

SUPPLEMENTARY APPENDIX
The Role of Digital Twin Technology in Transforming Medical Education: A Scoping Review



Table of Contents

Supplemental Table 1. PRISMA-ScR Checklist.	3
Supplemental Text 1. Details of the Search Strategy	5
Supplemental Table 2. Inclusion Justification	7
Supplemental Table 3. JBI Critical Appraisal Checklist for Text and Opinion Papers	9
Supplemental Table 4. JBI Critical Appraisal Checklist for Analytical Cross-Sectional Studies	10
Supplemental Table 5. JBI Critical Appraisal Checklist for Quasi-Experimental Studies	11
Supplemental Table 6a. Detailed characteristics	12
Supplemental Table 6b. Detailed characteristics (Continued)	17



Supplemental Table 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) Checklist.

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
TITLE			
Title	1	Identify the report as a scoping review.	1
ABSTRACT			
Structured summary	2	Provide a structured summary that includes (as applicable): background, objectives, eligibility criteria, sources of evidence, charting methods, results, and conclusions that relate to the review questions and objectives.	1
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known. Explain why the review questions/objectives lend themselves to a scoping review approach.	2
Objectives	4	Provide an explicit statement of the questions and objectives being addressed with reference to their key elements (e.g., population or participants, concepts, and context) or other relevant key elements used to conceptualize the review questions and/or objectives.	3
METHODS			
Protocol and registration	5	Indicate whether a review protocol exists; state if and where it can be accessed (e.g., a Web address); and if available, provide registration information, including the registration number.	3
Eligibility criteria	6	Specify characteristics of the sources of evidence used as eligibility criteria (e.g., years considered, language, and publication status), and provide a rationale.	3
Information sources*	7	Describe all information sources in the search (e.g., databases with dates of coverage and contact with authors to identify additional sources), as well as the date the most recent search was executed.	3, 4
Search	8	Present the full electronic search strategy for at least 1 database, including any limits used so that it can be repeated.	Supplementary
Selection of sources of evidence†	9	State the process for selecting sources of evidence (i.e., screening and eligibility) included in the scoping review.	4
Data charting process‡	10	Describe the methods of charting data from the included sources of evidence (e.g., calibrated forms or forms that the team has tested before their use, and whether data charting was done independently or in duplicate) and any processes for obtaining and confirming data from investigators.	5
Data items	11	List and define all variables for which data were sought and any assumptions and simplifications made.	5
Critical appraisal of individual sources of evidence§	12	If done, provide a rationale for conducting a critical appraisal of included sources of evidence; describe the methods used and how this information was used in any data synthesis (if appropriate).	4
Synthesis of results	13	Describe the methods of handling and summarizing the data that were charted.	5
RESULTS			
Selection of sources of evidence	14	Give the number of sources of evidence screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally using a flow diagram.	5
Characteristics of sources of evidence	15	For each source of evidence, present characteristics for which data were charted and provide the citations.	6
Critical appraisal of sources of evidence	16	If done, present data from the critical appraisal of the included sources of evidence (see item 12).	6



SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
Results of individual sources of evidence	17	For each included source of evidence, present the relevant data that were charted that relate to the review questions and objectives.	6-11
Synthesis of results	18	Summarize and/or present the charting results as they relate to the review questions and objectives.	6-11
DISCUSSION			
Summary of evidence	19	Summarize the main results (including an overview of concepts, themes, and types of evidence available), link to the review questions and objectives, and consider the relevance to key groups.	12-14
Limitations	20	Discuss the limitations of the scoping review process.	14
Conclusions	21	Provide a general interpretation of the results with respect to the review questions and objectives, as well as potential implications and/or next steps.	14
FUNDING			
Funding	22	Describe sources of funding for the included sources of evidence, as well as sources of funding for the scoping review. Describe the role of the funders of the scoping review.	Title page

JBİ = Joanna Briggs Institute; PRISMA-ScR = Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews.



Supplemental Text 1. Details of the Search Strategy

PubMed: 51

("digital twinning"[tiab] OR "digital twins"[tiab] OR "digital twin"[tiab]) AND ("area health education centers"[tiab] OR (education[tiab] AND medical[tiab]) OR (education[tiab] AND medical[tiab] AND continuing[tiab]) OR (education[tiab] AND medical[tiab] AND graduate[tiab]) OR (education[tiab] AND medical[tiab] AND undergraduate[tiab]) OR (education[tiab] AND premedical[tiab]) OR (education[tiab] AND "public health professional"[tiab]) OR "fellowships and scholarships"[tiab] OR "internship and residency"[tiab] OR "medical instruction"[tiab] OR "medical program"[tiab] OR "medical programme"[tiab] OR "medical teaching"[tiab] OR "medical training"[tiab] OR (training[tiab] AND medical[tiab]) OR "medical education"[tiab])

SCOPUS: 180

(TITLE-ABS ("digital twinning") OR TITLE-ABS ("digital twins") OR TITLE-ABS ("digital twin")) AND (TITLE-ABS ("area health education centers") OR TITLE-ABS ((education AND medical)) OR TITLE-ABS ((education AND medical AND continuing)) OR TITLE-ABS ((education AND medical AND graduate)) OR TITLE-ABS ((education AND medical AND undergraduate)) OR TITLE-ABS ((education AND premedical)) OR TITLE-ABS ((education AND "public health professional")) OR TITLE-ABS ("fellowships and scholarships") OR TITLE-ABS ("internship and residency") OR TITLE-ABS ("medical instruction") OR TITLE-ABS ("medical program") OR TITLE-ABS ("medical programme") OR TITLE-ABS ("medical teaching") OR TITLE-ABS ("medical training") OR TITLE-ABS ((training AND medical)) OR TITLE-ABS ("medical education"))

WOS: 153

(TS=("digital twinning") OR TS=("digital twins") OR TS=("digital twin")) AND (TS=("area health education centers") OR TS=((education AND medical)) OR TS=((education AND medical AND continuing)) OR TS=((education AND medical AND graduate)) OR TS=((education AND medical AND undergraduate)) OR TS=((education AND premedical)) OR TS=((education AND "public health professional")) OR TS=("fellowships and scholarships") OR TS=("internship and residency") OR TS=("medical instruction") OR TS=("medical program") OR TS=("medical programme") OR TS=("medical teaching") OR TS=("medical training") OR TS=((training AND medical)) OR TS=("medical education"))

Embase: 54

('digital twinning':ti,ab OR 'digital twins':ti,ab OR 'digital twin':ti,ab) AND ('area health education centers':ti,ab OR (education:ti,ab AND medical:ti,ab) OR (education:ti,ab AND medical:ti,ab AND continuing:ti,ab) OR (education:ti,ab AND medical:ti,ab AND graduate:ti,ab) OR (education:ti,ab AND medical:ti,ab AND undergraduate:ti,ab) OR (education:ti,ab AND premedical:ti,ab) OR (education:ti,ab AND 'public health professional':ti,ab) OR 'fellowships and scholarships':ti,ab OR 'internship and residency':ti,ab OR 'medical instruction':ti,ab OR 'medical program':ti,ab OR 'medical programme':ti,ab OR 'medical teaching':ti,ab OR 'medical training':ti,ab OR (training:ti,ab AND medical:ti,ab) OR 'medical education':ti,ab)





Supplemental Table 2. Extent to Which Each Included Study Satisfies the Three Defining Characteristics of a Digital Twin, Verified Against the Full Text of Each Source.

#	Study (ref.)	C1	C2	C3	Criteria met	Basis in the source
1	Chen et al., 2022	Proposed	Proposed	Proposed	0 Implemented	Perspective article. Proposes a medical education space with intelligent fabric sensors, "cyber-physical interaction and real-time tactile feedback", and a service system that "will evaluate and provide feedback on students' operational behaviors". No prototype, no empirical data.
2	Dang et al., 2022	Yes	Yes	Yes	3 of 3	Fetal heart geometry derived from a specific patient's CT data (C1, C2); a 3D-printed probe with sensor fusion streams live pose into the virtual scan (C2); binary space partitioning generates ultrasound for arbitrary, unscripted probe poses (C3).
3	Peshkova et al., 2023	Yes	Yes	No	2 of 3	An annotated colorectal cancer slide database linked to a biobank and to the donors' clinical and histological data (C1, C2). Database-driven prototype; no live data link and no generative or predictive model (C3).
4	Sosa-Méndez & García-Cena, 2023	Yes	No	Yes	2 of 3	Kinematic and dynamic model of one specific 5-DOF rehabilitation exoskeleton, built in SolidWorks and Matlab/Simulink (C1); computes joint motion and torque for arbitrary inputs (C3). Simulation only; no reported data link to the physical device (C2).
5	Alves Halpern et al., 2024	No	No	Yes	1 of 3	Conference abstract evaluating GPT-4 against manual thematic analysis of user feedback on the ICU Digital Twin app. The twin itself is a virtual sepsis patient with no identified physical counterpart (C1, C2); the underlying expert-rule engine is generative (C3).
6	Hein et al., 2024	Yes	Yes	No	2 of 3	Digital replica of a specific real spinal surgery scene, operating room, surgeon, anatomy, and instruments, reconstructed from RGB-D video captured by ceiling-mounted cameras (C1, C2). Dynamic point-cloud playback of recorded data; no model that generates unrecorded states (C3).
7	Jeising et al., 2024	Yes	Yes	No	2 of 3	Anatomical structures of one brain tumor patient segmented from that patient's CT and MRI to "create a digital twin of the case" (C1, C2). Static 3D print plus mixed reality overlay; the reported synchronization is marker-based registration between headsets, not a link to the patient (C3).
8	Kumar et al., 2024	No	Yes	Yes	2 of 3	"Dynamic virtual representations of tangible assets" with IoT-enabled "real-time simulation, monitoring, and feedback" (C2) and a visual response algorithm using subspace reduction and response surface methodology (C3). No specific counterpart is identified for the education use case (C1).
9	Rovati et al., 2024	No	No	Yes	1 of 3	A virtual sepsis patient rather than an identified individual; the user sets the initial state (C1). The twin updates from learner interventions, not from data acquired from a physical counterpart (C2). Expert-rule directed acyclic graphs with stochastic simulation generate unscripted trajectories (C3).
10	Trevena et al., 2024	No	No	Yes	1 of 3	Architecture paper; Neo4j-hosted expert-rule graph driving a serverless simulation engine (C3)—limitations on C1 and C2.
11	Trabelsi et al., 2024	Yes	Yes	Yes	3 of 3	The only included study reporting closed-loop synchronization: "physical and virtual environments... interconnected through bi-directional data flow", with incoming data from



#	Study (ref.)	C1	C2	C3	Criteria met	Basis in the source
						the real robots' encoders, force sensors, and endoscopic cameras used to synchronize the digital devices (C1, C2); URDF kinematic and dynamic models in ROS (C3).
12	Zackoff et al., 2024	Yes	Yes	No	2 of 3	Replica of one specific clinical facility, built from that facility's design data before it opened (C1, C2). Authored virtual reality environment; no live data link and no generative model (C3).
13	Altafi et al., 2025	Yes	Yes	Yes	3 of 3	The DenTeach platform "synchronizes video, audio, feel, and posture (VAFP) between the instructor and the student in real-time" via the DT-Rightway Articulator (C1, C2); deep learning performs automated grading of preparations (C3).
14	Choi et al., 2025	Yes	Yes	No	2 of 3	Reconstruction of one specific Korean cadaver obtained by 3D scanning of the full-body skeleton (C1, C2). A static mesh; the "real-time data synchronization" reported via Photon Cloud is networking between concurrent users, not a link to the cadaver (C3).
15	Flores-Martin et al., 2025	No	No	Yes	1 of 3	Waveforms are generated from user-set parameters and the training data are deliberately synthetic, "without relying on patient data", so there is no counterpart (C1, C2). Parametric waveform engine plus a three-hidden-layer classifier over six diagnostic classes (C3). The authors defend the designation as "grounded in its architecture and function, not merely in AI use".
16	Ou et al., 2025	Yes	Yes	No	2 of 3	Perpetual multimodal reconstruction of four specific cadaveric brain specimens from their own contrast-perfused CT and MRI (C1, C2). A static anatomical reconstruction; no generative or predictive model (C3).
17	Vidal et al., 2025	Yes	Yes	Yes	3 of 3	Twins of specific laboratory CT devices and of the DIAD synchrotron beamline, calibrated to the real machines including experimentally measured noise at differing mAs (C1, C2); the Beer–Lambert simulation generates scans that were never acquired (C3).

C1 (personalization): the virtual representation is instantiated to a specific individual, specimen, device, or environment rather than to a generic archetype. C2 (counterpart-derived data pathway): the representation is created or updated from data acquired from that counterpart. C3 (generative or predictive model): the representation can produce states, images, or trajectories that were not explicitly pre-authored. The eligibility rule applied during screening is stated in the Methods: author designation as a digital twin, plus a health professions education application, plus at least one of C1 to C3.

Summary: four of the 17 included studies satisfy all three characteristics; eight satisfy two; four satisfy one; and one proposes all three but implements none. Only Trabelsi et al. report continuous, closed-loop bidirectional synchronization between a physical and a virtual counterpart. Applying that stricter criterion as an eligibility requirement would reduce the review to a single study, which is why the inclusive rule was adopted and why the resulting heterogeneity is reported as a limitation.

Rows 5, 9, and 10 describe the same ICU Digital Twin platform reported in three publications.



Supplemental Table 3. JBI Critical Appraisal Checklist for Text and Opinion Papers

Study (Author, Year)	Q1	Q2	Q3	Q4	Q5	Q6	Overall Appraisal
	Is the source of the opinion clearly identified?	Does the source of the opinion have standing in the field of expertise?	Are the interests of the relevant population the central focus of the opinion?	Is the stated position the result of an analytical process, and is there logic in the opinion expressed?	Is there a reference to the extant literature?	Is any incongruence with the literature/sources logically defended?	
Vidal et al., 2025	Yes	Yes	Yes	Yes	Yes	Yes	Include
Peshkova et al., 2023	Yes	Yes	Unclear	Yes	Yes	Yes	Include
Flores-Martin et al., 2025	Yes	Yes	Yes	Yes	Yes	Yes	Include
Hein et al., 2024	Yes	Yes	Yes	Yes	Yes	Yes	Include
Sosa-Méndez & García-Cena (2023).	Yes	Yes	Unclear	Yes	Yes	Unclear	Include
Altafi et al., 2025	Yes	Yes	Yes	Yes	Yes	Yes	Include
Ou et al., 2025	Yes	Yes	Yes	Yes	Yes	Yes	Include
Trevena et al., 2024	Yes	Yes	Yes	Yes	Yes	Yes	Include
Choi et al., 2025	Yes	Yes	Yes	Yes	Yes	Yes	Include
Chen et al., 2022	Yes	Yes	Yes	Yes	Yes	Unclear	Include
Alves Halpern et al., 2024	Yes	Yes	Yes	Yes	Unclear	Unclear	Include
Kumar et al., 2024	Yes	Yes	Yes	Yes	Yes	Unclear	Include
Trabelsi et al., 2024	Yes	Yes	Yes	Yes	Yes	Yes	Include

Responses: Yes / No / Unclear / Not Applicable.



Supplemental Table 4. JBI Critical Appraisal Checklist for Analytical Cross-Sectional Studies

Study (Author, Year)	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Overall Appraisal
	Were the criteria for inclusion in the sample clearly defined?	Were the study subjects and the setting described in detail?	Was the exposure measured validly and reliably?	Were objective, standard criteria used for measurement of the condition?	Were confounding factors identified?	Were strategies to deal with confounding factors stated?	Were the outcomes measured validly and reliably?	Was an appropriate statistical analysis used?	
Rovati et al., 2024	Yes	Yes	Yes	Yes	Unclear	No	Yes	Yes	Include
Jeising et al., 2024	Unclear	Yes	Yes	Unclear	No	No	Unclear	Yes	Include
Zackoff et al., 2024	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Include

Responses: Yes / No / Unclear / Not Applicable.



Supplemental Table 5. JBI Critical Appraisal Checklist for Quasi-Experimental Studies

Study (Author, Year)	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Overall Appraisal
	Is it clear in the study what the 'cause' is and what the 'effect' is?	Were the participants included in any similar comparisons?	Were the participants included in any comparisons receiving similar treatment/care, other than the exposure or intervention of interest?	Was there a control group?	Were there multiple measurements of the outcome, both pre- and post-intervention/exposure?	Was the follow-up complete, and if not, were the differences between groups in terms of their follow-up adequately described and analyzed?	Were the outcomes of participants included in any comparisons measured in the same way?	Were outcomes measured reliably?	Was an appropriate statistical analysis used?	
Dang et al., 2022	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Include

Responses: Yes / No / Unclear / Not Applicable.



Supplemental Table 6a. Detailed characteristics of the included studies in this systematic review.

ID	First Author, Year	Country	Study Design	Learner Level	Educational Setting	Discipline / Domain	DT Type	Modeling Approach	Key Technologies Used
1.	Vidal et al., 2025	UK (lead), with collaborators from Taiwan, Spain, Belgium, Germany, Switzerland, France, Netherlands, USA, Sweden	Technical review / comprehensive multi-application case study of gVirtualXray (gVXR) framework	Undergraduate engineering students, Master of Engineering (MEng) students, clinical radiography trainees, and orthopedic surgery trainees	University simulation labs; online virtual laboratories (Docker-based); in-person lab sessions (JupyterLab); VR environments; web-based simulation (WebCT)	Radiology/radiography, physics, material science, engineering, orthopedic surgery, nuclear fuel research	Equipment/Device-level (digital twins of X-ray CT scanners, synchrotron beamlines, lab CT devices)	Physics-based deterministic simulation (Beer-Lambert law); GPU-accelerated computation; validated against Monte Carlo simulations and experimental data	GPU computing, gVirtualXray (open-source), Docker containerization, VR (Unreal Engine 5, haptic devices), Jupyter notebooks, web-based GUI (WebCT), AR, 3D Slicer, CIL reconstruction toolkit
2.	Peshkova et al., 2023	Russia	Short communication / technical description (proof-of-concept database creation)	Medical students and pathology trainees (implied); also relevant to researchers	Digital pathology laboratory; linked biobank	Pathology / digital pathology; colorectal cancer	Patient-specific / organ-specific (digital twin of colorectal tumor slides linked to clinical/histological data and biobank)	Database-driven digital twin prototype; QuPath software for slide annotation/markup into morphological classes; Microsoft Excel-based clinical data integration	Leica Aperio AT2 slide scanner, QuPath software, Microsoft Excel, biobank linkage
3.	Flores-Martin et al., 2025	Spain	Software publication with technical validation and pilot user evaluation	Medical students, early-career clinicians, and cardiology trainees also piloted with a multidisciplinary team (computer science, nursing, occupational therapy)	Cloud-based and edge-deployable platform (classroom, remote/home learning, Raspberry Pi, Android devices)	Cardiology / ECG interpretation	Patient-specific (virtual cardiac digital twin — parameter-driven ECG waveform generation that models cardiac electrophysiology)	AI-driven (deep learning classifier: 3 hidden-layer neural network, 128-64-32 neurons, Softmax output), combined with a piecewise-morphological ECG signal generation model; trained on 3000 synthetic samples.	TensorFlow/Keras, React, Python, TensorFlow Lite (edge), ONNX (AR/VR), AES encryption, API rate limiting, Android/Raspberry Pi deployment
4.	Hein et al., 2024	Switzerland	Technical demonstration/proof-of-concept (VR application for surgical digital twin)	Surgical trainees (orthopedic surgery); medical students (implied)	VR-based immersive surgical training environment (head-mounted display)	Orthopedic surgery (spinal surgery — pedicle drilling)	Environment-level surgical digital twin (SDT) — a complete digital replica of the surgical scene, including the operating room, surgeon, anatomy, and instruments	Physics-based/geometry-based: dynamic 3D point cloud reconstruction of the surgeon; photogrammetry-based mesh models of anatomy; real-time rendering on GPU; 30 FPS capture	Azure Kinect RGB-D cameras, FusionTrack 500 optical tracking, Unity game engine, Meta XR SDK, Meta Quest Pro HMD, custom compute shaders, PBR materials, photogrammetry
5.	Sosa-Méndez et al., 2023	Spain (Universidad Politécnica de Madrid)	Technical development/simulation study (Digital Twin Prototype of	Health personnel (physiotherapists) involved in rehabilitation	Virtual training platform (Matlab/Simulink-	Physical rehabilitation/rehabilitation robotics	Device-level (Digital Twin Prototype of an upper limb rehabilitation	Physics-based: SolidWorks CAD design exported to Matlab/Simulink	SolidWorks, Matlab/Simulink, 3D printing (ABS with



			rehabilitation exoskeleton)		based simulation environment)		exoskeleton — 5 DOF)	equivalent model; serial robotic model with 5 rotational joints; kinematics and dynamics simulation	carbon fiber), additive manufacturing
6.	Altafi et al., 2025	Canada	Technical description/platform presentation with comparative analysis	Dental students (pre-clinical and clinical); dental instructors	Cloud-based platform deployable in classroom, pre- clinical lab, and remote/home learning (portable suitcase system); also edge deployment on Raspberry Pi and Android	Dentistry / dental education (restorative dentistry focus)	Device/Environment- level (DenTeach system: DT-Rightway Articulator synchronizes instructor-student posture; digital twin of dental procedures via VAFP — Video, Audio, Feel, Posture)	AI-driven (deep learning for automated grading, AI-powered assessment), combined with augmented reality overlay; IoT-enabled sensor fusion; cloud- based data analytics	IoT, smart sensors, AR, cloud computing, 3D printing, advanced robotics, haptic technology (RealFeel sensor), DT-Rightway Articulator, DT- PrepScanner (robotic grading), TFLite for edge
7.	Ou et al., 2025	China (Sun Yat- sen University), with collaborators from Italy, USA, UK	Technical development study / stepwise methodological guide (original article with proof-of-concept on 4 specimens)	Medical students; neurosurgery residents/trainees; surgical trainees	Medical anatomy teaching laboratory; surgical training facility	Neuroanatomy/neurosurgery	Organ-specific (anatomical digital twins of human brain specimens — 3D reconstructed from cadaveric heads with vascular perfusion)	Physics-based imaging + computational reconstruction: vascular perfusion with contrast agents → multimodal CT/MRI DICOM acquisition → 3D Slicer software reconstruction and optimization; threshold-based segmentation with manual editing	3D Slicer (open-source), Dual-Source CT, 3-T MRI, contrast agent perfusion, DICOM imaging, photogrammetry (for comparison), 3D reconstruction algorithms (threshold, flood filling, smoothing tools)
8.	Dang et al., 2022	China (Tsinghua University, Chinese Academy of Sciences, Beijing Anzhen Hospital)	Technical development with user study (n=10) and clinical evaluation	Medical trainees (ultrasound operators); physicians in ultrasonography; and inexperienced operators (user study volunteers)	Hospital consulting room (clinical evaluation); computer-based virtual simulation (user study)	Ultrasonography/echocardiography (fetal cardiac imaging)	Patient-specific (digital twins of fetal heart structures derived from real patient CT data — 3 specimens with confirmed cardiac diseases)	Physics-based virtual ultrasound generation (PLUS toolkit using binary space partitioning for scan line intersection) + 3D- printed probe with sensor fusion (IMU + vision-based tracking); rendered in 3D Slicer	3D Slicer, PLUS toolkit, OpenIGTLink, 3D- printed probe model, IMU sensor, AprilTag vision camera, Arduino Nano, Python scripting
9.	Rovati et al., 2024	USA	Mixed methods study (usability testing with quantitative surveys and qualitative think- aloud/semi-structured interviews)	Post-graduate year one (PGY-1) internal medicine residents (n=35)	Skills laboratory/simulation center at Mayo Clinic, Rochester, MN; tablet-based iOS application	Critical care medicine / medical ICU	Patient-specific (digital twin patient model simulating physiological trajectories during the first 6 hours of critical illness based on EHR variables)	Expert rule-based physiological model; 70 expert rules describing organ system interactions; rules refined via multinational, multi- specialty modified	iOS (Swift, Xcode 14.2), iPad application, EHR- based digital twin engine, color-coded organ system interface, REDCap for data collection, GraphPad Prism 9.0



								Delphi consensus; medication effects derived from public drug databases	
10.	Trevena et al., 2024	USA	Technical development study with proof-of-concept case study demonstration	Medical practitioners and trainees (general; specific user testing described in companion study Rovati et al. 2024 with PGY-1 internal medicine residents)	Cross-platform application (iOS, Android, web); cloud-hosted simulation engine; also designed for bedside clinical decision support	Critical care medicine/sepsis management	Patient-specific (graph model-based virtual patient simulation modeling critical illness trajectories during first 6 hours)	Directed acyclic graph (DAG)-based causal model; expert rules stored in Neo4j graph database; stochastic simulation with probabilistic rule application; rules include temporal duration, delayed effects, simple/complex conditions; 70 rules for demonstration version	Neo4j graph database, AWS Lambda (serverless functions), React-Native (cross-platform front-end), Amazon Web Services cloud hosting, microservice architecture, CSV-based rule import
11.	Choi et al., 2025	Republic of Korea	Technical development study with pilot test feedback (open-ended survey from anonymous participants)	Medical and nursing students, college professors; corporate guests, participants at a medicine conference	Metaverse platform using HoloLens 2 AR HMD; cloud-rendered XR environment; also 3D printed physical models for tactile learning	Anatomy education (skeletal system)	Anatomical / cadaver-level (3D digital twin of Korean Standard Full-body Male Cadaver — KSMC; 206 individual bones scanned and digitized)	3D surface scanning, mesh refinement, retopology, polygon optimization (decimation); cloud-based remote rendering via Azure; no physiological simulation	Leica BLK360 3D scanner, Blender, Maya, Unity, HoloLens 2, Microsoft MRTK, Photon Cloud Network (real-time multiplayer), Azure Remote Rendering, C# scripting, 3D printing (internal filament removal method)
12.	Jeising et al., 2024	Germany	Technical development with evaluation by participants in a skills laboratory (questionnaire-based, n=34 medical students)	Medical students (19 with no neurosurgical experience, 12 with internship experience, 3 with clinical experience in neurosurgery)	Skills laboratory at University Hospital Düsseldorf, equipped with mixed reality headsets, neuronavigation system, Mayfield clamp, and neurosurgical instruments	Neurosurgery/brain tumor resection	Patient-specific / anatomical (digital twin of brain tumor patient case created from CT/MRI segmentation; combined with 3D printed physical model and mixed reality overlay)	Image segmentation (automatic and semi-automatic) using Brainlab Elements software; 3D printing of bony structures; fluorescent agar-agar tumor model (Kamp et al. protocol) injected into cadaveric calf brain; mixed reality spatial superimposition of virtual and physical models	Brainlab Elements software (cranial planning), Magic Leap 1 mixed reality headset, Brainlab Mixed Reality Viewer 5.3 (modified), Ultimaker S5 3D printer, white polylactic acid, neuronavigation system, fluorescence-guided resection (blue light), cadaveric calf brain, 5G.NRW Giga for Health project
13.	Chen et al., 2022	China	Perspective / conceptual framework paper with system architecture proposal	Medical students (general); also, public/laypersons for medical	Intelligent fabric space — digitized operating room/simulation environment with	Medical education (general surgical training); also, health monitoring and first aid knowledge popularization	Environment / system-level (digital twin of medical education space — mapping physical	Digital twin 'four-space' model: physical space, virtual space, service system, service interface; cyber-	Intelligent fabric sensors (piezoelectric, triboelectric, magnetoelectric, optical, capacitance,



				knowledge popularization	embedded fabric sensors; remote learning enabled via 5G/IoT		operating environment to virtual simulation space via intelligent fabric sensors)	physical mapping with real-time data exchange; AI-driven behavior evaluation and feedback	temperature), 5G/IoT networking, edge/cloud computing, AI/deep learning, smart gloves, smart surgical gowns, intelligent dummy body
14.	Alves Halpern et al., 2024	USA	Methodological study (comparison of LLM-based vs manual qualitative analysis of user feedback on ICU digital twin app)	Internal medicine residents (n=35; same cohort as Rovati et al. 2024)	Simulation testing of ICU Digital Twin app prior to ICU rotation (same setting as Rovati et al. 2024)	Critical care medicine / medical ICU; also health informatics / AI methodology	Patient-specific (ICU Digital Twin app simulating critically ill patients — same platform as Rovati et al. 2024 and Trevena et al. 2024)	GPT-4 large language model applied with custom-refined prompts for qualitative thematic analysis; compared to manual human review as gold standard	GPT-4 (OpenAI), custom prompt engineering, video transcription, ICU Digital Twin app
15.	Kumar et al., 2024	India / Saudi Arabia	Technical development study with comparative experimental analysis; proposes an IoT digital twin-based visualization method for medical education service development	Medical students with physical disabilities; physically challenged individuals (target learner group); not empirically tested with an actual student sample	IoT-based virtual laboratory; digital twin platform for medical procedure simulation; no specific institution described	Medical education (general); accessibility and inclusive design; IoT service development	Environment/System-level (IoT digital twin for visualizing IoT service development processes, applied to medical education accessibility)	Visual response algorithm using subspace dimension reduction; response surface methodology (second-order polynomial model); multi-dimensional variable iteration; finite element analysis for stress/constraint variables.	IoT, digital twin technology, wireless sensors, visual vector matrix design, response surface method (RSM), subspace iteration algorithm
16.	Trabelsi et al., 2025	France / Tunisia	Technical development study with proof-of-concept; describes design and implementation of a high-fidelity digital twin for a multi-robot teleoperated surgical platform	Surgical trainees; surgeons undergoing robotic surgery training (laparoscopic procedures); pre-clinical testing phase	Simulation-based surgical training environment using ROS/RViz/Unity digital twin platform; physical robotic platform (Kuka iiwa7 × 2, Franka Emika × 1) with digital counterpart	Surgical robotics / minimally invasive (laparoscopic) surgery	Equipment/System-level (high-fidelity digital twin of multi-robot teleoperated surgical slave system, including kinematic/dynamic models, haptic interfaces, and medical instruments)	Physics-based kinematic and dynamic modeling via URDF; bidirectional ROS-based shared control framework; data collected in shared control phase → virtual-physical mapping → kinematic/dynamic model → control law → optimization; real-time synchronization of robot states	ROS (Robot Operating System), RViz (3D visualization), Unity (3D rendering), URDF (Unified Robot Description Format), Kuka iiwa7 robots (7-DOF), Franka Emika robot (7-DOF), haptic devices (Falcon, two custom designs), Simscape Multibody (referenced)
17.	W. Zackoff et al., 2024	USA	Prospective, observational study (n=1522 healthcare staff); evaluates the tolerability and acceptability of autonomous immersive	Frontline healthcare staff: nurses (59.5%), PCAs (14.5%), physicians/APPs (10.1%), respiratory	Dedicated VR training laboratory at a large academic children's hospital (Cincinnati Children's Hospital Medical Center);	Healthcare staff onboarding; clinical systems training; critical care / neonatal/cardiac / bone marrow transplant units	Environment-level (digital twin of future new clinical hospital space, including ICU units, patient rooms, furniture, medical equipment, and	3D model construction using Autodesk Maya; game engine-based rendering and interaction (Unity 3D); PBR materials and lighting approximating	Unity 3D (rendering, game engine), Autodesk Maya (3D modeling), Adobe (texturing), VR head-mounted display (commercial), Meta XR SDK, REDCap (data



VR using digital twin
technology for large-
scale healthcare staff
onboarding

therapists (10%),
HUCs (4.3%),
pharmacists
(1.6%);
experience: <1 yr
to >5 yrs

autonomous
(facilitator-free);
head-mounted
display; ~30-minute
session

patient avatars —
built before physical
space opened)

real environment;
branching logic models
for autonomous
scenario progression;
object/time-based
triggers; ~4000 hours
total developer time;
~\$150,000 labor cost

collection), SAS 9.4
(statistics)



Supplemental Table 6b. Detailed characteristics of the included studies in this systematic review (Continued).

ID	First Author, Year	Integration with Curricula	Theoretical Framework	Kirkpatrick Level(s)	Outcome Measures / Key Findings	Transfer to Clinical Practice	Student Engagement Reported	Model Validation Strategy	Data Privacy / Ethical Issues
1.	Vidal et al., 2025	Integrated into MEng lab sessions (~150 students/year at INSA-Lyon); used in undergraduate engineering courses at UNIR Spain; clinical radiography training curriculum	Experiential/hands-on learning; simulation-based education; progressive complexity (mono-energy → polychromatic → beam hardening)	Level 1 (Reaction): usability survey scored >60 points for the LabCT game engine; face/content validation of the radiography simulator demonstrated realism and suitability. Level 2 (Learning): qualitative evidence of pedagogical success over multiple academic terms.	gVXR validated with high accuracy (ZNCC 99.99%, MAPE 2.23%, SSIM 0.99 vs Monte Carlo). Educational applications: VR haptic surgical simulator highly rated by orthopedic surgeons/trainees; online Docker-based labs proven attractive and pedagogically successful; radiography simulator validated as realistic and suitable for teaching. Digital twinning enables training on specific real devices, experiment planning, and scan parameter optimization.	Haptic femoral nailing simulator validated by orthopedic surgeons; radiography simulator designed to reduce active clinical training needs while preparing students for real clinical situations	Yes — Docker-based online labs described as 'very attractive' to students; progressive complexity in lab sessions engaged students across multiple semesters	Extensive quantitative validation: compared with Monte Carlo simulations (Geant4/Gate), real radiographs, and DRRs using ZNCC, MAPE, SSIM metrics; anthropomorphic phantom validation (pEdiatRic ERROR phantom and Lungman phantom)	Clinical radiology context: ionizing radiation regulations (IRMER) noted; ethical considerations around patient exposure; use of simulation avoids radiation risk
2.	Peshkova et al., 2023	Described as potentially useful for medical education; no specific curricular integration reported	Not explicitly stated; aligns with precision medicine and competency-based education principles	Not assessed (proof-of-concept only)	Created a validated database of colorectal cancer cases with 3 blocks: (1) annotated histological slide scans, (2) anonymized clinical/morphological/immunohistochemical data linked to the blood bank, (3) reference classifiers. Database covers 11 ICD codes for various colorectal cancer localizations. Algorithms developed are transferable to other digital twin projects.	Potential for improving advanced diagnostics and screening; not empirically tested for clinical transfer	Not reported	Slides evaluated by 3 pathologists, a biologist, and a lab technician; markup validated using QuPath; no formal educational outcome validation	Personal data management identified as key ethical issue; data anonymization performed; ethical challenges of DT in healthcare acknowledged
3.	Flores-Martin et al., 2025	Designed for integration into medical training; formal validation with medical/health science students planned; no specific curriculum mapping yet.	Active and experiential learning; learning through guided correction; interactive simulation pedagogy	Level 1 (Reaction): pilot participants reported increased confidence and better understanding.	Deep learning model: 95% accuracy, macro-averaged precision/recall/F1 all ~0.95, log-loss 0.1902. The platform provides 6 diagnostic classes. The dashboard tracks 971 total predictions, with 86% user accuracy. The confusion matrix shows occasional misclassifications between clinically related categories. Edge deployment validated on Raspberry Pi and Android. The system	Not formally assessed; designed to build diagnostic confidence applicable to clinical ECG reading	Yes — pilot participants reported increased confidence; dashboard shows active usage (971 predictions tracked)	DL model validated with train/validation split (80/20), classification metrics (precision, recall, F1), confusion matrix; pilot study with multidisciplinary team; formal clinical validation planned	AES encryption and API rate limiting implemented; synthetic training data (no patient data used); privacy by design



					provides contextual explanations linking parameter changes to waveform morphology.				
4.	Hein et al., 2024	Not yet integrated; proposed as supplement to wet lab training; designed for the surgical education pipeline.	Observational learning; expert modeling; deliberate practice (surgeon can be hidden for self-practice); experiential learning in immersive VR	Not formally assessed (technical demonstration only)	The system runs at an average of 90 FPS on an RTX 3070 (sufficient for a smooth VR experience). Asynchronous loading reduces animation frame loading times by 10x. Users can freely change the viewing angle, observe from the surgeon's perspective, interact with the virtual surgical drill, pause playback, and compare their drill pose to the expert's—the first VR system to offer a complete digital twin of an entire surgical scene.	Designed specifically for clinical transfer (surgical skill acquisition), allows comparison of trainee vs. expert drill positioning; not yet empirically validated for transfer.	Not formally reported; system designed for immersive engagement through VR interaction.	Technical performance validation (90 FPS, 10x loading improvement); based on previously published SDT creation pipeline (Hein et al., CVPR 2024); no educational outcome validation	Not discussed; involves recording of real surgical procedures (consent implied)
5.	Sosa-Méndez et al., 2023	Proposed as a health personnel training tool; no formal curricular integration reported	Health 4.0 / Industry 4.0 principles; simulation-based training; virtual commissioning	Not assessed (technical feasibility demonstration only)	DTP successfully simulated 5 independent joint movements (shoulder internal/external rotation, abduction/adduction, flexion/extension; elbow flexion/extension; wrist abduction/adduction) and 2 combined movement sequences. Joint torques calculated for all movements. Virtual representation shows each component. The system allows adjustment of patient weight (60 kg test case) and anthropometric parameters. Total DTP weight: 9.74 kg.	Designed to allow physiotherapists to plan and test treatments virtually before applying to real patients, reducing risks and costs	Not reported	Functional performance evaluation through kinematic/dynamic simulation; graphical output verification; no comparison with physical device or clinical outcomes	Not discussed
6.	Altafi et al., 2025	Designed for integration into existing dental workstation setup; instructor-led approach maintained; pre-built course library included	Cognitive apprenticeship model enhanced with technology; holistic teaching (sight, sound, touch); instructor-oriented pedagogy with AI augmentation	Not formally assessed in this paper (comparative table analysis only); designed for multi-level assessment through KPIs and learning curve tracking	Platform comparison shows DenTeach advantages over PerioSim, Forsslund, Simodont, Leonardo, and prepCheck: lower cost, automatic grading, AI-powered assessment, anywhere access, portability, and course library. Synchronizes VAFP between instructor and student. DT-PrepScanner provides robotic automated grading. Dashboard tracks more than 30 psychomotor performance metrics.	Designed to emulate real dental clinic scenarios; holistic sensory approach (VAFP) aims to develop transferable psychomotor skills; COVID-19 demonstrated the need for remote training equivalence	Expected benefits described (24/7 access, self-assessment, multiple video feeds, AR overlay, haptic feedback); no empirical engagement data in this paper	Comparative analysis with existing dental simulators; AI model performance metrics referenced but not detailed in this paper; clinical validation studies referenced as separate work	Cloud-based data storage mentioned; student data accessibility discussed; no detailed privacy analysis
7.	Ou et al., 2025	Proposed as a supplement to traditional anatomy	Experiential anatomy education; surgical apprenticeship model	Not formally assessed (technical proof-of-concept)	Successfully reconstructed intracranial vasculature and brain parenchyma from 4 aged (>3 years	Designed for surgical training; digital virtual neurosurgery paradigm	Not formally reported; method designed to make	Demonstrated on 4 human specimens + porcine organs;	Study conducted per Declaration of Helsinki; donor



		dissection; paradigm shift from 'disposable' to 'perpetual' anatomical specimens; applicable to pre-dissection preview workflow similar to surgical imaging reading.	enhanced by digital visualization; 3D spatial learning theory		formaldehyde-fixed) human brain specimens. CT is better for vascular visualization; MRI is better for soft tissue. Arterial perfusion reached the M1-M3 segments of the MCA and the P1-P3 segments of the PCA. Method validated on fresh porcine livers and kidneys. Vessel diameter < 1 mm limits perfusion effectiveness. Cost-effective using expired contrast agents. Each basic 3D model completed in 0.5-1 hour.	— shifting from 2D mental visualization to 3D model-based surgical planning; applicable to preoperative planning workflow	anatomy learning more 'vivid, intuitive, and efficient'	qualitative comparison of CT vs. MRI modalities; radiologist-supervised image acquisition; neurosurgeon-guided reconstruction; no quantitative accuracy metrics for educational impact.	consent obtained; ethics waiver granted (voluntary body donation); only age/gender known to investigators
8.	Dang et al., 2022	Proposed for medical school and hospital training; not yet formally integrated into a specific curriculum	Hands-on experiential learning; WYSIWYG (what-you-see-is-what-you-get) interaction; skill acquisition through intuitive device interaction	Level 1 (Reaction): subjective evaluation via 5-point Likert scale — probe model rated higher on intuitiveness, learnability, usability, applicability, and lower complexity than slider control. Level 2 (Learning): objective task completion — median time 32.0s (probe) vs. 66.5s (slider), $p<0.001$; accuracy improved for z-axis translation and pitch angle.	User study ($n=10$): Probe model significantly faster (median 32.0s vs. 66.5s, $p<0.001$). Accuracy: significantly better for z-axis (6.01mm vs. 14.49mm, $p<0.001$) and pitch angle (0.21 vs. 0.56 rad, $p<0.01$). Subjective ratings favored the probe model across all 6 dimensions. Clinical evaluation: The doctor successfully collected standard LVOT and RVOT views from 3 different fetal heart digital twins. 3D trajectory and rotation data were recorded during examination.	Applicable to both manual ultrasound scanning and robot-based remote scanning; clinical evaluation conducted with a real physician on real patient-derived data	Yes — users preferred probe model interaction; rated it as more intuitive, easier to learn, and more applicable to clinical scenarios.	Quantitative user study with Wilcoxon signed-rank tests; clinical evaluation with an ultrasound specialist at Beijing Anzhen Hospital; comparison with baseline (slider) interaction method	Clinical data collection approved by Medical Ethics Committee of Beijing Anzhen Hospital (Approval No. 2019030); written informed consent from patients' parents; follows the Declaration of Helsinki.
9.	Rovati et al., 2024	Residents proposed incorporating practice sessions into the existing critical care education curriculum, designed for use before and during medical ICU rotations; there was no formal curricular integration at the time of the study.	Simulation-based education; deliberate practice; serious gaming; user-centered design	Level 1 (Reaction): SUS usability score median 70 (IQR 62.5–82.5), NASA-TLX workload score median 29.2 (IQR 22.5–34.2); >60% of residents would use the app a moderate amount or a great deal for ICU preparation and rotation. Level 2 (Learning): not formally assessed.	Median SUS score of 70 (good usability); median NASA-TLX of 29.2 (low-to-moderate workload). The greatest perceived difficulty was task performance; physical and temporal demand were low; mental demand and effort were moderately high. Five qualitative themes for improvement: clinical fidelity, interface organization, learning experience, serious gaming, and implementation strategies. 63% would use the tool a moderate amount or a great deal for ICU preparation; 69% would do so during ICU rotation.	Designed to foster trainee autonomy and advance clinical skills in a safe environment; plans to connect the model to real-time EHR data for bedside decision support; not empirically tested for clinical transfer	Yes — residents expressed willingness to use the app before and during ICU rotations; interest in gamification features (point/badge system); identified busy clinical schedules as a barrier to use.	Digital twin model previously validated on a small cohort of sepsis patients (Lal et al., 2020); expert rules refined via multinational Delphi consensus; prospective validation on larger cohorts planned	IRB approved as exempt (Mayo Clinic IRB 21-010982); verbal consent obtained; ethical/regulatory issues of clinical implementation acknowledged for future real-patient DT applications



10.	Trevena et al., 2024	Companion study (Rovati et al., 2024) describes user testing with internal medicine residents, designed for integration into critical care education; no formal curricular mapping is reported in this paper.	Model-driven engineering; causal inference via directed acyclic graphs; simulation-based education	Not assessed in this paper (technical architecture focus); companion study (Rovati et al., 2024) reports Level 1 data	A proof-of-concept case study (respiratory acidosis) demonstrated that the simulation output aligned with expected clinical trajectories based on expert rules. Architecture scales successfully through serverless functions and microservice design. Graph database enables modular, iterative rule refinement without code changes. Stochastic rule application maintains realistic clinical variability.	Explicitly designed for future bedside decision support via real-time EHR plug-in; architecture supports deployment across multiple device types (laptops, tablets, smartphones)	Not reported in this paper; referenced in companion study	Manual prospective validation of case study trajectory against expert rules; formal validation with real patient data planned; companion mixed-methods usability study conducted separately	IRB approved (Mayo Clinic); no patient data used in proof-of-concept; future real-time EHR integration raises data privacy considerations (not discussed in detail)
11.	Choi et al., 2025	Professors expressed interest in integrating into school curricula; designed to supplement traditional cadaver use; no formal curricular integration at time of publication.	Immersive/experiential learning; collaborative learning; XR-enhanced education; metaverse-based pedagogy	Level 1 (Reaction): 100% positive pilot test feedback on interactive and immersive features; students found it engaging and fun; conference attendees were optimistic about collaborative applications	Successfully created a 3D digital twin of 206 bones of a Korean male cadaver; developed a metaverse platform with manipulation tools (move, detach, color, cross-section), partial palette (body regions), collaboration features (room creation/joining, model sharing). A 3D-printed physical model was also produced. Pilot feedback: students appreciated interactive quiz-like features and real-time collaboration; professors were interested in cross-departmental use; corporate guests inquired about pricing and content pipeline; conference attendees saw potential for integrating Western and Asian medicine.	Not directly assessed; platform proposed as applicable to telemedicine and various medical specialties (ophthalmology, dentistry, cardiology, veterinary medicine); AR elements evaluated as improving concentration and immersion.	Yes — students found interactive bone manipulation engaging; described as 'fun' and 'like floating bones with quiz cards'; appreciated real-time collaboration capability.	Anatomical accuracy maintained through consultation with medical resources and atlases during retopology; synostosis cases addressed with expert guidance; no formal educational outcome validation	Cadaver ethically procured from certified Korean institution (Department of Anatomy, Catholic University of Korea); ethical considerations of DT development emphasized; cadaver kept intact during scanning.
12.	Jeising et al., 2024	Presented in Connectome Student Association skills laboratory; designed as a training model for neurosurgical residents; no formal curricular integration described	Simulation-based education; hands-on skills acquisition; hybrid (mixed reality + physical model) training; progressive skill levels (planning → instrument setup → surgical execution)	Level 1 (Reaction): overall evaluation median 5 (IQR 1) on 1–5 scale; neuroanatomy understanding improvement median 5 (IQR 0.75); MR advantages over textbooks median 5 (IQR 1); combination of MR + 3D printing for surgical understanding median 5 (IQR 1); wish for more hands-on models	Model-enabled training of the entire brain tumor surgery procedure across 3 levels: (1) planning (virtual 3D exploration, craniotomy simulation via eraser tool), (2) instrument setup (Mayfield clamp, neuronavigation registration), (3) surgical execution (skin incision, craniotomy, dural opening, fluorescence-guided resection, closure). 85% of participants agreed MR + 3D printing develops surgical procedure understanding. 97% agreed MR will play a role in	Concept described as bridging technology toward intraoperative MR application; neuronavigation registration practiced on physical model; participants can train on real instruments; not empirically tested for clinical performance transfer	Yes — students strongly wished for more hands-on models (median 5, IQR 0); high overall evaluation scores; collaborative group work during skills laboratory was observed.	Proof-of-principle evaluation; no controlled educational trial; skull models matched patient imaging data; tumor positioned in anatomically correct location enabling neuronavigation registration without additional imaging	Based on real patient imaging data (anonymized), a cadaveric animal brain obtained from a local butcher and disposed of per regulation, processed at a distant location from patient care



				median 5 (IQR 0); intuitive handling of MR system median 4 (IQR 1); MR role in future clinical practice median 5 (IQR 1).	future clinical practice. Model cost <\$50 vs ~\$600 for commercial alternatives.				
13.	Chen et al., 2022	Proposed as comprehensive medical education platform; no specific curricular integration reported (conceptual framework)	Digital twin networking; cyber-physical systems; experiential/immersive learning; human-machine-fabric interaction	Not assessed (conceptual framework only)	Proposed four typical applications: (1) medical education training with 3D visualization and automated posture/skill evaluation, (2) health and behavior tracking of trainees via fabric sensors, (3) operation playback and reproduction using recorded sensor data from smart gloves/gauze, (4) medical knowledge popularization for public first aid training. System architecture comprises the fabric, the network transmission layer, and the edge cloud layer.	Designed to bridge the gap between institutional teaching and clinical practice, real-time tactile feedback is intended to replicate clinical conditions; operation playback enables learning from real surgical cases.	Not reported (conceptual framework only)	No validation reported; conceptual architecture only; references advances in fabric sensor technologies as enabling foundations	Not explicitly discussed; multimodal physiological monitoring raises privacy considerations (not addressed)
14.	Alves Halpern et al., 2024	Same context as Rovati et al. 2024 — app used pre-ICU rotation; LLM analysis proposed as a tool for accelerating educational tool development	AI-augmented qualitative research methods; user-centered design; human-AI collaboration for educational evaluation	Level 1 (Reaction): LLM successfully identified and categorized usability feedback themes (organization, labeling, interactive elements) matching human analysis	LLM analyzed 18 full video transcripts in under 2 minutes vs ~15 hours for manual human review. LLM matched humans in accuracy and reliability for identifying key themes. Human prompt refinement took ~15 minutes with multiple iterations. LLM identified themes on organization, labeling, interactive elements, and feature recommendations. AI analysis supplemented but did not replace human evaluation as the gold standard.	LLM-based qualitative analysis proposed for accelerating user experience evaluation of clinical decision support systems, EMRs, and medical education tools in healthcare settings	NR (focus was on methodology of feedback analysis, not on learner engagement with the DT app itself)	LLM output compared against manual human review (gold standard); AI-driven evaluations reviewed by two researchers for accurate interpretation	NR (abstract does not discuss data privacy; transcripts were de-identified in parent study)
15.	Kumar et al., 2024	Proposed as an integrative platform for medical education curricula; no specific curriculum mapping or institutional deployment described	Industry 4.0/5.0 inclusive design principles; IoT-enabled learning; accessibility-centered technology design	Not assessed; visualization quality measured by intrinsic variable merging values (technical proxy metric); no educational outcome data collected	The digital twin-based IoT visualization method achieved the highest intrinsic variable-merging values across 7 test groups (range: $2.040\text{--}2.593 \times 10^4$) compared with the operation/maintenance monitoring ($1.150\text{--}1.914 \times 10^4$) and multi-terminal display ($1.084\text{--}1.895 \times 10^4$) methods, demonstrating superior visualization clarity. Case studies described (but not empirically	Not empirically assessed; proposed that improved visualization enables physically disabled students to practice medical procedures virtually, bridging the gap to real-world clinical skills	Not empirically reported; benefits for physically challenged students described conceptually (interactive, immersive educational experiences; personalized learning)	Comparative experimental analysis against two alternative visualization methods using intrinsic variable merging values as the primary performance metric; no external validation or educational outcome measurement	Not discussed; funding from King Salman Center for Disability Research (KSRG-2023-309)



					tested) showing physically disabled students engaging with digital twins of medical equipment in a virtual environment.				
16.	Trabelsi et al., 2025	Proposed as a training platform for surgical robotics education; no formal curricular integration is described; DT currently used for abdominal surgical application validation.	Simulation-based education; pre-clinical virtual commissioning; digital twin-enabled safe experimentation before physical deployment	Not formally assessed; no learner outcome data collected; proof-of-concept focused on technical platform development.	High-fidelity DT successfully validated optimal robot base placement via a capability map optimization algorithm. Franka robot laparoscopic camera placement and tool mounting configuration validated through simulation. Medical instrument virtual prototypes (tool holder, medical clips, laparoscopic camera) tested and refined before physical fabrication. Control laws validated using 3 haptic devices (a commercial Falcon and 2 custom-designed interfaces). DT serves as a comprehensive surgical training platform that demonstrates diverse laparoscopic scenarios (Fig. 19.8). Virtual modifications appear less transferable to the physical system.	Explicitly designed for pre-clinical testing and clinical transfer, any DT-developed optimizations are transferable to a physical multi-robot system; DT provides a safe environment for skill refinement without patient risk; real-time simulation enhances task efficiency and reduces cognitive strain.	Not formally reported; surgical training scenarios are described as comprehensive and immersive with haptic feedback, reducing cognitive strain for surgeons in training.	Kinematic/dynamic simulation validated against physical platform via numerical model study; qualitative comparison between digital twin and real platform (Fig. 19.2); robot placement results validated through numerical analysis; no formal educational outcome assessment.	Not discussed; no patient data involved in current phase
17.	W. Zackoff et al., 2024	Implemented as a mandatory onboarding component prior to the opening of the new hospital expansion; 1522 of 2086 eligible staff participated; 3-phase learning progression (guided navigation → independent practice → assessment exercise)	Adult learning theory (Knowles, 1975); experiential learning (Kolb, 1984); guided-independent-assessed progression model; autonomous learning design	Level 1 (Reaction): adverse effects reported but low severity (46% no adverse effects; 25.7% dizziness as most common); high immersion scores (94.3% senses captured, 94.9% dedicated completely, 89.1% felt physically present, 86.7% retained environment image); strong preference for VR over low-fidelity methods (87.2% over reading, 85% over online learning, 82.3% over didactics); mixed vs manikin simulation (42.7%) and real-time care (22.4%). Level 2	n=1522 (the largest healthcare VR training study to date). Adverse effects: 54% reported any effect; dizziness was the most common (25.7%); no participants required to stop or recover. Immersion: 94.3% of senses captured; 89.1% felt physically present. VR preference: 87.2% > reading; 85% > online learning; 82.3% > didactics; mixed ratings vs simulation or real clinical care. Regression: prior VR experience → increased odds of no adverse effects (p=0.012); older age → decreased immersion (all items p<0.001) and lower VR preference over low-fidelity methods (p<0.001); female participants → higher adverse effect rates (p<0.001 for most items); unit staff (HUCs, pharmacists) → lower immersion	Onboarding designed to prepare staff for a real new clinical environment prior to facility occupancy; VR experience enables familiarization before high-acuity patient care begins; no empirical pre-post clinical performance comparison conducted.	Yes — 46% reported no adverse effects; high immersion rates across all demographic groups; 63% would use the tool a moderate amount or a great deal for ICU preparation; 69% during ICU rotation; prior VR experience improved tolerability.	Digital twin environment collaboratively validated with clinical experts and simulation educators for accuracy and realism; piloted with simulation educators and clinical educators from target units before full rollout; ~1000 developer hours for DT environment; ~1000 hours for avatar development; ~2000 hours for gamification; no formal spatial accuracy metrics vs physical space reported	IRB approved (institutional review board); participation mandated for some staff, but study opt-out available; verbal consent; VR equipment hygiene protocols implied but not detailed



and above: not
assessed.

odds vs bedside staff ($p=0.001-0.02$).



