JOURNAL OF Surgical Simulation

Journal of Surgical Simulation (2024) **11**, 11–24
DOI: https://doi.org/10.1102/2051-7726.2024.0002

REVIEW ARTICLE

The use of augmented reality in laparoscopic surgical training: an overview

Courtney Ludick,[a,*] David Rawaf,[b] Ahmet Omurtag,[a], Ben Simpson[a] Ahmed Swealem[c] and Ali Waleed Khalid[d]

[a]*Nottingham Trent University, Clifton Lane, Nottingham, NG11 8NS, UK;* [b]*Imperial College London, Exhibition Road, South Kensington, London, SW7 2BX, UK;* [c]*Kettering General Hospital, Rothwell Road, Kettering NN16 8UZ, UK;* [d]*The University of Buckingham Medical School, Hunter Street, Buckingham, MK18 1EG, UK*

**Corresponding author at: 14 Warton Street, St Helens, WA9 5AA, UK. Email: c.ludick.research@gmail.com*

Date accepted for publication: 19 December 2023

Abstract

Introduction: Laparoscopic surgery, a minimally invasive and intricate procedure, offers substantial risk reduction and numerous patient advantages. The increasing demand for this technique has forced the derivation of efficient training methods to cultivate a competent workforce. Though various evaluation methods and programmes are available to score and teach the vast and specific set of skills required, the predominant apprenticeship model, relying on patient interaction, results in a prolonged learning curve. Alternative training modalities, including human cadavers, box trainers, virtual reality (VR) simulators and augmented reality (AR) simulators, each possess distinct benefits and limitations. AR, a cutting-edge addition to laparoscopic surgical training, combines digital images and physical models, offering a unique blend of visual realism and haptic feedback. This study aims to provide an overview of laparoscopic training modalities and assess how augmented reality compares. **Methodology:** Reviewing 31 papers from diverse databases, findings were compiled and discussed. **Results:** Evaluation of current market simulators revealed variations in price, modules, assessment metrics and feedback method. ProMIS AR, validated for accurately assessing laparoscopic skills, exhibits subjective limitations. Comparatively, AR demonstrates faster skill acquisition and widespread preference. **Discussion:** While insufficient information hinders a decisive conclusion, AR simulation holds potential as the new gold standard for laparoscopic surgical training. Further research, encompassing a variety of simulators and modules, along with assessing mental and/or physical workload, will enhance understanding. AR's evolution and the increased literature exploring its capabilities promise to redefine laparoscopic surgical training, pending technological advancements for heightened clinical realism.

Keywords: *augmented reality; surgical simulation; laparoscopic surgical training; minimally invasive surgery*

Introduction

Shorter hospital stays, faster recovery periods, less pain, reduced bleeding, minimised scarring and the 40% reduction in postoperative complications compared to the open surgery counterparts are just some of the many advantages of laparoscopic surgery. Commonly referred to as keyhole surgery or minimally invasive surgery (MIS), it enables access to the inside of the abdomen and pelvis through 0.5–1.5 cm incisions. A small tube, light source/laparoscope (or a variety of types such as laser or fluoroscopy) and a camera relaying internal imagery to a monitor are used. Prior to the addition of a camera to the procedure, scopes were used.[1–3] Kelley[4] states that, in 1929, Heinz Kalk created a forward viewing scope with improved lenses. Surgeons would look through this or have an additional member of staff look through this and provide verbal navigation, complicating the procedure further. While gasless laparoscopy is possible, commonly gas is temporarily pumped into the abdomen to allow the surgeon more room and improved vision during the procedure. Recovery can take between 5 days and 12 weeks depending on the procedure.[1–4] Laparoscopy can be used diagnostically (visual assessment or biopsies) or for surgical procedures, such as in gynaecology, gastroenterology and urology to remove or repair affected structures. Severe complications are rare and only occur in 1 in 1000 cases.[2] Laparoscopic surgery has been found to be approximately 20 min shorter and reduced the volume of blood loss by 42.5 mL in a radial resection for rectal cancer treatment, resulting in better patient outcomes than its open surgery counterpart.[5]

While laparoscopic surgery increases in popularity, the lack of a workforce coupled with the exponentially increasing demand requires the derivation of methods to grow a competent workforce efficiently.[6,7] To do this would require a standardised, reliable and repeatable process with a shortened and flattened learning curve that can be applicable to a variety of training groups. Though learning curves vary from person to person, the additional skills and techniques required by laparoscopic surgeons result in the well researched prolonged learning curve.

Laparoscopic surgeons are required to look at the monitor in front of them providing an indirect 2D view of the operating field. The limited field of view, lacking depth visualisation, requires surgeons to rely on other cues to navigate, such as tactile feedback or visual understanding of observer position on object observation (e.g. the parallax effect).[8] However, the instruments utilised provide limited haptic feedback, fewer degrees of freedom and amplification of surgeon's movements beyond the fulcrum of the abdominal entry point. Surgeons are also required to familiarise themselves with this fulcrum effect, which distorts their actions.[1,9–11]

The surgical skills required to perform laparoscopic surgery can be categorised into technical and non-technical skills. A technical skill is defined as a psychomotor or mental skill developed via practice, including manual dexterity, hand–eye coordination and haptic feedback interpretation. In addition, surgeons must utilise mental interpretation of 2D visuals translating to a 3D environment required for intricate manoeuvres, such as complex bi-manual manipulation, suturing and knot tying.[12–16] Non-technical skills play an important role and are characterised into three dimensions (interpersonal, cognitive and personal resource skills), with each relating to surgical competence and clinical outcome. Interpersonal skills such as communication have been identified as one of the causes of near misses in surgery.[12] Furthermore, cognitive skills are employed during intraoperative decision making, where the identification of the correct solution and error management is vital to minimise complications and patient mortality.[16]

Cognitive load assessment is one way of assessing surgeons' competence[17] though traditionally performance measures have been used as the sole assessment method for technical skills. Metrics such as task completion time, instrument path length, number of movements, number of errors, camera navigation, procedure completion time and maintenance of a horizontal view are often used to assess performance.[18–21] However, these metrics are not indicative of a competent surgeon when used independently, instead they must be viewed in combination.[22] Therefore, an overall performance score is commonly calculated using an equation derived from the experimental procedure, often incorporating the maximum time available, completion time and number of errors, such as:

$$300 - \textit{task time} - \textit{errors} * 30$$

or

$$600 - \textit{task completion time} - (10 * \textit{accuracy error}) - (100 * \textit{security error})^2.$$ [18,21]

There are a variety of programs designed to teach and assess the skills required for laparoscopic surgery. The systematic and comprehensive Fundamentals of Laparoscopic Surgery (FLS) program[22] was specifically developed to teach and evaluate the skills required for laparoscopic surgery in the United States. It includes a multiple-choice cognitive test and manual skill testing of the efficiency and precision of five simulation exercises through tasks such as peg transfer, cutting and suturing. Despite this, basic FLS training is unable to provide enough experience for trainees in real surgical procedures.[1,11,23] FLS offers a scoring method for suture quality with penalties applied for inaccuracy and poor quality. Shorter movement times, reduced movement mistakes and a higher number of completed sutures yield a higher overall normalised score out of 100.[24] Similarly, OSATS is a workplace-based assessment tool that is the current gold standard of objective skill assessment, rating the following domains 1–5 on a Likert scale.

- Respect for tissue
- Time of motion
- Instrument handling
- Flow of operation and forward planning[25,26]

Courses such as the Association of Laparoscopic Surgeons of Great Britain and Ireland's (ALSGBI) 'LapPass' course enable a trainee's proficiency in five basic technical laparoscopic skills, including camera holding, to be formally recognised. The desire is that those possessing the LapPass can progress onto 'accelerated operative training'.[27]

While scoring is beneficial as an objective form of feedback, providing a numerical value of competence to enable benchmarking and a numerical form of measuring competence, studies such as the one by Botden et al.[22] have highlighted that the lack of understandability made numerical feedback less valuable than expert feedback. While not an accurate measure of surgical competence, Zahiri et al.[28] found trainees preferred a time indicator despite it causing some distraction and highlighted motivation as the leading influence in performance.

Feedback must be meaningful and support the learning process, and can be divided into the following categories:

- Extrinsic feedback: aims to guide and motivate through meaningful and informative information.
- Intrinsic feedback: performance feedback that is directly available to the trainee's sensory system.[29]

The surgical education system still largely operates on a 'see one, do one, teach one' methodology widely referred to as the apprenticeship model. This model was developed in 1890 on the basis that progressive responsibility fosters near-independence.[30,31] However, as it is performed at the patient's bedside, it not only compromises a patient's comfort but also increases the time taken to complete the procedure, the cost of the operation and potentially the risk of complication.[32] As this model evolves due to legal, ethical and malpractice concerns, and work hour restrictions in the USA and Europe, we are witnessing pressure to address the lengthy technical skill acquisition process for laparoscopic surgery outside of the operating room in an efficient and effective manner.[11,30,33] Surgical training certainly has progressed from the use of wax models to cadavers and simulators. As technological innovation occurs, the future of surgical education appears to be simulator-based training, providing objective performance assessment, full and unusual procedure planning, failure opportunities without consequences and repetitive practice, all whilst helping move the learning curve away from the patient's bedside.[32] As these new modalities are introduced into the surgical training program, the transferability of skills must be determined to be equally if not more effective as current modalities to prove their suitability. Though the transferability of skills is a greatly under documented area, results have shown 'simulation-based training leads to superior performance in the operative setting compared to conventional training.'[34]

Overview of currently available simulation modalities

The following shows a comparison of the currently available modalities and their pros and cons.

Animal models and cadavers

The current gold standard is to use real instruments on cadavers or anaesthetised live animals. The advantages and disadvantages are shown in Table 1.

Table 1. Animal models and cadavers, advantages and disadvantages[10,11,37,38,47]

Advantages	Disadvantages
High fidelity, non-patient environment	Require wet rooms, operative platforms, funeral service and expert observers
Most like clinical environment	Expensive
Use of real instruments	Limited supply
	Cultural, anatomical and ethical issues

Table 2. Box trainers, advantages and disadvantages[1,11,14,32,35,38,39]

Advantages	Disadvantages
Simple	Can be costly and impractical due to model replacement
Affordable/low cost	Require expert supervision
Widely available	Static training only
Portable	Longer orientation periods
Promotes concentration	
Most validated modality	
Realistic force feedback from tool–tissue interaction	
Effective	
Use of real instruments	
Economic	
Safe training platform	

Box Trainers

Real instruments and a camera simulating an endoscope are used to manipulate synthetic or inanimate models at abdominal height. Advantages and disadvantages of box trainers are shown in Table 2.

VR simulators

Through visual and haptic rendering, a virtual environment is created with custom set up with sensors, display monitors, diathermy foot pedals and an endoscope replicator of 3D computerised databases and environments in real time.

The training on a VR simulator consists of three stages:

- Automated 3D modelling
- Surgical planning, simulation and rehearsal
- Superimposition of data intraoperatively

Advantages and disadvantages of VR simulators are shown in Table 3.

AR simulators

AR simulation combines physical and virtual reality through the superimposition of graphics and audio. The use of visual

Table 3. Virtual reality simulation, advantages and disadvantages[1,11,14,32,35–37,58]

Advantages	Disadvantages
No consumables required No expert observation Advanced models can provide haptic feedback to increase realism Repeatable and flexible training scenarios Certified tool for technical and cognitive skill acquisition at a fundamental and advanced level Objective performance assessment through kinematic parameters and ergonomic assessment of skills and competence (completion time, number of errors and instrument path length) Real-time data acquisition Able to identify trainees who find psychomotor skill acquisition difficult Enables part-task training Not impeded by work hour restrictions Safe training platform	Expensive/ significant financial investment Moderate to no tactile and haptic feedback making fine motor skills difficult, e.g. suturing Prolonged warm-up period Assessment difficulties Potentially unrealistic graphics rely upon users to block external stimuli to achieve immersion Lack meaningful assessment protocols

Table 4. AR simulation, advantages and disadvantages[10,11,14,29,35,37,38,46,47,58,59]

Advantages	Disadvantages
Use of real instruments/device agnostic Visual cues Objective assessment Opportunity for telementoring and telestrating Do not rely on graphics which may be unrealistic Tactile and haptic feedback Reuseable Easy to transport Automatic performance recording for assessment Enables part-task training Not impeded by work hour restrictions Safe training platform Recommended for the procedural training of component tasks (laparoscopic suture training) Flexibility to integrate other modalities	Most effective with mentors, specific goals and complete procedure simulation Expensive (installation and set up plus consumables) Lack meaningful assessment protocols Not widely integrated into current curricula

rendering, tracking image registration and spatially recognised elements allows interaction between digital information in real-world environments and with real-world stimuli. This tracking is commonly carried out using electromagnetic (EM) sensors, optical–infrared sensors, visual pattern markers and colour tags. Display modalities include video monitors, head-mounted displays and projection-based devices. Table 4 lists the advantages and disadvantages of AR simulation.

The variety of simulators available aim to make more effective and practice-oriented education for individuals and teams. Studies have shown simulators' effectiveness and potential time and cost saving capability to be a valuable investment to supplement current training protocols. Furthermore, these platforms are able to 'overtrain' surgeons for unsafe situations and situations that have not arisen yet, as well as being able to provide dynamically moving targets instead of static training.[11,35] The reduction or loss of haptic feedback from the real world, lag and tracking problems in addition to potential simulator sickness are some of the disadvantages of extended reality. Despite this, the use of both virtual and augmented reality simulators in surgical training has been found to improve procedural skills and reduce performance time and error rate.[35–38] The use of AR in healthcare is not new and can be categorised into either:

- Treatment programs such as ultrasound guided needle navigation to neurological applications.
- Educational programs such as virtual cadavers enabling better understanding of the spatial inter-relationships within anatomy as well as internal body functions. As a result, its use in the education of practical skills is not unsupported and those integrating it into laparoscopic training curricula can learn from the successful adoption of AR in other areas of healthcare education.[1,39]

Methodology for literature review

A systematic literature search was performed to search for reports which would answer the following question: 'In laparoscopic surgical training how does AR compared with existing modalities affect training outcomes such as skill acquisition using AR for laparoscopic surgical training.'

To ensure appropriate studies were found the key terms were defined.

- AR simulation was deemed to be a system that utilised digital content, combined with physical interactions.
- Studies incorporating VR without AR were excluded.
- Laparoscopic surgical training was defined as a process aiming to improve the performance or skills of participants in laparoscopic surgery.

Google Scholar, Pubmed, Pubmed Central Sage Journals, Web of Science, Science Direct, Embase, Eric, SCOPUS, NCBI, Springer, Research Gate, IEEE Xplore, DOAJ and JSTOR were searched using the key terms (augmented reality AND laparoscopic training). The last search was conducted on 18 May 2023. All study types were considered.

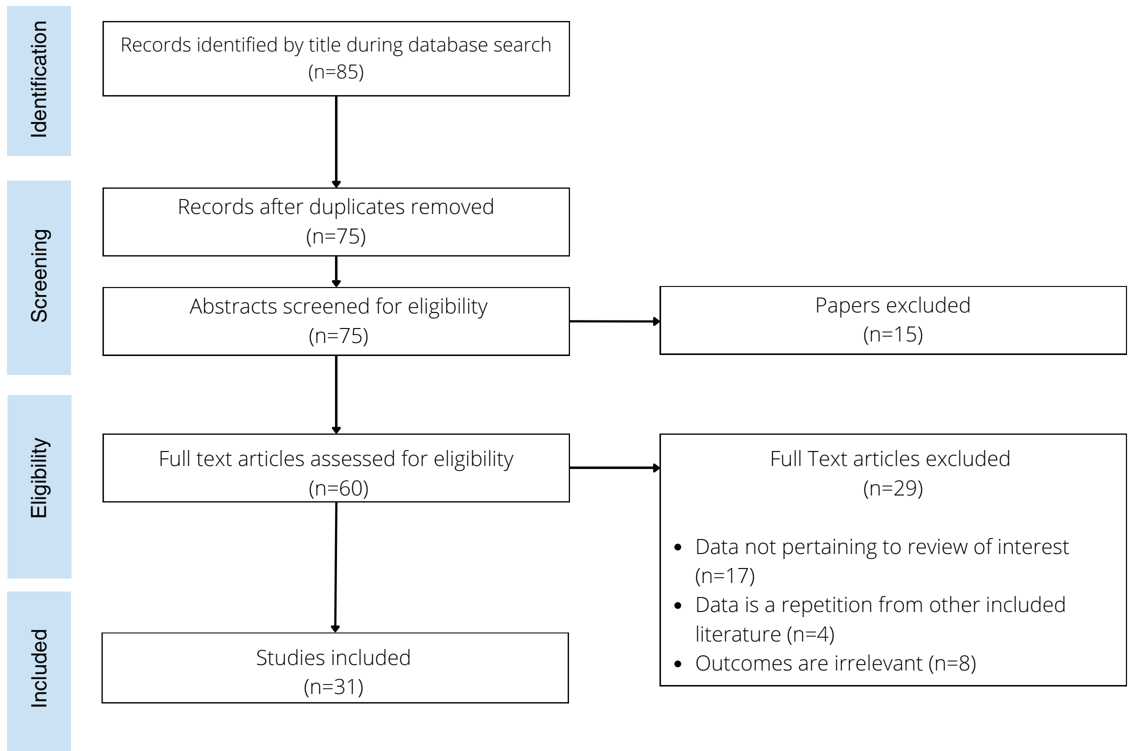

Figure 1. PRISMA flow diagram.

Those studies that did not involve an analysis of AR relating to laparoscopic surgery were excluded. The sought-after outcomes involved those directly comparing AR to other modalities specifically within laparoscopic training, with a focus on training outcomes such as skill acquisition and trainee opinion. Reports were initially screened by title, then by abstract and then by full text with irrelevant papers excluded using Covidence. The ROBIS risk advice tool was used to eliminate bias during screening.

A PRISMA flow diagram of this screening process is shown in Fig. 1. The list of relevant articles sorted alphabetically by author can be found in Appendix 1. This paper covers a critical analysis of AR as a laparoscopic surgical training modality including common features and shortcomings of simulators on the market, and their validity, as well as an economical and financial analysis, while also considering user preference and quality and speed of skill acquisition. A statistical/meta-analysis was not carried out.

Results

A total of 60 articles reached the full text screening stage and following their review a total of 31 relevant papers remained. The papers reviewed covered a wide range of topics relating to the incorporation of AR into laparoscopic surgical training, including the simulators available on the market and their common features, as well as comparing AR simulation against other training modalities, with a focus on user preference, skill acquisition and determining the best method of incorporation into the current curricula. A table summarising the included papers can be found in Appendix 1.

Simulators on the market

Data from the literature and commercial sources for a variety of AR simulators on the market and in research (ProMIS, LapAR Pro, Blue DRAGON, CELTS and LTSE-3) were gathered to evaluate some of the common modules, assessment metrics, feedback and instructional methods, unique selling points and shortcomings.

Modules and tasks

Common modules and tasks include:

- Navigation
- Touching
- Grasping
- Traction
- Translocation

- Clip application
- Transection
- Dissection
- Diathermy
- Suturing
- Knot tying

Assessment metrics
While assessment metrics vary between available simulators, all include the following:

- Time
- Path length
- Smoothness
- Economy of movement
- Errors
- Hand dominance
- Time in field of view
- Tool tissue in interaction (force, tension and velocity)
- Ambidexterity

Feedback methods
Feedback methods can be either objective/metric-based progression curves or qualitative/subjective feedback, on top of real task or virtual task playbacks to enable user progression. The instructional methods for these simulators range from a combination of written descriptions, demonstrational videos, spoken instructions, task animation and live faculty remote proctoring. Despite their unique selling points, each simulator also had shortcomings most commonly surrounding the range of modules offered and the initial investment cost.[36,40,41]

Costs
The costs associated with AR simulators are divided into three categories:

- Hardware
- Software
- Consumables

While initial costs may be higher than other modalities, manufacturers often offer package deals for the hardware and software, and subscriptions for consumables, making the overall cost dependent on the chosen modules, models and requirements of the purchasing location. One study described comparable costs between AR and VR simulators.[36] However, we have found in our experience the end user cost of AR is much less than VR with simulation centres being able to purchase higher quantities of AR simulators within a constrained budget, and in some cases aim for a 'hub and spoke' model of hardware availability to learners.

Validity of AR in laparoscopic surgical training

The degree to which a simulator accurately measures and reflects skill is known as validity. When applied to AR simulation for laparoscopic surgical training the following forms of validity are described:

- Content validity—reflects a positive evaluation of the educational content by an expert.
- Construct validity—the ability to accurately reflect a subject's skill level.
- Concurrent validity—the degree to which participant performance improvement replicates the performance improvement using the gold standard.
- Face validity—the ability to replicate and resemble a real situation.
- Predictive validity—the simulator's ability to anticipate future performance in real-life scenarios.[31,42]

Some of the studies reviewed investigated multiple types of validity in the context of AR-based simulator training. Many studies on construct, face and concurrent validity have used the ProMIS AR.[42,43] Botden et al.[22] used an adapted assessment methodology that allowed numerical determination based upon instrument placement, construct and concurrent validity. The face validity was determined via participant questionnaire for the suturing module.[22] Further studies[44–47] supported these findings, and found the realism and haptic feedback available during suturing regarding needle and thread resistance to be good–excellent. This implied face validity as this scoring was indicative of good replication of the operating environment.[48] Furthermore, the path length and smoothness demonstrated concurrent validity, when compared to the FLS score.[49] Construct validity was supported as comparison occurred between the peg transfer task and the FLS program, and subjects of different experience levels in the translocation and suturing task.[49–51] Construct and face validity have been determined by some studies for the CELTS simulator, as reviewed by Botden and Jakimowicz[36]

AR compared to other modalities in skill acquisition and user preference

The efficiency of skill acquisition is an important factor to consider when implementing a training modality into the curricula. Although AR is gaining increased acceptance in medical skill acquisition, problems persist regarding simultaneous viewing of the physical environment and the superimposed digital images. Studies by Herron[44] and Sheik-Ali et al.,[45] however, reported relatively increased speed of learning, improved ability to multitask, procedural accuracy, hand–eye coordination and bimanual operation in a reduced practice time and increased success rate with AR in healthcare education.

In a study conducted in 2009 by Botden et al.[29] exploring skill transfer within AR simulation, an average of eight repetitions were required on the AR simulator to reach the top of the performance curve determined by metrics including assessment score, completion time and knot strength. Following these repetitions, the time parameter had significantly improved and plateaued, while the knot strength score showed no significant difference except when the initial and final knot were compared. This proved the simulator to be a good tool for suture training, though 'advanced modules' may be more beneficial to those with a native ability as increased motivation through progressive difficulty enhances learning.[29]

In other studies,[35,46] the steep short learning curve produced by AR users proved faster skill acquisition, with fewer total fails or critical errors per attempt. Those using AR were found to have more errors per subject than the verbally instructed participants. However, upon evaluation and calculation, this increase was found to be a result of the greater number of attempts. This increased number of attempts was possible as AR allows more hands-on practice with decreased operating time and expenses compared to other modalities, due to the superimposition of expert movements onto the field of view, improving the clarity, positioning and movements of trainees, while remote mentoring allows immediate high-fidelity feedback, resulting in a shorter, steeper learning curve enabling self-correction and resulting in faster and more accurate training.[35,46]

In a study by Leblanc et al.,[47] the AR simulator was compared against a cadaver model for hand-assisted laparoscopic sigmoid colectomy skills acquisitions. The results showed that the cadaver model group outperformed the simulator group with the occurrence of fewer generic events. However, the occurrence of specific events was lower in the simulator group. No difference was found between the two groups in generic and specific skills. Nonetheless, all participants were able to accurately assess their own skills with the cadaver model group's accuracy superseding the simulator group's. Participants also found the cameras on the simulator impeded their ability to operate and did not replicate clinical settings.[47] In a separate study on straight laparoscopic colorectal skill acquisition training, a similar pattern was seen. Perforation of the bowel was the most common specific event to occur in both the AR and cadaver group. This implied that the AR simulator replicated the same difficulties experienced on the cadaver.[10] While Williams et al.[38] found the operative duration increased with AR-based training, this increase was deemed to be acceptable due to the improved results, competency and reduced postoperative complications.[38]

Rawaf et al.[52] showed that AR simulation within laparoscopic appendectomy training resulted in a reduction of trainees' completion time by 19% and a reduction in distance travelled of 25%, thus proving AR simulation is 'more effective at providing clinically translatable, and scalable cost-effective laparoscopic training'.[52]

While AR has been found to be effective at skill acquisition, Lungu et al.[32] indicated that the integration of simulation into the curriculum depends on appropriate fidelity as well as user preference. With user preference playing a vital role in the uptake of new technology, the Hawthorne effect must be considered as this can alter the participant's opinion based on their performance.[50] Outside of laparoscopic surgery, AR has generally subjective positive experiences in the medical education sector due to its ability to incorporate all three elements of the Mayers cognitive theory of multimedia learning (delivery, presentation and use of sensory systems).[39]

When compared with VR simulation, box trainers and cadavers, AR simulation was preferred, except when compared against a human cadaver model for straight laparoscopic colorectal skills acquisition.[38] The cadaver model was preferred due to the better clinical and anatomical accuracy (preservation of anatomical planes and accurate tissue consistency). Despite the cadaver model being deemed more difficult, it enabled improved understanding, technique and instrument use, which increased its user satisfaction rating.[10,47]

In a study by Botden et al.[50], despite the advantageous features of VR simulators, the non-VR environments were preferred by participants. Chowriappa et al.[53] highlighted that surgical training with haptic-enabled AR could improve trainee confidence and showed improvement in needle driving, positioning and suture placement.

In line with user preference is knowledge of augmented reality, virtual reality and mixed reality within surgery. In a study carried out by Balla et al.[54], the mean perceived knowledge was reported as 4.9 out of 10 ± 2.4 with 56.2% of participants not having any first-hand experience with AR, VR or MR. They also explored the evaluation of the technologies with 80% of the participants stating they believe VR, AR and MR 'should be used more frequently for the teaching and training in surgery and during the clinical activity (170, 80.3%) and that such technologies would make a significant contribution, especially in training (183, 84.3%)'.[54]

With a variety of training modalities available, integration into the training curricula as a single modality or part of a multimodal training program is an important consideration. Brinkman et al.[9] found that both single modality (VR) and multimodality (AR, VR and box trainer) training programs improve operative time, path length and number of movements scores significantly. These improvements were significantly better in the single modality group for all metrics except object translocation. However, this difference in improvement between the two groups can be explained by the increased repetition and training time the single modality group spent on the VR simulator, which was then used for testing. Therefore, when considered, this result did not reflect on the suitability of single or multimodality training programs, as the performance outcomes did not differ between the two groups. While this proves VR simulators can replicate the full training curriculum, it also shows multimodality training outcomes are not inferior, suggesting basic laparoscopic skills training can be acquired through multimodality training programs. When deciding which implementation strategy is appropriate, the cost, trainee opinion and convenience can influence this choice. While it may appear disadvantageous to use a variety of training tools, it has the potential to improve training outcomes as it reduces monotonous training and boredom.[9] It is important to note that appropriate and effective dissemination of AR into the curriculum requires 'well-structured theoretical and practical knowledge of these technologies'.[54]

Discussion

Critical analysis of AR in laparoscopic surgical training

To determine the suitability of AR simulators for laparoscopic training, it must first be considered whether they are worth incorporating into the curricula. For the simulator to be worth incorporating, it must be effective, reliable and absent of bias; the cost must be justified, it must be easy to use and, overall, it must add value to the curricula.

The reliability and fairness of AR simulation can be determined through the objective feedback acquired and removal of the subjective nature of other modalities by removing the human assessment. Effectiveness and value can be considered by the analysis of skill acquisition, user preference and validity. AR simulators have proven their ability to aid in skill acquisition when quantitatively compared to other modalities, while also offering the opportunity for telementoring, enabling instantaneous high-fidelity feedback. A review article written by Williams et al.[38] shows that many studies focus on skill acquisition for colorectal procedures (hand-assisted and straight colectomy); the AR simulators perform as well as other training modalities in these studies and in the peg transfer task.[38] These results may not reflect the simulator's performance in complete laparoscopic skill acquisition, due to the wide range of laparoscopic procedures requiring different skills, whose acquisition process may differ. Furthermore, most studies were performed in controlled environments and therefore skill transferability has not been assessed. The majority of studies neglect the other essential skills required by laparoscopic surgeons such as inter-personal competencies. In other areas of medical education, such as the improvement of knowledge, AR has been shown to enhance such competencies in a supervised and regulated environment.[39]

When user preference was considered, Williams et al.'s review article[38] showed the AR simulators performed well, with no complaints regarding ease of use.[38] This can be explained due to the increasing digital literacy of medical students which in turn enables an increased confidence in adopting new high-level technology for learning.[39] The use of real instruments and physical objects make AR the preferred modality, except when compared against cadaver models. These results showed that users valued the more accurate clinical representation due to the preservation of anatomical planes and tissue consistency despite the increased difficulty. However, the subjective measure of user opinion must be taken into consideration when interpreting these findings. It can be noted that new technology is often more desirable, and the novelty may encourage trainee engagement. This can be seen through the adoption of LapAR by LapPass and EMIGS as an official supplier, and subsequent accreditation by the Royal College of Surgeons. Despite the novelty, the continuing challenge for AR simulation is the accurate digital clinical representation as reflected in users' opinions of the modality.

The cost of AR simulation must be comparable to currently used modalities and/or offer additional features so the benefits of the system outweigh higher financial investment required. Information regarding the cost of individual simulators on the market and in literatures is limited. A standard FLS test requires a proctor's presence for which costs are around $2000 USD for five students per day. For example, to justify the cost of the ProMIS simulator at least 70 trainees must be trained. This would be difficult to achieve; however, the simulator offers a wide range of other components which make it valuable to the laparoscopic surgical training curriculum.[49] AR tends to have a higher initial purchasing cost but does not require the costly specialist facilities or services that cadaver or animal models do.

Although measuring validity can be beneficial, each method has its limitations. Construct validity assesses only objective metrics and does not consider performance parameters outside of psychomotor skills.[51] As concurrent validity assesses the degree of skill acquisition, it is a good indicator of effectiveness; however, it cannot reflect future skill. Face validity is valuable when considering skill transferability; however, it is subjective and may not sufficiently reflect the realism of the device. Consequently, results may vary greatly among different trainees and face validity alone becomes unreliable.[55] Similar limitations are found with content validity as expert feedback is also subjective and may be biased.[56] Furthermore, there is a big gap in the literature regarding the predictive validity of AR simulation which may be a result of ethical limitations as investigations of predictive validity would require trainee exposure to real patients.

Areas of further investigation

While the results indicate that AR simulation provides a valuable addition to surgical training curricula, improving patient safety is one of the main requirements of training. The capability of AR simulation-based training to reduce surgical errors has yet to be accurately assessed and would require further research to determine its ability to reduce surgical errors.

When choosing to incorporate simulation into the curricula there are a variety of considerations. Firstly, the users' requirements and consumer budget must be considered, to ensure the simulator has compatible modules and performance metrics within budget. Furthermore, trainees' needs must be considered, to ensure the simulator offers the best instructional method and most beneficial feedback. In this review, no difference was found between single and multimodal incorporation of AR into laparoscopic surgical training curricula. Though multimodality training may be preferred, this may be based on boredom prevention due to the versatility of multimodal training. The ALSGBI currently runs a variety of successful multimodality courses to support this assumption. Further research should be carried out to determine the best form of implementation and the appropriate stage of training to incorporate AR.

As well and 'if' and 'how' to incorporate AR simulation into the curricula, 'when' must also be considered for optimal skill acquisition. At the time of writing, very few studies have investigated this topic and research is indicating the stage of integration into the trainees' curricula will have a large effect on skill acquisition. It is understood that ethical restrictions may be in place when exploring this topic. In addition to requiring further exploration on effective integration, further research is required on a wider variety of brands and models of AR simulators available on the market.

Though commonly assessed through OSATS and FLS, current studies suggest surgical competence is not sufficiently determined by performance metrics alone. An assessment on the effects of AR simulation on mental workload and thus skill acquisition and autonomy would be beneficial to enable the further comparison of training modalities. The literature shows the acquisition of skills such as manual dexterity, coordination, communication and decision making can be impaired by a variety of factors beyond training methods, including cognitive load. Incorporating cognitive load measurements within assessment methods could enable a more accurate assessment of surgical competence.[16,21]

Technological improvement

To improve user preference and potentially skill acquisition, work should be carried out to improve the accurate replication of operative conditions through the restoration of anatomical planes and tactile feedback. The reduction of simulator costs could increase consumer uptake, potentially resulting in more research in AR simulator validity and suitability for laparoscopic surgical training. It is important to note that, while the objective feedback was beneficial, the qualitative assessment is important due to its transparency. Therefore, the incorporation of quantitative scores should be supplemented with additional explanatory information, possibly via telementoring such as TOTUM (https://inovus.org/totum/). Though each simulator has its own unique selling points, a standardisation of performance metrics and assessment methods would be beneficial in allowing trainees to broaden the range of devices they can train on. The standardisation is important, as it is difficult for feedback to remain meaningful when scores are compared inter-modality but also intra-modality.

In order to overcome the translation gap faced by AR systems in surgical education, the rigorous adoption of a user-centred design is suggested in the early stages of research development.[57] To provide accessibility, surgeons, operating room nurses and other stakeholders should be included in the user-centred design process.

This paper focuses specifically on the use of AR simulators in laparoscopic surgical training. Technological innovation and adaptations to the mechanical set up of AR simulators could enable the use of this modality for other forms of surgical education. In turn, AR may be beneficial in providing a safe training environment for other forms of surgical training.

Limitations of this paper

Due to the nature of this study, there may have been some omission of results due to the combination of search terms employed or bias from the reviewers. Two reviewers were used to try and eliminate this bias. Furthermore, it is recognised that the presented literature shows a clear bias towards the ProMIS AR simulator and therefore the findings cannot necessarily be applied to all forms of AR simulation for laparoscopic surgery as technology and the associated evidence base continue to progress. This bias may be explained due to the newness of other simulators.

Conclusion

AR shows promise in becoming a highly effective method of laparoscopic skill acquisition. With the current level of information available, it would not be recommended to introduce AR simulation in the laparoscopic surgical training curriculum as a single modality training program. When choosing an AR simulator, budget and consumer needs must be considered, in conjunction with the validity of the simulator and the output of meaningful performance metrics. Human cadaver models remain the current gold standard; however, box trainers and simulators can effectively supplement the curriculum. Trainees generally prefer AR simulators to box trainers and VR simulation. Technological improvements are required to enable AR simulation to reflect clinical settings more accurately, through anatomical plane preservation and realistic tactile feedback. This could overcome the ethical and financial implications of cadaver models, and lead to AR becoming the new gold standard in laparoscopic surgical training.

Conflict of interest

Courtney Ludick declares no conflicts of interest. David Rawaf declares no conflicts of interest. David Rawaf works as the clinical excellence lead at Inovus Medical. Ahmet Omurtag declares no conflicts of interest. Ben Simpson declares no conflicts of interest. Ahmed Swealem declares no conflicts of interest. Ahmed Swealem is the senior health officer of orthopaedics and trauma at the Kettering General Hospital and has worked with Inovus Medical in the capacity of an intern as part of the Clinical Excellence Team. Ali Waleed Khalid declares no conflicts of interest. Ali Waleed Khalid is a medical student at the University of Buckingham and has worked with Inovus Medical in the capacity of an intern as part of the Clinical Excellence Team.

Data availability

Data sharing is not applicable to this article as no new data were created or analysed in this study.

Acknowledgements

Adapted from an undergraduate Master of Engineering dissertation by Courtney Ludick from Nottingham Trent University in collaboration with Inovus Medical Ltd.

References

1. Lahanas V, Georgiou E, Loukas C. Surgical simulation training systems: box trainers, virtual reality and augmented reality simulators. Int J Adv Robot Autom 2016; 1: 1-9. https://doi.org/10.15226/2473-3032/1/2/00109
2. NHS. Laparoscopy (keyhole surgery). NHS website. 2018 Available from: https://www.nhs.uk/conditions/laparoscopy/ (accessed 17 November 2020).
3. Li P, Han Y, Yang Y, Guo H, Hao F, Tang Y, et al. Retrospective review of laparoscopic versus open surgery in the treatment of appendiceal abscess in pediatric patients. Medicine (Baltimore) 2017; 96(30): e6747. https://doi.org/10.1097/MD.0000000000007514
4. Kelley WE Jr. The evolution of laparoscopy and the revolution in surgery in the decade of the 1990s. JSLS 2008; 12(4): 351-357. PMID: 19275847
5. Huang C, Shen JC, Zhang J, Jiang T, Wu WD, Cao J, et al. Clinical comparison of laparoscopy vs open surgery in a radical operation for rectal cancer: a retrospective case–control study. World J Gastroenterol 2015; 21(48): 13532-13541. https://doi.org/10.3748/wjg.v21.i48.13532
6. Rose J, Weiser TG, Hider P, Wilson L, Gruen RL, Bickler SW. Estimated need for surgery worldwide based on prevalence of diseases: a modelling strategy for the WHO Global Health Estimate. Lancet Glob Health 2015; 3(Suppl 2): S13-S20. https://doi.org/10.1016/S2214-109X(15)70087-2
7. Tercatin R. Shortage of health workers is a 'ticking time bomb' – even in Europe. Health Policy Watch. 2022. Available from: https://healthpolicy-watch.news/shortage-of-health-workers-is-a-ticking-time-bomb-even-in-europe/ (accessed 27 May 2023).
8. Cahais J, Schwarz L, Bridoux V, Huet E, Tuech JJ. Is the image "right" for everyone? Introduction to the parallax effect in

laparoscopic surgery. J Visc Surg 2017; 154(1): 11-14. https://doi.org/10.1016/j.jviscsurg.2016.06.007
9. Brinkman WM, Havermans SY, Buzink SN, Botden SMBI, Jakimowicz JJ, Schoot BC. Single versus multimodality training basic laparoscopic skills. Surg Endosc 2012; 26(8): 2172-2178. https://doi.org/10.1007/s00464-012-2184-9
10. Leblanc F, Champagne BJ, Augestad KM, Neary PC, Senagore AJ, Ellis CN, et al. A comparison of human cadaver and augmented reality simulator models for straight laparoscopic colorectal skills acquisition training. J Am Coll Surg 2010; 211(2): 250-255. https://doi.org/10.1016/j.jamcollsurg.2010.04.002
11. Sándor J, Lengyel B, Haidegger T, Saftics G, Papp G, Nagy Á, et al. Minimally invasive surgical technologies: challenges in education and training. Asian J Endosc Surg 2010; 3(3): 101-118. https://doi.org/10.1111/j.1758-5910.2010.00050.x
12. Agha RA, Fowler AJ, Sevdalis N. The role of non-technical skills in surgery. Ann Med Surg 2015; 4(4): 422-427. https://doi.org/10.1016/j.amsu.2015.10.006
13. Hanly EJ, Marohn MR, Bachman SL, Talamini MA, Hacker SO, Howard RS, et al. Multiservice laparoscopic surgical training using the daVinci surgical system. Am J Surg 2004; 187(2): 309-315. https://doi.org/10.1016/j.amjsurg.2003.11.021
14. Lahanas V, Loukas C, Smailis N, Georgiou E. A novel augmented reality simulator for skills assessment in minimal invasive surgery. Surg Endosc 2015; 29(8): 2224-2234. https://doi.org/10.1007/s00464-014-3930-y
15. Yiannakopoulou E, Nikiteas N, Perrea D, Tsigris C. Virtual reality simulators and training in laparoscopic surgery. Int J Surg 2015; 13: 60-64. https://doi.org/10.1016/j.ijsu.2014.11.014
16. Zakeri Z, Mansfield N, Sunderland C, Omurtag A. Physiological correlates of cognitive load in laparoscopic surgery. Sci Rep 2020; 10(1): 12927. https://doi.org/10.1038/s41598-020-69553-3
17. Díaz-García J, González-Ponce I, Ponce-Bordón JC, López-Gajardo MÁ, Ramírez-Bravo I, Rubio-Morales A, et al. Mental load and fatigue assessment instruments: a systematic review. Int J Environ Res Public Health 2021; 19(1): 419. https://doi.org/10.3390/ijerph19010419
18. Montero P, Acker C, Heniford BT, Stefanidis D. Single incision laparoscopic surgery (SILS) is associated with poorer performance and increased surgeon workload compared with standard laparoscopy. Am Surg 2011; 77: 73-77. https://doi.org/10.1177/000313481107700125
19. Sarker S-J, Telfah MM, Onuba L, Patel BP. Objective assessment of skills acquisition during laparoscopic surgery courses. Surg Innov 2013; 20(5): 530-538. https://doi.org/10.1177/1553350612468960
20. Scerbo MW, Britt RC, Stefanidis D. Differences in mental workload between traditional and single-incision laparoscopic procedures measured with a secondary task. Am J Surg 2017; 213(2): 244-248. https://doi.org/10.1016/j.amjsurg.2016.09.056
21. Yurko YY, Scerbo MW, Prabhu AS, Acker CE, Stefanidis D. Higher mental workload is associated with poorer laparoscopic performance as measured by the NASA-TLX tool. Simul Healthc 2010; 5(5): 267-2671. https://doi.org/10.1097/SIH.0b013e3181e3f329
22. Botden SMBI, de Hingh IHJT, Jakimowicz JJ. Meaningful assessment method for laparoscopic suturing training in augmented reality. Surg Endosc 2009; 23(10): 2221-2228. https://doi.org/10.1007/s00464-008-0276-3
23. FLS. Fundamentals of Laparoscopic Surgery. Fundamentals of Laparoscopic Surgery. Available from: https://www.flsprogram.org/ (accessed 25 July 2023).
24. Zheng B, Cassera MA, Martinec DV, Spaun GO, Swanström LL. Measuring mental workload during the performance of advanced laparoscopic tasks. Surg Endosc 2009; 24(1): 45-50. https://doi.org/10.1007/s00464-009-0522-3
25. van Hove PD, Tuijthof GJM, Verdaasdonk EGG, Stassen LP, Dankelman J. Objective assessment of technical surgical skills. Br J Surg 2010; 97(7): 972-987. https://doi.org/10.1002/bjs.7115
26. Royal College of Obstetricians & Gynaecologists. OSATS. London: Royal College of Obstetricians & Gynaecologists. Available from: https://www.rcog.org.uk/careers-and-training/starting-your-og-career/specialty-training/assessment-and-progression-through-training/workplace-based-assessments-wpbas/osats/ (accessed 24 November 2023).
27. ALSGBI. LapPass®. London: Association of Laparoscopic Surgeons of Great Britain and Ireland (ALSGBI). 2022. Available from: https://www.alsgbi.org/lappass/ (accessed 14 February 2022).
28. Zahiri M, Nelson CA, Oleynikov D, Siu KC. Evaluation of augmented reality feedback in surgical training environment. Surg Innov 2018; 25(1): 81-87. https://doi.org/10.1177/1553350617739425
29. Botden SMBI, de Hingh IHJT, Jakimowicz JJ. Suturing training in augmented reality: gaining proficiency in suturing skills faster. Surg Endosc 2009; 23(9): 2131-2137. https://doi.org/10.1007/s00464-008-0240-2
30. Forgione A, Guraya SY. The cutting-edge training modalities and educational platforms for accredited surgical training: systematic review. J Res Med Sci 2017; 22: 51. https://doi.org/10.4103/jrms.JRMS_809_16
31. Viglialoro RM, Condino S, Turini G, Carbone M, Ferrari V, Gesi M. Augmented reality, mixed reality, and hybrid approach in healthcare simulation: a systematic review. Appl Sci 2021; 11(5): 2338. https://doi.org/10.3390/app11052338
32. Lungu AJ, Swinkels W, Claesen L, Tu P, Egger J, Chen X. A review on the applications of virtual reality, augmented reality and mixed reality in surgical simulation: an extension to different kinds of surgery. Expert Rev Med Devices 2021; 18(1): 47-62. https://doi.org/10.1080/17434440.2021.1860750
33. Diesen DL, Erhunmwunsee L, Bennett KM, Ben-David K, Yurcisin B, Ceppa EP, et al. Effectiveness of laparoscopic

computer simulator versus usage of box trainer for endoscopic surgery training of novices. J Surg Educ 2011; 68(4): 282-289. https://doi.org/10.1016/j.jsurg.2011.02.007

34. Spiliotis AE, Spiliotis PM, Palios IM. Transferability of simulation-based training in laparoscopic surgeries: a systematic review. Minim Invasive Surg 2020; 2020: 5879485. https://doi.org/10.1155/2020/5879485
35. Kaplan AD, Cruit J, Endsley M, Beers SM, Sawyer BD, Hancock PA. The effects of virtual reality, augmented reality, and mixed reality as training enhancement methods: a meta-analysis. Hum Factors 2020; 63(4): 706-726. https://doi.org/10.1177/0018720820904229
36. Botden SMBI, Jakimowicz JJ. What is going on in augmented reality simulation in laparoscopic surgery? Surg Endosc 2009; 23(8): 1693-1700. https://doi.org/10.1007/s00464-008-0144-1
37. Vallas C, Alexiou K, Alexandrou A, Economou N. Different forms of laparoscopic training: review and comparison. Hell J Surg 2014; 86: 337-346. https://doi.org/10.1007/s13126-014-0157-2
38. Williams MA, McVeigh J, Handa AI, Lee R. Augmented reality in surgical training: a systematic review. Postgrad Med J 2020; 96(1139): 537-542. https://doi.org/10.1136/postgradmedj-2020-137600
39. Dhar P, Rocks T, Samarasinghe RM, Stephenson G, Smith C. Augmented reality in medical education: students' experiences and learning outcomes. Med Educ Online 2021; 26(1): 1953953. https://doi.org/10.1080/10872981.2021.1953953
40. Inovus Medical. LapAR. Inovus Medical. 2021. Available from: https://inovus.org/lapar/ (accessed 29 April 2021).
41. Inovus Medical. Inovus Medical Shop Accessories. Available from: https://www.inovus.org/shop/ (accessed 25 April 2021).
42. Barsom EZ, Graafland M, Schijven MP. Systematic review on the effectiveness of augmented reality applications in medical training. Surg Endosc 2016; 30(10): 4174-4183. https://doi.org/10.1007/s00464-016-4800-6
43. Kovoor JG, Gupta AK, Gladman MA. Validity and effectiveness of augmented reality in surgical education: a systematic review. Surgery 2021; 170(1): 88-98. https://doi.org/10.1016/j.surg.2021.01.051
44. Herron J. Augmented reality in medical education and training. J Electron Resour Med Libr 2016; 13(2): 51-55. https://doi.org/10.1080/15424065.2016.1175987
45. Sheik-Ali S, Edgcombe H, Paton C. Next-generation virtual and augmented reality in surgical education: a narrative review. Surg Technol Int 2019; 35: 27-35. PMID: 31498872.
46. Vera AM, Russo M, Mohsin A, Tsuda S. Augmented reality telementoring (ART) platform: a randomized controlled trial to assess the efficacy of a new surgical education technology. Surg Endosc 2014; 28(12): 3467-3672. https://doi.org/10.1007/s00464-014-3625-4
47. Leblanc F, Senagore AJ, Ellis CN, Champagne BJ, Augestad KM, Neary PC, et al. Hand-assisted laparoscopic sigmoid colectomy skills acquisition: augmented reality simulator versus human cadaver training models. J Surg Educ 2010; 67(4): 200-204. https://doi.org/10.1016/j.jsurg.2010.06.004
48. Botden SMBI, Buzink SN, Schijven MP, Jakimowicz JJ. ProMIS augmented reality training of laparoscopic procedures face validity. Simul Healthc 2008; 3(2): 97-102. https://doi.org/10.1097/SIH.0b013e3181659e91
49. Ritter EM, Kindelan TW, Michael C, Pimentel EA, Bowyer MW. Concurrent validity of augmented reality metrics applied to the fundamentals of laparoscopic surgery (FLS). Surg Endosc 2007; 21(8): 1441-1445. https://doi.org/10.1007/s00464-007-9261-5
50. Botden SMBI, Buzink SN, Schijven MP, Jakimowicz JJ. Augmented versus virtual reality laparoscopic simulation: what is the difference? World J Surg 2007; 31(4): 764-772. https://doi.org/10.1007/s00268-006-0724-y
51. Nugent E, Shirilla N, Hafeez A, O'Riordain DS, Traynor O, Harrison AM, et al. Development and evaluation of a simulator-based laparoscopic training program for surgical novices. Surg Endosc 2013; 27(1): 214-21. https://doi.org/10.1007/s00464-012-2423-0
52. Rawaf D, El-Bahnasawi M, Toms J, Harris M, Sheikh M, Beghal G, et al. Measuring the impact of augmented reality surgical training; a Kirkpatrick level approach. J Minim Invasive Gynecol 2023; 30(11): S16-S17. https://doi.org/10.1016/j.jmig.2023.08.047
53. Chowriappa A, Raza SJ, Fazili A, Field E, Malito C, Samarasekera D, et al. Augmented-reality-based skills training for robot-assisted urethrovesical anastomosis: a multi-institutional randomised controlled trial. BJU Int 2015; 115(2): 336-345. https://doi.org/10.1111/bju.12704
54. Balla A, Sartori A, Botteri E, Podda M, Ortenzi M, Silecchia G, et al. Augmented reality (AR) in minimally invasive surgery (MIS) training: where are we now in Italy? The Italian Society of Endoscopic Surgery (SICE) ARMIS survey. Updates Surg 2023; 75(1): 85-93. https://doi.org/10.1007/s13304-022-01383-6
55. Science Struck. How reliable is face validity for research and surveying? Irvine: Science Struck. 2014. Available from: https://sciencestruck.com/face-validity-for-research-surveying (accessed 25 April 2021).
56. Zamanzadeh V, Ghahramanian A, Rassouli M, Abbaszadeh A, Alavi-Majd H, Nikanfar AR. Design and implementation content validity study: development of an instrument for measuring patient-centered communication. J Caring Sci 2015; 4(2): 165-178. https://doi.org/10.15171/jcs.2015.017
57. Kübler A, Nijboer F, Kleih S. Hearing the needs of clinical users. Handb Clin Neurol 2020; 168: 353-368. https://doi.org/10.1016/B978-0-444-63934-9.00026-3
58. Hong M, Rozenblit JW, Hamilton AJ. Simulation-based surgical training systems in laparoscopic surgery: a current review. Virtual Real 2020; 25: 491–510. https://doi.org/10.1007/s10055-020-00469-z
59. Kamphuis C, Barsom E, Schijven M, Christoph N. Augmented reality in medical education? Perspect Med Educ 2014; 3(4): 300-311. https://doi.org/10.1007/S40037-013-0107-7

Appendix 1. Papers included in this review

Authors	Reference	Title	Category	Experimental procedure
Balla et al. (2023)	54	Augmented reality (AR) in minimally invasive surgery (MIS) training: where are we now in Italy? The Italian Society of Endoscopic Surgery (SICE) ARMIS survey	Modality comparison	A study carried out to evaluate knowledge of simulation modalities as well as interest in modalities. A total of 217 doctors completed the questionnaire that was distributed.
Barsom et al. (2016)	42	Systematic review on the effectiveness of augmented reality applications in medical training	Validity	Systematic review—findings were divided into three groups, only the first category was relevant for this report. ProMIS AR simulator use.
Botden & Jakimowicz (2009)	36	What is going on in augmented reality simulation in laparoscopic surgery?	Simulator comparison	Review of AR simulators— manufacturers were approached and asked to complete questionnaire.
Botden et al. (2007)	50	Augmented versus virtual reality laparoscopic simulation: what is the difference?	Skill acquisition	ProMIS AR vs LapSim VR in basic skills and a suturing tasking on three groups of participants of varying experience levels.
Botden et al. (2008)	48	ProMIS augmented reality training of laparoscopic procedures face validity	Validity	Fifty-five participants completed the basic skills and suturing task followed by a questionnaire on the ProMIS AR to determine face validity.
Botden et al. (2009)	22	Meaningful assessment method for laparoscopic suturing training in augmented reality	Validity	Construct, concurrent and face validity of ProMIS AR determined through 24 participants completing suturing module on ProMIS AR v2.0. An independent observer was used to rate participant performance and a questionnaire to identify face validity.
Botden et al. (2009)	29	Suturing training in augmented reality: gaining proficiency in suturing skills faster	Skill acquisition	Eighteen participants completed suturing module on ProMIS v2.0 after training on MIST-VR. The second knot was assessed by objective independent observers as well as the seventh knot.
Brinkman et al. (2012)	9	Single versus multimodality training basic laparoscopic skills	Skill acquisition	Thirty-six participants were divided into two groups for basic task training. One group completed all six training sessions on the VR simulator and the other group completed the two sessions on a VR simulator (LAP Mentor), an AR simulator (ProMIS) and a box trainer. The performance was assessed before and after on the VR simulator.
Chowriappa et al. (2015)	53	Augmented-reality-based skills training for robot-assisted ureterovesical anastomosis: a multi-institutional randomised controlled trial	Skill acquisition	Procedure-based training with haptic-enabled AR-based HoST compared with control group without training.
Dhar et al. (2021)	39	Augmented reality in medical education: students' experiences and learning outcomes	Modality comparison	Narrative review with extensive literature research to determine the adoption success rate of AR within medical education.
Diesen et al. (2011)	33	Effectiveness of laparoscopic computer simulator versus usage of box trainer for endoscopic surgery training of novices	Skill acquisition	Randomised, blinded controlled trial where participants were either trained for laparoscopic surgery using computer simulator laboratory or a box trainer.
Forgione & Guraya (2017)	30	The cutting-edge training modalities and educational platforms for accredited surgical training: systematic review	Modality comparison	Literature review of training modalities.
Herron (2016)	44	Augmented reality in medical education and training	Skill acquisition	Non-experimental report of AR in medical education.
Hong et al. (2020)	58	Simulation-based surgical training systems in laparoscopic surgery: a current review	Modality comparison	Non-experimental report of simulators in medical education.

(continued)

Authors	Reference	Title	Category	Experimental procedure
Kamphius et al. (2014)	[59]	Augmented reality in medical education?	Modality comparison	Non-experimental report of AR in medical education.
Kaplan et al. (2020)	[35]	The effects of virtual reality, augmented reality, and mixed reality as training enhancement methods: a meta-analysis	Modality comparison	Literature review of mixed reality, virtual reality and augmented reality.
Kovoor et al. (2021)	[43]	Validity and effectiveness of augmented reality in surgical education: a systematic review	Validity Skill acquisition	Review of studies that explore the effectiveness and validity of AR in surgical education.
Lahanas et al. (2016)	[1]	Surgical simulation training systems: box trainers, virtual reality and augmented reality simulators	Modality comparison	Literature review of box trainers, and virtual and augmented reality simulators.
Lahanas et al. (2015)	[14]	A novel AR simulator for skills assessment in minimal invasive surgery	Modality comparison	Development of AR simulator tested with three basic AR tasks to evaluate construct and face validity.
Leblanc et al. (2010)	[10]	A comparison of human cadaver and AR simulator models to straight laparoscopic colorectal skills acquisition training	Modality comparison Skill acquisition	Seven participants performed a sigmoid colectomy on a cadaver and 28 on the ProMIS AR simulator.
Leblanc et al. (2010)	[47]	Hand-assisted laparoscopic sigmoid colectomy skills acquisition: AR vs human cadaver	Modality comparison Skill acquisition	Seven participants performed a hand-assisted sigmoid colectomy on a cadaver and 27 on the ProMIS AR simulator.
Lungu et al. (2021)	[32]	A review on the applications of virtual reality, augmented reality and mixed reality in surgical simulation: an extension to different kinds of surgery	Modality comparison	A review exploring the success and development of surgical simulation to replace the apprenticeship model.
Nugent et al. (2013)	[51]	Development and evaluation of a simulator-based laparoscopic training program for surgical novices	Validity	Forty novices and 40 trainees performed three laparoscopic modules on the ProMIS AR simulator. The performance scores were compared to assess construct validity.
Rawaf et al. (2023)	[52]	Measuring the impact of augmented reality surgical training; a Kirkpatrick level approach	Skill acquisition	An abstract produced with trainees setting benchmarks prior to and after performing several laparoscopic tasks including appendectomies and LapPass tasks.
Ritter et al. (2007)	[49]	Concurrent validity of augmented reality metrics applied to the fundamentals of laparoscopic surgery (FLS)	Validity	Sixty subjects performed five trials of the peg transfer task with the ProMIS AR simulator.
Sándor et al. (2010)	[11]	Minimally invasive surgical technologies: challenges in education and training	Modality comparison	Non-experimental report of AR in medical education.
Sheik-Ali et al. (2019)	[45]	Next-generation virtual augmented reality in surgical education: a narrative review	Skill acquisition	Review of virtual and augmented reality in surgical education.
Vallas et al. (2014)	[37]	Different forms of laparoscopic training review and comparison	Modality comparison	Review of literature on forms of laparoscopic training.
Vera et al. (2014)	[46]	Augmented reality telementoring (ART) platform: a randomised controlled trial to assess the efficacy of a new surgical education technology	Modality comparison Skill acquisition	Nineteen participants were divided into two group to undergo laparoscopic suture and knot-tying training. One group used traditional training while the other used AR telementoring.
Viglialoro et al. (2021)	[31]	Augmented reality, mixed reality, and hybrid approach in healthcare simulation: a systematic review	Modality comparison	A multimodality view of simulation in healthcare.
Williams et al. (2020)	[38]	Augmented reality in surgical training: a systematic review	Modality comparison Skill acquisition	Literature review of augmented reality in surgical training.