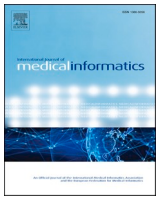
International Journal of Medical Informatics 212 (2026) 106359

Contents lists available at ScienceDirect

International Journal of Medical Informatics

journal homepage: www.elsevier.com/locate/ijmedinf



Review article

Digital twin applications in healthcare for people living with disability

David B. Olawade [a,b,c,*], Saria Almarzook [d], Muyiwa Ademola Ogunbona [e], Babajide David Makanjuola [f], Olabanke Florence Olawuyi [g], Ojima Z. Wada [h,i]

[a] Department of Allied and Public Health, School of Health, Sport and Bioscience, University of East London, London, United Kingdom
[b] Department of Research and Innovation, Medway NHS Foundation Trust, Gillingham ME7 5NY, United Kingdom
[c] Department of Public Health, York St John University, London, United Kingdom
[d] Department of Health and Care Management, School of Leadership and Service Industry Management, Arden University, Dessauer Straße 3-5, 10963 Berlin, Germany
[e] Cell Biology and Genetics Unit, Department of Zoology, University of Ibadan, Ibadan, Nigeria
[f] Sheffield Business School, Department of Accounting, Banking and Finance, Sheffield Hallam University, Howard St, Sheffield City Centre, Sheffield S1 1WB, United Kingdom
[g] Department of Biomedical Sciences, College of Medical Sciences, University of Calabar, Calabar, Cross River State, Nigeria
[h] Division of Sustainable Development, College of Science and Engineering, Hamad Bin Khalifa University, Doha, Qatar
[i] Global Eco-Oasis Sustainable Initiative (GESI), Ibadan, Nigeria

ARTICLE INFO

Keywords:
Digital twin
Disability healthcare
Assistive technology
Personalised medicine
Rehabilitation technology

ABSTRACT

Background: Digital twin technology represents a transformative innovation in healthcare, creating virtual replicas of physical entities that enable real-time monitoring, prediction, and personalised intervention. People living with disability face multifaceted healthcare challenges requiring continuous monitoring, adaptive assistive technologies, and individualised treatment approaches. The convergence of digital twin technology with disability healthcare presents unprecedented opportunities for enhancing quality of life, independence, and clinical outcomes.

Aim: This review examines the current applications, benefits, challenges, and future directions of digital twin technology in healthcare delivery for people living with disability.

Method: A narrative review methodology was employed, synthesising literature from academic databases including PubMed, IEEE Xplore, Scopus, and Web of Science. The review encompassed peer reviewed articles, conference proceedings, and technical reports published between 2015 and 2025, focusing on digital twin implementations in disability healthcare contexts.

Results: Digital twin applications in disability healthcare span multiple domains, including rehabilitation, assistive device optimisation, cognitive support systems, mobility enhancement, and chronic condition management. The technology demonstrates significant potential in personalising interventions, predicting health deteriorations, optimising assistive technologies, and facilitating remote monitoring. Key applications include virtual prosthetic fitting, wheelchair optimisation, rehabilitation progress tracking, and predictive analytics for secondary complications. However, implementation faces challenges including data privacy concerns, technological accessibility, interoperability issues, and cost barriers.

Conclusion: Digital twin technology offers transformative potential for disability healthcare, enabling personalised, predictive, and preventive care models. Successful implementation requires addressing technological, ethical, and accessibility challenges whilst ensuring equitable access for diverse disability populations. Critical research priorities include large-scale clinical trials, cost-effectiveness analyses, longitudinal outcomes studies, and ethical frameworks balancing surveillance concerns with care benefits.

1. Introduction

The healthcare landscape for people living with disability has undergone a significant transformation over recent decades, shifting from purely medical models towards holistic, person-centred approaches that emphasise autonomy, quality of life, and social

* Corresponding author.
E-mail address: d.olawade@uel.ac.uk (D.B. Olawade).

https://doi.org/10.1016/j.ijmedinf.2026.106359
Received 17 November 2025; Received in revised form 13 February 2026; Accepted 16 February 2026
Available online 18 February 2026

participation. According to the World Health Organisation, approximately 1.3 billion people, representing 16% of the global population, experience significant disability [1]. This substantial demographic encounters complex healthcare needs characterised by multimorbidity, increased vulnerability to secondary conditions, and requirements for continuous monitoring and adaptive interventions [2,3]. Traditional healthcare delivery models often struggle to provide the personalised, responsive, and anticipatory care that individuals with disabilities require, creating gaps in service provision and suboptimal health outcomes.

Digital twin technology, originating from manufacturing and aerospace industries, has emerged as a revolutionary paradigm in healthcare delivery. A digital twin constitutes a dynamic virtual representation of a physical entity, system, or process that spans its lifecycle, continuously updated with real-time data, and capable of simulation, prediction, and optimisation [4,5]. In healthcare contexts, digital twins create personalised virtual models of patients, incorporating physiological parameters, genetic information, lifestyle data, and environmental factors. This technology facilitates predictive analytics, enabling clinicians to anticipate health deteriorations, simulate treatment outcomes, and personalise interventions before implementing them in reality [6]. The integration of Internet of Things devices, artificial intelligence, machine learning algorithms, and advanced sensor technologies has accelerated the practical implementation of digital twins in clinical settings [7,8].

For people living with disability, digital twin technology presents particularly compelling applications (Fig. 1). The inherent variability in disability experiences, progression patterns, and individual responses to interventions necessitates highly personalised healthcare approaches. Digital twins can model complex interactions between assistive devices and users, predict equipment failures, optimise rehabilitation protocols, and provide early warning systems for secondary complications [8,9]. Applications range from virtual prosthetic limb design and wheelchair configuration optimisation to cognitive support systems for individuals with intellectual disabilities and predictive monitoring for those with chronic neurological conditions [10]. The technology's capacity to integrate data from multiple sources, including wearable sensors, smart home devices, assistive technologies, and electronic health records, enables comprehensive health status monitoring and proactive intervention.

The convergence of digital twin technology with disability healthcare aligns with broader movements towards precision medicine, patient empowerment, and value-based care. By creating individualised virtual models, healthcare providers can move beyond one-size-fits-all approaches, tailoring interventions to specific physiological characteristics, lifestyle patterns, and personal preferences. Digital twins facilitate shared decision-making by enabling patients and clinicians to visualise potential outcomes of different treatment pathways, fostering informed choices and collaborative care planning [11]. Furthermore, the technology supports continuity of care across healthcare settings and throughout disease trajectories, maintaining comprehensive health profiles that evolve in response to changing needs and circumstances.

Despite growing interest in digital twin applications across healthcare domains, systematic examination of their specific implementation in disability contexts remains limited. People living with disability represent a heterogeneous population with diverse needs, and digital twin applications must address unique considerations, including accessibility requirements, communication accommodations, and ethical dimensions of data ownership and algorithmic bias. Current literature exhibits considerable variation in how digital twin is conceptualised and operationalised across studies, with some focusing on simple data visualisation whilst others describe sophisticated predictive models integrating multiple data streams [12,13]. This definitional heterogeneity complicates synthesis and comparison across implementations. Current literature predominantly focuses on general healthcare applications or specific disability types in isolation, often omitting a comprehensive analysis of cross-disability applications, implementation frameworks, and scalability challenges.

This review addresses these gaps by synthesising current evidence on digital twin applications in disability healthcare, examining benefits and opportunities, identifying implementation barriers, and proposing future research directions. The specific aim of this review is to critically evaluate the application of digital twin technology in healthcare delivery for people living with disabilities, assess the evidence for clinical effectiveness, identify key challenges hindering its widespread adoption, and propose recommendations for future development and implementation. The objectives include: mapping current applications across different disability types, analysing technological architectures and data integration approaches, evaluating clinical outcomes and user experiences, examining ethical and accessibility considerations, and identifying research priorities for advancing the field.

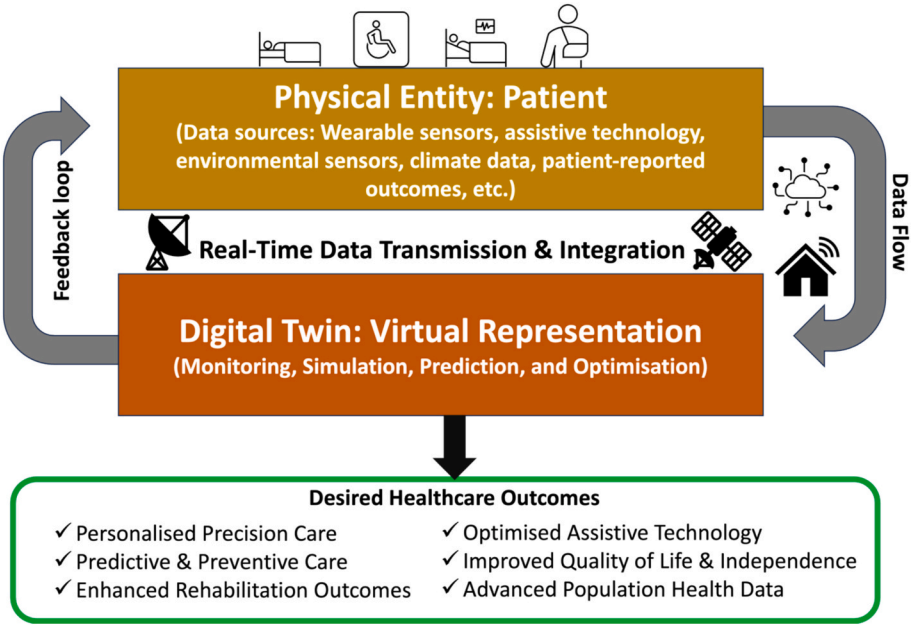


Fig. 1. Digital twin technology in healthcare for persons living with disability.

2. Methods

This narrative review synthesised literature on digital twin applications in healthcare for people living with disability using a structured but not systematic search strategy across multiple databases. A narrative review methodology was selected over a systematic review approach because the nascent and rapidly evolving nature of digital twin technology in disability healthcare necessitates broad exploration across diverse evidence types, including technical implementation reports, proof-of-concept studies, and conceptual frameworks, that would be excluded from systematic reviews focused on answering specific clinical questions using standardised study designs. The narrative approach enables comprehensive mapping of applications, challenges, and future directions across heterogeneous disability populations and implementation contexts, providing the flexible synthesis framework appropriate for an emerging interdisciplinary field.

Searches were conducted in PubMed, IEEE Xplore, Scopus, Web of Science, and the Cochrane Library for publications between January 2015 and September 2025. *The search strategy combined terms related to digital twins (*"*digital twin*", "*virtual twin*", "digital replica*", "virtual model*") with disability and healthcare terms ("disabilit*", "impairment*", "assistive technolog*", "rehabilitation", "prosthe*", "wheelchair*", "mobility aid*", "cognitive support"). Boolean operators (AND, OR) and database-specific filters were applied to refine results.

Inclusion criteria comprised: peer-reviewed journal articles, conference proceedings, and technical reports; publications focusing on digital twin technology applications in healthcare contexts; studies involving people with physical, sensory, cognitive, or intellectual disabilities; empirical research, case studies, technical implementations, and conceptual frameworks; and publications in English. **Exclusion criteria included:** studies focusing solely on digital twins in non-healthcare contexts; publications without specific relevance to disability populations; purely theoretical papers without implementation insights; and non-peer-reviewed sources, excluding grey literature from established organisations.

The selection process involved initial title and abstract screening by two reviewers independently, followed by full-text review of potentially relevant articles. Disagreements were resolved through discussion and consensus. However, this review did not follow PRISMA guidelines, and a formal flow diagram documenting the number of records identified, screened, and included at each stage was not generated. The lack of systematic selection and documentation procedures introduces potential for selection bias and limits reproducibility.

Where studies presented conflicting findings or employed varying definitions of digital twin technology, these discrepancies were noted and discussed narratively. For instance, variations in defining digital twin, ranging from simple digital representations to complex predictive models, were acknowledged when comparing study outcomes and implementation approaches. However, formal conflict resolution protocols or *meta*-analytical techniques were not employed.

Thematic synthesis was employed to organise findings into coherent categories, including technological frameworks, clinical applications across disability types, benefits and opportunities, implementation challenges, and future directions. Quality assessment considered methodological rigour, clarity of digital twin implementation descriptions, evidence quality for claimed benefits, and transferability of findings. Given the nascent nature of the field and the inclusion of technical implementation papers alongside clinical studies, a flexible quality assessment framework was applied rather than standardised checklists designed for specific study types. The quality assessment primarily involved descriptive evaluation of study design, sample characteristics, outcome measures, and reporting transparency, without formal scoring or categorisation by evidence level. This approach, whilst appropriate for capturing diverse evidence types in an emerging field, limits ability to weight findings by study quality.

The narrative synthesis approach enabled integration of diverse evidence types, providing a comprehensive understanding of the current state, potential, and challenges of digital twin technology in disability healthcare. However, the methodology's inherent subjectivity and lack of quantitative synthesis techniques should be considered when interpreting findings.

3. Applications of digital twin in healthcare for people with disabilities

Digital twin technology is being applied across multiple key domains in disability healthcare, addressing diverse needs and challenges. These applications range from the optimisation of assistive devices to the management of chronic conditions and cognitive support (Fig. 2). The following subsections explore these domains in detail.

3.1. Assistive technology optimisation

Digital twin technology has demonstrated substantial potential in optimising assistive devices for individual users. Traditional assistive technology provision follows standardised assessment and fitting protocols that may not capture the full complexity of person-device-environment interactions. Digital twins enable virtual prototyping and testing of assistive devices before physical fabrication, reducing costs, iteration time, and user frustration [12,14]. In prosthetic limb design, digital twins model the biomechanics of the residual limb, simulate forces during various activities, and predict comfort and functionality with different socket designs and component configurations [15,16]. Research demonstrated that digital twin-guided prosthetic fitting reduced the number of physical socket iterations by 60% and improved user satisfaction scores significantly compared to traditional fitting approaches [17–20].

Wheelchair prescription and configuration represent another significant application domain. Digital twins model user anthropometry, pressure distribution, postural stability, and propulsion biomechanics to optimise seating systems, cushioning, and wheelchair specifications [14]. Studies have shown that digital twin-optimised wheelchairs reduce pressure ulcer incidence by predicting high-risk areas and recommending preventive adjustments before tissue damage occurs [21,22]. For powered wheelchair users, digital twins can simulate navigation in home environments, predict collision risks, and optimise control parameters for individual motor abilities. Recent research developed a digital twin system for wheelchair users that integrated pressure mapping, environmental sensors, and machine learning to predict pressure ulcer risk [23], with 89% accuracy up to 48 h before clinical signs appeared [24,25].

3.2. Rehabilitation and therapy

Rehabilitation represents a core application area where digital twin technology enhances therapy personalisation, progress monitoring, and outcome prediction [8]. Traditional rehabilitation follows standardised protocols with periodic assessments, potentially missing subtle changes requiring intervention adjustments. Digital twins enable continuous monitoring of rehabilitation progress, real-time feedback during therapy sessions, and predictive analytics for outcome forecasting [26]. For stroke rehabilitation, digital twins model motor recovery trajectories based on initial assessments, lesion characteristics, and therapy engagement patterns, enabling clinicians to personalise exercise prescriptions and predict functional outcomes.

Virtual reality-based rehabilitation systems integrated with digital twins provide immersive therapy environments whilst simultaneously collecting detailed performance data. The digital twin analyses movement patterns, compensatory strategies, and fatigue indicators, adjusting exercise difficulty and providing feedback to optimise therapy effectiveness [9,27]. Recent randomised controlled studies and *meta*-analyses indicate that digital twin and immersive virtual reality

Fig. 2. Overview of key application domains for digital twin technology in healthcare for people with disabilities, summarising the primary areas of implementation discussed in this review.

rehabilitation for upper limb recovery post-stroke is associated with significantly greater functional improvements than conventional therapy, as measured by standardised clinical scores such as the Fugl-Meyer Assessment and Barthel Index [28–31]. The system continuously adapts exercise parameters based on real-time performance and fatigue monitoring, maintaining optimal challenge levels throughout sessions.

3.3. Cognitive support and monitoring

For individuals with cognitive disabilities or neurodegenerative conditions, digital twins offer sophisticated monitoring and support systems. These applications track cognitive performance patterns, detect early signs of decline, predict challenging situations, and provide timely prompts and assistance. Digital twins for individuals with intellectual disabilities integrate data from smart home sensors, wearable devices, and activity tracking applications to model daily routines, identify deviations suggesting health changes or support needs, and alert caregivers to potential concerns [32,33]. The technology supports independent living by providing context-aware reminders, navigation assistance, and emergency response capabilities whilst respecting user autonomy and privacy.

In dementia care, digital twins monitor behavioural patterns, sleep quality, activity levels, and social engagement to detect early indicators of disease progression or acute health issues [34–36]. The models can predict periods of increased confusion or wandering risk, enabling proactive interventions. Researchers developed sophisticated digital twin approaches that combine smart home sensors, wearable monitors, and cognitive assessments for older adults with mild cognitive impairment. For instance, Wang et al. [37] created an unobtrusive sensor system that constructs a virtual representation of home events, enabling continuous health monitoring. Rawtaer et al. [38] used a comprehensive sensor system including passive infrared, door contact, bed, and wearable sensors to distinguish between normal ageing and MCI, achieving up to 91% accuracy in identifying cognitive states. The system detected clinically significant cognitive decline an average of 4.7 months earlier than standard clinical assessments, enabling earlier intervention and care planning [34].

3.4. Chronic condition management

Many people with disabilities experience chronic health conditions requiring ongoing monitoring and management [39]. Digital twins facilitate proactive chronic disease management by continuously monitoring relevant parameters, predicting exacerbations, and recommending preventive interventions [6,40]. For individuals with spinal cord injuries, digital twins monitor autonomic dysreflexia indicators, bladder and bowel patterns, and respiratory function, predicting complications before they become acute. The integration of data from multiple sources, including wearable sensors, smart catheters, and environmental monitors, enables comprehensive health status assessment and early warning systems.

For people with multiple sclerosis, digital twins track symptom patterns, medication adherence, environmental triggers, and disease progression biomarkers [41,42]. The models predict relapse risk, enabling proactive medication adjustments and lifestyle modifications. Research demonstrates that predictive analytics for secondary complications in disability populations can reduce emergency department visits and hospitalisations through early intervention, though the strength of evidence varies across studies and disability types [43]. Recent studies showed that digital twin-based monitoring for spinal cord injury patients reduced pressure injury and urinary tract infection complications, improving prevention and timely intervention [23,43].

3.5. Communication and sensory support

Digital twin applications extend to communication support for individuals with speech and language disabilities. These systems model communication patterns, predict communication needs in different

contexts, and optimise augmentative and alternative communication device configurations. The digital twin learns individual communication preferences, frequently used phrases, and contextual communication patterns, enabling predictive text and symbol selection that accelerates communication rates [44,45]. For individuals with sensory disabilities, particularly deaf-blind individuals, digital twins can model optimal tactile communication parameters and predict technology needs across different environments and activities.

Table 1 summarises key application domains and specific implementations reported in the literature.

4. Benefits and opportunities

While the applications described above demonstrate technical feasibility, the evidence base for clinical effectiveness and patient-centred outcomes remains nascent. The following benefits represent both demonstrated advantages and theoretical potential, with the strength of evidence varying considerably across domains.

4.1. Personalisation and precision care

The foremost benefit of digital twin technology in disability healthcare lies in enabling truly personalised care approaches. Traditional healthcare often applies population-based protocols that may not account for individual variability in disability presentation, progression patterns, and intervention responses [46,47]. Digital twins create individualised models capturing unique physiological characteristics, lifestyle factors, environmental contexts, and personal preferences [6,48]. This personalisation extends across assessment, intervention planning, device configuration, and ongoing monitoring. The technology enables precision rehabilitation prescriptions tailored to individual recovery trajectories, assistive device specifications optimised for specific user characteristics and usage patterns, and medication regimens adjusted based on individual responses and side effects profiles [6,8,11].

Personalisation through digital twins also addresses the heterogeneity within disability categories. Two individuals with the same diagnostic label may have vastly different functional abilities, support needs, and health priorities. Digital twin models capture this individual variation, moving beyond diagnostic categories to person-centred care planning. The technology facilitates shared decision-making by enabling individuals and families to visualise potential outcomes of different intervention choices, fostering informed decisions aligned with personal values and preferences [6,8].

4.2. Predictive and preventive care

Digital twins enable a fundamental shift from reactive to predictive healthcare delivery. By continuously monitoring multiple parameters and employing machine learning algorithms, digital twins can identify subtle patterns indicating impending health deteriorations before clinical symptoms manifest [8,49]. This predictive capability is particularly valuable in disability healthcare where secondary complications significantly impact quality of life and healthcare costs. Early prediction of pressure ulcers, urinary tract infections, respiratory complications, and other preventable conditions enables timely interventions that maintain health and prevent hospitalisations.

The economic implications of preventive care facilitated by digital twins are substantial [50]. Hospitalisations for preventable complications represent significant costs for both healthcare systems and individuals [51,52]. Digital twin-based early warning systems can potentially lower preventable hospitalisation costs and improve quality of life by supporting ongoing health monitoring and reducing acute care episodes, though robust health economic evaluations are limited [53–55]. The return on investment for digital twin implementations in disability healthcare remains inadequately quantified, representing a critical gap for decision-makers.

Beyond secondary complication prevention, digital twins predict functional decline trajectories, enabling proactive care planning including timely introduction of supportive services, assistive technology upgrades, and environmental modifications.

4.3. Enhanced rehabilitation outcomes

The application of digital twins in rehabilitation offers multiple benefits including continuous progress monitoring, real-time feedback during therapy, objective outcome measurement, and therapy protocol optimisation [26]. Traditional rehabilitation relies on periodic clinical assessments, which can miss important changes that occur between sessions due to limited frequency and sensitivity. These assessments often lack real-time data, reducing the ability to capture dynamic fluctuations in a patient's condition, potentially delaying intervention and affecting outcomes [53,56]. Digital twins provide continuous monitoring, capturing subtle improvements or concerning patterns requiring intervention adjustments. Real-time feedback during therapy sessions, enabled by digital twin integration with exercise equipment and virtual reality systems, optimises motor learning by providing immediate knowledge of results and performance corrections.

Objective outcome measurement through digital twins addresses limitations of subjective assessments and reduces assessment burden. The technology automatically captures relevant metrics during daily activities and therapy sessions, providing comprehensive performance data without requiring dedicated assessment appointments [8,57]. Digital twin technology uses continuous therapy and activity data to identify the most effective interventions for specific cases, allowing protocols to be optimised with real-world evidence. This enables personalised treatment recommendations based on predicted responses, improves outcomes, and refines clinical protocols to match individual needs [8,57,58].

4.4. Remote monitoring and telehealth integration

Digital twin technology facilitates sophisticated remote monitoring

Table 1
Digital Twin Applications in Disability Healthcare by Domain.

Application Domain	Specific Implementation	Key Functions	Reported Outcomes
Prosthetic Optimisation [17,53]	Virtual socket fitting and component selection	Biomechanical simulation, pressure distribution analysis, and activity prediction	personalized prosthetic fitting and 25–35% improvement in satisfaction. Iterations and adjustment times are reduced,
Wheelchair Configuration [53,54]	Pressure mapping and postural optimization	Pressure ulcer risk prediction, seating adjustment recommendations	89% accuracy in ulcer risk prediction 48 h advance, 52% reduction in ulcer-related hospitalisations
Stroke Rehabilitation [28,31,93]	Virtual reality therapy with adaptive parameters	Movement analysis, fatigue monitoring, outcome prediction	20–30% greater functional improvement over conventional therapy
Cognitive Support [13]	Smart home integrated monitoring for intellectual disabilities	Routine modelling, deviation detection, caregiver alerting	Enhanced independent living, earlier intervention for health changes
Dementia Monitoring [34]	Behaviour and cognition tracking	Decline detection, wandering prediction, and acute issue identification	4–12 months earlier detection of significant cognitive decline, sooner than routine monitoring
Spinal Cord Injury Management [23]	Multi-parameter chronic condition monitoring	Autonomic dysreflexia prediction, complication prevention	Digital twin monitoring reduces complications like pressure injuries and urinary tract infections

capabilities, particularly valuable for individuals with mobility limitations, those living in rural areas with limited specialist access, or during periods restricting in-person healthcare access such as pandemic situations [7,57]. Remote monitoring through digital twins goes beyond simple parameter tracking, incorporating predictive analytics, automated alerts for concerning patterns, and decision support for both patients and remote clinicians. This enables proactive care management whilst reducing travel burden and enabling individuals to remain in their communities.

Integration with telehealth platforms creates comprehensive remote care models where clinicians access real-time digital twin data during virtual consultations, review trend analyses, adjust interventions based on predictive insights, and collaborate with patients in care planning. This integration supports continuity of care across settings and providers, with the digital twin serving as a consistent health record that travels with the individual.

4.5. Assistive technology innovation

Digital twins accelerate assistive technology innovation by enabling rapid prototyping, virtual testing, and iterative refinement without requiring physical device fabrication at each iteration [59,60]. This reduces development costs and timelines whilst enabling more user-centred design processes. Users can trial virtual device prototypes, provide feedback on functionality and comfort, and compare multiple design options before committing to physical production [61]. For customised assistive technologies, particularly prosthetics and orthotics, digital twin-enabled virtual fabrication and testing streamlines provision processes, reduces costs, and improves outcomes.

Beyond individual device development, digital twins contribute to assistive technology innovation more broadly by generating extensive data on device usage patterns, user needs, and performance across diverse conditions [12]. This aggregated data, appropriately anonymised, informs future device design, identifies unmet needs, and guides research priorities. The technology also facilitates post-market surveillance, detecting device issues or performance problems across user populations more rapidly than traditional reporting systems.

5. Challenges and barriers

The challenges outlined below represent both practical implementation barriers and fundamental tensions requiring careful navigation rather than simple technical solutions. Understanding these as complex, interrelated issues, rather than discrete problems amenable to straightforward fixes, is essential for responsible development.

5.1. Data privacy and security

Digital twin implementations in healthcare generate and process extensive personal health information, raising significant privacy and security concerns. For disability populations, privacy concerns are amplified by historical experiences of surveillance, institutionalisation, and autonomy restrictions [48]. Digital twin systems continuously collect data on location, activities, physiological parameters, and behaviours, often via wearables and smart sensors, resulting in comprehensive digital profiles that could be misused if inadequately protected [13,53]. Security vulnerabilities could enable unauthorised access to intimate health information or manipulation of device settings, potentially causing harm.

Regulatory frameworks for health data protection, including the General Data Protection Regulation in Europe and the Health Insurance Portability and Accountability Act in the United States, establish requirements for data handling, but implementation of these frameworks in digital twin contexts presents challenges [62,63]. The continuous, real-time nature of data flows, the integration of data from multiple sources including non-medical devices, and the use of cloud computing infrastructure create complex compliance requirements. Ensuring individuals understand what data is collected, how it is used, who has access, and what rights they have regarding their data is essential but challenging given the technical complexity of digital twin systems [64].

5.2. Accessibility and digital divide

The effectiveness of digital twin technology depends on accessible system design, affordable technology access, digital literacy, and reliable connectivity [54]. Many people with disabilities face barriers in one or more of these areas, risking the creation of digital divides where benefits accrue primarily to those with resources and abilities to engage with technology [65]. Accessible design of user interfaces, including compatibility with assistive technologies such as screen readers and alternative input devices, is essential but often overlooked in initial development.

Cost represents a significant barrier, as digital twin implementations may require wearable sensors, smartphones or tablets for data visualisation, and reliable internet connectivity [12]. These costs may limit access for some individuals with disabilities, particularly those in low-resource settings or with limited financial means, unemployment, potentially widening existing health disparities [66,67]. Addressing affordability, infrastructure, and training is crucial to ensure equitable use and maximise the technology's benefits across diverse populations. The risk of creating a two-tier system, where affluent, technologically literate populations benefit from advanced digital twin monitoring whilst marginalised disability communities continue receiving standard care, represents a critical ethical concern insufficiently addressed in current implementations.

Digital literacy varies widely, and systems must accommodate diverse technology skills without requiring advanced technical knowledge. Infrastructure limitations, particularly in rural and underserved areas, create connectivity challenges that impede real-time data transmission and system functionality.

5.3. Technical and interoperability challenges

Implementing digital twin systems requires integration of data from multiple sources including electronic health records, wearable devices, assistive technologies, environmental sensors, and patient-reported measures [7]. These sources often use different data formats, communication protocols, and storage systems, creating interoperability challenges. Lack of standardisation in disability-related data elements and outcome measures further complicates integration [68]. Building comprehensive digital twin models requires sophisticated technical infrastructure including secure data transmission capabilities, sufficient processing power for real-time analytics, robust storage solutions, and reliable backup systems.

Model accuracy and validation present ongoing challenges. Digital twin predictions are only as good as the underlying models and data quality. Validating models for diverse disability presentations requires extensive testing across heterogeneous populations, which may be resource-intensive and time-consuming [55]. Maintaining model accuracy over time as individual characteristics change and new data becomes available requires continuous learning capabilities and periodic revalidation [53,55,69]. Ensuring that models avoid bias and perform equitably across diverse populations necessitates careful attention to training data representativeness and ongoing bias monitoring.

5.4. Ethical considerations

Digital twin applications in disability healthcare raise important ethical questions regarding autonomy, consent, algorithmic bias, and equitable access [70]. Continuous monitoring, whilst offering health benefits, creates a fundamental tension: the very surveillance that enables predictive care may simultaneously undermine autonomy and

dignity for disability populations who have historically experienced paternalistic oversight and control [48]. This is not simply a matter of inadequate consent processes or privacy protections, it reflects deeper questions about whether continuous digital monitoring is compatible with self-determination, regardless of how carefully it is implemented.

Ensuring meaningful informed consent when systems are complex and continuously evolving requires innovative consent processes that go beyond one-time approvals [71]. Individuals should maintain control over data sharing decisions, system functionality, and the extent of monitoring, but balancing this autonomy with the clinical benefits that may depend on comprehensive data collection requires careful navigation.

Algorithmic bias represents a significant concern, as machine learning models may perpetuate or amplify existing healthcare disparities if training data is not representative of diverse disability populations [72]. Historical underrepresentation of people with disabilities in research and data sets may result in models that perform less accurately for this population [73]. Ensuring equitable access to digital twin technologies requires deliberate efforts to prevent the creation of a two-tier system where advanced technologies benefit only privileged populations, whilst others continue receiving standard care.

5.5. Clinical integration and workforce readiness

Integrating digital twin technology into clinical workflows requires significant changes in healthcare delivery models, staff training, and organisational culture. Clinicians must develop skills in interpreting digital twin outputs, integrating predictive insights into clinical decision-making, and communicating complex technical information to patients. Healthcare organisations require investment in technical infrastructure, data governance frameworks, and quality assurance processes [74,75]. Resistance to change, common in any innovation adoption, may be amplified by concerns about liability, particularly if predictive algorithms suggest interventions that clinicians override or if failures to act on automated alerts result in adverse outcomes.

Payment models in many healthcare systems remain oriented towards episodic care rather than continuous monitoring and prevention, creating financial disincentives for digital twin implementation [76]. Demonstrating return on investment, particularly in short-term financial terms, may be challenging even when long-term benefits in reduced complications and hospitalisations are substantial. Regulatory pathways for digital twin technologies remain evolving, with uncertainty regarding classification as medical devices, requirements for clinical validation, and approval processes [77].

Table 2 summarises major implementation challenges and potential mitigation strategies identified in the literature.

Table 2
Summarises major implementation challenges and potential mitigation strategies identified in the literature.

Challenge Category	Specific Barriers	Potential Mitigation Strategies
Data Privacy and Security [54,94]	Extensive data collection, security vulnerabilities, and regulatory compliance complexity	End-to-end encryption, edge computing for local processing, transparent data governance policies, and user-controlled access permissions
Accessibility and Digital Divide [6,54,94]	Cost barriers, interface accessibility, digital literacy gaps, and connectivity limitations	Subsidised device programmes, universal design principles, simplified interfaces, offline functionality, and digital literacy support
Technical and Interoperability [53,55,68]	Data format inconsistencies, lack of standardisation, and integration complexity	Adoption of FHIR and other healthcare interoperability standards, open APIs, modular architectures, and standardised disability data elements
Ethical Concerns [53,94]	Autonomy limitations, consent complexity, algorithmic bias, equity gaps	Granular user controls, dynamic consent frameworks, diverse training data sets, bias monitoring protocols, equitable access policies
Clinical Integration [95,96]	Workflow disruption, training requirements, payment model misalignment, and regulatory uncertainty	Workflow redesign with clinician input, comprehensive training programmes, value-based payment models, and regulatory pathway clarification
Model Accuracy and Validation [54,95]	Heterogeneity challenges, validation resource intensity, bias risks	Diverse validation cohorts, continuous learning algorithms, performance monitoring, bias detection and mitigation protocols

6. Future directions

The future directions outlined below should be understood not merely as technological possibilities, but as strategic priorities addressing the specific, substantive gaps and unmet needs identified throughout this review. Each proposed advancement directly responds to current limitations in evidence, implementation, or equity. Fig. 3 provides a conceptual map of this journey, illustrating how the future enablers discussed here are essential for navigating the identified challenges to achieve the vision of personalised, equitable care.

6.1. Technological advancements

Future developments in digital twin technology for disability healthcare will benefit from advances in several technological domains, each specifically targeting limitations identified in current implementations. Improved sensor technologies, including non-invasive biomarkers monitoring and miniaturised devices with extended battery life, will enhance data collection capabilities whilst reducing user burden, directly addressing accessibility and user acceptance barriers documented in Section 5.2 [78,79]. Advances in artificial intelligence, particularly in areas such as federated learning enabling model training across distributed data sets without centralising sensitive information, and explainable AI providing transparent reasoning for predictions, will address current limitations in privacy protection and algorithmic transparency raised in Sections 5.1 and 5.4 [80,81]. Edge computing developments will enable more sophisticated local processing, reducing latency and privacy concerns whilst maintaining functionality during connectivity disruptions, mitigating the digital divide and infrastructure challenges outlined in Section 5.2 [82].

Integration of genomic and biomarker data into digital twin models promises enhanced prediction accuracy for disease progression and treatment responses, addressing the model accuracy and personalisation needs discussed in Sections 4.1 and 5.3. Advances in virtual and augmented reality technologies will create more immersive and effective rehabilitation environments integrated with digital twins, expanding the rehabilitation applications described in Section 3.2 with stronger evidence for clinical effectiveness [83]. Quantum computing may eventually enable simulation of highly complex biological systems at scales currently impossible, though this remains a longer-term prospect [84]. Blockchain technology applications in health data management could provide secure, patient-controlled health data sharing mechanisms addressing current privacy and interoperability challenges detailed in Sections 5.1 and 5.3 [85].

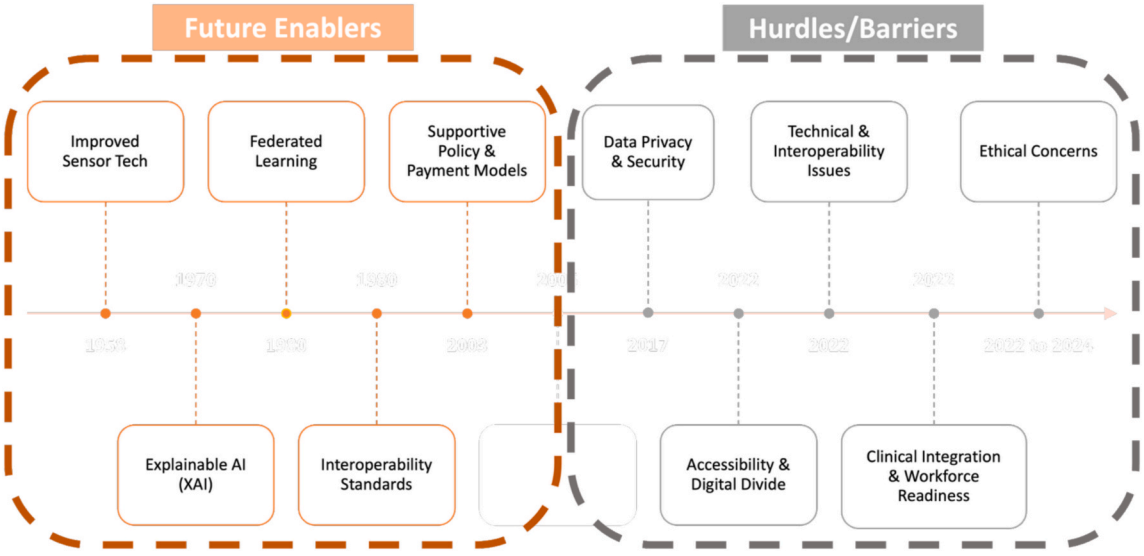


Fig. 3. Summary of future enablers and potential hurdles of implementing digital twin for healthcare.

6.2. Expanded application domains targeting underserved populations and settings

Current digital twin applications in disability healthcare, whilst promising, remain limited in scope and scale, predominantly focused on physical rehabilitation and assistive device optimisation for well-resourced populations, as evidenced in Section 3. Future expansion opportunities include comprehensive care coordination systems integrating medical, rehabilitation, social, and environmental data to support holistic wellbeing management, addressing the fragmented care delivery patterns that contribute to suboptimal outcomes noted in Section 1. Mental health monitoring and support for people with disabilities represents an underexplored application area where digital twins could detect early signs of depression, anxiety, or other psychological concerns common in disability populations, filling a critical gap given the high prevalence of comorbidities.

Paediatric applications supporting development monitoring and early intervention for children with disabilities offer significant potential but require addressing unique ethical considerations regarding child data and parental consent [86]. Workplace accommodation optimisation using digital twins could model ergonomic needs, predict fatigue patterns, and recommend modifications supporting employment success for people with disabilities, addressing employment participation barriers that contribute to socioeconomic disadvantage [87]. Educational applications could personalise learning environments and assistive technology configurations for students with disabilities, expanding beyond healthcare to support educational inclusion [88]. Community participation support systems could integrate transportation accessibility, venue information, and personal assistance needs to facilitate social engagement and community integration, targeting social isolation and participation restrictions frequently experienced by disability populations.

6.3. Population health and research generating missing evidence

Beyond individual-level applications, aggregated digital twin data could transform population health management and disability research, addressing the critical evidence gaps identified throughout this review. Anonymised data from large digital twin networks could identify population-level patterns, unmet needs, and health disparities requiring policy attention [48]. Real-world evidence generated through digital twin systems could accelerate assistive technology evaluation, rehabilitation protocol refinement, and medication effectiveness assessments in disability populations often underrepresented in traditional clinical trials, directly addressing the lack of large-scale effectiveness studies and cost-effectiveness analyses noted in Section 7 [8,89].

Digital twin-enabled research could facilitate the longitudinal outcomes studies currently absent from the literature, tracking quality of life, functional independence, and social participation over months and years rather than the short follow-up periods typical of existing studies. This would address one of the most significant substantive gaps in the field: understanding long-term impact and sustainability of digital twin interventions. The technology could facilitate pragmatic trials embedded within routine care, rapidly generating evidence on comparative effectiveness of different approaches. Integration of social determinants of health data with clinical digital twins could illuminate pathways through which social factors influence disability health outcomes, addressing the equity concerns raised throughout Section 5 by enabling evidence-based interventions targeting structural disadvantages [42,90].

6.4. Policy and regulatory development creating enabling frameworks

Realising the potential of digital twin technology in disability healthcare requires supportive policy and regulatory frameworks that address the implementation barriers documented in Section 5. Clear regulatory pathways for digital twin systems, balancing innovation promotion with safety assurance, will reduce uncertainty and facilitate responsible development, addressing the regulatory ambiguity noted in Section 5.5. Data governance policies must protect privacy whilst enabling beneficial uses, including research and quality improvement. Interoperability standards and requirements will facilitate system integration and data portability [91]. Accessibility regulations ensuring digital twin technologies are usable by people with diverse disabilities are essential to prevent the creation of new barriers, codifying the universal design principles discussed in Section 5.2.

Payment and reimbursement policies must evolve to support preventive, continuous monitoring models rather than only episodic care, directly addressing the financial misalignment identified as a major implementation barrier in Section 5.5 [76,92]. This may include new reimbursement codes for digital twin monitoring services, value-based payment models rewarding prevention of complications, and coverage policies for devices and technologies enabling digital twin implementation. Workforce development policies should support training in digital health competencies for healthcare professionals and direct care workers, addressing the workforce readiness challenges outlined in

Section 5.5. Research funding priorities should explicitly include digital twin applications in disability contexts, addressing current underinvestment in disability-focused health technology research.

These future directions collectively form a strategic research and implementation agenda that, if pursued systematically, would address the substantive gaps identified in this review: the predominance of proof-of-concept studies over rigorous clinical trials, the absence of health economic evidence, the lack of long-term outcomes data, and the insufficient attention to equity and accessibility in technology design and deployment.

7. Limitations of the review

This narrative review has several methodological and substantive limitations that should be considered when interpreting findings.

8. Methodological limitations

The review did not follow PRISMA guidelines for systematic reviews. No PRISMA flow diagram was created, and detailed numbers of articles identified, screened, excluded, and included at each stage were not documented. This lack of systematic transparency limits reproducibility and introduces potential selection bias. The rapidly evolving nature of digital twin technology means that published literature may lag behind current implementations, particularly in commercial or proprietary contexts not reflected in academic publications. The search strategy, whilst comprehensive, was limited to English language publications and may have missed relevant work published in other languages.

The narrative review methodology, whilst appropriate for synthesising diverse evidence types across a nascent field, does not include the systematic quality assessment and synthesis procedures of systematic reviews, potentially introducing selection bias in included studies and interpreted findings. The flexible quality assessment framework employed, whilst justified by the heterogeneity of evidence types, was not formally described or reported. Results of quality appraisal for individual studies were not presented, limiting readers' ability to judge the strength of evidence supporting specific claims. This represents a significant limitation in a field where distinguishing robust evidence from preliminary findings is critical.

The heterogeneity of disability populations and digital twin implementations made direct comparisons across studies challenging, limiting the ability to draw definitive conclusions about effectiveness for specific disability types or implementation approaches. Variations in how digital twin was defined and operationalised across studies complicated synthesis. Some studies describing simple data visualisation dashboards were grouped with sophisticated predictive modelling implementations, potentially conflating distinct levels of technological complexity and clinical utility. This definitional ambiguity was noted but not systematically resolved, limiting precision in comparing outcomes across implementations.

9. Substantive limitations: Gaps in the research field

Beyond methodological concerns with the review itself, several critical gaps in the underlying research literature limit what can be concluded about digital twin technology in disability healthcare:

Predominance of Proof-of-Concept Studies Over Clinical Trials: Many included studies represented early-stage implementations with small sample sizes, short follow-up periods, and limited diversity in participant characteristics, restricting generalisability of findings. The field lacks large-scale, multicentre randomised controlled trials comparing digital twin interventions to standard care with adequate power to detect clinically meaningful differences. Most evidence comes from pilot studies, case series, and technical feasibility demonstrations rather than rigorous effectiveness evaluations. This limits confidence in claims about clinical benefits and prevents definitive conclusions about which digital twin applications should be prioritised for implementation.

Almost Complete Absence of Cost-Effectiveness Analyses: Economic evaluations were sparse in the literature, limiting conclusions about cost-effectiveness and value propositions. Only a handful of studies attempted even basic cost analyses, and none employed robust health economic methods (e.g., cost-utility analysis with quality-adjusted life years, cost-benefit analysis with comprehensive societal perspective). The return on investment for digital twin implementations remains inadequately quantified across all application domains, representing a critical gap for healthcare decision-makers, policymakers, and payers. Without this evidence, claims about the economic benefits of digital twin technology, including reduced hospitalisations and complications, remain largely speculative.

Lack of Longitudinal Studies on Real-World Impact: The rapid technological change means that technical architectures and implementation approaches described in older publications may no longer represent current best practices. Long-term outcomes data, particularly regarding sustained use, outcomes durability, and potential unintended consequences, remain largely unavailable given the recent emergence of these technologies. Most studies reported outcomes over weeks to months; virtually none tracked participants for years. This prevents understanding whether benefits are sustained, whether users maintain engagement with digital twin systems over time, and whether long-term quality of life, functional independence, and social participation improve. The absence of longitudinal evidence is particularly concerning given historical patterns of health technology abandonment in disability populations.

Ethical Tensions Inadequately Examined: The fundamental tension between surveillance and care for vulnerable disability populations, raised conceptually in Sections 5.1 and 5.4, has received limited empirical investigation. Few studies examined user perspectives on continuous monitoring, explored how digital twin implementations affect autonomy and self-determination, or investigated whether predictive interventions are experienced as supportive or controlling. The ethics literature on digital twins in disability healthcare is nascent, with most discussions remaining theoretical rather than grounded in lived experience or participatory research with disability communities. This represents a critical gap given the historical context of surveillance and paternalism in disability services.

Limited Representation of Diverse Disability Populations: Publication bias towards positive results may mean that unsuccessful implementations or identified limitations are underrepresented in the literature. Most studies focused on specific, well-defined disability types (stroke rehabilitation, prosthetic users) with limited attention to complex, multiple, or intellectual disabilities. Very few studies included participants from diverse socioeconomic, cultural, or geographic backgrounds, limiting understanding of how digital twin technology performs across the heterogeneous global disability population. The predominance of research from high-income countries raises questions about applicability in resource-limited settings.

Absence of Standardised Outcome Measures: The lack of standardised outcome measures across studies complicated assessment of clinical effectiveness and comparison of different approaches. Different studies employed different functional scales, satisfaction measures, and success criteria, preventing *meta*-analysis and making it difficult to synthesise evidence about effectiveness. The field would benefit enormously from consensus on core outcome sets for digital twin research in disability healthcare.

The review's focus on healthcare applications may have underrepresented important applications in other life domains such as education, employment, and community participation that also significantly impact health and wellbeing for people with disabilities. These substantive limitations in the research literature, not just the review methodology, constrain what can confidently be concluded about digital twin technology's role in disability healthcare and underscore the need

for the research priorities outlined in Section 6.

10. Conclusion

Digital twin technology represents a transformative innovation with substantial potential to improve healthcare delivery, health outcomes, and quality of life for people living with disability. Current applications spanning assistive technology optimisation, rehabilitation enhancement, chronic condition management, and predictive monitoring demonstrate feasibility and early evidence of effectiveness. The technology enables personalisation, prediction, and prevention that align with contemporary person-centred care models and address long-standing limitations of standardised approaches in disability healthcare. However, the evidence base remains nascent, dominated by proof-of-concept studies rather than large-scale clinical trials, lacking health economic evaluations, and offering limited longitudinal data on sustained outcomes and real-world impact.

Key findings from this review include: (1) digital twin applications show promising early results across multiple disability healthcare domains, with strongest evidence in prosthetic optimisation and stroke rehabilitation; (2) implementation faces significant barriers including data privacy concerns, accessibility challenges, interoperability limitations, and ethical tensions between surveillance and autonomy; (3) critical evidence gaps exist regarding long-term effectiveness, cost-effectiveness, and impact on quality of life; (4) equitable access remains a major concern, with risk of widening health disparities if implementations primarily serve affluent, technologically literate populations.

Realising the potential of digital twin technology requires systematic action across multiple fronts:

For Researchers:

- Prioritise large-scale, multicentre randomised controlled trials comparing digital twin interventions to standard care with adequate follow-up to assess durability of benefits
- Conduct rigorous health economic evaluations employing established methods to quantify costs, cost-effectiveness, and return on investment
- Implement longitudinal cohort studies tracking outcomes over years to assess sustained engagement, long-term quality of life, and functional independence
- Engage disability communities through participatory research to understand lived experiences of digital twin monitoring, autonomy implications, and user-defined outcome priorities
- Establish consensus on core outcome sets enabling comparison across studies and synthesis of evidence

For Clinicians and Healthcare Organisations:

- Adopt user-centred, accessible design principles ensuring digital twin systems are compatible with diverse assistive technologies and accommodate varying digital literacy
- Implement robust data governance frameworks with transparent policies, user-controlled access permissions, and strong security protections
- Develop comprehensive training programmes building clinician capacity to interpret digital twin outputs and integrate predictive insights into care planning
- Redesign workflows collaboratively with frontline staff to integrate digital twin technology without creating undue burden

For Policymakers and Funders:

- Establish clear regulatory pathways for digital twin technologies balancing innovation with safety and effectiveness requirements
- Reform payment models to support preventive, continuous monitoring approaches through value-based reimbursement
- Invest strategically in disability-focused digital health research addressing current evidence gaps
- Mandate accessibility standards preventing creation of new barriers and ensuring equitable access
- Fund infrastructure development in underserved areas to prevent digital divides

For Technology Developers:

- Engage disability communities from design inception through co-design processes that centre lived experience
- Prioritise interoperability by adopting healthcare data standards enabling integration across systems
- Build in user controls allowing granular management of data sharing, monitoring extent, and system functionality
- Address algorithmic bias proactively through diverse training data and ongoing bias monitoring

People with disabilities must be centred in the design, implementation, and governance of digital twin systems to ensure technologies serve rather than surveil, empower rather than restrict, and include rather than exclude. Participatory design approaches, robust privacy protections, commitment to equitable access, and attention to the social model of disability are essential.

The convergence of technological capabilities, evolving healthcare delivery models, and growing recognition of the importance of personalised approaches creates a promising environment for digital twin advancement in disability healthcare. Success will require collaboration across disciplines including engineering, healthcare, disability studies, ethics, and policy. Most importantly, it will require genuine partnership with disability communities, ensuring that technological innovation advances the rights, autonomy, and wellbeing of people with disabilities. Digital twins should be tools for empowerment, enabling individuals to understand their health, make informed decisions, prevent complications, and live fully in their communities. With thoughtful development, rigorous evaluation, and equitable implementation, digital twin technology can contribute meaningfully to a more equitable, effective, and person-centred healthcare system for people living with disability.

CRediT authorship contribution statement

David B. Olawade: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Saria Almarzook:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation. **Muyiwa Ademola Ogunbona:** . **Babajide David Makanjuola:** . **Olabanke Florence Olawuyi:** . **Ojima Z. Wada:** .

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] World Health Organization, Global report on health equity for persons with disabilities, WHO, Geneva, 2022.
[2] S.T. Skou, F.S. Mair, M. Fortin, B. Guthrie, B.P. Nunes, J.J. Miranda, et al., Multimorbidity, Nat. Rev. Dis. Primers 8 (1) (2022) 1–22.
[3] D.B. Olawade, O.A. Bolarinwa, Y.A. Adebisi, S. Shongwe, The role of artificial intelligence in enhancing healthcare for people with disabilities, Soc Sci Med 364 (2025) 117560.
[4] M. Singh, E. Fuenmayor, E.P. Hinchy, Y. Qiao, N. Murray, D. Devine, Digital Twin: Origin to Future, Appl Syst Innov. 4 (2) (2021) 36.

[5] Y. Zheng, S. Yang, H. Cheng, An application framework of digital twin and its case study, J. Ambient. Intell. Humaniz. Comput. 10 (3) (2018) 1141–1153.
[6] A. Vallée, Digital twin for healthcare systems. Front digit, Health 5 (2023).
[7] S. Adibi, A. Rajabifard, D. Shojaei, N. Wickramasinghe, Enhancing healthcare through sensor-enabled digital twins in smart environments: A comprehensive analysis, Sensors 24 (9) (2024) 2793.
[8] S.L. Chaparro-Cárdenas, J.A. Ramirez-Bautista, J. Terven, D.M. Córdova-Esparza, J.A. Romero-Gonzalez, A. Ramírez-Pedraza, et al., A technological review of digital twins and artificial intelligence for personalized and predictive healthcare, Healthcare 13 (14) (2025) 1763.
[9] M.W. Lauer-Schmaltz, P. Cash, J.P. Hansen, N. Das, Human digital twins in rehabilitation: A case study on exoskeleton and serious-game-based stroke rehabilitation using the ETHICA methodology, IEEE Access (2024) 1.
[10] P. Szabó, J. Ara, B. Halmosi, C. Sik-Lanyi, T. Guzsvinecz, Technologies designed to assist individuals with cognitive impairments, Sustainability 15 (18) (2023) 13490.
[11] A. Balasubhramanyam, R. Ramesh, R. Sudheer, P.B. Honnavalli, Revolutionizing healthcare: A review unveiling the transformative power of digital twins, IEEE Access 12 (2024) 69652–69676.
[12] S. Mihai, M. Yaqoob, D.V. Hung, W. Davis, P. Towakel, M. Raza, et al., Digital twins: A survey on enabling technologies, challenges, trends and future prospects, IEEE Commun Surv Tutor. 24 (4) (2022) 2255–2291.
[13] K. Zhang, H.Y. Zhou, D.T. Baptista-Hon, Y. Gao, X. Liu, E. Oermann, et al., Concepts and applications of digital twins in healthcare and medicine, Patterns 5 (8) (2024) 101028.
[14] C. Lagartinho-Oliveira, F. Moutinho, L. Gomes, Digital twin in the provision of power wheelchairs context: Support for technical phases and conceptual model, Computers 11 (11) (2022) 166.
[15] D. Chen, P. Su, S. Ottikkutti, P. Vartholomeos, K.N. Tahmasebi, M. Karamousadakis, Analyzing dynamic operational conditions of limb prosthetic sockets with a mechatronics-twin framework, Appl. Sci. 12 (3) (2022) 986.
[16] T. Sun, J. Wang, M. Suo, X. Liu, H. Huang, J. Zhang, et al., The digital twin: A potential solution for the personalized diagnosis and treatment of musculoskeletal system diseases, Bioengineering 10 (6) (2023) 627.
[17] D.R.C. Lee, X. Yang, F. Riccio-Ackerman, B. Alemón, M. Ballesteros-Escamilla, D. Solav, et al., A clinical comparison of a digital versus conventional design methodology for transtibial prosthetic interfaces, Sci. Rep. 14 (1) (2024).
[18] F. Mbithi, M. Donovan-Hall, J. Bramley, J. Steer, C. Rossides, P. Worsley, et al., Evidence-generated sockets for transtibial prosthetic limbs compared with conventional computer-aided designs: A multiple-methods study from the patient's perspective, JMIR Rehabil Assist Technol. 12 (2025) e69962.
[19] C. Phillips, L. Li, M. Miguel, A. Eshraghi, W. Heim, S. Dilkas, et al., User perspectives of digital manufacturing for lower-limb prosthetic sockets, Prosthet. Orthot. Int. 48 (1) (2024) 100.
[20] J.W. Steer, P.A. Grudniewski, M. Browne, P.R. Worsley, A.J. Sobey, A.S. Dickinson, Predictive prosthetic socket design: part 2—generating person-specific candidate designs using multi-objective genetic algorithms, Biomech. Model. Mechanobiol. 19 (4) (2019) 1347–1360.
[21] N. Ramanan, N. Muralikumar, S. Kalimuthukumar, M.P. Rajasekaran, T.A. Prasath, S.S. Priya, Designing and developing a smart wheelchair system using raspberry Pi comprising hydrogel based cushion and pressure mapping system to prevent decubitus ulcers, in: In: the Third International Conference on Intelligent Techniques in Control, Optimization and Signal Processing (INCOS). IEEE, 2024, pp. 1–4.
[22] Tyagi AK. Sensors and Digital Twin Application in Healthcare Facilities Management. In: Artificial Intelligence-Enabled Blockchain Technology and Digital Twin for Smart Hospitals. 2024. p. 369-90.
[23] S.D. Williamson, M.Z. Geisler, R.K. Steensgaard, K. Søgaard, S.S. Nielsen, L. T. Dalsgaard, et al., Self-managed digital technologies for pressure injury prevention in individuals with spinal cord injury: a systematic scoping review, Spinal Cord 63 (9) (2025) 492–498.
[24] M. Kim, T.H. Kim, D. Kim, D. Lee, D. Kim, J. Heo, et al., In-advance prediction of pressure ulcers via deep-learning-based robust missing value imputation on real-time intensive care variables, J. Clin. Med. 13 (1) (2023) 36.
[25] Y. Kim, M. Lim, S.Y. Kim, T.U. Kim, S.J. Lee, S.K. Bok, et al., Integrated machine learning approach for the early prediction of pressure ulcers in spinal cord injury patients, J. Clin. Med. 13 (4) (2024) 990.
[26] E. Mikołajewska, J. Masiak, D. Mikołajewski, Applications of artificial intelligence-based patient digital twins in decision support in rehabilitation and physical therapy, Electronics 13 (24) (2024) 4994.
[27] K. Tao, J. Lei, J. Huang, Physical integrated digital twin-based interaction mechanism of artificial intelligence rehabilitation robots combining visual cognition and motion control, Wirel. Pers. Commun. (2024).
[28] C.D. Kenea, T.G. Abessa, D. Lamba, B. Bonnechère, Immersive virtual reality in stroke rehabilitation: A systematic review and meta-analysis of its efficacy in upper limb recovery, J. Clin. Med. 14 (6) (2025) 1783.
[29] A. Ratschat, T.M.C. Lomba, S.D. Gasperina, L. Marchal-Crespo, Development and validation of a kinematically accurate upper-limb exoskeleton digital twin for stroke rehabilitation. In: 2023 International Conference on Rehabilitation Robotics (ICORR). IEEE, 2023.
[30] S. Shin, G. Hwang, Y. Kim, E. Park, D.R. Cho, H. Baik, et al., Role of fully-immersive virtual reality for paretic arm recovery in stroke rehabilitation, Front. Neurol. 16 (2025).
[31] J. Zhang, M. Liu, J. Yue, J. Yang, Y. Xiao, J. Yang, et al., Effects of virtual reality with different modalities on upper limb recovery: a systematic review and network meta-analysis on optimizing stroke rehabilitation, Front. Neurol. 16 (2025).
[32] G. Araniti, C. Garibotto, A. Jose, F. Marcello, V. Pilloni, A. Sciarrone, et al., Medical digital twin and IoT devices: Monitoring patients through human-centered technologies, IEEE Internet Things Mag. (2025) 1–7.
[33] J. Chen, W. Wang, B. Fang, Y. Liu, K. Yu Victor, et al., Digital twin empowered wireless healthcare monitoring for smart home, IEEE J. Sel. Areas Commun. 41 (11) (2023) 3662–3676.
[34] L.G. Amato, M. Lassi, A.A. Vergani, J. Carpaneto, S. Mazzeo, V. Moschini, et al., Digital twins and non-invasive recordings enable early diagnosis of Alzheimer's disease, Alzheimers Res. Ther. 17 (1) (2025).
[35] L. Rigny, N. Fletcher-Lloyd, A. Capstick, R. Nilforooshan, P. Barnaghi, Assessment of sleep patterns in dementia and general population cohorts using passive in-home monitoring technologies, Commun. Med. 4 (1) (2024).
[36] N. Wickramasinghe, N. Ulapane, A. Andargoli, C. Ossai, N. Shuakat, T. Nguyen, et al., Digital twins to enable better precision and personalized dementia care, JAMIA Open. 5 (3) (2022).
[37] Y. Wang, J.C. Leung, M. Chen, Z. Zeng, B. Toh, Y. Qiu, et al., An Intelligent and Privacy-Preserving Digital Twin Model for Aging-in-Place, in: In: 2017 IEEE Region 10 Symposium (TENSYMP), 2025, pp. 1–8.
[38] I. Rawtaer, K.B.A. Jabbar, B. Subagdja, E. Saffari, A.H. Tan, 299. Sensors in-home for elder wellbeing (sinew): digital phenotyping and artificial intelligence for early detection of dementia, Int. J. Neuropsychopharmacol. 28(Supplement_2):ii67-ii68 (2025).
[39] K. Froehlich-Grobe, D. Jones, M.S. Businelle, D.E. Kendzor, B.A. Balasubramanian, Impact of disability and chronic conditions on health, Disabil. Health J. 9 (4) (2016) 600–608.
[40] S.T. Mulder, A.H. Omidvari, A.J. Rueten-Budde, P.H. Huang, K.H. Kim, B. Bais, et al., Dynamic digital twin: Diagnosis, treatment, prediction, and prevention of disease during the life course, J. Med. Internet Res. 24 (9) (2022) e35675.
[41] M. Dini, G. Comi, L. Leocani, Digital remote monitoring of people with multiple sclerosis, Front. Immunol. 16 (2025).
[42] I. Voigt;, H. Inojosa, A. Dillenseger, R. Haase, K. Akgün, T. Ziemssen, Digital twins for multiple sclerosis, Front. Immunol. 12 (2021).
[43] M.M. Morrow, L.C. Hughes, D.M. Collins, T.L. Vos-Draper, Clinical remote monitoring of individuals with spinal cord injury at risk for pressure injury recurrence using mHealth: Protocol for a pilot, pragmatic, Hybrid Implementation Trial. JMIR Res Protoc. 13 (2024) e51849.
[44] Cosmas A, Cruz G, Cubela S, Huntington M, Rahimi S, Tiwari S. Digital twins and generative AI: A powerful pairing [Internet]. McKinsey & Company. 2024. Available from: https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/tech-forward/digital-twins-and-generative-ai-a-powerful-pairing.
[45] J. Sun, Z. Tian, Y. Fu, J. Geng, C. Liu, Digital twins in human understanding: a deep learning-based method to recognize personality traits, Int. J. Comput. Integr. Manuf. 34 (7–8) (2020) 860–873.
[46] K. Feldman, G. Stiglic, D. Dasgupta, M. Kricheff, Z. Obradovic, N.V. Chawla, Insights into population health management through disease diagnoses networks, Sci. Rep. 6 (1) (2016).
[47] J.S. Leeder, Who believes they are 'just average': Informing the treatment of individual patients using population data, Clin. Pharmacol. Ther. 106 (5) (2019) 939–941.
[48] K. Bruynseels, F. Santoni de Sio, J. van den Hoven, Digital twins in health care: Ethical implications of an emerging engineering paradigm, Front. Genet. 9 (2018) 31.
[49] Awasthi M, Raghuvanshi CS, Dudhagara C, Awasthi A. Exploring virtual smart healthcare trends using digital twins. In: Digital twins for smart cities and villages. Elsevier; 2024. p. 377-406.
[50] G. Ahmadi-Assalemi, H. Al-Khateeb, C. Maple, G. Epiphaniou, Z.A. Alhaboby, S. Alkaabi, et al., Digital twins for precision healthcare, in: In: Advanced Sciences and Technologies for Security Applications, 2020, pp. 133–158.
[51] S. Lu, Y. Zhang, L. Zhang, N.S. Klazinga, D.S. Kringos, Characterizing potentially preventable hospitalizations of high-cost patients in rural China. front, Public Health 10 (2022).
[52] J.V.M. Rocha, A.P. Marques, B. Moita, R. Santana, Direct and lost productivity costs associated with avoidable hospital admissions, BMC Health Serv. Res. 20 (1) (2020).
[53] M. Nadeem, S. Kostic, M. Dornhöfer, C. Weber, M. Fathi, A comprehensive review of digital twin in healthcare in the scope of simulative health-monitoring. Digit, Health 11 (2025).
[54] K. Papachristou, P.F. Katsakiori, P. Papadimitroulas, L. Strigari, G.C. Kagadis, Digital twins' advancements and applications in healthcare, towards precision medicine, J Pers Med. 14 (11) (2024) 1101.
[55] E. Katsoulakis, Q. Wang, H. Wu, L. Shahriyari, R. Fletcher, J. Liu, et al., Digital twins for health: A scoping review, Npj Digit Med. 7 (1) (2024) 1–11.
[56] R. Ye, Y. Gao, K. Xue, Z. Zhang, J. Long, Y. Li, et al., The reliability and validity of a novel clinical tool for distributing rehabilitation patients: a multicenter cross-sectional study in China, Sci. Rep. 14 (1) (2024).
[57] H. Li, J. Zhang, N. Zhang, B. Zhu, Advancing emergency care with digital twins, JMIR Aging. 8 (2025) e71777.
[58] T. Sun, J. Lu, Q. Li, Y. Kou, Can digital twin technology revolutionize public health emergency management? Insights from the PPRR framework. Front, Public Health 13 (2025).
[59] M. Attaran, B.G. Celik, Digital Twin: Benefits, use cases, challenges, and opportunities, Decis Anal J. 6 (1) (2023) 100165.
[60] A. Kantaros, T. Ganetsos, E. Pallis, M. Papoutsidakis, From mathematical modeling and simulation to digital twins: bridging theory and digital realities in industry and emerging technologies, Appl. Sci. 15 (16) (2025) 9213.

[61] Z. Johnson, M.J. Saikia, Digital twins for healthcare using wearables, Bioengineering 11 (6) (2024) 606.
[62] S.S. Bakare, A.O. Adeniyi, C.U. Akpuokwe, N.E. Eneh, Data privacy laws and compliance: A comparative review of the EU GDPR and USA regulations, Comput Sci IT Res J. 5 (3) (2024) 528–543.
[63] Fernandes FA, Chaltikyan GV. Analysis of Legal and Regulatory Frameworks in Digital Health: A Comparison of Guidelines and Approaches in the European Union and United States. J Int Soc Telemed eHealth. 2020;8.
[64] F. Mureddu, A. Paciaroni, T. Pavelka, A. Pemberton, L.A. Remotti, Rights and responsibilities: legal and ethical considerations in adopting local digital twin technology, In: Decide Better. (2025) 291–317.
[65] T.B. Willingham, J. Stowell, G. Collier, D. Backus, Leveraging emerging technologies to expand accessibility and improve precision in rehabilitation and exercise for people with disabilities, Int. J. Environ. Res. Public Health 21 (1) (2024) 79.
[66] A.K. Sharma, M.K. Srivastava, R. Sharma, Barriers and challenges for digital twin adoption in healthcare supply chain and operations management. Glob, Bus Rev. (2025).
[67] T. Sun, X. He, Z. Li, Digital twin in healthcare: Recent updates and challenges, Digit Health. 9 (2023) 205520762211496.
[68] K. Wang, Y. Wang, Y. Li, X. Fan, S. Xiao, L. Hu, A review of the technology standards for enabling digital twin, Digit Twin. 2 (2022) 4.
[69] S.G. Patchipala, Tackling data and model drift in AI: strategies for maintaining accuracy during ML model inference, Int J Sci Res Arch. 10 (2) (2023) 1198–1209.
[70] P. Huang, K. Kim, M. Schermer, Mapping the Ethical Issues of Digital Twins for Personalised Healthcare Service, J. Med. Internet Res. 24 (1) (2021).
[71] D.I. Shah, Managing user consent in big data: techniques, challenges, and future directions, J Big Data Priv Manag. 2 (1) (2024) 15–27.
[72] G. Franklin, R. Stephens, M. Piracha, S. Tiosano, F. Lehouillier, R. Koppel, et al., The sociodemographic biases in machine learning algorithms: A biomedical informatics perspective, Life 14 (6) (2024) 652.
[73] S. Cunningham, A.M. Russell, E. Lidington, F. Shiely, Lack of data collection in clinical trials prevents us from evaluating inclusion of people with disabilities, J. Clin. Epidemiol. 181 (2025) 111715.
[74] G.D.K. Kuruppu Appuhamilage, M. Hussain, M. Zaman, W.A. Khan, A health digital twin framework for discrete event simulation based optimised critical care workflows, Npj Digit Med. 8 (1) (2025).
[75] Sargiotis D. Data Governance Frameworks: Models and Best Practices. In: Data Governance. 2024. p. 165-95.
[76] L. Lindner, L. Lorenzoni, Innovative providers' payment models for promoting value-based health systems, OECD Health Work Pap. (2023).
[77] C. Tudu, S. Sharma, D. Kumar, Computational modeling and digital twin technologies in medical device development, Biomed. Mater. Devices (2025).
[78] D. Sim, M.C. Brothers, J.M. Slocik, A.E. Islam, B. Maruyama, C.C. Grigsby, et al., Biomarkers and detection platforms for human health and performance monitoring: A Review, Adv. Sci. 9 (7) (2022) 2104426.
[79] T. Wasilewski, W. Kamysz, J. Gębicki, AI-assisted detection of biomarkers by sensors and biosensors for early diagnosis and monitoring, Biosensors 14 (7) (2024) 356.
[80] O. Aouedi, A. Sacco, K. Piamrat, Marchetto G, Challenges and Future Directions. IEEE J Biomed Health Inform, Handling Privacy-Sensitive Medical Data With Federated Learning, 2022, pp. 1–14.
[81] B. Yurdem, M. Kuzlu, M.K. Gullu, F.O. Catak, M. Tabassum, Federated learning: Overview, strategies, applications, tools and future directions, Heliyon 10 (19) (2024) e38137.
[82] G. Carvalho, B. Cabral, V. Pereira, J. Bernardino, Edge computing: current trends, research challenges and future directions, Computing 103 (5) (2021).
[83] Pandey PK, Pandey PK, Mahajan S, Paul J, Iyer S. Digital Twin and Virtual Reality, Augmented Reality, and Mixed Reality. In: Digital Twins for Smart Cities and Villages. Elsevier; 2024. p. 273-93.
[84] H. Ali, Quantum computing and AI in healthcare: Accelerating complex biological simulations, genomic data processing, and drug discovery innovations, World J. Adv. Res Rev. 20 (02) (2023) 1466–1484.
[85] R.G. Sonkamble, A.M. Bongale, S. Phansalkar, A. Sharma, S. Rajput, Secure data transmission of electronic health records using blockchain technology, Electronics 12 (4) (2023) 1015.
[86] Thompson S, Cannon M, Wickenden M. Exploring critical issues in the ethical involvement of children with disabilities in evidence generation and use. 2020.
[87] F. Caputo, A. Greco, M. Fera, R. Macchiaroli, Digital twins to enhance the integration of ergonomics in the workplace design, Int. J. Ind. Ergon. 71 (2019) 20–31.
[88] J.T. Nganji, M. Brayshaw, Disability-aware adaptive and personalised learning for students with multiple disabilities, Int. J. Inf. Learn. Technol. 34 (4) (2017) 307–321.
[89] S. Kumari, A.K. Tyagi, S.AK. Emerging, Assistive, and digital technology in telemedicine systems, in: In: Advances in Medical Technologies and Clinical Practice Book Series, 2024, pp. 184–206.
[90] M. Milne-Ives, L.K. Fraser, A. Khan, D. Walker, M.H. van Velthoven, J. May, et al., Life course digital twins-intelligent monitoring for early and continuous intervention and prevention (LifeTIME): Proposal for a retrospective cohort study, JMIR Res Protoc. 11 (5) (2022) e35738.
[91] D. Rubinfeld, Data portability and interoperability: An E.U.-U.S. comparison. Eur J. Law Econ. (2023).
[92] A.O. Mbata, O.S. Soyege, C.N. Nwokedi, B.O. Tomoh, A.Y. Mustapha, O. D. Balogun, et al., Preventative medicine and chronic disease management: Reducing healthcare costs and improving long-term public health, Int J Multidiscip Res. Growth Eval. 5 (6) (2024) 1584–1600.
[93] K.E. Laver, B. Lange, S. George, J.E. Deutsch, G. Saposnik, M. Chapman, et al., Virtual reality for stroke rehabilitation, Cochrane Database Syst. Rev. 2025 (6) (2025).
[94] M. Ringeval, F.A.E. Sosso, M. Cousineau, G. Paré, Advancing healthcare with digital twins: A meta-review of applications and implementation challenges, J. Med. Internet Res. (2024).
[95] C. Meijer, H.W. Uh, S. el Bouhaddani, Digital twins in healthcare: Methodological challenges and opportunities, J Pers Med. 13 (10) (2023) 1522.
[96] C. Sadée, S. Testa, T. Barba, K. Hartmann, M. Schuessler, A. Thieme, et al., Medical digital twins: enabling precision medicine and medical artificial intelligence. Lancet digit, Health (2025), 100864.