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Digital Twin Applications in Medical Education: A Scoping Review

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Abstract: This scoping review aims to investigate the current applications of Digital Twin (DT) technology within the field of medical education, evaluating its advantages, limitations, and implications for future research and practice. A comprehensive search was conducted across seven authoritative databases, including PubMed, Web of Science, and China National Knowledge Infrastructure (CNKI), covering the period from the inception of each database until November 20, 2024. Data extraction was carried out using NoteExpress and EndNote software, and studies were selected based on strict inclusion and exclusion criteria. A total of 112 articles were identified in the initial search, of which eight met the criteria for final inclusion in the analysis. These studies predominantly addressed the application of DT in medical imaging education, critical care training, and medical education for individuals with disabilities. The findings reveal that DT technology has shown significant promise in enhancing teaching effectiveness, improving student engagement, and increasing overall satisfaction. However, several limitations were identified, including the nascent stage of the technology, challenges related to system integration, high resource demands, and the difficulties faced by educators in mastering and implementing the technology. Despite these challenges, the application of DT in medical education is progressing, demonstrating substantial potential to advance the modernization of educational practices, improve learning outcomes, and enhance educational efficiency. To fully realize the benefits of DT, further research is needed to address the technological, economic, and pedagogical barriers currently limiting its widespread adoption. Additionally, the development of more effective "digital-physical fusion" teaching models is essential for maximizing the utility and scalability of DT technology in medical education.

Keywords: Digital twin; Application status; Medical education; Medical training; Scope review

1. Introduction

The DT concept was first introduced in 2003 by Grieves (2005), who defined it as a virtual digital representation corresponding to an actual physical product, also known as the "mirror space model". DTs have the key property of dynamic bi-directional mapping, where there is a dynamic bi-directional connection between a physical entity and its corresponding twin in the digital domain (Kamel Boulos & Zhang, 2021).

In today's digital era, the rapid development of science and technology is profoundly affecting the educational models and practice paths in various fields. Medical education is also in the midst of this wave of change. In 2019, China's National Development and Reform Commission released the "China's DT Development Plan (2020 - 2022)", which set specific development goals and strategic directions for DT technology in the manufacturing industry, energy industry, and healthcare. DT is one of the latest technology trends in all sectors (Nour El-Din et al., 2022). As an emerging cutting-edge technological force, it also presents opportunities and challenges for innovation in medical education with its unique digital mapping and accurate simulation capabilities. As the world's most populous country and second-largest economy, China has established the largest clinical medical education system in the world (Liao & Wang, 2021). Medical education shoulders the important task of cultivating high-quality medical professionals, which requires students not only to have a solid grasp of rich medical theoretical knowledge but also to have adept clinical practice skills. Although the traditional medical education model has a solid foundation, there are some limitations in the richness of the practice scene, the repetitive nature of operation training, and the controllability of medical risks. DT technology provides students with an immersive learning experience by creating highly realistic virtual teaching scenarios and human organ models, effectively compensating for the practical shortcomings of traditional teaching. At the same time, DT technology can simulate complex clinical scenarios and help students practice repeatedly in the virtual environment to improve their clinical response skills. Because of these advantages, DT technology has great potential to improve the quality of medical education, increase student satisfaction, and promote modern educational transformation.

However, despite the many advantages demonstrated by the application of DT technology in medical education, its promotion and implementation still face several challenges. The fact that the technology is not yet fully mature, the difficulty of system integration, the high demand for resources, and the limited mastery of new technologies by teachers are the main factors limiting its wide application (Chen et al., 2021a). Therefore, an in-depth investigation of the current status, effectiveness, challenges, and future development of DT technology in medical education is not only of great theoretical value but also of great practical significance for promoting the innovation and development of medical education. The purpose of this study is to analyze the practice and research results of DT technology in medical education, analyze the existing problems, and make a prospective outlook on the future development trend, thereby providing useful reference for medical educators, researchers, and related technology developers.

2. Methodology

2.1 Identification of Research Questions

By reviewing the literature and conducting discussions, the main problem of this study was identified, i.e., the current status, advantages, and limitations of DT technology in medical education in existing studies.

2.2 Sources of Data and Search Strategy

To perform this search, several terms, such as DT, DTs, digital mirror, digital mapping, digital reproduction, medical education, medical teaching, medical training, medical education and training, medical skill training, medical simulation teaching, medical simulation instruction, nursing education, nursing teaching, nursing training, nursing skill training, clinical nursing education, clinical skill training, clinical teaching, clinical internship, clinical skill simulation, surgical skill training, and clinical surgery training, were used to search the Chinese and English databases, including CNKI, Wanfang Data, VIP, PubMed, Web of Science, the Cochrane Library, and Embase. Articles published from the inception of these databases through November 20, 2024 were included in the search.

2.3 Inclusion and Exclusion Criteria of the Literature

The criteria were determined according to the principle of participants, concept, and context (PCC). Inclusion criteria are as follows: a) Participants, who are medical education participants at all levels and should be directly involved in or receive medical education, training, or assessment activities, including DT technology; b) Concept, which refers to DT technology, including but not limited to the creation of 3D models of human anatomy, surgical simulation, and training simulation of medical procedures; c) Context, which means that the research should be conducted in a real or simulated medical education environment, covering a wide range of scenarios, such as classroom teaching, online learning, and clinical practice. Exclusion criteria are as follows: a) Language other than Chinese or English; b) Unavailable full text and abstracts; c) Reported cases or literature with insufficient or duplicated data; d) Non-research articles where the type of research is notices, announcements, compilation of abstracts, etc.

2.4 Analysis Methods

In this study, the included literature was systematically analyzed to ensure the scientific validity of the data sources and the reliability of the findings. The specific steps are as follows:

2.4.1 Literature screening and data extraction

All retrieved literature was imported into EndNote and NoteExpress software, and duplicates were removed through computerized screening and manual checking. Two researchers independently screened the literature, read the full text, and extracted the key data, including the study population, sample size, study design, data analysis methods, and main conclusions. In case of disputes, the team resolved them through discussion and invited third-party experts to assist if necessary.

2.4.2 Literature quality assessment

In the initial quality assessment of the included literature, the key evaluation indicators include:

• Study design: Priority was given to randomized controlled trial (RCT) and high-quality observational studies.

• Data completeness and analytic methods: studies that reported experimental data completely and used standard statistical analyses were preferred for inclusion.

The quality of the literature was independently rated by two researchers. The results showed that 50% of the eight articles included were of high quality. As for the rest of the literature, their quality met the needs of the study and analysis.

2.4.3 Statistical analysis

Descriptive statistics were performed on the extracted data to analyze the literature for the type of research design, sample size distribution, and findings. In addition, the quality of the literature was discussed in conjunction with the findings to explore the current status of the application of DT technology in medical education and its limitations.

3. Results

3.1 Results of Literature Screening

A total of 112 relevant articles were obtained through a systematic search. After removing duplicates, a total of 98 articles were retained. After screening the titles and abstracts, 38 articles that did not fit the topic were excluded; after further reading the full text, another 47 articles with inconsistent content or incomplete data were excluded; another five articles were excluded because the full text was unavailable, and ten articles were excluded because the type of study did not meet the inclusion criteria. A total of eight articles were finally included, including two Chinese articles and six English articles. The screening process is shown in Figure 1.

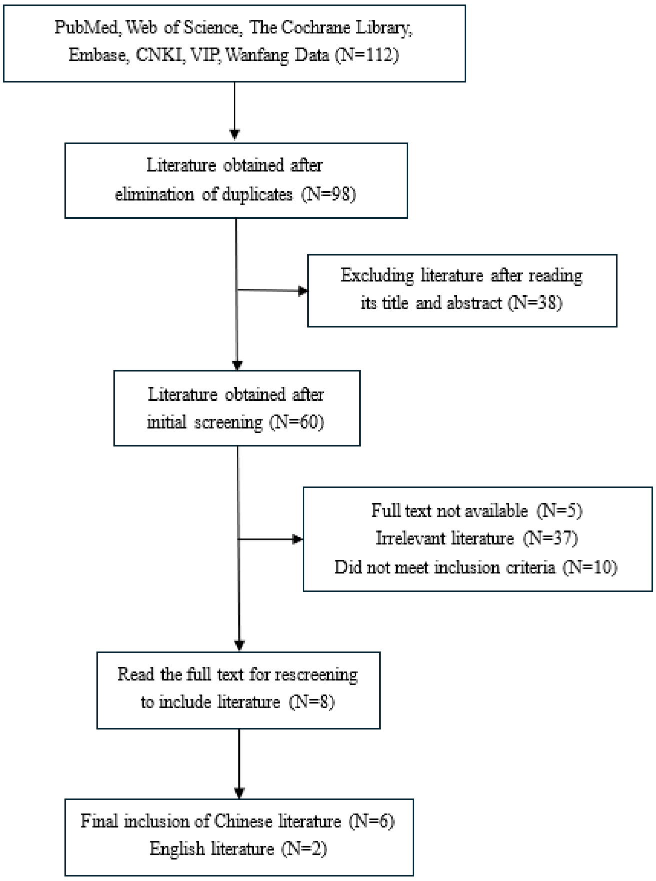

Figure 1. Literature screening flowchart

3.2 Basic Information on the Inclusion of Literature

Eight included articles were identified, with two from Chinese journals and six from foreign journals. The research subjects cover the DT technology itself, multiple areas of medical education and practice, and medical education for specific groups, such as people with physical disabilities. The content of the studies focuses on the application and evaluation of the technology, including empirical studies on improving learner adaptability and reducing training costs, as well as pedagogical innovations and methodological reforms, such as the promotion of transforming medical education to preventive medicine and the construction of smart medical imaging laboratories to support personalized learning. The basic information on the included literature is detailed in Table 1.

Table 1. Basic information on the included literature

Author	Country (Region)	Object of Study	Specific Application	Content of Study	Conclusion of Study
Rovati et al. (2024)	USA	DT patient modeling based on Electronic Health Record (EHR) variables	EHR-based adult twin patient modeling software for critical care nursing education	DT modeling with EHR variables to simulate critical care clinical trajectories and evaluate its usability, workload, and acceptability as a critical care nursing education tool	The use of a new DT application with high usability is welcome and beneficial in providing realistic practice, reducing medical risk, and aiding Intensive Care Unit (ICU) case management
Peshkova et al. (2023)	Russia	Colorectal cancer patients	A complex digital model based on a library of tumor tissue biospecimens and patient biofluids representing disease dynamics	Creation of a validated database of colorectal cancer slice scans linked to a blood bank and discussion of the potential of DTs in colorectal cancer diagnosis, treatment and personalized medical education	Introducing a DT for multidisciplinary collaboration facilitates the creation of an oncology database and links to a blood bank, providing a wide range of opportunities for medical education and research
Kumar et al. (2024)	Saudi Arabia	People with disabilities requiring medical education learning	Designing medical education for people with disabilities using DT technology; facilitating real-time simulation through dynamic virtual representation and developing unique visual algorithms to enhance data processing efficiency	Exploring new ways to integrate DT technology into the development of Internet of Things (IoT) services and developing a unique visual response algorithm	DT technology can facilitate optimized medical education, enable IoT visualization, and facilitate the future of integrating strong innovations to transform medical education
Zackoff et al. (2023)	USA	Health nursing staff	Utilizing immersive virtual reality (VR) technology in the creation of new ICUs, Emergency Intensive Care Unit (EICU), and new emergency departments and in nursing staff training	New ways to deliver high-throughput, standardized VR experiences to healthcare workers before new environments are built using DTs	Introducing DT VR experiments can prove that VR is feasible and can facilitate staff adaptability and clinical transformation
Zackoff et al. (2024)	USA	Patients in need of critical and emergency care	Role simulation in clinical training is widely used in medical centers and is useful for healthcare, stem cell transfer, and onboarding; simulation optimizes clinical care, identifies and mitigates security threats ahead of time	Developing and implementing a new approach to large-scale training using immersive VR and DTs	The team developed DT VR training that facilitates medical staff onboarding to new wards, promotes efficiency of medical staff interaction with equipment, and adapts to digital training
Toofaninejad et al. (2024)	Iran	Students in need of medical education studies	This study was innovatively designed for people with physical	Transformation of medical education using DT technology	DTs benefit medical education, promote medical technology, and

			disabilities to facilitate real-time simulation through dynamic virtual representation		benefit people with disabilities
Chen et al. (2022)	China	Faculty and students in the medical program	Constructing an intelligent medical imaging laboratory based on physical data generation, virtual data acquisition, iterative optimization of DT and application development	To address the practical teaching difficulties of large-scale medical imaging equipment, such as site constraints, limited time, and invisible imaging process, to build an intelligent medical imaging laboratory based on DT technology	Incorporating DTs into smart medical imaging labs, combined with new teaching concepts, is conducive to creating an immersive environment and facilitating cognitive understanding
Chai et al. (2022)	China	Fourth-year undergraduate students majoring in biomedical engineering	Using integrated virtual simulation technology to create a virtual operation platform for practical teaching of the medical imaging devices course	Exploring the value of virtual simulation and DT technologies in medical imaging clinical teaching, and using chest computed tomography (CT) scanning as an example to highlight the crucial role of virtual simulation	The integration of virtual simulation technology of the DT for medical education to improve the effect, reduce the burden, increase efficiency, and strengthen the knowledge of the students is of great significance

4. Discussion

4.1 Current Status Analysis of DT Technology in Medical Education

DT technology, as a bridge connecting the physical world and the digital world, has been more and more widely and deeply applied in the field of medical education in recent years. Although still in its infancy, DT technology has been widely used in the field of medical and educational research, from basic medical knowledge learning to advanced clinical skills training, and has shown its unique advantages (Peshkova et al., 2023). By analyzing the included literature, it is understood that patient DTs based on clinical variables of EHRs have been applied to critical care medical education, where DTs are used to simulate complex cases and provide medical students with a near-realistic clinical environment to effectively improve their emergency management and decision-making skills, showing good user experience and acceptance (Rovati et al., 2024). Some of the existing applications also pay attention to the special needs of people with physical disabilities in medical education, and through the integration of IoT and DT technologies, they provide such students with accessible learning pathways, offer enhanced medical education experiences, and realize the inclusive development of medical education (Kumar et al., 2024). In addition, large-scale extended clinical space training and onboarding for healthcare professionals are provided through the integration of immersive VR and DT technologies (Zackoff et al., 2023), providing highly realistic simulation environments and allowing students to personalize their learning according to their individual needs, such as DT-based smart medical imaging labs (Chen et al., 2022). In addition, the Chinese People's Political Consultative Conference (CPPCC) reported that Zhongshan Ophthalmic Center and Huawei Technologies Co. jointly developed the ChatZOC ophthalmology macro model and its DT-patient teaching system, which opens up a whole new world of learning and practice for medical students, greatly relieves the dilemma of limited resources in traditional teaching, and enhances the practical ability of medical students and the depth of their understanding of ophthalmic diseases.

4.2 Advantages of DT Technology in Medical Education

In traditional medical education, there are problems, such as disconnection between theory and practice, single teaching method, limited internship opportunities, insufficient interdisciplinary education, unequal distribution of resources, neglect of students' individual development, and limited evaluation methods (Chen & Du, 2024), which have a negative impact on the quality and efficiency of education. DT technology, with its high-precision scanning, modeling, and analysis capabilities, brings new solutions to medical education.

First, DT technology facilitates the creation of both analog and virtual environments, which helps students better understand and master medical knowledge and skills (Toofaninejad et al., 2024). The high degree of simulation allows students to practice in a near-real clinical environment, effectively shortening the distance between theory and practice. Combined with VR technology, these simulated environments are even more immersive, allowing students to perform complex clinical operations in an immersive environment, and this realism greatly enhances the learning effect and experience (Shi et al., 2020). Moreover, users can perform experimental operations in the twin scene, and the DT system makes corresponding judgments and responses according to the users' operations, guiding them to the next step, and realizing the two-way interaction between the user and the DT system (Iliuţă et al., 2024). In addition, through comparative analysis, it was found that students who used DTs for simulation training performed significantly better in clinical practice than those who used traditional teaching methods (Zackoff et al., 2023). Second, the repeatability of DTs allows students to practice repeatedly until they master the skills, and this "trial-and-error learning" model is particularly important for medical education. A case study demonstrates the significant effect of DTs in improving the surgical skills of medical students. In addition, DT technology can also support the personalized learning mode, according to the specific learning progress and personal ability of students, to provide tailored teaching content and the appropriate level of difficulty to maximize the teaching effect. For example, the intelligent medical imaging laboratory (Chen et al., 2022) allows students to choose the learning content according to their own needs, thus realizing truly personalized teaching.

In addition, the application of DT technology in medical education also promotes the balanced distribution of educational resources, breaking the constraints of geographical location and time. Therefore, more medical students have the opportunity to access high-level medical education resources. Combined with VR technology, students can remotely access realistic simulation environments, which greatly promotes the popularization of medical education resources (Shi et al., 2020). At the same time, DT-based teaching data collection and analysis can provide medical students with accurate feedback on their learning situation, which can help personalize the development of teaching programs and improve the quality of teaching.

4.3 Limitations of Using DT Technology in Medical Education

As Richard Meier explained in his study, when an emerging technology was introduced into the field of educational practice, it was often accompanied by high hopes and expectations, with no exceptions for DT technology. Although the application of this technology in medical education offers unique opportunities, it inevitably faces several challenges and problems, including data security, model trust, dynamic updating, and collaborative application. In particular, in solving the trust issues of "inaccurate computation and measurement," how to ensure the privacy and security of patient data while meeting the needs of medical education has become a key challenge for its sustainable development and wide application (Zhou & Xia, 2022). In addition, the accuracy and reliability of DT models are also a major challenge. The accuracy of model predictions directly affects students' learning outcomes and future medical practice. To address the problems of "inaccurate computation and measurement," research on dynamic updating of models should be strengthened in the future to ensure their real-time synchronization with the actual clinical environment. Meanwhile, how to balance the contradiction between the demand for medical education and the protection of patient data under the premise of data privacy and security also requires policy and technical support (Loh, 2021). For example, distributed ledger (e.g., blockchain) technology has been used to ensure data security and tamper resistance, and artificial intelligence (AI) technology has been combined to realize the dynamic balance between privacy protection and data sharing (Yue et al., 2016).

4.4 Future Research Directions

4.4.1 Technology integration and innovation

As the fourth industrial revolution promotes the integration of the physical and digital worlds (Drummond & Gonsard, 2024), the application of DT technology in the field of medical education is technically feasible, but realizing full integration is still a challenge (De Maeyer & Markopoulos, 2021). In the future, it is necessary to deepen the integration with the IoT, AI, 5G communication, extended reality (XR), which includes VR, augmented reality (AR), and mixed reality (MR), and other technologies, and to promote the medical education asset digitization (Nele et al., 2024). This enables comprehensive simulation and real-time feedback to optimize teaching content and improve education quality (Chai et al., 2022; Zhu, 2024). In addition, studies have been conducted to develop a secure and efficient DT medical record system through cloud encryption and blockchain verification. Other directions include IoT monitoring of medical devices, big data analysis of learning behavior, and AI teaching assistance (Sun et al., 2022).

4.4.2 Standardization and interoperability implementation

Interoperability is crucial for DT platforms (Klar et al., 2023). Current research focuses on improving the efficiency of data integration, but there is less exploration of information sharing (Zhu, 2024). In the future, unified technical standards and interface specifications need to be developed to improve data consistency and integration efficiency, such as developing interface specifications for educational platforms through the International Organization for Standardization (ISO), and promoting technical compatibility and landing at the national or regional level (Grieves & Vickers, 2017).

4.4.3 Evaluation and feedback of teaching results

Strengthening the evaluation of the DT teaching effect and quality is an important direction for future research

(Toofaninejad et al., 2024). It is necessary to establish a comprehensive evaluation system, including the assessment of student learning outcomes, the effectiveness of teaching methods, and the quality of education. At the same time, it is necessary to collect student learning data and teacher feedback to optimize teaching strategies and system functions (Zhu, 2024).

4.4.4 Interdisciplinary cross-disciplinary collaboration

Interdisciplinary collaboration is crucial for the innovative application of DT technology in medical education by constructing digital mirrors to facilitate accurate simulation and information sharing across disciplines (Chen et al., 2021b). For example, Dang et al. (2022) developed a cloud infrastructure combining statistical modeling and 3D numerical simulation to design a DT deep learning framework for healthcare systems. In the future, cooperation in the fields of medicine, pedagogy, computer science, and engineering should be strengthened to promote knowledge sharing and technology transfer.

4.4.5 Application strategies in low-resource environments

The popularization of DT technology in low-resource environments is a key direction for the future. Lightweight systems based on cloud platforms should be developed to deliver high-quality educational resources to marginalized areas through remote operation and online collaboration (Armbrust et al., 2010). For example, a remote DT medical education system based on mobile devices can be designed to adapt to different teaching environments and resource conditions, thus effectively alleviating the problem of uneven resource distribution (Leung & Chan, 2003).

5. Conclusion

The application of DT technology in medical education is a comprehensive technological system that plays a crucial role in promoting the transformation of education to digitalization. Its construction and application are a gradual, iterative, and continuous development process rather than a short-term behavior (Qian et al., 2024). However, despite the difficulties in data collection, data fusion, and accurate simulation at this stage, the application of DT technology in medical education has shown a wide range of development prospects and great potential. In the future, the deep integration of DT technology with a variety of cutting-edge technologies, such as VR, AI, and the IoT, will further improve the quality and accessibility of medical education (Yi, 2023). Some of its challenges and problems need to be overcome through the joint efforts of the medical education community, technology developers, and policymakers. However, with the continuous advancement of technology and deepening of research, DTs will certainly play an increasingly important role in the field of medical education, making immeasurable contributions to cultivating more excellent medical talents and promoting the continuous innovation and development of medical education. Therefore, this technological change should be actively embraced, and its research and application should be strengthened to achieve more brilliant achievements in the field of medical education.

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Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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