JPRAS Open 41 (2024) 295–310

Contents lists available at ScienceDirect

JPRAS Open

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

Review Article

Characterizing the untapped potential of virtual reality in plastic and reconstructive surgical training: A systematic review on skill transferability ☆

Madeleine Landau [a,*], Marie Comeaux [a], Tatjana Mortell [a], Rebecca Boyle [a], Kory Imbrescia [b], Abigail E. Chaffin [b]

[a] School of Medicine, Tulane University, New Orleans, LA 70112, USA
[b] Division of Plastic and Reconstructive Surgery, Department of Surgery, School of Medicine, Tulane University, New Orleans, LA 70112, USA

ARTICLE INFO

Article history:
Received 19 June 2024
Accepted 27 June 2024
Available online 6 July 2024

Keywords:
Plastic surgery
Residency
Virtual reality
Surgical training
Immersive
Education

ABSTRACT

Virtual reality (VR) integration into surgical education has gained immense traction by invigorating skill-building in ways that are unlike the traditional modes of training. This systematic review unites current literature relevant to VR in surgical education to showcase tool transferability, and subsequent impact on knowledge acquisition, skill development, and technological innovation. This review followed the PRISMA guidelines and included three databases. Among the 1926 studies that were screened, 31 studies met the inclusion criteria. ChatGPT assisted in generating variables for data extraction, and the authors reached unanimous consensus on 13 variables that provided a framework for assessing VR attributes. Surgical simulation was examined in 26 studies (83.9%). VR applications incorporated anatomy visualization (83.9%), procedure planning (67.7%), skills assessment (64.5%), continuous learning (41.9%), haptic feedback (41.9%), research and in-

☆ This work is scheduled for poster presentation at the 2024 American Council of Educators in Plastic Surgery 11th Annual Winter Meeting (St. Louis, MO).

* Corresponding author.
E-mail address: mlandau@tulane.edu (M. Landau).

https://doi.org/10.1016/j.jpra.2024.06.015

novation (41.9%), case-based learning (22.6%), improved skill retention (19.4%), reduction of stress and anxiety (16.1%), and remote learning (12.9%). No instances of VR integration addressed patient communication or team-based training. Novice surgeons benefited the most from VR simulator experience, improving their confidence and accuracy in tackling complex procedural tasks, as well as decision-making efficiency. Enhanced dexterity compared to traditional modes of surgical training was also notable. VR confers significant potential as an adjunctive teaching method in plastic and reconstructive surgery (PRS). Studies demonstrate the utility of virtual simulation in knowledge acquisition and skill development, though they lack targeted approaches for augmenting training related to collaboration and patient communication. Given the underrepresentation of PRS among surgical disciplines regarding VR implementation in surgical education, longitudinal curriculum integration and PRS-specific technologies should be further investigated.

Introduction

The interest in virtual reality (VR) within surgical education is attributable to the immersive and practical qualities that distinguish this method of learning from the conventional training approaches. In contrast with the traditional surgical training that often relies on didactic lectures, cadaveric dissections, and technical learning in the operating room, VR allows surgical residents to approach training in a hands-on, risk-free, and replicable manner.[1,2] The surgical community has already begun witnessing a shift in its approach to training as VR platforms have become integrated into residency education within several specialties. In contrast to the success observed in minimally invasive surgery[2-6], otolaryngology[7,8], orthopedics[9,10], and neurosurgery[8], the integration of VR components into plastic surgery training has stalled owing to the difficulties in realistically replicating the feeling of operating on soft tissue in a virtual setting.[1,8,11,12] However, simulation software continues to improve and show increasing realism, making it feasible for preoperative planning in soft tissue, flap, and microscopy-based surgery.[3,13]

Technological advancements in recent years have transformed traditional surgical training practices into more immersive and dynamic approaches.[14] VR integration has provided a practical method for enhancing traditional training translated into improved patient outcomes, such as reduced ischemia, shorter procedure duration and hospital stay, lower revision rates and operative injury occurrences, and greater preservation of healthy tissue and precision with defect removal.[15] However, there is a further need for implementing educational platforms that provide trainees with an immersive operating room experience with realistic scenarios. Currently, this is especially true as surgical cases are becoming more complex, leading to an increased necessity for operating room efficiency, precision, and cost-effectiveness.[9,16] These realistic, risk-free virtual environments could augment the residents' preparedness to perform surgeries on their own.[17,18] The ability of VR to simulate intricate surgical procedures in a controlled, yet repeatable manner, has the potential to bridge this gap.[14]

Recent evidence supports potential VR applications in enhancing skill development among plastic surgery trainees. These applications aid in the visualization of anatomical structures in a 3D space, understanding of procedural complexities, and ability to practice surgical decision-making in a risk-free space.[11,19] Furthermore, the hands-on, replicable nature of these simulations has been shown to improve the self-confidence in the learners.[16,17] This supplemental process of virtual learning addresses some of the limitations of traditional instruction. Combined with conventional training methodologies, VR offers an enriched educational model that allows surgery residents to learn and improve skills inside and outside the operating room, resulting in enhanced surgical abilities and clinical performance.[3,20,21]

This systematic review aimed to clarify the role of VR in surgical training and elucidate how this technology will shape the future trajectory of plastic surgery education. This study boasts an extensive synthesis of evidence through intentionally generalized search terms that allowed for a comprehensive discussion on this topic. Our collaboration with AI allowed us to generate an exhaustive analysis of attributes that can shape successful VR simulators. Furthermore, the observation of chronological trends in VR aids in the understanding of its previous and current utilization, illuminating future educational demands and applications of VR in plastic surgery residency training.

Methods

Protocol overview

Review of the literature consisted of searching a subset of databases for studies in accordance with the preferred reporting items for systematic reviews and meta-analyses guidelines.

Database search terms

Three separate databases, Elsevier, Web of Science Core Collection, and Embase, were used in this study. Terms queried consisted of virtual reality, training, or simulation, combined with medical/resident education, residency, or medical learning, which were further coupled with plastic surgery, reconstructive surgery, or surgery. Searches were completed on August 7, 2023 and uploaded to Covidence (Veritas Health Innovation, Melbourne, Australia) for screening.

Search criteria

Initially, 1926 studies were independently screened by two reviewers in a two-stage process (M.B.L. and M.C.). First, the authors solely screened the titles and abstracts for relevance. Once all studies were filtered for relevance in this manner, the authors then separately screened full-text studies for inclusion into the final pool of eligible studies for analysis.

Eligibility criteria

The beginning timepoint was selected as 1999, when the first application of an interactive VR model for developing suture technique was identified within this search. To capture the full extent of relevant studies regarding the use of VR in surgical education, and potential skill transferability to plastic surgery, studies from 1999 to 2023 were included. Review articles, meta-analyses, and commentaries were excluded. Papers investigating robotic surgery, 3D-printing, or VR intraoperatively did not meet eligibility criteria. Studies invoking VR with observable impact within the training regimen and involving relevant procedural techniques for assessing outcomes were included. Thus, 31 studies screened met the inclusion criteria (Figure 1).

Variable generation and data collection process

ChatGPT assisted in generating variables for data extraction, from which the authors unanimously selected 13 variables that provided a framework for assessing the applications of VR in surgical education (Table 1). A data collection form was generated and included all 13 variables and bibliometrics. The authors selected "yes," "no," or "unclear" in response to whether a study included information aligning with the respective variable and definition derived from ChatGPT (Table 1). Qualitative data were also collected for each variable, in which authors participating in data collection were expected to explain study congruency for qualitative analysis with an emphasis on technological applications

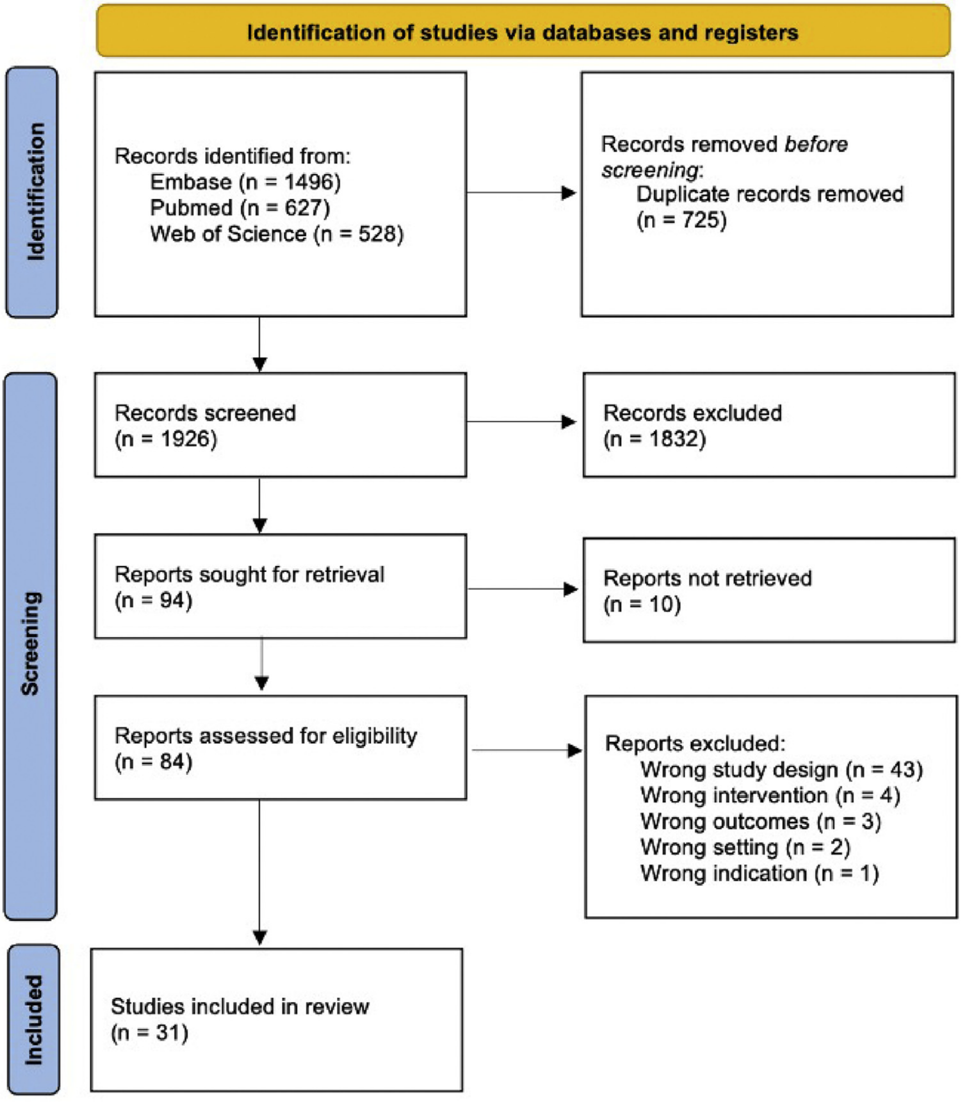

Figure 1. PRISMA diagram.

and learning outcomes. The authors then provided a summary of the application of VR technology to education and identified the goals for each study.

Results

Publication timeline

The publication year for eligible studies spanned from 1999 to 2023, with increasing study volume roughly corresponding to timeline progression (Figure 2).

Table 1
ChatGPT-generated variables and corresponding definitions.

Variable	Definition
Surgical Simulation	VR platforms offer realistic surgical simulations that allow residents to practice various plastic surgery procedures in a controlled, risk-free environment. These simulations can replicate the look and feel of different surgeries, helping the residents develop their surgical skills without the need for a live patient.
Anatomy Visualization	VR can provide three-dimensional, immersive views of human anatomy. Residents can explore and understand the complexities of anatomical structures in ways that traditional textbooks or two-dimensional images cannot offer. This is particularly valuable in plastic surgery, where precise knowledge of anatomy is crucial.
Procedure Planning	VR tools can aid in surgical planning by allowing the residents to virtually plan and simulate surgical procedures before they are performed on actual patients. This can enhance preoperative decision-making and help residents anticipate potential challenges.
Skills Assessment	VR systems can track and assess a resident's performance during simulated surgeries. Metrices such as hand steadiness, instrument handling, and technique precision can be measured and used to provide feedback for improvement.
Continuous Learning	VR can be used for ongoing professional development, allowing practicing plastic surgeons to refine their skills and stay updated on the latest techniques and technologies.
Haptic Feedback	VR with haptic feedback strengthens the virtual surgical experience by providing a sense of touch. This can help authenticate the resident's surgical training.
Research and Innovation	VR environments can serve as testing grounds for innovative surgical techniques and technologies. Residents can experiment with new approaches in a safe and controlled setting.
Case-Based Learning	VR can present residents with complex clinical cases and allow them to make decisions on diagnosis and treatment. This interactive learning approach promotes critical thinking and problem-solving skills.
Improved Skill Retention	VR training may allow for greater skill retention when compared to tradition training methods owing to its fully immersive nature.
Reduction of Stress and Anxiety	By allowing residents to repeatedly practice procedures and build confidence in a low-stakes environment, VR can help reduce stress and anxiety associated with real surgical experiences.
Remote Learning	VR can be accessed remotely, enabling residents to train and collaborate with experts or peers from different locations. This is particularly valuable for distributed residency programs.
Team-Based Training	Plastic surgery often involves collaboration with other medical professionals. VR can facilitate team training exercises, where residents can practice working in interdisciplinary teams to enhance communication and coordination skills.
Patient Communication	VR can be used to create 3D visualizations of surgical procedures, which can be shown to patients to help them better understand the planned surgery, potential outcomes, and expected results. This aids in patient communication and informed consent.

Discrete attributes

Surgical simulation was examined in 26 studies (83.9%), in contrast to purely anatomical simulation. Representation of VR characteristics within the pool of included studies is specified in Table 2.

VR applications were found to incorporate anatomy visualization (83.9%), procedure planning (67.7%), skills assessment (64.5%), continuous learning (41.9%), haptic feedback (41.9%), research and innovation (41.9%), case-based learning (22.6%), improved skill retention (19.4%), reduction of stress and anxiety (16.1%), and remote learning (12.9%). No instances of VR integration addressed patient communication or team-based training. The full assessment of variables pertaining to VR applications of the included studies is shown in Figure 3.

Characterization of studies by their individual accumulation of identifiable VR attributes is shown in Table 3.

The transferability of skills acquired through VR simulation applicable to key areas of plastic surgery is underscored in Table 4.

Table 2
Virtual reality characteristics of the included studies.

Author	Year	Software	Hardware	Depth of Simulation Integration	Population of Users
de Lotbiniere-Basset, M[22]	2023	SurgiSim	Oculus Rift or Quest	Isolated Surgical Techniques	Non-specified Users
Feinmesser, G[23]	2023	In-house Developed VR	Vive system	Isolated Surgical Techniques	Surgeons, Residents
Feeley, AA[15]	2023	Precision OS	Precision OS	Full Surgical Procedure	Residents
Ulbrich, M[24]	2023	Elucis version 1.4	HTC Vive Pro + HTC Vive Controller 2.0	Anatomy Visualization	Residents
Wan, T[25]	2023	In-house Developed VR	HTC VIVE Pro 2	Full Surgical Procedure	Surgeons, Medical Students
Poole, M[26]	2022	Surgery Tutor	Computer + electromagnetic (EM) field generator with control box	Full Surgical Procedure	Medical Students
Quesada-Olarte, J[27]	2022	In-house Developed VR	Microsoft HoloLens 2	Full Surgical Procedure	Surgeons
Zhou, Z[28]	2022	In-house Developed VR	zSpace + Vive	Isolated Surgical Techniques	Non-specified Users
Bing, EG[29]	2021	In-house developed VR by Unreal Engine	Oculus Rift	Full Surgical Procedure	Residents
Shenoy, V[30]	2021	In-house Developed VR utilizing Unity's Game Engine	Oculus Quest	Isolated Surgical Techniques	Surgeons, Residents, Medical Students
Belvroy, VM[31]	2020	Non-specified	ANGIO Mentor	Isolated Surgical Techniques	Surgeons, Residents, Medical Students
Lo, S[32]	2020	In-house Developed VR utilizing Autodesk 3DS max and Bodyparts3D	Computer	Anatomy Visualization	Anatomy Undergraduate
Sung, MY[33]	2020	In-house Developed VR	Non-specified	Isolated Surgical Techniques	Non-specified Users
Logishetty, K[34]	2020	In-house Developed VR	Non-specified commercially available VR headsets	Full Surgical Procedure	Residents

(*continued on next page*)

Table 2 (*continued*)

Author	Year	Software	Hardware	Depth of Simulation Integration	Population of Users
Xin, B[35]	2020	Non-specified	Non-specified	Full Surgical Procedure	Surgeons
Pulijala, Y[36]	2018	Non-specified	Oculus Rift + Leap Motion devices	Full Surgical Procedure	Residents
Gmeiner, M[37]	2018	In-house developed by RISC Software	Computer	Full Surgical Procedure	Surgeons
Pulijala, Y[38]	2018	In-house Developed VR	Oculus Rift + Leap Motion devices	Full Surgical Procedure	Surgeons
Siff, LN[39]	2018	In-house Developed VR	Non-specified	Full Surgical Procedure	Residents
Wijewickrema, S[40]	2018	Non-specified	Non-specified	Full Surgical Procedure	Medical Students
Ros, M[41]	2017	In-house Developed VR utilizing Adobe Premiere Pro CC	prototype Rift DK2 and Gear VR Innovator	Full Surgical Procedure	Surgeons
Andersen, SA[42]	2016	Visible Ear Simulator	Computer + Geomagic Touch	Full Surgical Procedure	Medical Students
Deuchler, S[43]	2016	Eyesi	Eyesi	Full Surgical Procedure	Surgeons
Girod, S[44]	2016	In-house Developed VR	Geomagic Touch	Full Surgical Procedure	Residents
Lam, CK[45]	2016	In-house Developed VR	Computer + Phantom Omni	Full Surgical Procedure	Surgeons, Residents
de Sena, DP[46]	2013	Non-specified	Computer	Full Surgical Procedure	Medical Students
Zhao, YC[47]	2011	In-house Developed VR	CrystalEyes Stereographics 3D Glasses + Phantom Omni	Full Surgical Procedure	Medical Students
Smith, DM[48]	2007	In-house Developed VR Alias Maya versions 4.5 and 6.0	Non-specified	Anatomy Visualization	Non-specified Users
Smith, DM[49]	2005	In-house Developed VR Alias's Maya 4.0	Non-specified	Anatomy Visualization	Non-specified Users
Smith, DM[50]	2005	In-house Developed VR Alias Maya 4.0	Non-specified	Full Surgical Procedure	Non-specified Users
O'Toole, RV[51]	1999	In-house Developed VR	Non-specified	Isolated Surgical Techniques	Surgeons, Medical Students

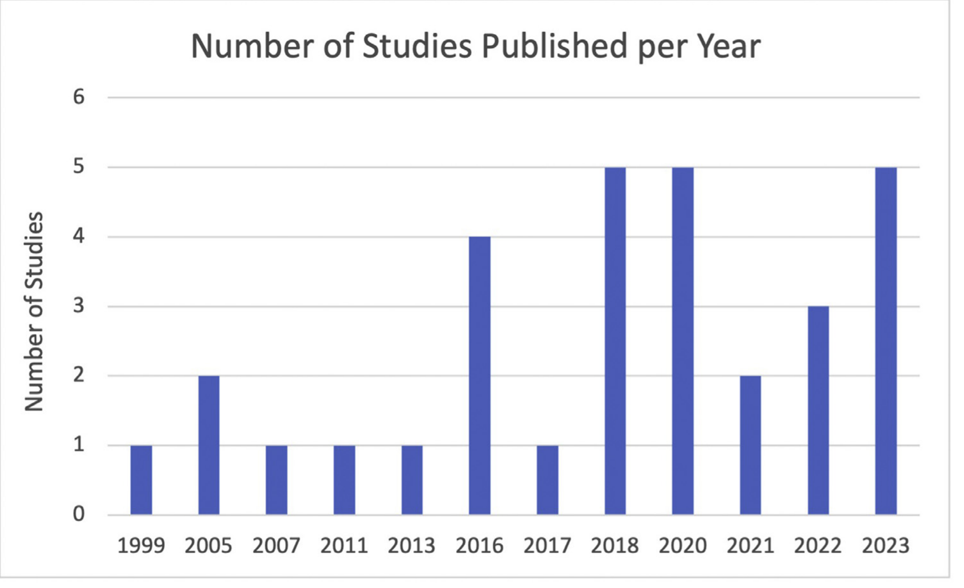

Figure 2. Study density timeline showing the number of included studies published per fiscal year between 1999 and 2023.

Evolving trends in virtual reality integration

General qualitative analysis revealed the global utility of VR in surgical training, citing increased affordability compared to cadaver models. The use of low-cost VR simulators presented the opportunity to provide tailored surgical skill development to trainees who lacked sufficient training and mentorship opportunities. Advances in commercial VR gaming equipment offered a cost-effective means to bridge the gap in low-middle income countries. Additionally, novice surgeons benefited the most from VR simulator experience, which improved their confidence and accuracy in tackling complex procedural tasks, as well as decision-making efficiency. Enhanced dexterity compared to traditional modes of surgical training was also notable.

Discussion

The “Next Accreditation System” (NAS) was created by the Accreditation Council for Graduate Medical Education (ACGME) in 2013.[52] In 2014, all programs were under NAS and were thus required to implement educational milestones from six core clinical competency domains.[53] These domains include patient care and technical skills, medical knowledge, practice-based learning and improvement, interpersonal and communication skills, professionalism, and systems-based practice. Plastic and reconstructive surgery has slowly been transitioning to a competency-based education. Though a specialty marked by its innovation, the field is not prominently represented in surgical education literature with respect to the use of VR simulations.[2] Characterizing VR simulation by attribute categorization allows for direct assessment of this technology’s integration in the surgical setting, plausibly asserting areas of plastic surgery residency education where VR may provide the most benefit.

Extended reality and VR simulations have garnered significant attention in medical education, given the capacity of the technology to optimize resource utilization and provide a learner-centric, rather than patient-centric environment.[54] Relevant to this type of education is the ability of VR to create anatomically accurate 3D organs with authenticity, including the accurate display of intricate tissue layers and delicate microvasculature. As one of the most common attributes of existing VR mod-

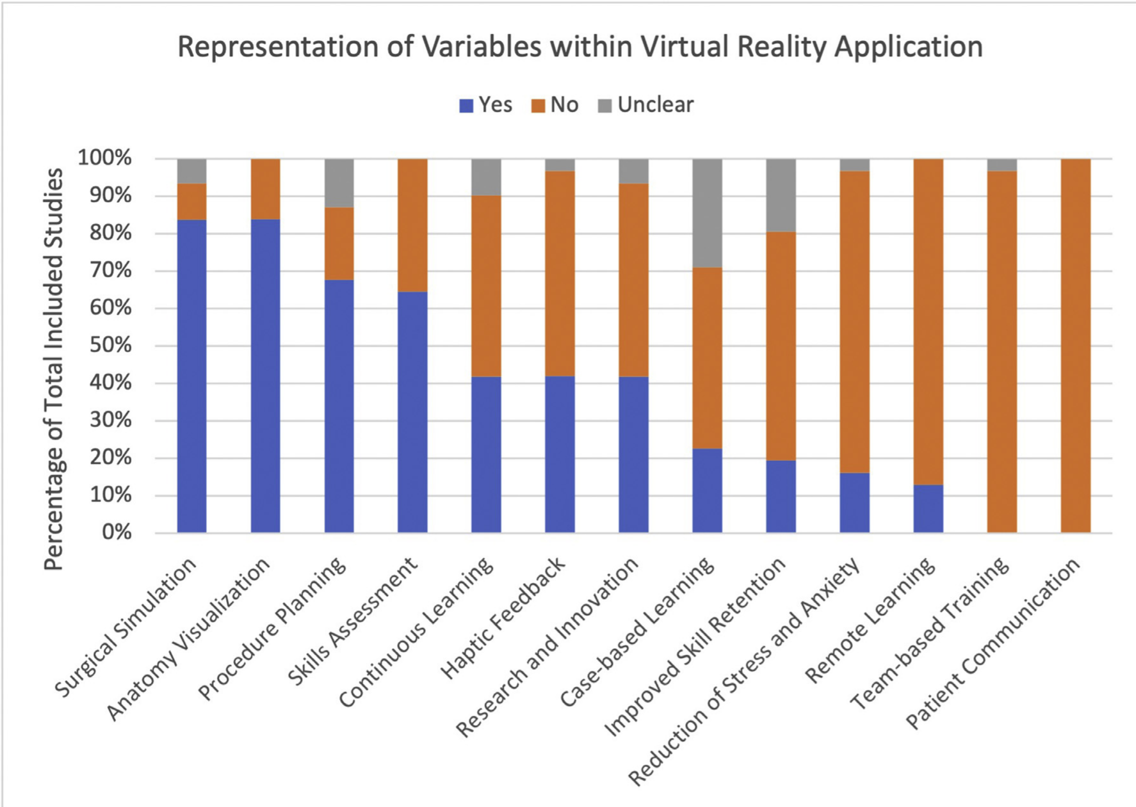

Figure 3. Representation of AI-generated virtual reality variables within the pool of included studies for review. Authors designated studies as *yes*, *no*, or *unclear*, based on the contextual information provided in each study concerning the implementation of the respective virtual reality model.

Table 3
Representation of VR variables within each study.

Author	SS	AV	PP	SA	CL	HF	RI	CB	SR	RS	RL	TB	PC
de Lotbiniere-Basset, M	X	X	X	X		X	X						
Feinmesser, G	X	X	X	X						X			
Feeley, AA	X	X	X	X	X	X	X						
Ulbrich, M	X												
Wan, T	X	X	X										
Poole, M	X	X	X	X	X	X	X		X				
Quesada-Olarte, J													
Zhou, Z	X	X	X	X	X	X	X	X					
Bing, EG	X	X	X		X						X		
Shenoy, V	X	X	X	X			X			X			
Belvroy, VM	X	X	X	X			X						
Lo, S	X	X											
Sung, MY	X	X	X	X	X	X			X				
Logishetty, K	X		X	X	X								
Xin, B	X	X	X	X	X	X	X	X	X				
Pulijala, Y	X	X		X	X	X	X			X			
Gmeiner, M	X	X			X	X		X					
Pulijala, Y	X	X	X										
Siff, LN	X	X		X	X			X		X			
Wijewickrema, S	X			X									
Ros, M		X	X								X		
Andersen, SAW	X	X	X	X	X	X	X		X				
Deuchler, S	X	X		X							X		
Girod, S	X	X	X	X		X		X		X			
Lam, CK	X		X	X		X							
de Sena, DP		X		X					X				
Zhao, YC	X	X	X	X	X	X	X	X	X				
Smith, DM		X									X		
Smith, DM		X	X				X						
Smith, DM	X	X	X				X	X					
O'Toole, RV	X	X	X	X	X	X	X						
Percentage	**83.9**	**83.9**	**67.7**	**64.5**	**41.9**	**41.9**	**41.9**	**22.6**	**19.4**	**16.1**	**12.9**	**0**	**0**

Table 3. SS: surgical simulation, AV: anatomy visualization, PP: procedural planning, SA: skills assessment, CL: continuous learning, HF: haptic feedback, RI: research and innovation, CB: case-based learning, SR: improved skills retention, RS: reduction of stress and anxiety, RL: remote learning, TB: team-based training, PC: patient communication.

els in preoperative planning, anatomy visualization ranges from displaying generalized representations to engaging patient-specific anatomical structures derived from computed tomography scans.

Beyond anatomy visualization and surgical simulation, procedural planning, skills assessment, and haptic feedback were among the top attributes represented in our final study pool. Objective measures, such as final product score, relative reaction time, tool tip position and velocity, movement smoothness, idle time, and path length, enrich the quality and efficiency of periodic feedback throughout residency education. Exhibition of poorer performance in outlining the boundaries of a procedure, mistaking anatomical landmarks, or falling short of technical effectiveness or efficiency help identify specific deficits for continued training progress. Therefore, novel advances in objective skill assessment with VR integration assists in pinpointing personalized needs for skill-building to achieve greater proficiency.

Moreover, haptic feedback has been largely responsible for expanding the applicability of the role VR simulators play in surgical residency education by intensifying the element of immersion. The introduction of bimanual control and variable degrees of haptic feedback regulated using handheld devices has gradually allowed trainees to acquire a more refined sense of control and options for customization of their simulation experience. For example, the calculation of distance from the tip of a surgical tool to vital organs and the supply of haptic feedback used in VR simulation instill precision, real-time correction mechanisms through force feedback to encourage techniques for patient safety. Haptic feedback has been shown to improve simulation performance not only for novice trainees, but

Table 4
Procedure and skill transferability to plastic and reconstructive surgery.

Procedure	Transferable Skills
Microsurgery (general)[22]	• Reducing magnification errors • Controlling the selection of surgical field of view
Sentinal Lymph Node Biopsy[23]	• Accurately localizing small structures • Identifying optimal incision site(s) • Rehearsing surgical approach
1. Removal of meta, carpal tunnel release, excision soft tissue tumor 2. Knee arthroscopy, distal radius ORIF, TA rupture repair 3. Ankle ORIF, supracondylar fracture fixation, shoulder arthroscopy 4. Hip Fracture management: proximal femoral nail, hemi arthroplasty, dynamic hip screw 5. Total hip replacement, total knee replacement, revision surgery, open fracture fixation[15]	• Practicing time and motion with escalating procedural complexity • Instrument handling • Acquiring knowledge of instruments • Navigating flow of operation • Using assistants • Acquiring procedural knowledge
Oral and maxillofacial reconstruction, segmentation of the fibula and os coxae[24]	• Delivering functional and esthetic results with microvascular reconstruction of bone and soft tissue defects
Orthognathic surgical procedures (general)[25]	• Refining technical dexterity with instrument control • Rehearsing soft tissue handling with instrument manipulation
Resection of non-palpable soft tissue tumors[26]	• Visualizing scalpel position during simulated soft tissue resection • Improvement in positive margin rate of tumor removal
Complex penile revision surgery[27]	• Preoperative strategizing via VR-MRI image integration for surgical evaluation • Visualizing vascular structures and prosthetic materials in 3D landscape
Percutaneous needle insertion procedures[28]	• Reducing placement time of the needle considerably with personalized simulation training • Different VR technologies suited for either the quality of immersion or procedural preparedness
Radical abdominal hysterectomy[29]	• Improved self-perception of surgical knowledge • Goal formation and motivation to improve technique • Acquisition of highly transferrable skillset applicable to related surgical procedures
Ultrasound guided vascular access[30]	• Applying small-scale techniques on microvasculature • Utilization of ultrasound • Bimanual dexterity training • Needle handling
Guidewire, catheter, and sheath combination for VR model navigation[31]	• Evaluating smoothness of hand movements, position of tool placement, and spatial and depth awareness • Reducing idle time
Anterolateral thigh flap surgery[32]	• Visualizing highly detailed anterolateral thigh (ALT) for ALT flap creation
1. Simple interrupted suture 2. Running locked suture 3. Vertical mattress suture 4. Horizontal mattress suture 5. Running subcuticular sutures[33]	• Refining fundamental suturing techniques • Haptic feedback facilitating depth perception and precision of needle placement
Anterior approach to total hip replacement[34]	• Evaluating smoothness of hand movements • Minimizing overall procedural timing and increasing workflow efficiency • Preoperative planning with precise anatomical modeling
Pedicle screw placement[35]	• Microvascular navigation • Comfortability and efficiency improvements during procedural workflow • Repetitive rehearsal minimizing procedural risks

(*continued on next page*)

Table 4 (*continued*)

Procedure	Transferable Skills
Le Fort I osteotomy[36]	• Head and neck 3D, anatomically accurate anatomy visualization, decision-making (non-technical)
Cerebral aneurysm surgery[37]	• Refining bimanual surgical skills • Tool-based manipulation of small blood vessels
Le Fort I osteotomy[38]	• Stepwise surgical approach practice with procedural rehearsal • Head and neck 3D, anatomically accurate anatomy visualization
Uterosacral ligament suspension and sacrospinous ligament fixation[39]	• 3D pelvic anatomy visualization via high-resolution virtual model for preoperative planning • Guided procedural rehearsal of assorted vaginal surgeries
Temporal bone surgery[40]	• Identification of major anatomical landmarks involving temporal bone structures • Practicing instrument handling with haptic feedback
Neurological surgery[41]	• Immersive observation of surgical techniques in the context of high-risk, complex procedures modeled by highly experienced surgeons
Mastoidectomy[42]	• Improving technique retention with reinforcement through repeat simulation practice • Enhanced technical skills with increased workflow efficiency and effectiveness
Pars plana vitrectomies[43]	• Training to perform asynchronous hand movements • Engaging use of the non-dominant hand to strengthen bilateral dexterity • Practicing microsurgical techniques
Mandibular fracture reduction[44]	• Learning object placement techniques using mandibular bone fragments by placing into designated positions guided by haptic feedback • Interactive use of patient-specific head and neck model simulations
Phacoemulsification (cataract surgery)[45]	• Maneuvering surgical tools to accomplish a variety of hand motions in sequence • Structured simulations allowing for practice of microsurgical techniques
Cutaneous rhomboid flap[46]	• Honing skills amenable to constructing cutaneous skill flaps for functional and aesthetic results
Cortical mastoidectomy[47]	• Improving instrument handling skills that respect key anatomical features and boundaries of the temporal bone
Virtual reality model of adult craniofacial anatomy[48]	• Visualizing high-resolution 3D craniofacial anatomy for studying complexities of head and neck surgeries
Virtual reality model of surgical superficial facial anatomy[49]	• Examining superficial facial anatomy • Interactive manipulation of soft tissue structures
Rhytidectomy[50]	• Animation of aesthetic face lift procedure respecting superficial structures • Highly detailed portrayal of facial aging processes
Suturing on a large flexible vessel[51]	• Developing manual dexterity for suturing technique of delicate vasculature • Engaging the use of the non-dominant hand to strengthen bilateral dexterity

also for experienced surgeons through objective metrics determined by the simulator itself, which supports the functional value of advanced VR simulators in long-term training. Arguably, several of these categorical variables describing VR attributes developed using AI have significant thematic overlap with the 6 ACGME domains, though no studies overlapped with the interpersonal and communication skills domain.

Simulation-based medical education with deliberate practice was first reported to be superior to traditional learning methods in 2012.[55] VR simulators have the capacity to teach what is expected for optimal performance and endow trainees with the foreknowledge of the typical precautions that must be taken during future practice and advise on common areas for improvement. This information guides residents with a retrospective assessment of outcomes from each simulation and refines further consideration of planning for surgical procedures. Simulators enable detailed monitoring of user progress and changes in performance between VR educational sessions by tracking metrics such as technical errors, surgery completion time, stepwise accuracy, and efficiency using the dominant and non-dominant hands. With the growing emphasis on graduated responsibility and learner-competency, effective competency assessment has become a pronounced discussion topic in graduate medical education.[56]

Indeed, the American college of surgeons has already implemented a 3-phase approach for integrating surgical simulation into the curricula. The three phases include core skills, advanced procedures, and team-based skills, further ascertaining the potential for existing VR technology to fulfill this need. With the ability for integrated case-based learning within interactive surgical simulation, there is a significantly taller ceiling for thorough and tailored practice. VR simulators heavily assist in stepwise planning efforts and precisely guide fundamental tasks from the moment of first incision, to anatomical manipulation, to closure methodology, actualizing the experience of a real surgical setting. The multisensory experience inherent in the current capabilities of VR simulation permits visual, auditory, and tactile feedback, all of which contribute to enhancing the learning experience such that it translates into long-term retention. Moreover, the ability of residents to rotate, zoom, and remove elements from virtual models can improve rehearsal and diminish the uncertainty of confronting certain anatomical features or technical nuances for the first time in real surgeries.

The push for VR integration in plastic surgery residency programs aligns with discussions regarding the potential changes in the PRS fellowship training landscape. At the 10th Annual ACAPS Winter Meeting a strengths, weaknesses, opportunities, and threats assessment of embedded fellowships and focused training occurred and revealed that most individuals believed that allowing extended 3-month to 6-month elective training would be beneficial.[57] Among the available PRS fellowships hand (31.3%), micro (27.0%), and craniofacial (22.8%) surgeries were found to be the most pursued fellowships before academic appointment.[58] Multiple included studies detail transferable VR-acquired skills applicable to the most common PRS fellowships. For example, VR was found to interactively portray the delicate features of craniofacial structure or incorporate haptic-based procedural planning in facial defects or trauma cases.[24,25,38,44,48] Hand fellowship was represented in studies that entailed procedural rehearsal of complex extremity reconstruction.[34,35] Finally, others integrate educational models for microvascular repair[22,30,31,37], which is pertinent to microsurgery.

Moreover, with the increase in robot-assisted microsurgery, demand for training in innovative surgical tools usage is increasing. In 2016, Theman et al. surveyed members of the American Society for Reconstructive Microsurgery and found that 84% of the respondents could not identify a reason why simulation would not be useful in microsurgery training.[59] Microscope adjustment, landmark identification, structure localization, incision placement and surgical approach rehearsal, instrument dexterity and motion smoothness, soft tissue handling, and anatomical manipulation of superficial parts are emergent skills with high transferability to plastic and reconstructive surgery expertise. This underscores a large window of opportunity to further develop PRS-specific VR technology for training PRS residents.

Further studies investigating the integration of VR-assisted technical skill acquisition and resident confidence in the proposed extended electives or fellowships are warranted. Notably, the less quantifiable VR attributes in this review were those that evaluated changes in learner confidence and memory retention. Spaced repetition serves as a powerful mechanism for long-term memory storage, and when this mechanism is applied to repetitive VR simulation experiences for educational purposes, trainees are afforded practical reinforcement of their knowledge and skills over time. Such models can be effective in settings with unpredictable or fluctuating case volumes, where practice need not solely rely on the inflow of patient surgeries to retain knowledge and physical skills. Given the severely lagging promotion and assessment of patient communication and team-based training through the implementation of current VR systems in surgical residency training, in-house development of applications involving these attributes are an untapped area of potential growth.

To our knowledge, this systematic review has screened the largest pool of studies with skills transferable to VR integration into plastic surgery residency. Furthermore, this study included analysis of the greatest number of assessed variables to date on the topic, uniquely facilitated by employing the assistance of AI and validated by human scholars. Ultimately, VR serves *"to replace the physical world with a virtual world and render the 3D environment immersive, semi-immersive, or non-immersive"*.[24] This systematic review harmonizes human-developed conceptualization with AI-generated objective structure. Similarly, VR integration into traditional surgical training proposes synergistic competency-based improvement as an adjunctive teaching modality.

Study limitations

A standardized simulation tool with demonstrated reliability and validity across various contexts, including various contexts within PRS training is lacking. This limitation is partly attributable to the inherent procedural diversity across the different specialties represented (Orthopedics, Head and Neck Surgery, Oral and Maxillofacial Surgery, Vascular Surgery, Neurosurgery, Gynecologic Surgery, Urology, and General Surgery) alongside PRS. Furthermore, the variable design of each study in terms of metrics analyzed through VR integration posed barriers to quantitative comparison of measurable outcomes. Moreover, only a few studies have specifically and directly investigated the role of VR in plastic surgery graduate medical education. Thus, our study relies on the transferability of skillsets across specialties in a way that could align with training of PRS residents.

Conclusion

VR confers significant advantages as a medium for immersive surgical education within the field of PRS. Studies demonstrate the utility of virtual simulation in knowledge acquisition and simulation training, highlighted through the high level of skill transferability across procedures included in this study. Nonetheless, targeted approaches for augmenting training related to collaboration and patient communication are lacking, indicating potential areas for further VR model development to meet the demands of competency-based training ideology. Our study also identified continued underrepresentation of PRS in literature regarding VR applications in surgical education. Ultimately, exploring how VR could teach intrapersonal and communication skills in residency training, the effects of longitudinal curriculum integration, and PRS-specific VR models may assist AI in supporting the professional development of future plastic and reconstructive surgeons.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Institutional review board statement

Not applicable.

Informed consent statement

Not applicable.

Data availability statement

Not applicable.

Use of AI statement

ChatGPT 3.5 was used exclusively for the generation of variables and corresponding definitions (Table 4) included in the data collection form. The authors did not use any form of AI or AI-assisted technologies outside of this purpose as a part of this study or during the preparation of this manuscript.

Declaration of competing interest

The authors declare no conflict of interest.

CRediT authorship contribution statement

Madeleine Landau: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Project administration. **Marie Comeaux:** Conceptualization, Software, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Project administration. **Tatjana Mortell:** Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Rebecca Boyle:** Investigation, Writing – original draft, Writing – review & editing. **Kory Imbrescia:** Validation, Investigation, Supervision. **Abigail E. Chaffin:** Conceptualization, Validation, Investigation, Supervision, Project administration.

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