technological capabilities before they become ubiquitous realities (Hanna, 2019).

For digital twins, speculative design can provide a structured approach to envision and critique different applications and futures in a low-risk space (Auger, 2013). Diverse stakeholders could collaborate to explore boundary cases that stress-test ethical limits or identify cultural flashpoints (Blythe, 2014). From reimagining birthing experiences augmented by digital twins to gaming out equitable data sharing protocols,

these types of tangible speculations can make complex issues around technology and humanity more accessible and actionable (Coulton and Lindley, 2019; Tsekleves et al. 2022). By situating speculations in context and providing an immersive engagement, for example placing speculative sensors and AI-driven interventions in public spaces, it is easier to relate directly impacts in a more immediate sense than may be provided by an abstract scenario. (Kwon et al. 2023)

Such approaches open up space for stakeholders to confront uncomfortable societal tensions, like grappling with differing notions of agency and consent if digital twins evolve towards cognitive models that simulate human decision-making faculties. Speculative artifacts could probe public acceptance boundaries by embodying future experiences like consulting AI doppelgangers for health advice.

On the flip side, speculative design could inspire awe around digital twins' potential benefits - like modelling food policies on digital twins to better understand chronic disease, or simulating inclusive product designs in digital twins, tailored around the accessibility needs of disabled populations historically overlooked in clinical trials (Hoang et al. 2018).

Ultimately, grounding digital twin development with on-the-ground speculative processes featuring the very people who will be impacted creates vital opportunities for participatory knowledge exchange, building trust, and shaping more equitable technological futures. These types of transdisciplinary approaches are essential for catalyzing collaborative foresight on the ethical governance of digital twin technologies as they evolve.

Recommendations and Conclusions

The emergence of digital twins in healthcare presents a paradigm shift in how we approach patient care and medical research. While the challenges are significant - ranging from technical hurdles and operational barriers to ethical minefields - the potential benefits are equally profound.

Design research, with its multidisciplinary approach and focus on human-centered solutions, is uniquely positioned to navigate this complex landscape. By employing methodologies such as speculative design, participatory processes, and design for policy, we can anticipate potential pitfalls, foster inclusive development, and shape policies that ensure responsible innovation.

As we move forward, it is crucial that we engage diverse stakeholders, from healthcare providers and patients to policymakers and ethicists, in co-creating the future of digital twins. By doing so, we can harness the transformative power of this technology to improve health outcomes, enhance medical training, and ultimately reimagine healthcare delivery for the digital age. Below we present six key recommendations for researchers working on digital twins in healthcare:

Digital Human Twins and Design's Holistic Perspective: As digital twins evolve from micro to macro scales in healthcare, design thinking could offer valuable perspectives on holistic integration. Design approaches may help bridge the gap between technical capabilities and human needs, potentially supporting the development of digital twins with user-centric approaches that consider the broader spectrum of healthcare interactions.

Design's Multifaceted Contribution: Design research methods could offer valuable approaches for exploring the complexities of digital twins. Through the application of systems thinking, service design, prototyping, and visualization techniques, design approaches might contribute to more intuitive and accessible digital

twin interfaces. Speculative design and storytelling could provide frameworks for stakeholders to explore and evaluate potential futures, potentially fostering responsible innovation.

Navigating Complexity through Design: Design methodologies may offer useful approaches for facilitating multi-stakeholder collaboration when addressing the technological, operational, ethical, and social challenges of digital twins. Participatory design methods might help incorporate diverse voices, while design justice approaches could suggest ways to consider marginalized communities, potentially promoting more equitable outcomes.

Connecting Systems through Speculative Design: Design fiction and speculative design approaches might provide useful frameworks for exploring the integration of human digital twins with other systems. These methodologies could help identify potential implications and opportunities, potentially contributing to more considered development of interconnected digital twin ecosystems.

Life Course Perspective through Design Research: Design research methods might offer insights into how digital twins could evolve throughout a person's lifetime. Through approaches such as longitudinal studies and user journey mapping, design research could contribute to understanding how digital twins might remain relevant across different life stages.

Transforming Healthcare Journeys with Service Design: Service design methodologies could play a valuable role in reimagining healthcare delivery through digital twins. By exploring and mapping the patient journey, service design approaches might help identify ways that digital twin implementations could enhance the healthcare experience, potentially contributing to improvements in both efficiency and patient outcomes.

Looking ahead, the integration of digital twins in healthcare represents both extraordinary opportunities and significant responsibilities. The success of this technological transition will largely depend on our ability to balance innovation with ethical considerations, technical capabilities with human needs, and individual privacy with collective benefit. By fostering collaborative approaches that bring together diverse perspectives and expertise, we can work toward a future where digital twins serve as powerful tools for improving healthcare outcomes while maintaining human agency and dignity at the centre of medical practice. The journey ahead requires continued research, careful evaluation, and ongoing dialogue among all stakeholders to ensure that digital twins fulfil their promise of enhancing, rather than replacing, the human elements of healthcare.

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