https://doi.org/10.51408/issi2025_015

Digital Twins in Healthcare: State of the Art, Bibliometric Analysis and Future Perspectives

Cinzia Daraio[1], Simone Di Leo[2], Jacopo Orsini[3]

[1] *daraio@diag.uniroma1.it*,[2]*dileo@diag.uniroma1.it*,[3]*orsini.2099929@studenti.uniroma1.it*
DIAG Sapienza University of Rome, via Ariosto, 25, I-00185 Rome (Italy)

Abstract

Digital Twins (DTs) are reshaping healthcare by providing dynamic, digital counterparts of physical systems, enabling real-time interaction, simulation, and analysis. These systems leverage advanced modeling and real-world data integration to optimize medical training, planning, and patient-specific care. This paper explores the evolution of DTs in healthcare, presenting a bibliometric analysis of trends and outlying future directions.

The state-of-the-art section highlights technological advances in DTs, with a particular focus on simulating complex physiological behaviors. These advancements align with the growing demand for precision in surgical training and planning. The bibliometric analysis reveals an exponential increase in research interest, driven by advancements in Artificial Intelligence (AI), immersive technologies, and real-time data processing. Cross-disciplinary efforts, combining fields such as computer science, biomechanics, and medical engineering, are highlighted as key enablers, expanding the applicability of DTs. Future perspectives emphasize the transformative potential of DTs in remote surgical procedures, augmented diagnostics, and personalized medicine. The integration of Augmented Reality (AR) and Virtual Reality (VR) enhances the user experience by providing immersive, interactive environments. Additionally, the inclusion of haptic feedback and sensor-based tracking further augments realism, improving usability and adoption. Through the case study of the Rome Technopole project "*Phygital Twin Technologies for Innovative Surgical Training & Planning*", this paper showcases how DTs are already impacting healthcare, from training simulators to patient-specific planning tools. Furthermore, the discussion points to new frontiers, such as integrating predictive analytics for proactive healthcare interventions.

Introduction and aim

The healthcare field has been profoundly transformed by technological advancements over the past few decades. These innovations have paved the way for numerous new frontiers, each reshaping how medical professionals diagnose, treat, and manage various health conditions.

Digital Twins (DTs) are at the forefront of transformative innovations in healthcare, offering groundbreaking applications in training, planning, and personalized medicine. These advanced digital counterparts of physical systems allow real-time interaction and data-driven decision-making.

Phygital Twin technologies represent an advanced evolution of next-generation enabling technologies, building upon the foundational concept of DTs. DTs have already demonstrated their versatility across a wide range of applications, including Industry 4.0 and Connected Health (Pires et al., 2019; Bagaria et al., 2020; Evangeline, 2020; Aziz et al., 2024; El-Agamy et al., 2024). The Phygital approach emphasizes that DTs should not only replicate, monitor, predict, and optimize the processes and characteristics of their physical counterparts, referred to as Physical Twins, but also maintain real-time interconnectivity (Grieves & Vickers, 2017; Jones et al., 2020; Mourtzis et al., 2023; van Dinter et al., 2022). The rapid growth of big data and continuous advancement in data science and artificial intelligence have the potential to significantly advance DTs and phygital research and development. Although various DTs initiatives have been underway in the industrial sector, DTs for health are still in their early stages **(**Katsoulakis et al., 2024**).**

This paper provides an in-depth exploration of the current landscape, a review of bibliometric trends, and identifies venues for future directions. Furthermore, by applying established bibliometric techniques to the emerging and interdisciplinary field of DTs in healthcare, this study offers insights into the challenges and specific characteristics of analyzing the scientific literature in such rapidly evolving domains. It aligns with the goals of the Rome Technopole project "Phygital Twin Technologies for Innovative Surgical Training & Planning".

The state-of-the-art technologies discussed in the paper highlight a critical shift from traditional simulation methodologies like Finite Element Methods (FEM) to newer paradigms such as Physics-Informed Neural Networks (PINNs). FEM, while reliable, struggles with the computational demands of real-time simulation, which is essential for applications involving interactive digital twins. PINNs, on the other hand, offer a promising alternative by enabling rapid, accurate modeling of complex systems, including deformable tissues. This innovation is particularly relevant to the Rome Technopole project's work on developing a Digital Phantom (DP), a digital replica of anatomical structures designed to enhance surgical training. By simulating realistic tissue behavior in response to external forces, the DP promises to transform how surgeons learn and practice their craft (see Distefano et al., 2023; De Santis et al., 2024).

An integral part of this advancement is the immersive environment created through a seamless combination of technologies. Virtual Reality (VR) and augmented reality (AR) frameworks are employed to offer practitioners a fully interactive experience. Using wearable haptic devices like WeART TouchDiver and precision tracking tools such as the NDI Polaris Vega XT, users can engage with digital models as if they were physical objects. This approach not only enhances the realism of training exercises but also provides additional sensory feedback, such as tactile sensations, visual cues, and real-time alarms, enriching the learning process.

The Rome Technopole project has gone a step further by integrating these capabilities into demonstrators showcasing the possibilities of DTs. These demonstrators use advanced physics engines like MuJoCo to simulate 3D deformations in anatomical models. By optimizing computational processes through multithreading and synchronization techniques, these simulations achieve the real-time responsiveness required for immersive VR applications. This marks a significant leap in usability and interaction quality, addressing one of the major limitations of earlier approaches. The main objective of this research is to map the technological frontiers related to DTs in the medical field, identifying the gaps in the literature, the main topics and clinical areas covered, and the trends and advantages and disadvantages of applying these technologies in the medical field. To address this topic, we provide a systematic literature review, supporting it with bibliometric analyses to assess trends and main topics of the state of the art literature. The paper is organized as follows. The next section presents the systematic review approach. The following section reports the bibliometric analyses carried out. The next section illustrates the results of the systematic review, and the final section concludes the paper.

Methods

A systematic literature review (SLR) is a research method designed to precisely identify, evaluate, and summarize all relevant evidence on a specific research question on the base of systematic procedures to minimize human error and bias. The SLR carried out to identify how DTs have been used in the medical field, was performed following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA; Page et al., 2021) framework. The applied procedure follows Avenali et al. (2023). Key steps in conducting a SLR include:

1. Establishing clear objectives and pre-defined eligibility criteria for study inclusion.
2. Employing an explicit and reproducible methodology.
3. Conducting a systematic search to identify all studies meeting the eligibility criteria.
4. Assessing and screening the identified studies.
5. Systematically presenting, describing, and summarizing the included studies.

These steps are designed to minimize bias and ensure robust and reliable results.

As eligibility criteria for the inclusion of the studies, this research adopts language, type of article and type of source. A keyword-based search was done on "Title", "abstract" and "keywords" using Scopus (https://www.scopus.com/, last accessed 17/01/2025) and Web of Science (https://www.webofscience.com/wos/woscc/basic-search, last accessed 17/01/2025) databases. We selected only reviews, chapter book and articles in English or in Italian, published in indexed journals or indexed books. The query executed for both databases is as follows:

"Digital twin" OR "Digital twins" OR "Digital phantom" OR "Digital phantoms" (All Fields)
AND **Practice OR Training OR "Teaching purpose" OR "Surgical training" OR "Robot assisted surgery"** (All Fields)
AND **healthcare OR "health care"** (All Fields)
AND NOT **"industry 5.0" OR "industry 4.0"** (All Fields)
AND **Article** or **Review Article** (Document Types)
AND **English** or **Italian** (Languages)

According to the reproducibility characteristic of SLR, all steps related to the skimming of articles are reported in detail. Initially, we obtained 54 articles from Scopus and 101 articles from Web of Science. After collection and subsequent selection of articles according to the search objective and predefined selection criteria we obtained 104 articles. After reading and deepening these articles, 32 articles were discarded because the main topic treated in the article was not in the healthcare field.

At the end of the screening and selection process, we obtained 72 articles, which will be analysed below. Figure 1 reports the PRISMA diagram, detailing the performed screening and selection procedure.
For each article retained, information was extracted on the technologies used or proposed, the advantages and disadvantages of these technologies and the clinical field in which they were used.

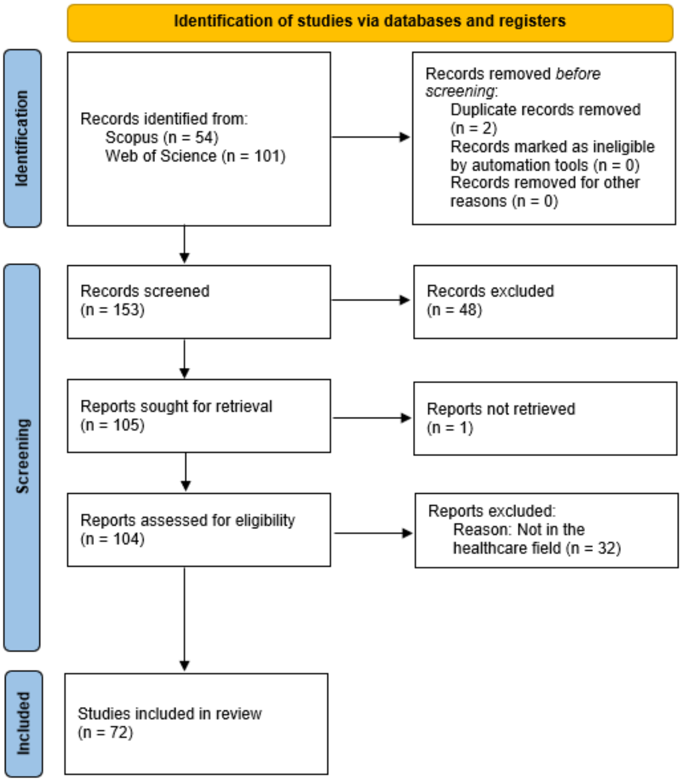

Figure 1. PRISMA 2020 flow diagram (Page et al. 2021).

To complement our SLR and gain a comprehensive understanding of the existing literature, we employed several bibliometric analyses. Combining bibliometric analysis with a SLR facilitates the efficient and reproducible generation of new knowledge from existing research (Avenali et al., 2023). Bibliometric analysis leverage articles metadata to uncover insights into various aspects, such as author collaborations, relationships between countries, and prominent authors (see e.g. Broadus, 1987). Specifically, our bibliometric analyses includes:

- An analysis of the relationships between authors' countries, keywords (representing key topics), and publication sources.
- An analysis of the frequency of author keywords.
- A factorial analysis using dimensionality reduction techniques on bigrams (sequences of two adjacent words) extracted from abstracts.
- A thematic analysis using bigrams from the abstract.

The relationships between authors' countries, keywords (representing key topics), and publication sources were analyzed using a Sankey diagram (Yang, 2022), a data visualization technique that illustrates associations between different article characteristics. This diagram visually represents the magnitude of flows between interconnected elements. The thickness of the links between nodes (representing keywords, countries, or publication sources in this study) is proportional to the volume of interactions between them. By mapping these flows, the analysis aimed to uncover patterns of international research collaboration, thematic clusters, and the influence of various publication sources on digital twin research in the healthcare field.

To further examine thematic trends, keyword occurrence analysis was conducted to determine the frequency and distribution of the most used terms in literature. Calculating keyword frequencies helped identify predominant research areas (Donthu et al., 2021). Beyond keyword analysis, bigram analysis of abstracts was performed to gain deeper insights into thematic connections and domain-specific vocabulary. Since keywords serve as proxies for the main topics of articles, analyzing abstract bigrams provided a more comprehensive understanding of underlying research themes. To explore key thematic areas, we applied Multiple Correspondence Analysis (MCA), a factorial and dimensionality reduction technique, to the abstract bigrams. MCA projects keywords into a two-dimensional space, revealing thematic clusters and underlying relationships within the field (Greenacre, 2017). This analysis highlighted distinct research themes, each representing a specific area of interest. Finally, co-word network analysis and clustering, following the method proposed by Cobo et al. (2011), were used for a thematic analysis of abstract bigrams. The identified clusters were positioned within a four-quadrant diagram based on their centrality and density, classifying them into central, niche, emerging/declining, or cross-cutting/basic themes. This approach helped delineate the primary research areas and the prevailing conceptual links within the field. All analyses were conducted using the R package Bibliometrix (Aria & Cuccurullo, 2017).

Results from the bibliometric analyses

This section presents the results of the bibliometric analyses conducted on the selected articles. Before delving into these findings, we provide a brief overview of the selected publications. A total of 72 articles, published between 2018 and 2024, were sourced from 53 journals and books. The field has experienced rapid growth, with an annual publication increase of 75.28%, highlighting its expanding significance. The average document age of 1.03 years reflects the field’s recent rise in research interest, largely driven by the increasing focus on DTs.

Analysis of the relationships between authors' countries, keywords and sources

Figure 2 visually depicts the intricate relationships between countries, author keywords, and publication sources within the medical research landscape. The central column, dominated by keywords such as artificial intelligence, digital twins, and machine learning, highlights a strong focus on emerging technologies and their applications in medicine. The results further illustrate the dynamic nature of research collaborations, as shown by the connections between various countries, keywords, and sources. Notably, the United States emerges as a key player, exhibiting extensive connections across diverse research areas. Likewise, Germany, the United Kingdom, and Switzerland demonstrate significant research activity and strong international collaborations. On the right-hand column, the sources primarily consist of scientific journals, reflecting the preferred publication venues for this research. The presence of journals such as IEEE Transactions on Consumer Electronics, Scientific Reports, and IEEE Access suggests a tendency to publish in high-impact, multidisciplinary outlets spanning computer science, medicine, and engineering. Overall, the findings indicate that research on digital twins in healthcare is a globally collaborative effort, with major contributions from countries such as the USA, India, the United Kingdom, and Germany. The emphasis on keywords like digital twin, artificial intelligence, and machine learning underscores the technological advancements driving this field.

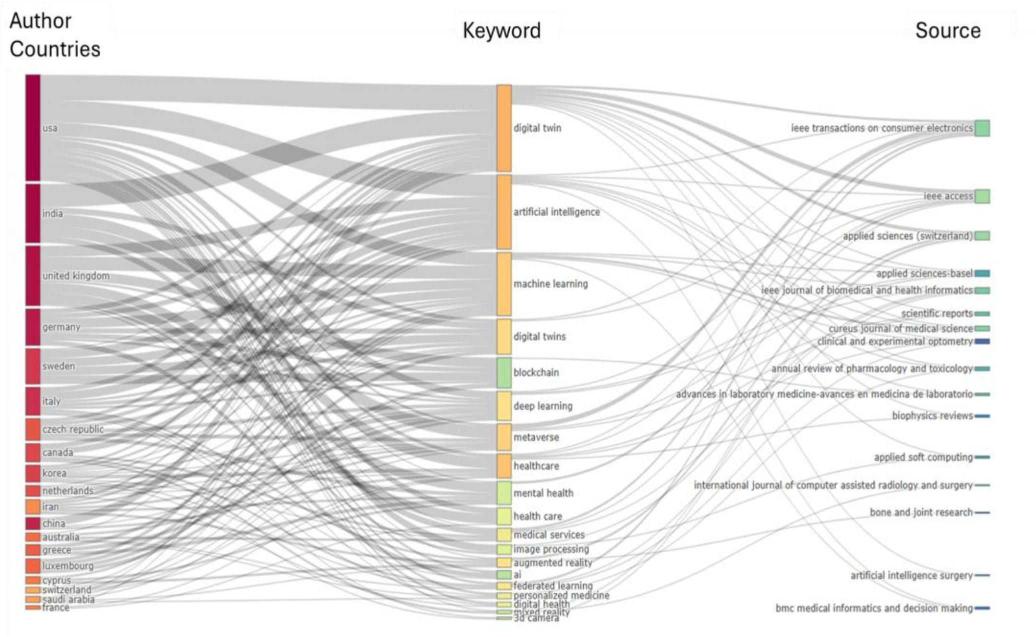

Figure 2. Analysis of the relationships between authors' countries, keywords and sources.

Analysis of the frequency of author keywords

Figure 3 presents a frequency analysis of the keywords used by authors in the 72 analyzed articles. The most frequently occurring keyword, "Digital Twin" appears in 27 articles, underscoring its central role in the research. "Artificial Intelligence" follows closely with 14 mentions, highlighting AI's pivotal role in the development and implementation of digital twins. The keyword "Healthcare" appears 12 times, reinforcing the study's domain. Additionally, terms such as "Machine Learning", "Metaverse", and "Deep Learning" reflect the technological foundations of digital twin solutions. Meanwhile, "Augmented Reality" and "Federated Learning" suggest emerging applications and privacy-preserving approaches in the field. Notably, "Medical Services" appears only four times, indicating a gap in research on how DTs translate into practical healthcare solutions. This analysis reveals a strong focus on the technological aspects of digital twins, while the relatively lower frequency of "Medical Services" suggests the need for further exploration of their real-world applications in healthcare.

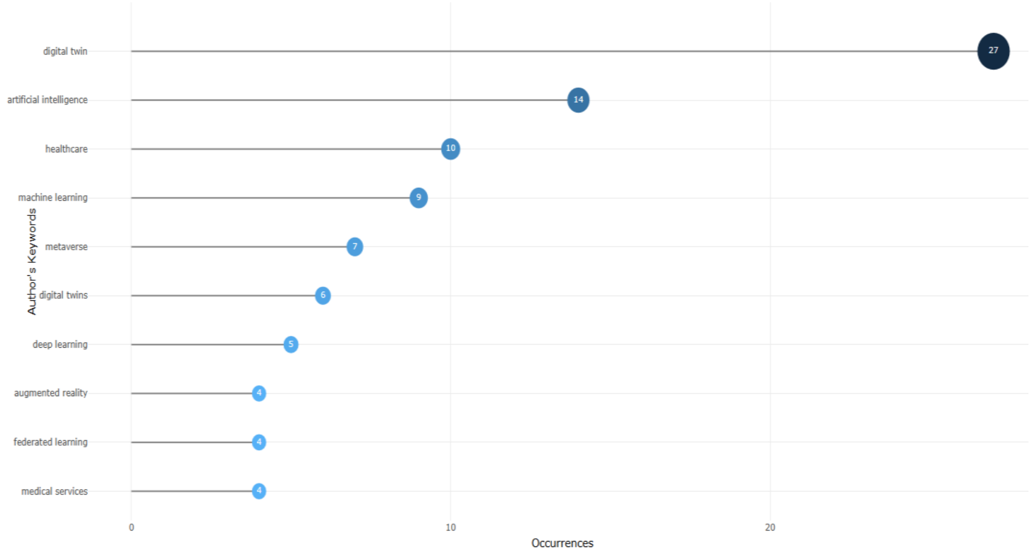

Figure 3. Keyword frequency analysis of the authors of the selected articles.

Factorial analysis results

Figure 4 presents a factorial analysis of bigrams extracted from the abstracts of 72 articles, revealing two dominant dimensions, Dim 1 and Dim 2, that together account for 61.64% of the variance in the data. Dim 1 (32.41%) captures the contrast between clinical applications and technological advancements. On one end, terms related to clinical decision-making, drug discovery, and research highlight the practical application of DTs in healthcare. On the other end, terms such as deep learning, neural networks, and proposed systems emphasize the technical foundations of DTs technology. Dim 2 (29.23%) differentiates between theoretical exploration and practical implementation. One pole, characterized by terms like “healthcare system” and “patient care”, underscores the real-world impact of digital twins on healthcare delivery. The opposite pole, with terms such as “potential applications” and “smart healthcare” suggests an ongoing discussion on future possibilities and advancements. The analysis identifies three distinct research clusters. The first, located in the top right quadrant of Figure 4, focuses on the clinical applications of DTs, with terms such as "clinical decision", "drug discovery", and "clinical practice" indicating an interest in how DTs can enhance patient care, from diagnosis and treatment planning to drug development. The second, situated in the left quadrant, highlights the technological advancements driving DTs development. Bigrams such as "deep learning", "neural networks", and "proposed system" suggest a strong focus on artificial intelligence, machine learning, and other cutting-edge technologies that enhance DTs models for healthcare. The third cluster, positioned in the bottom right quadrant, emphasizes the integration of DTs within the healthcare system. Bigrams such as "healthcare system", "healthcare industry", and "patient care" suggest a focus on how DTs can be implemented and scaled within existing healthcare structures to improve efficiency, decision-making, and patient outcomes. Overall, the findings reveal a dynamic research landscape that balances theoretical exploration with practical implementation. The strong emphasis on clinical applications reflects a growing interest in translating DTs research into real-world patient care solutions. The focus on technological advancements highlights ongoing efforts to refine neural networks and deep learning techniques that support DTs development. Finally, the emphasis on healthcare system integration underscores the importance of seamless adoption within healthcare organizations. However, further exploration is needed to bridge the gap between technological innovation and its practical applications in healthcare.

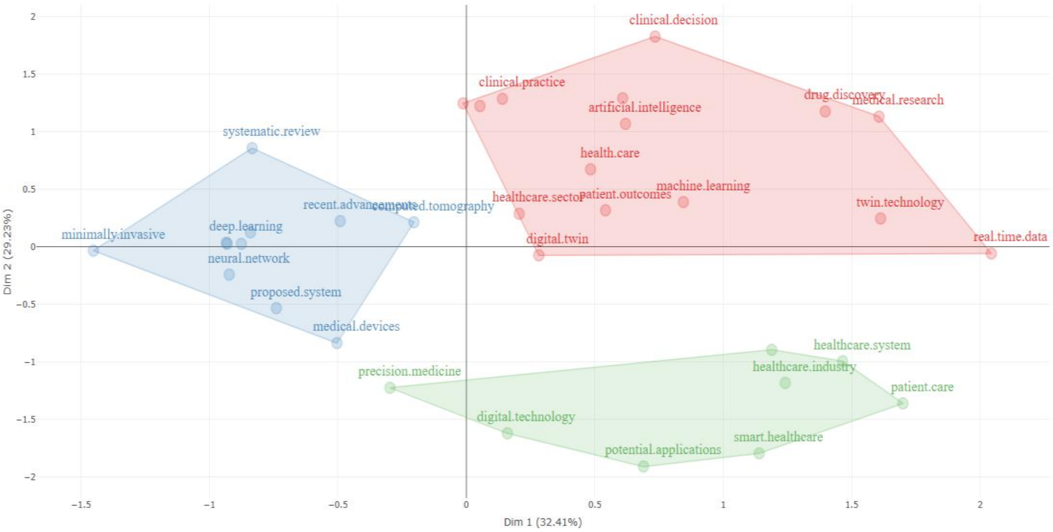

Figure 4. Factor analysis (MCA) of the abstract bigrams of the selected articles. The color of the points represents the cluster to which they belong.

Thematic analysis

Figure 5 presents a thematic map of the bigrams extracted from the abstracts of the 72 selected articles, revealing several distinct thematic clusters. A key cluster, located in the upper right quadrant, includes the bigrams “digital twin”, “artificial intelligence”, and “machine learning.” This cluster represents the motor (or core) themes of the field, highlighting areas of rapid technological advancement and active scholarly research. The presence of these concepts suggests their transformative potential in healthcare and their role at the forefront of innovation. Another significant group of core theme clusters, also in the upper right quadrant, consists of “clinical practice”, “personalized medicine”, “healthcare”, “augmented reality”, and "digital technology". These motor themes serve as the foundational principles for DTs applications in healthcare, providing the structural basis upon which more advanced solutions are built. The only basic theme identify is "deep learning" (bottom right quadrant). Given that deep learning serves as the backbone for many cutting-edge technologies in this domain, further exploration of its applications and implications is essential. This theme will be discussed in greater detail in the next section. In the upper left quadrant, a niche theme emerges, encompassing "potential applications", "proposed systems", and "enabling technologies." This cluster aligns with previous analyses, reinforcing the notion that emerging technologies are still in the early stages of adoption. The literature is gradually engaging with these innovations, but widespread implementation remains limited. Finally, clusters related to "surgical robot", "complex medical", "recent advancements" and "computed tomography" are identified as emerging themes. These concepts represent highly promising yet specific applications of DTs within the broader healthcare landscape, indicating areas of ongoing exploration and future potential.

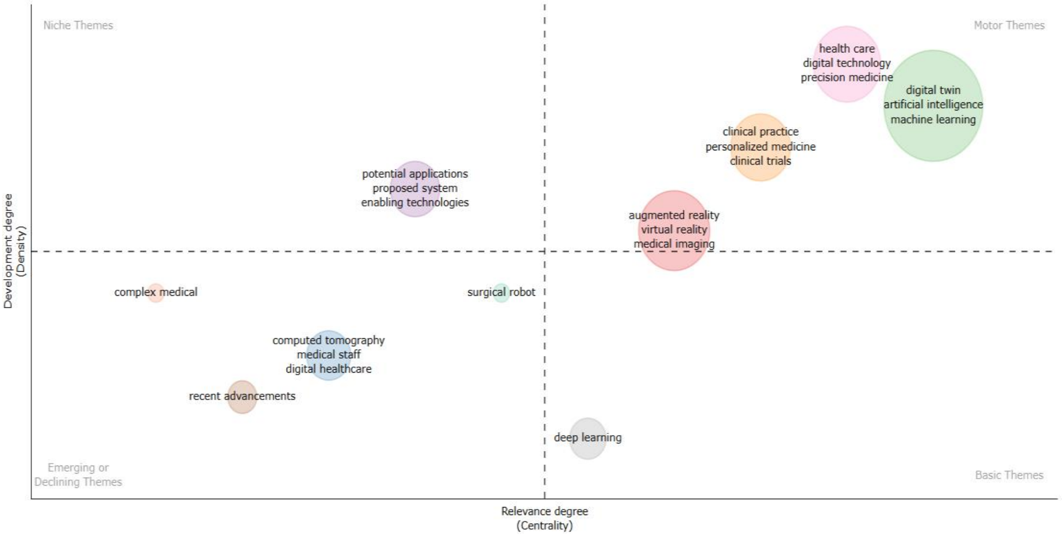

Figure 5. Thematic analysis of abstract bigrams. The chart is divided into 4 quadrants (starting from the top left quadrant and proceeding clockwise): niche themes, driving themes, basic themes and declining/emerging themes.

The bibliometric analysis presented highlights the rapid growth of interest in digital twins and the use of high technology in healthcare and the need for scientific maturation. Research efforts increasingly focus on AI-driven simulations, cross-disciplinary technologies, and real-time data integration, underscoring the expanding role of DTs across various domains. As this momentum builds, the Rome Technopole project positions itself at the cutting edge of these developments, particularly by advancing personalized surgical planning and enabling remote procedures with high-fidelity feedback systems.

Results from the SLR

As we presented in the previous Section, the application of DTs within the healthcare sector doesn't appear as an isolated technology, but they are often integrated with multiple types of other technologies, coming from different fields, such as medical engineering or computer science. We identified a diverse landscape of these technologies, categorized into several distinct but interconnected domains. Artificial intelligence (AI) and machine learning (ML) emerged as a foundational pillar, with applications spanning from image analysis using models like YOLOv3 and ResNet, (Zinchenko et al., 2021) to the development of explainable, human-centered, and trustworthy AI systems. Generative models such as ClinicalGAN (Chandra et al., 2024) and advanced learning paradigms like federated learning (Ali M. et al., 2023), split learning and FedAVG (Stephanie et al., 2024) were also noted, alongside specialized applications like neural radiance fields (NeRFs), Neuralangelo (Kleinbeck et al., 2024), and models for medical dialogue such as Med-PaLM (Vidovszky,et al., 2024) Furthermore, AI-powered digital health tools like Wysa and Ada Health (Abilkaiyrkyzy et al., 2024) were observed, indicating a trend towards personalized and accessible healthcare solutions. Virtual and augmented reality (VR/AR) technologies play a crucial role in creating immersive and interactive digital twin environments. AR and VR serve as pivotal tools for bridging the gap between the real world and its virtual counterpart. By enabling immersive visualization and interaction, VR and AR play a crucial role in enhancing the practical application of DTs in clinical settings, such as simulating surgeries for training or for planning or modelling complex physiological processes. Platforms like Unity 3D (Sunt et al., 2023; Balasubramanyam et al., 2024; Zackoff et al., 2023), coupled with hardware such as Meta Quest 2 (Balasubramanyam et al., 2024), Oculus Quest 2 (Zackoff,et al., 2023), HTC Vive Pro (Balasubramanyam et al., 2024), and HoloLens (Barcali et al., 2022; Seetohul et al., 2023; Aliani et al., 2024; Mikolajewski et al., 2024; Prasad et al., 2024; Balasubramanyam et al., 2024), are employed for diverse applications, including surgical training (e.g., Simbionix ArthroMentor, Simendo arthroscopy simulator) and visualization of complex anatomical structures (e.g., UCSF ChimeraX, YASARA). The use of haptic training and specialized VR/AR systems like VisAR (Seetohul et al., 2023), MetaMedicsVR (Hulsen et al. 2024), and Narupa iMD (Hulsen et al. 2024) further underscores the growing importance of these technologies in medical education and procedural planning. Biomedical imaging and diagnosis are significantly enhanced by DTs through the integration of advanced imaging modalities. Techniques such as shear-wave elastography (Bjelland et al., 2022), CBCT imaging (Lee et al., 2023), digital breast tomosynthesis (Pinto et al., 2023), and 3D echocardiography (Sachdeva et al., 2024) provide detailed anatomical and functional data that can be integrated into DTs models. Medical imaging equipment from manufacturers like Philips (e.g., IntelliVUE MX800) and GE Healthcare (e.g., Vivid S6), along with vein visualization technologies like AccuVein and NextVein (Seetohul et al., 2023), contribute to more precise diagnostics and treatment planning within the digital twin framework. Robotic surgery and medical planning represent another area where DTs are transforming healthcare. Surgical robots like the DaVinci system (Seetohul et al., 2023), along with advanced planning software such as Virtual Cardiac Surgery Planning, ImmersiveView Surgical Plan, iPlan Flow, HeartFlow Analysis technology (Wu et al., 2022), Philips HeartNavigator, Acorys Mapping system and Feops' HEARTguide (Sun et al., 2023), enable surgeons to simulate and optimize procedures before execution. This integration of robotic systems with digital twin technology allows for greater precision, minimally invasive approaches, and improved patient outcomes. Biomedical simulation models form the core of many DTs applications. Tools and platforms such as BioSecure (Elkefi, et al., 2022), HumMod (Montgomery et al., 2023), Archimedes (Montgomery et al., 2023), UCSF ChimeraX (Hulsen et al. 2024), and the concept of the Digital Human Twin are used to simulate physiological processes, disease progression, and treatment responses. These models, often addressing specific surgical simulation challenges (e.g., EndoVis, SAR-RARP50, CATARACTS), provide valuable insights for personalized medicine and clinical decision-making. Information systems and digital health infrastructure are essential for the effective implementation of digital twins in healthcare. Electronic health records, personal wearables and remote monitoring devices, cloud-based personal health record systems, and platforms like Ali Health (Liu et al., 2019), Baidu Medical Cloud (Liu et al., 2019), Health@Hand (Elkefi et al., 2022), CloudDTH (Liu et al., 2019), eHealth systems (Liu et al., 2019), HospiTwin (Elkefi et al., 2022), and HealthVault (Liu et al., 2019) facilitate data collection, integration, and analysis within the digital twin environment. This interconnectedness promotes better communication between healthcare providers and patients, enabling more proactive and personalized care. Furthermore, 3D modeling and project tools like Autodesk Revit (Madubuike et al., 2023), Rhino (Wang et al., 2024), CAD modeling software, AnyLogic Simulink (Balasubramanyam, et al., 2024), COMSOL Multiphysics (Balasubramanyam et al., 2024), and Bentley Architecture (Madubuike et al., 2023) are used to create detailed representations of physical spaces and medical devices within the digital twin framework. Algorithms and networks, including the pendulum algorithm (Jiang et al., 2022), Levenberg-Marquardt algorithm (Sai et al., 2024), Damped Least-Squares algorithm (Sai et al., 2024), Time Sensitive Networking (Lu et al., 2023), and DetNet (Lu et al., 2023), provide computational grounds for simulating complex interactions and optimizing system performance. Specialized devices like building information models, DTs for 3D print clouds, VITASCOPE (Wang et al., 2024), Eclipse Ditto (Balasubramanyam et al., 2024), eMI MED, and MoodPath (Abilkaiyrkyzy et al., 2024) further contribute to the diverse applications of DTs in healthcare. Robot and human collaboration platforms like ManipulaTHOR (Long et al., 2023), iGibson (Long et al., 2023), ThreeDworld (Long et al., 2023), SAPIEN (Long et al., 2023), dVRL platform (Long et al., 2023), and AMBF platform (Long et al., 2023), along with technologies for education, metaverse, and recognition, including Virtual Classroom (Preshaw et al., 2024), DTCoach (Elkefi et al., 2022), Metaversespinal, MeTAI metaverse (Wang et al., 2022), face and posture emotion recognition using techniques like Haar classifiers, highlight emerging trends in training, communication, and personalized interventions within digital twin-enabled healthcare environments. Given the technologies presented, the use of haptics and deep learning technologies (in particular PINNs) in the context of the Rome Technopole project relating to '*phygital*' is fully in the new growth technologies in use in this field, positioning itself at the existing technology frontier. Considering the wide world of medicine, however, it is necessary to investigate which clinical areas have been involved in DTs works in the past.

The distribution of research on DTs across various clinical fields reveals a concentration of interest in several key areas (Table 1). Medical education, surgery, and orthopedics emerge as prominent domains, each represented by a substantial number of articles (11, 10, and 10, respectively). In surgery, DTs emerge as transformative tools that enable preoperative planning, intraoperative guidance, and postoperative evaluation. By creating highly detailed virtual replicas of a patient's anatomy, DTs empower surgeons to simulate procedures, identify potential complications, and optimize surgical strategies, adapting them to specific cases. This capability not only enhances surgical precision but also reduces risks, shortens recovery times, and improves overall patient outcomes. In precision medicine, DTs provide a personalized approach to treatment by leveraging patient-specific data. These models integrate information from imaging, genomics, and other diagnostic tools to predict how an individual might respond to various treatments. This approach enables clinicians to adapt interventions to the unique characteristics of each patient. The distribution of clinical application suggests a strong focus on utilizing DTs for training purposes, surgical planning and simulation, and the management of musculoskeletal conditions. Precision medicine and preventive care also represent a significant area of investigation (9 articles), indicating a growing interest in leveraging digital twins for personalized healthcare strategies and proactive interventions. The use of DTs in precision medicine also includes disease management, such as monitoring disease progression and adjusting treatments to evolving situations. By offering interactive and immersive learning environments, DTs allow medical students and trainees to practice procedures, face complicated physiological systems, and visualize the effects of interventions in a risk-free setting. Several other clinical fields demonstrate a moderate level of research activity. Cardiovascular applications, diagnosis and treatment methodologies, oncology, and neurosurgery are each represented by a smaller but notable number of articles (5, 5, 4, and 4, respectively), highlighting the potential of DTs in addressing complex conditions and optimizing therapeutic approaches within these specialties. Pharmacy and drug discovery also feature in the literature (4 articles), suggesting the exploration of digital twins for accelerating drug development and personalized pharmaceutical interventions.

Specific medical disciplines such as rehabilitation, telemedicine, cardiology, and radiology are represented by a smaller number of studies (3 articles each), indicating emerging interest in these areas and potential for future expansion of digital twin applications. Other areas, such as pulmonology and dentistry, have two articles each. Finally, a selection of highly specialized clinical areas, including brain diseases, urology, gastrointestinal conditions, maxillofacial surgery and mental health, are each represented by a single article. While these areas currently have a limited number of publications related to digital twin technology, their inclusion suggests a broadening scope of investigation and the potential for future growth as technology matures and its applications become more widely explored across diverse medical specialties.

Table 1. Distribution of research on digital twins across various clinical fields.

Clinical application		
Clinical field	Number of articles in this field	Reference(s)
Medical education	11	Balasubramanyam et al. (2024); Edgar et al. (2024); Hulsen (2024); Sai et al. (2024); Cellina et al. (2023); Kim & Kim (2023); Lee et al. (2023); Zackoff et al. (2023); Barcali et al. (2022); Denecke & Baudoin (2022); Zhang & Tai (2022)
Surgery	10	Aliani et al. (2024); Ding et al. (2024); Baumann et al. (2023); Long et al. (2023); Jiang et al. (2022); Razek (2023); Sun et al. (2023); Barcali et al. (2022); Denecke & Baudoin (2022); Zinchenko & Song, (2021)
Orthopaedics	11	Sun et al. (2023) ; Barcali et al. (2022); Bjelland et al. (2022); Lisacek-Kiosoglous et al. (2023); Seetohul et al. (2023); Liang et al. (2024); Ding et al. (2024); Aliani et al. (2024); Prasad et al. (2024); Zsidai et al. (2023); Zhou et al. (2024)
Precision medicine and preventive care	9	Sun et al. (2023); Vallée (2023); Suchetha et al. (2024); Sai et al. (2024); Bruynseels et al. (2018); Balasubramanyam et al. (2024); Liu et al. (2019) ;Venkatesh et al. (2024); Milne-Ives et al. (2022)
Cardiovascular	5	Sun et al. (2023); Wu et al. (2022); Ding et al. (2024); Aliani et al. (2024); Rouhollahi et al. (2023)
Diagnosis and treatment	5	Sun et al. (2023); Pregowska & Perkins (2024); Balasubramanyam et al. (2024); Venkatesh et al. (2024); Sharma et al. (2024)
Pharmacy and drug discovery	4	Sun et al. (2023); Balasubramanyam et al. (2024); Cellina et al. (2023); Venkatesh et al. (2024)

Oncology	4	Barcali et al. (2022); Wu et al. (2022); Aliani et al. (2024); Prasad et al. (2024)
Neurosurgery and neuroscience	4	Barcali et al. (2022); Seetohul et al. (2023); Prasad et al. (2024); Fekonja et al. (2024)
Rehabilitation	3	Denecke & Baudoin (2022); Mikolajewski et al. (2024); Tao et al. (2024)
Telemedicine	3	Denecke & Baudoin (2022); Kim & Kim (2023); Hulsen (2024)
Cardiology	3	Seetohul et al. (2023); Mikolajewski et al. (2024); Sachdeva et al. (2024)
Radiology	3	Pesapane et al. (2022); Geissler et al. (2021); Panayides et al. (2020)
Pneumology	2	Zhang & Tai (2022); Montgomery et al. (2023)
Dentistry	2	Lee et al. (2023); Preshaw et al. (2024)
Brain diseases	1	Wu et al. (2022)
Urology	1	Kim & Kim (2023)
Gastrointestinal	1	Seetohul et al. (2023)
Maxillofacial surgery	1	Aliani et al. (2024)
Mental health	1	Abilkaiyrkyzy et al. (2024)

Despite the various instruments and clinical applications in literature, considering how sensitive the medical field is, it is important to evaluate the advantages and disadvantages identified. This is necessary to assess the benefits and costs of using frontier technologies and DTs in a field where patients' lives are at stake. This step is critical before we can have full deployment of these technologies. Disadvantages and advantages identified in the literature are presented in Table 2 (advantages) and Table 3 (disadvantages). The reviewed literature highlights a range of advantages associated with the application of digital twin technology in healthcare. The most frequently cited benefit pertains to improvements in patient care (20 articles), encompassing enhancements in both pre-clinical and post-clinical phases, and facilitating more personalized treatments. This broad category is supported by numerous studies (e.g., Lisacek-Kiosoglous et al., 2023; Kim & Kim, 2023; Zinchenko & Song, 2021; Chandra et al., 2024), indicating a strong consensus on the potential of digital twins to revolutionize patient management. Several other key advantages emerged prominently. Digital twins were frequently reported to improve physicians' accuracy in surgery and decision-making (10 articles), with studies such as Wu et al. (2022), Bjelland et al. (2022) and Lu et al. (2023), providing evidence for this claim. Similarly, the technology's potential to enhance medical education through flexible and adaptable online learning was highlighted in 10 articles (e.g., Long et al., 2023; Preshaw et al., 2024). Real-time data extraction, precise treatments, and improved predictive abilities were each identified as advantages in nine articles. Studies such as Sun et al. (2023), Lee et al. (2023), and Pinto et al. (2023) support the role of digital twins in enabling timely data analysis, tailoring interventions to individual patient needs, and forecasting disease progression or treatment outcomes. Improvements in surgery, including applications with robotic systems, were noted in eight articles (e.g., Yang, 2023; Wang, 2024; Vallée, 2023), further emphasizing the technology's impact on surgical practice. Enhancements in diagnosis were reported in six articles (e.g., Zhang & Tai, 2022, Yang, 2023, Bhattad & Jain, 2020), while interoperability and improvements to healthcare structures were each mentioned in five articles (e.g., Bjelland et al., 2022; Yang, 2023; Wang, 2024). Real-time monitoring was identified as a benefit in three articles (e.g., Liu et al. 2019; Venkatesh et al., 2024), and improvements in security and increasing drug development were each noted in two articles (e.g., Upreti et al., 2024; Hulsen, 2024). Finally, several more specific advantages were each mentioned in a single article: the use of finite element (FE) methods for non-invasive, controllable, and repeatable procedures (Sun et al., 2023), efficiency of visualization and reduction of exposure to ionizing radiation (Barcali et al., 2022), and the establishment of a link between the real and virtual worlds (Garg et al., 2022). This distribution of reported advantages underscores the multifaceted impact of digital twins technology across various aspects of healthcare, from patient care and surgical precision to medical education and drug development. The concentration of articles on patient care, surgical accuracy, and medical education suggests these areas are currently the primary focus of research and application, while the presence of more specific advantages indicates the potential for further exploration and development in diverse sub-domains. At the same time, several disadvantages associated with digital twin technology in healthcare were identified in the reviewed literature. Security and privacy concerns emerged as the most frequently cited drawback, mentioned in 16 articles (e.g., Zhang & Tai, 2022; Denecke & Baudoin, 2022; Stephanie et al., 2024). This highlights the critical need for robust data protection measures and ethical considerations surrounding the sensitive information managed within digital twin systems. The scarcity, accuracy, and quality of data were identified as a significant challenge in 10 articles (e.g., Sun et al., 2023, Wu et al., 2022; Geissler et al., 2021). This underscores the importance of reliable data sources and rigorous data validation processes to ensure the integrity and effectiveness of digital twin models. Ethical, social, and legal risks were also frequently discussed, appearing in seven articles (e.g., Sun et al., 2023, Pregowska & Perkins, 2024; Vidovszky et al., 2024), emphasizing the need for careful consideration of the broader societal implications of this technology. High costs associated with implementation and maintenance were noted in four articles (e.g., Bjelland et al., 2022; Lisacek-Kiosoglous et al., 2023) highlighting the economic barriers that may hinder widespread adoption. The dependency on the accuracy of simulations and potential model errors was identified as a disadvantage in three articles (Sun et al., 2023; Barcali et al., 2022; Kim & Kim, 2023), emphasizing the importance of continuous model refinement and validation. Medical interoperability, referring to the ability of different systems and devices to exchange and utilize data, was also mentioned in three articles (e.g., Yang, 2023; Ding et al., 2024; Khater et al., 2024). Several disadvantages were noted in two articles each: the need for further validation of digital twin models (e.g., Sun et al., 2023; Wu et al., 2022), challenges in establishing accurate and intuitive action mapping between human input devices and surgical robots (e.g., Long et al., 2023; Jiang et al., 2022), the potential for incorrect connections between the real and virtual worlds due to sensor reliability and accuracy (e.g., Seetohul et al., 2023; Liu et al., 2019), and the presence of biases in data or model design (e.g., Gwon et al., 2024, Pesapane et al., 2022). A range of highly specific disadvantages were each mentioned in a single article: vergence-accommodation conflict in VR/AR applications (Barcali et al., 2022), challenges in connecting phenomena at different scales and calibrating model parameters (Wu et al., 2022), technological limitations related to computational techniques, model selection, validation, uncertainty quantification, and data interoperability (Zhang & Tai, 2022), dependence on Magnetic Resonance Imaging (MRI) (Bjelland et al., 2022), discomfort associated with wearable devices (Kim & Kim, 2023), the difficulty of building realistic physical simulations with high-fidelity scene visualization (Long et al., 2023) the influence of ambient air humidity during the setting phase (a phenomenon that is not always easily simulated, Lee et al., 2023), inconsistency in delivery and assessment methods across online learning platforms (Preshaw et al., 2024), the need for advanced haptic training tools (which has a huge impact in the diffusion and in the costs of implementation of the different solutions available, Preshaw et al., 2024), concerns related to distribution through virtual pharmacies (Yang, 2023), challenges in real-time modeling of tissues (especially computational problems, Razek, 2023), limitations in real-time information updates and bi-directional coordination in hospital facilities management (Madubuike et al., 2023), and the potential lack of individualization in certain applications (Milne-Ives et al., 2022). This diverse array of disadvantages highlights the ongoing challenges and areas for improvement in the development and implementation of digital twin technology in healthcare. The prevalence of concerns related to security, data quality, and ethical considerations underscores the need for careful planning and robust safeguards to ensure responsible and effective utilization of this technology. Of the various advantages and disadvantages identified, the Rome Technopole project is at the forefront in several respects. Firstly, the development of real-time soft tissue simulation systems using computational capacity reduction techniques required (using PINNs) makes it possible to solve one of the problems listed above. Other projects in the Rome Technopole are currently working on solving another of the problems listed above, namely that of security and data. In the future, the implementation of phygital technology within the project will have to take account of what has been identified, especially in relation to the communication and sensor issues adopted to avoid the serious problem of poor data quality.

Table 2. Advantages identified in the literature on the application of DTs and emerging technologies in the medical field.

Advantages	*Number of articles*	*Reference(s)*
Patient care (improving pre-clinical phase and post-clinical phase, reducing the distance for personalised treatments)	20	Lisacek-Kiosoglous et al. (2023); Kim & Kim (2023); Zinchenko & Song, (2021); Preshaw et al. (2024); Yang (2023); Gwon et al. (2024); Liang et al. (2024); Jiang et al. (2022) ; Upreti et al. (2024); Mikolajewski et al. (2024); Razek (2023); Suchetha et al. (2024); Sai et al. (2024); Cellina et al. (2023); Elkefi & Asan (2022); Subramanian et al. (2022); Hulsen (2024); Tao et al. (2024); Stephanie et al. (2024); Chandra et al. (2024)
Improves the physicians' accuracy in surgery and decision making	10	Wu et al. (2022); Bjelland et al. (2022); Liang et al. (2024); Balasubramanyam et al. (2024); Cellina et al. (2023); Elkefi & Asan (2022); Montgomery et al. (2023); Kleinbeck et al. (2024); Khater et al. (2024); Lu et al. (2023)
Improves medical education (Flexibility and adaptability of online learning)	10	Long et al. (2023); Preshaw et al. (2024); Yang (2023); Pregowska & Perkins (2024); Aliani et al. (2024); Edgar et al. (2024); Mikolajewski et al. (2024); Razek (2023); Vallée (2023); Jamshidi et al. (2023)
Real-time data extraction	10	Abilkaiyrkyzy et al. (2024); Ding et al. (2024); Sun et al. (2023); Zhang & Tai (2022); Denecke & Baudoin (2022)Lisacek-Kiosoglous et al. (2023); Wang (2024); Garg et al. (2022); Bhatia (2024); Joo et al. (2024)
Precise treatments	9	Sun et al. (2023); Lee et al. (2023) Seetohul et al. (2023); Milne-Ives et al. (2022); Kim & Kim (2023); Elkefi & Asan (2022); Chandra et al. (2024); Khater et al. (2024); Bhattad & Jain (2020)

Improves predicting ability	9	Lisacek-Kiosoglous et al. (2023);Upreti et al. (2024); Zsidai et al. (2023); Panayides et al. (2020); Vallée (2023); Pesapane et al. (2022); Khater et al. (2024); Kulkarni et al. (2024); Pinto et al. (2023)
Improves surgery	8	Yang (2023); Liang et al. (2024); Jiang et al. (2022); Baumann et al. (2023); Vallée (2023); Ding et al. (2024); Wang (2024); Khater et al. (2024)
Improves diagnosis	6	Zhang & Tai (2022); Yang (2023); Sharma et al. (2024); Vidovszky et al. (2024); Sachdeva et al. (2024); Bhattad & Jain (2020)
Interoperability	5	Bjelland et al. (2022); Yang (2023); Ding et al. (2024); Prasad et al. (2024); Balasubramanyam et al. (2024)
Improves healthcare structures	5	Wang (2024); Lisacek-Kiosoglous et al. (2023); Yang (2023); Madubuike (2023); Vidovszky et al. (2024)
Real time monitoring	3	Liu et al. (2019); Venkatesh et al. (2024); Bhatia (2024)
Improves security	2	Upreti et al. (2024); Bhatia (2024)
Increasing drug development	2	Vidovszky et al. (2024); Hulsen (2024)
non-invasiveness and repeatability	1	Sun et al. (2023)
Efficiency of visualization	1	Barcali et al. (2022)
Reduction of exposure to ionizing radiation	1	Barcali et al. (2022)
Link between real world and virtual world	1	Garg et al. (2022)

Table 3. Disadvantages identified in the literature on the application of DTs and emerging technologies in the medical field.

Disadvantages	*Number of articles*	*Reference(s)*
Security and privacy	16	Zhang & Tai (2022); Denecke & Baudoin (2022); Preshaw et al. (2024) Gwon et al. (2024); Upreti et al. (2024); Khater et al. (2024); Stephanie et al. (2024); Suchetha et al. (2024); Bruynseels et al. (2018); Balasubramanyam et al. (2024); Cellina et al. (2023); Venkatesh et al. (2024); Hulsen (2024); Garg et al. (2022); Ali et al. (2023); Wang (2024)
Scarsity, accuracy and quality of data	10	Sun et al. (2023); Wu et al. (2022); Upreti et al. (2024); Baumann et al. (2023); Pesapane et al. (2022); Cellina et al. (2023); Milne-Ives et al. (2022); Rouhollahi et al. (2023); Geissler et al. (2021); Vidovszky et al. (2024)
Ethical, social and legal risks	9	Sun et al. (2023); Pregowska & Perkins (2024); Upreti et al. (2024); Suchetha et al. (2024); Bruynseels et al. (2018); Balasubramanyam et al. (2024); Vidovszky et al. (2024); Zhou et al. (2025); Joo et al. (2024)
High costs	4	Bjelland et al. (2022); Lisacek-Kiosoglous et al. (2023); Liang et al. (2024); Lu et al. (2023)
Dependency from accuracy of simulation and model's errors	3	Sun et al. (2023); Barcali et al. (2022); Kim & Kim (2023)
Medical interoperability	3	Yang (2023); Ding et al. (2024); Khater et al. (2024)
Need for further validation	2	Sun et al. (2023); Wu et al. (2022)
Scarse mechanism between human input device and surgical robots	2	Long et al. (2023); Jiang et al. (2022)
Incorrect connection between (sensor reliability and accuracy)	2	Seetohul et al. (2023); Liu et al. (2019)
Biases	2	Gwon et al. (2024); Pesapane et al. (2022)

Vergence-accomodation conflict	1	Barcali et al. (2022)
Scales and calibration of model parameters	1	Wu et al. (2022)
Technological limitations	1	Zhang & Tai (2022)
Dependence on MRI	1	Bjelland et al. (2022)
Discomfort of the wearable devices	1	Kim & Kim (2023)
Complexity in realistically and faithfully simulating physical interactions	1	Long et al. (2023)
Humidity of the ambient air during the setting phase	1	Lee et al. (2023)
Inconsistency in delivery and assessment methods across online platforms	1	Preshaw et al. (2024)
Haptic training required	1	Preshaw et al. (2024)
Virtual Pharmacies using Extended Reality are complex to implement	1	Yang (2023)
Real time modeling of tissues	1	Razek (2023)
Lack of real time information	1	Madubuike et al. (2023)
Lack of individualization	1	Milne-Ives et al. (2022)

Preliminary Conclusions

Looking ahead, the future of DTs in healthcare lies in broader applications of these technologies. Personalized medicine, adaptive diagnostics, and real-time surgical interventions are among the key areas of expansion. The Rome Technopole project exemplifies this forward-thinking vision by emphasizing not only immediate training applications but also the potential for remote and augmented surgical systems to redefine medical practices. Through its innovative use of AI, haptics, and immersive technologies, the project has already made significant strides. Its publications, including studies on haptic interactions with virtual deformable objects, reflect this progress. Indeed, this project, drawing upon existing literature and through the integration of various haptic technologies and VR technologies, is moving towards highly evolved phygital twins technology, also known as autonomous twins (Zhang et al., 2024). Autonomous twins operate independently while seamlessly interacting with the physical world, potentially creating metaverses populated by autonomous virtual entities. This evolution promises to revolutionize healthcare through applications such as autonomic DTs brains for personalized interventions, realistic surgical training with tailored feedback, and ultimately, the realization of precision medicine by accelerating medical discoveries and improving treatment outcomes. As digital twins evolve towards this autonomous stage, their integration into healthcare will undoubtedly lead to new standards of precision, efficiency, and accessibility, paving the way for revolutionary advancements in medical care.

Acknowledgments

This paper is done within the Research Project "Phygital Twin Technologies for Innovative Surgical Training & Planning (ECS 0000024 – Rome Technopole)" within the Rome Technopole, which is the first multi-technology hub for education, research and technology transfer in the fields of Energy Transition and Sustainability, Digital Transformation and Health & Bio-Farma. The project is part of the National Recovery and Resilience Plan (PNRR). It creates for the first time an innovation ecosystem for the Lazio Region, in which 7 universities, 4 research organizations, the Lazio Region the Municipality of Rome and other public bodies, 20 industrial groups and enterprises participate.

References

Abilkaiyrkyzy, A., Laamarti, F., Hamdi, M., & Saddik, A. E. (2024). Dialogue System for Early Mental Illness Detection: Toward a Digital Twin Solution. *IEEE ACCESS*, *12*, 2007–2024.

Ali, M., Naeem, F., Tariq, M., & Kaddoum, G. (2023). Federated Learning for Privacy Preservation in Smart Healthcare Systems: A Comprehensive Survey. *IEEE Journal of Biomedical and Health Informatics*, *27*(2), 778–789.

Aliani, C., Morelli, A., Rossi, E., Lombardi, S., Civale, V. Y., Sardini, V., Verdino, F., et al. (2024). Realistic Texture Mapping of 3D Medical Models Using RGBD Camera for Mixed Reality Applications. *Applied Sciences (Switzerland)*, *14*(10). Multidisciplinary Digital Publishing Institute (MDPI).

Aria, M., & Cuccurullo, C. (2017). bibliometrix: An R-tool for comprehensive science mapping analysis. *Journal of Informetrics*, *11*(4), 959–975. Elsevier.

Avenali, A., Daraio, C., Di Leo, S., Matteucci, G., & Nepomuceno, T. (2023). Systematic reviews as a metaknowledge tool: caveats and a review of available options. *International Transactions in Operational Research*, *30*(6), 2761–2806. John Wiley & Sons, Ltd.

Aziz, S., Jung, D. W., Uz Zaman, U. K., & Aqeel, A. Bin. (2024). Digital Twins in Smart Manufacturing. *Handbook of Manufacturing Systems and Design: An Industry 4.0 Perspective* (pp. 53–68). Taylor & Francis.

Bagaria, N., Laamarti, F., Badawi, H. F., Albraikan, A., Velazquez, R. A. M., & El Saddik, A. (2020). Health 4.0: Digital Twins for Health and Well-Being. *Connected Health in Smart Cities* (pp. 143–152). Springer, Cham.

Balasubramanyam, A., Ramesh, R., Sudheer, R., & Honnavalli, P. B. (2024). Revolutionizing Healthcare: A Review Unveiling the Transformative Power of Digital Twins. *IEEE ACCESS*, *12*, 69652–69676.

Barcali, E., Iadanza, E., Manetti, L., Francia, P., Nardi, C., & Bocchi, L. (2022). Augmented Reality in Surgery: A Scoping Review. *Applied Sciences (Switzerland)*, *12*(14). MDPI.

Baumann, O., Lenz, A., Hartl, J., Bernhard, L., & Knoll, A. C. (2023). Intuitive teaching of medical device operation to clinical assistance robots. *International Journal of Computer Assisted Radiology and Surgery*, *18*(5), 865–870. Springer Science and Business Media Deutschland GmbH.

Bhatia, M. (2024). An AI-enabled secure framework for enhanced elder healthcare. *ENGINEERING APPLICATIONS OF ARTIFICIAL INTELLIGENCE*, *131*.

Bhattad, P. B., & Jain, V. (2020). Artificial Intelligence in Modern Medicine - The Evolving Necessity of the Present and Role in Transforming the Future of Medical Care. *CUREUS JOURNAL OF MEDICAL SCIENCE*, *12*(5).

Bjelland, O., Rasheed, B., Schaathun, H. G., Pedersen, M. D., Steinert, M., Hellevik, A. I.,

& Bye, R. T. (2022). Toward a Digital Twin for Arthroscopic Knee Surgery: A Systematic Review. *IEEE Access*, *10*, 45029–45052. Institute of Electrical and Electronics Engineers Inc.

Broadus, R. N. (1987). Toward a definition of "bibliometrics." *Scientometrics*, *12*(5–6), 373–379. Kluwer Academic Publishers.

Bruynseels, K., de Sio, F. S., & van den Hoven, J. (2018). Digital Twins in Health Care: Ethical Implications of an Emerging Engineering Paradigm. *FRONTIERS IN GENETICS*, *9*.

Cellina, M., Cè, M., Alì, M., Irmici, G., Ibba, S., Caloro, E., Fazzini, D., et al. (2023). Digital Twins: The New Frontier for Personalized Medicine? *APPLIED SCIENCES-BASEL*, *13*(13).

Chandra, S., Prakash, P. K. S., Samanta, S., & Chilukuri, S. (2024). ClinicalGAN: powering patient monitoring in clinical trials with patient digital twins. *SCIENTIFIC REPORTS*, *14*(1).

Cobo, M. J., López-Herrera, A. G., Herrera-Viedma, E., & Herrera, F. (2011). An approach for detecting, quantifying, and visualizing the evolution of a research field: A practical application to the Fuzzy Sets Theory field. *Journal of Informetrics*, *5*(1), 146–166. Elsevier.

Denecke, K., & Baudoin, C. R. (2022). A Review of Artificial Intelligence and Robotics in Transformed Health Ecosystems. *Frontiers in Medicine*, *9*. Frontiers Media S.A.

De Santis, E., Le Jeune, Y., Marchal, M., Pacchierotti, C., & Vendittelli, M. (2024, October). Haptic interaction with virtual deformable objects. In *Proc. Italian Institute of Robotics and Intelligent Machines* (I-RIM) 3D 2024.

Ding, H., Seenivasan, L., Killeen, B. D., Cho, S. M., & Unberath, M. (2024). Digital twins as a unifying framework for surgical data science: the enabling role of geometric scene understanding. *Artificial Intelligence Surgery*, *4*(3), 109–138. OAE Publishing Inc.

Distefano, L., Fumagalli, A., Giampietro, G., Naffati, J., Romaniello, C., Vitale, V. M., & Vendittelli, M. (2023, ottobre 20). An Integrated Environment for Medical Training and Procedure Planning in Virtual Reality. https://doi.org/10.5281/zenodo.10722622

van Dinter, R., Tekinerdogan, B., & Catal, C. (2022). Predictive maintenance using digital twins: A systematic literature review. *Information and Software Technology*, *151*, 107008. Elsevier.

Donthu, N., Kumar, S., Mukherjee, D., Pandey, N., & Lim, W. M. (2021). How to conduct a bibliometric analysis: An overview and guidelines. *Journal of Business Research*, *133*, 285–296. Elsevier.

Edgar, A. K., Chong, L. X., Wood-Bradley, R., Armitage, J. A., Narayanan, A., & Macfarlane, S. (2024). The role of extended reality in optometry education: a narrative review. *Clinical and Experimental Optometry*. Taylor and Francis Ltd.

El-Agamy, R. F., Sayed, H. A., AL Akhatatneh, A. M., Aljohani, M., & Elhosseini, M. (2024). Comprehensive analysis of digital twins in smart cities: a 4200-paper bibliometric study. *Artificial Intelligence Review*, *57*(6), 154. Springer.

Elkefi, S., & Asan, O. (2022). Digital Twins for Managing Health Care Systems: Rapid Literature Review. *JOURNAL OF MEDICAL INTERNET RESEARCH*, *24*(8).

Evangeline, P. (2020). Digital twin technology for "smart manufacturing." *Advances in computers* (Vol. 117, pp. 35–49). Elsevier.

Fekonja, L. S., Schenk, R., Schröder, E., Tomasello, R., Tomšič, S., & Picht, T. (2024). The digital twin in neuroscience: from theory to tailored therapy. *Frontiers in Neuroscience*, *18*, 1454856. Frontiers Media SA.

Garg, H., Sharma, B., Shekhar, S., & Agarwal, R. (2022). Spoofing detection system for ehealth digital twin using EfficientNet Convolution Neural Network. *MULTIMEDIA TOOLS AND APPLICATIONS*, *81*(19), 26873–26888.

Geissler, F., Heiss, R., Kopp, M., Wiesmüller, M., Saake, M., Wuest, W., Wimmer, A., et al. (2021). Personalized computed tomography - Automated estimation of height and weight of a simulated digital twin using a 3D camera and artificial intelligence. *ROFO-FORTSCHRITTE AUF DEM GEBIET DER RONTGENSTRAHLEN UND DER BILDGEBENDEN VERFAHREN*, *193*(4), 437–445.

Greenacre, M. (2017). Correspondence analysis in practice, third edition. *Correspondence Analysis in Practice, Third Edition*, 1–310. CRC Press.

Grieves, M., & Vickers, J. (2017). Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems. *Transdisciplinary perspectives on complex systems: New findings and approaches* (pp. 85–113). Springer.

Gwon, Y. N., Kim, J. H., Chung, H. S., Jung, E. J., Chun, J., Lee, S., & Shim, S. R. (2024). The Use of Generative AI for Scientific Literature Searches for Systematic Reviews: ChatGPT and Microsoft Bing AI Performance Evaluation. *JMIR Medical Informatics*, *12*. JMIR Publications Inc.

Hulsen, T. (2024). Applications of the metaverse in medicine and healthcare. *ADVANCES IN LABORATORY MEDICINE-AVANCES EN MEDICINA DE LABORATORIO*, *5*(2), 159–165.

Jamshidi, M., Sargolzaei, S., Foorginezhad, S., & Moztarzadeh, O. (2023). Metaverse and microorganism digital twins: A deep transfer learning approach. *APPLIED SOFT COMPUTING*, *147*.

Jiang, F., Jia, R., Jiang, X., Cao, F., Lei, T., & Luo, L. (2022). Human-Machine Interaction Methods for Minimally Invasive Surgical Robotic Arms. *Computational Intelligence and Neuroscience*, *2022*. Hindawi Limited

Jones, D., Snider, C., Nassehi, A., Yon, J., & Hicks, B. (2020). Characterising the Digital Twin: A systematic literature review. *CIRP journal of manufacturing science and technology*, *29*, 36–52. Elsevier.

Joo, Y., Camacho, D., Boi, B., Esposito, C., & Choi, C. (2024). Blockchain and Federated Learning Empowered Digital Twin for Effective Healthcare. *Human-centric Computing and Information Sciences*, *14*. Korea Information Processing Society.

Katsoulakis, E., Wang, Q., Wu, H., Shahriyari, L., Fletcher, R., Liu, J., ... & Deng, J. (2024). Digital twins for health: a scoping review. *NPJ digital medicine*, 7(1), 77.

Khater, H. M., Sallabi, F., Serhani, M. A., Barka, E., Shuaib, K., Tariq, A., & Khayat, M. (2024). Empowering Healthcare with Cyber-Physical System - A Systematic Literature Review. *IEEE Access*, *12*, 83952–83993. Institute of Electrical and Electronics Engineers Inc

Kim, E. J., & Kim, J. Y. (2023). The Metaverse for Healthcare: Trends, Applications, and Future Directions of Digital Therapeutics for Urology. *International Neurourology Journal*, *27*, S3–S12. Korean Continence Society.

Kleinbeck, C., Zhang, H., Killeen, B. D., Roth, D., & Unberath, M. (2024). Neural digital twins: reconstructing complex medical environments for spatial planning in virtual reality. *International Journal of Computer Assisted Radiology and Surgery*, *19*(7), 1301–1312. Springer Science and Business Media Deutschland GmbH.

Kulkarni, C., Quraishi, A., Raparthi, M., Shabaz, M., Khan, M. A., Varma, R. A., Keshta, I., et al. (2024). Hybrid disease prediction approach leveraging digital twin and metaverse technologies for health consumer. *BMC MEDICAL INFORMATICS AND DECISION MAKING*, *24*(1).

Lee, J.-H., Lee, H.-L., Park, I.-Y., On, S.-W., Byun, S.-H., & Yang, B.-E. (2023).

Effectiveness of creating digital twins with different digital dentition models and cone-beam computed tomography. *Scientific Reports*, *13*(1). Nature Research.

Liang, W., Zhou, C., Bai, J., Zhang, H., Jiang, B., Wang, J., Fu, L., et al. (2024). Current advancements in therapeutic approaches in orthopedic surgery: a review of recent trends. *Frontiers in Bioengineering and Biotechnology*, *12*. Frontiers Media SA.

Lisacek-Kiosoglous, A. B., Powling, A. S., Fontalis, A., Gabr, A., Mazomenos, E., & Haddad, F. S. (2023). Artificial intelligence in orthopaedic surgery EXPLORING ITS APPLICATIONS, LIMITATIONS, AND FUTURE DIRECTION. *Bone and Joint Research*, *12*(7), 47–454. British Editorial Society of Bone and Joint Surgery.

Liu, Y., Zhang, L., Yang, Y., Zhou, L. F., Ren, L., Wang, F., Liu, R., et al. (2019). A Novel Cloud-Based Framework for the Elderly Healthcare Services Using Digital Twin. *IEEE ACCESS*, *7*, 49088–49101.

Long, Y., Wei, W., Huang, T., Wang, Y., & Dou, Q. (2023). Human-in-the-Loop Embodied Intelligence With Interactive Simulation Environment for Surgical Robot Learning. *IEEE Robotics and Automation Letters*, *8*(8), 4441–4448. Institute of Electrical and Electronics Engineers Inc.

Lu, Y. Z., Zhao, G. F., Chakraborty, C., Xu, C., Yang, L., & Yu, K. P. (2023). Time-Sensitive Networking-Driven Deterministic Low-Latency Communication for Real-Time Telemedicine and e-Health Services. *IEEE TRANSACTIONS ON CONSUMER ELECTRONICS*, *69*(4), 734–744.

Madubuike, O. C., Anumba, C. J., & Agapaki, E. (2023). Scenarios for digital twin deployment in healthcare facilities management. *JOURNAL OF FACILITIES MANAGEMENT*.

Mikolajewski, D., Bryniarska, A., Wilczek, P. M., Myslicka, M., Sudol, A., Tenczynski, D., Kostro, M., et al. (2024). THE MOST CURRENT SOLUTIONS USING VIRTUAL-REALITY-BASED METHODS IN CARDIAC SURGERY – A SURVEY. *Computer Science*, *25*(1), 107–128. AGH University of Science and Technology Press.

Milne-Ives, M., Fraser, L. K., Khan, A., Walker, D., van Velthoven, M. H., May, J., Wolfe, I., et al. (2022). Life Course Digital Twins-Intelligent Monitoring for Early and Continuous Intervention and Prevention (LifeTIME): Proposal for a Retrospective Cohort Study. *JMIR RESEARCH PROTOCOLS*, *11*(5).

Montgomery, A. J., Litell, J., Dang, J., Flurin, L., Gajic, O., & Lal, A. (2023). Gaining consensus on expert rule statements for acute respiratory failure digital twin patient model in intensive care unit using a Delphi method. *BIOMOLECULES AND BIOMEDICINE*, *23*(6), 1108–1117.

Mourtzis, D., Angelopoulos, J., & Panopoulos, N. (2023). The future of the human–machine interface (HMI) in society 5.0. *Future Internet*, *15*(5), 162. MDPI.

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., et al. (2021). The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ*, *372*. British Medical Journal Publishing Group.

Panayides, A. S., Amini, A., Filipovic, N., Sharma, A., Tsaftaris, S. A., Young, A., Foran, D. J., et al. (2020). AI in Medical Imaging Informatics: Current Challenges and Future Directions. *IEEE JOURNAL OF BIOMEDICAL AND HEALTH INFORMATICS*, *24*(7), 1837–1857.

Pesapane, F., Rotili, A., Penco, S., Nicosia, L., & Cassano, E. (2022). Digital Twins in Radiology. *JOURNAL OF CLINICAL MEDICINE*, *11*(21).

Pinto, M. C., Mauter, F., Michielsen, K., Biniazan, R., Kappler, S., & Sechopoulos, I. (2023). A deep learning approach to estimate x-ray scatter in digital breast tomosynthesis: From phantom models to clinical applications. *MEDICAL PHYSICS*, *50*(8), 4744–4757.

Pires, F., Cachada, A., Barbosa, J., Moreira, A. P., & Leitão, P. (2019). Digital twin in industry 4.0: Technologies, applications and challenges. *2019 IEEE 17th international conference on industrial informatics (INDIN)* (Vol. 1, pp. 721–726). IEEE.

Prasad, K., Fassler, C., Miller, A., Aweeda, M., Pruthi, S., Fusco, J. C., Daniel, B., et al. (2024). More than meets the eye: Augmented reality in surgical oncology. *Journal of Surgical Oncology, 130*(3), 405–418. John Wiley and Sons Inc.

Pregowska, A., & Perkins, M. (2024). Artificial intelligence in medical education: Typologies and ethical approaches. *Ethics and Bioethics (in Central Europe), 14*(1–2), 96–113. Sciendo.

Preshaw, P. M., Ramseier, C. A., Loos, B. G., Balčiūnaitė, A., Crnić, T., Davey, K., Dommisch, H., et al. (2024). Contemporary educational methods in periodontology. *Journal of Clinical Periodontology, 51*(S27), 117–192. John Wiley and Sons Inc.

Razek, A. (2023). Image-Guided Surgical and Pharmacotherapeutic Routines as Part of Diligent Medical Treatment. *Applied Sciences (Switzerland), 13*(24). Multidisciplinary Digital Publishing Institute (MDPI).

Rouhollahi, A., Willi, J. N., Haltmeier, S., Mehrtash, A., Straughan, R., Javadikasgari, H., Brown, J., et al. (2023). CardioVision: A fully automated deep learning package for medical image segmentation and reconstruction generating digital twins for patients with aortic stenosis. *COMPUTERIZED MEDICAL IMAGING AND GRAPHICS, 109*.

Sachdeva, R., Armstrong, A. K., Arnaout, R., Grosse-Wortmann, L., Han, B. K., Mertens, L., Moore, R. A., et al. (2024). Novel Techniques in Imaging Congenital Heart Disease *JACC* Scientific Statement. *JOURNAL OF THE AMERICAN COLLEGE OF CARDIOLOGY, 83*(1), 63–81.

Sai, S., Prasad, M., Garg, A., & Chamola, V. (2024). Synergizing Digital Twins and Metaverse for Consumer Health: A Case Study Approach. *IEEE TRANSACTIONS ON CONSUMER ELECTRONICS, 70*(1), 2137–2144.

Seetohul, J., Shafiee, M., & Sirlantzis, K. (2023). Augmented Reality (AR) for Surgical Robotic and Autonomous Systems: State of the Art, Challenges, and Solutions. *Sensors, 23*(13). Multidisciplinary Digital Publishing Institute (MDPI).

Sharma, V., Kumar, A., & Sharma, K. (2024). Digital twin application in women's health: Cervical cancer diagnosis with CervixNet. *COGNITIVE SYSTEMS RESEARCH, 87*.

Stephanie, V., Khalil, I., & Atiquzzaman, M. (2024). DSFL: A Decentralized SplitFed Learning Approach for Healthcare Consumers in the Metaverse. *IEEE TRANSACTIONS ON CONSUMER ELECTRONICS, 70*(1), 2107–2115.

Subramanian, B., Kim, J., Maray, M., & Paul, A. (2022). Digital Twin Model: A Real-Time Emotion Recognition System for Personalized Healthcare. *IEEE ACCESS, 10*, 81155–81165.

Suchetha, M., Preethi, S., Veluvolu, K. C., & Raman, R. (2024). An insight in the future of healthcare: integrating digital twin for personalized medicine. *HEALTH AND TECHNOLOGY, 14*(4), 649–661.

Sun, T., He, X., & Li, Z. (2023). Digital twin in healthcare: Recent updates and challenges. *Digital Health, 9*. SAGE Publications Inc.

Tao, K., Lei, J. C., & Huang, J. (2024). Physical Integrated Digital twin-based Interaction Mechanism of Artificial Intelligence Rehabilitation Robots Combining Visual Cognition and Motion Control. *WIRELESS PERSONAL COMMUNICATIONS*.

Upreti, D., Yang, E., Kim, H., & Seo, C. (2024). A Comprehensive Survey on Federated Learning in the Healthcare Area:Concept and Applications. *CMES - Computer Modeling in Engineering and Sciences, 140*(3), 2239–2274. Tech Science Press.

Vallée, A. (2023). Digital twin for healthcare systems. *FRONTIERS IN DIGITAL HEALTH,* *5*.

Venkatesh, K. P., Brito, G., & Boulos, M. N. K. (2024). Health Digital Twins in Life Science and Health Care Innovation. *ANNUAL REVIEW OF PHARMACOLOGY AND TOXICOLOGY*, *64*, 159–170.

Vidovszky, A. A., Fisher, C. K., Loukianov, A. D., Smith, A. M., Tramel, E. W., Walsh, J. R., & Ross, J. L. (2024). Increasing acceptance of AI-generated digital twins through clinical trial applications. *CTS-CLINICAL AND TRANSLATIONAL SCIENCE*, *17*(7).

Wang, X., Yu, H., McGee, W., Menassa, C. C., & Kamat, V. R. (2024). Enabling Building Information Model-driven human-robot collaborative construction workflows with closed-loop digital twins. *Computers in Industry*, *161*. Elsevier B.V.

Wu, C., Lorenzo, G., Hormuth, D. A., Lima, E. A. B. F., Slavkova, K. P., DiCarlo, J. C., Virostko, J., et al. (2022). Integrating mechanism-based modeling with biomedical imaging to build practical digital twins for clinical oncology. *Biophysics Reviews*, *3*(2). American Institute of Physics.

Yang, E. (2023). Implications of immersive technologies in healthcare sector and its built environment. *Frontiers in Medical Technology*, *5*. Frontiers Media SA.

Yang, T.-Y., Chien, T.-W., & Lai, F.-J. (2022). Citation analysis of the 100 top-cited articles on the topic of hidradenitis suppurativa since 2013 using Sankey diagrams: bibliometric analysis. *Medicine*, *101*(44), e31144. LWW.

Zackoff, M. W., Rios, M., Davis, D., Boyd, S., Roque, I., Anderson, I., NeCamp, M., et al. (2023). Immersive Virtual Reality Onboarding using a Digital Twin for a New Clinical Space Expansion: A Novel Approach to Large-Scale Training for Health Care Providers. *JOURNAL OF PEDIATRICS*, *252*.

Zhang, J., & Tai, Y. (2022). Secure medical digital twin via human-centric interaction and cyber vulnerability resilience. *Connection Science*, *34*(1), 895–910. Taylor and Francis Ltd.

Zhou, X., Chen, Y., Miao, G., Guo, Y., Zhang, Q., & Bi, J. (2024). Computer-aided robotics for applications in fracture reduction surgery: Advances, challenges, and opportunities. *Iscience*. Elsevier.

Zinchenko, K., & Song, K.-T. (2021). Autonomous Endoscope Robot Positioning Using Instrument Segmentation with Virtual Reality Visualization. *IEEE Access*, *9*, 72614–72623. Institute of Electrical and Electronics Engineers Inc.

Zsidai, B., Hilkert, A. S., Kaarre, J., Narup, E., Senorski, E. H., Grassi, A., Ley, C., et al. (2023). A practical guide to the implementation of AI in orthopaedic research - part 1: opportunities in clinical application and overcoming existing challenges. *JOURNAL OF EXPERIMENTAL ORTHOPAEDICS*, *10*(1).

Zhang, K., Zhou, H. Y., Baptista-Hon, D. T., Gao, Y., Liu, X., Oermann, E., ... & Wu, J. (2024). Concepts and applications of digital twins in healthcare and medicine. *Patterns*, 5(8).