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REVIEW ARTICLE

Analysing the design elements and effectiveness of laparoscopic box trainers for laser surgery skill acquisition: a systematic review of the literature

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Abstract

Objective: This study systematically reviews the literature on laparoscopic surgery simulation trainers, to identify common design elements and discuss their applicability to laser laparoscopic surgical training. **Methods:** A systematic search of MEDLINE, Embase, Cochrane CENTRAL, and IEEE Xplore was conducted for relevant articles, published before July 2023. We reviewed 3609 studies. Primary research articles describing the design and construction of a laparoscopic trainer were included. Studies were excluded if they did not describe simulator construction or described virtual reality or animal training models. **Results:** A total of 22 studies met the inclusion criteria, describing 24 laparoscopic trainers. Data were extracted by two independent authors. Most trainers were made from plastic ($n = 16$) and wood ($n = 3$), were rectangular in shape ($n = 17$), with a closed air-permissible design ($n = 19$). Sixteen trainers used a webcam as the camera, and most ($n = 15$) were fixed in place. Most trainers included two to four ports ($n = 16$), and most ports were constructed with commonly available materials [holes drilled directly into the outer wall ($n = 6$), rubber grommets ($n = 5$), or felt or plastic overlay ($n = 4$)]. Thirteen studies included an assessment of their laparoscopic trainer, most commonly reporting on content, construct, and face validity. Overall, the trainers were highly regarded and deemed useful tools for developing laparoscopic skills. **Conclusion:** There is heterogeneity in the design of laparoscopic trainers, the materials used, and trainers' airtight properties. No trainer was specifically designed to simulate laser laparoscopy. Adaptations must be made to current common design elements for use in this setting.

Keywords: *laparoscopy; simulation; gynaecological surgery; endometriosis; laser laparoscopy*

Introduction

The acquisition of laparoscopic skills is essential for surgical trainees in many fields. The technical skills required for laparoscopic surgery are distinct from those needed for open surgery via laparotomy. In laparoscopic surgery, depth perception and tactile feedback are reduced, and laparoscopic instruments create a fulcrum effect which amplifies tremor and challenges accuracy.[1] Simulation-based laparoscopic surgical training has been well demonstrated to improve knowledge, skills performance, and surgical time when compared with non-simulation instruction.[2–4] Laparoscopic simulation trainers allow surgical trainees to practice skills in a structured environment that encourages deliberate practice and allows for feedback without threatening patient safety.[5]

Traditional laparoscopic box trainers have demonstrated comparable efficacy in improving novices' surgical skills to higher fidelity simulators (i.e. virtual reality simulators),[6–8] and have been shown to be superior for outcomes of trainee satisfaction and skills performance time.[2] Laparoscopic box trainers are an essential aspect of surgical training given their integral role in the Fundamentals of Laparoscopic Surgery (FLS) course,[9] which is now required for certification by the American Board of Surgery and the American Board of Obstetrics and Gynecology. In addition, a recent Canadian consensus on simulation in obstetrics and gynaecology encourages the use of task-based simulation activities such as laparoscopic box trainers.[10] Despite this consensus, currently no specific laser laparoscopy simulator is widely available nor recommended for learners.

Laser laparoscopy is a unique surgical technique that has been effectively used in the field of gynaecology, most commonly for the treatment of endometriosis.[11] In advanced endometriosis, ectopic endometrial-like tissue deposits can significantly distort pelvic anatomy. CO_2 laser technology allows tissue vaporization with a relatively small spread of tissue necrosis and no residual debris,[11] thus facilitating the accurate dissection of tissues and precise excision of endometriosis. The CO_2 laser is commonly used through the operating channel of the laparoscope, and its effective use requires advanced laparoscopic skills, as imperfect application can result in unintended damage to adjacent structures. A learning curve has been described in the performance of laser surgery for the treatment of foetal twin-to-twin transfusion syndrome (TTTS),[12] and although this has not been described in the literature for laser laparoscopy, we anticipate a similar learning curve in gynaecologic surgery. Without simulation opportunities, surgical trainees must learn laser laparoscopy through real-time exposure in the operating room (OR) on live patients. This likely contributes to prolonged operative times and increased healthcare costs and is potentially at the expense of patient safety. Although there are costs to developing simulation models, simulated activities have been demonstrated to reduce adverse outcomes in obstetrics and gynaecology,[13,14] and have been demonstrated to be cost effective as they reduce resultant costs to health care systems[14,15] and litigation.[16] The purpose of this systematic review is, therefore, to survey the literature describing the design and construction of laparoscopic trainers to identify common design components and apply these to the setting of laser laparoscopy, with the intended goal of developing a laser laparoscopic trainer.

Materials and methods

We conducted a systematic search of articles in accordance with the Preferred Reporting Items in Systematic Reviews and Meta-Analyses (PRISMA) guidelines.[17] The online databases MEDLINE, Embase, Cochrane CENTRAL, and IEEE Xplore were searched from inception to July 2023. The following search strategy was employed: [Design OR Develop] AND [Laparoscop OR Minimally invasive surg OR MIS] AND [Simulator OR Box trainer].

Study selection

We included primary research articles that describe the design and construction of a laparoscopic trainer in any surgical field. We excluded all articles that describe the use of a pre-made laparoscopic trainer without description of the trainer design/construction, or articles that describe only the design/development of task models to be used within a pre-made laparoscopic trainer. We also excluded articles that described virtual reality training models, animal training models, pilot studies, review articles, or studies wherein the full text was not available in English. Research ethics board approval was not required as the review exclusively relied on information within the public domain and there is no reasonable expectation of privacy.

Data extraction and synthesis

Data were extracted during full-text review by two independent authors and recorded in a pre-specified data collection form. Collected data included the documented purpose of the laparoscopic trainer, materials used in construction, shape of the trainer, whether it was opaque or transparent, whether the trainer was an open or closed design, and whether it was airtight in closed designed models. We also recorded the number of surgical ports, port diameter, configuration of the ports, the length/width/depth dimensions of the trainer, weight of the trainer, the type and mobility of the camera, light source, display screen used, trainer portability, and cost of development (presented in USD). Lastly, we documented whether an assessment of the validity of the trainer was performed, who was involved in validation (i.e. novices such as medical students/residents versus expert surgeons), assessment methods, and the results of such assessments.

The collected data for each numeric variable were summarized using the most appropriate descriptive statistic. We provide a qualitative synthesis of evidence focusing on categorical design features and used previously identified key features and themes as a starting framework.[18] We noted where data were missing and present our results according to the number of studies which provided data for a specific variable.

Results

A total of 5366 results were returned by the search. Studies were screened for duplicates at the title, abstract, and full-

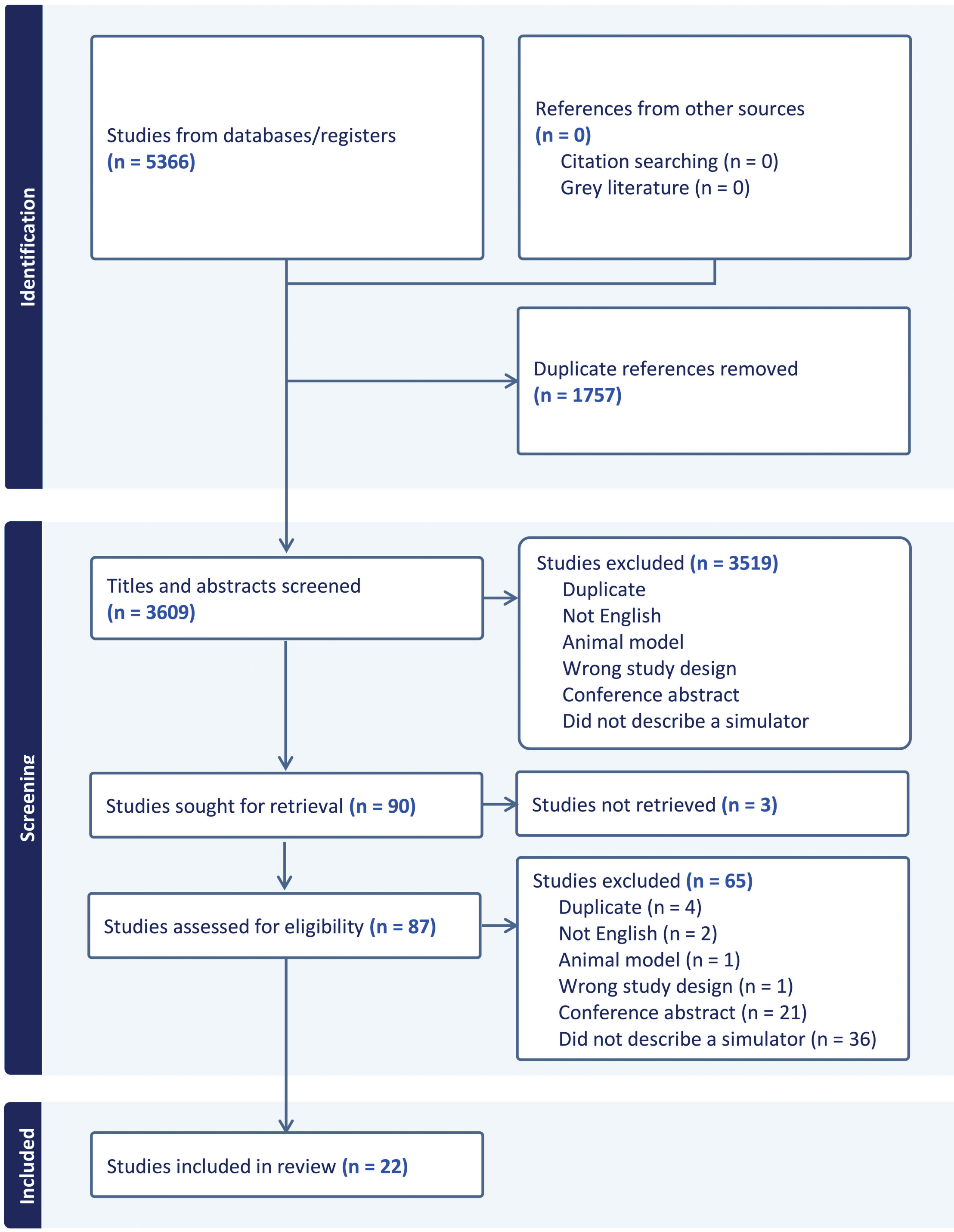

Figure 1. PRISMA flow diagram of study selection.

text review stages. In total, 1757 duplicate studies were removed, and 3609 abstracts and titles were screened for eligibility by two independent blinded reviewers (EP and RK). Discrepancies at the title/abstract review stage were resolved by consensus discussion. Eighty-seven studies underwent full-text review, of which 22 studies were included. A flowchart of these search results is shown in Fig. 1. Notably, two included studies each described two laparoscopic trainers,;[19,20] therefore, a total of 24 trainers were evaluated in this systematic review.

Table 1. Overview of included studies

Authors	Year of Publication	Country	Box trainer purpose	Validated
Afuwape[32]	2012	Nigeria	Generic laparoscopic box trainer	No
Chen et al.[33]	2016	China	Generic laparoscopic box trainer	No
Horeman et al.[21]	2015	Netherlands	Generic laparoscopic box trainer with motion and force assessment	No
Hruby et al.[27]	2008	USA	Generic laparoscopic box trainer	Yes
Hwang et al.[22]	2010	USA	Model for laparoscopic ventral herniorrhaphy	Yes
Jaber[34]	2010	Saudi Arabia	Generic laparoscopic box trainer	No
Lin et al.[35]	2019	USA	Generic laparoscopic box trainer combining Xbox technology	Yes
Lysak et al.[36]	2023	Poland	Generic laparoscopic box trainer	Yes
Martín-Calvo et al.[28]	2023	Spain	Generic laparoscopic box trainer	Yes
Martinez & Espinoza.[37]	2007	Mexico	Generic laparoscopic box trainer	No
Silveira et al.[38]	2022	Brazil	Generic laparoscopic box trainer	Yes
Soriero et al.[39]	2020	Italy	Generic laparoscopic box trainer	Yes
Torres et al.[24]	2021	Brazil	Neonatal laparoscopic box trainer	Yes
Walczak et al.[19]	2014	Poland	Generic laparoscopic box trainer	No
			Generic laparoscopic box trainer	No
Wright et al.[40]	2023	USA	Generic laparoscopic box trainer	No
Xiao et al.[41]	2013	Netherlands	Generic laparoscopic box trainer	Yes
Arden et al.[23]	2008	USA	Pelvic laparoscopic box trainer	Yes
Azzie et al.[25]	2011	Canada	Paediatric laparoscopic box trainer	Yes
Damas et al.[42]	2016	Haiti	Generic laparoscopic box trainer	No
Del Rio et al.[26]	2015	Italy	Generic laparoscopic box trainer	Yes
Gavrilovic et al.[20]	2018	Canada	Generic laparoscopic box trainer with motion and force assessment	No
			Paediatric laparoscopic box trainer with motion and force assessment	No
Sellers et al.[43]	2019	USA	Generic laparoscopic box trainer	Yes

The majority of the described laparoscopic trainers were developed for general laparoscopic simulation (Table 1). Horeman et al.[21] and Gavrilovic et al.[20] developed specialized trainers with technology that can measure motion and force applied to the instruments by the user. Hwang et al.[22] and Arden et al.[23] created a trainer that specifically simulates ventral hernia repair and pelvic laparoscopy, respectively. Finally, Torres et al.,[24] Azzie et al.,[25] and Gavrilovic et al.[20] developed smaller trainers to allow trainees to practice neonatal and paediatric laparoscopy in a more realistic setting.

Table 2 outlines the design features of the 24 trainers evaluated in this systematic review. Most trainers were developed with common materials such as plastic ($n = 18$) and wood ($n = 3$), and most were rectangular in shape ($n = 17$) similar to commercially available simulators. Nineteen trainers had a closed design and were opaque but none were airtight. Most trainers ($n = 16$) had two to four ports of entry and used a webcam to project the inside view onto an external screen ($n = 16$). A variety of light sources were used, including webcam lights, fluorescent and LED lights, a cell phone light source, and room lighting. Fifteen trainers used stationary cameras that were fixed in position, and six used moveable cameras. Of the moveable cameras, three had four degrees of freedom, akin to conventional cameras used in laparoscopy. Seventeen of the trainers were portable, primarily to allow trainees to practice at home. Construction costs were reported for 17 trainers, 14 of which were under $500 USD.

The dimensions of the trainers and their port design are also relevant features for the development of a laser laparoscopy simulator. The average dimensions of the generic box trainers were 48.3 (SD 9.8) cm long, 36.0 (SD 7.9) cm wide, and 28.1 (SD 12.7) cm deep. The average dimensions of the paediatric box trainers were 15.5 (SD 4.3) cm long, 11.3 (SD 2.3) cm wide, and 12.7 (SD 4.7) cm deep. The port design was reported for 17 trainers, the majority of which were constructed using commonly available material. Six of the box trainers used holes drilled directly into the wall and five used drilled holes fixed with rubber grommets. Similarly, four trainers used felt or plastic hole covers with slits to allow instruments to pass through. The simulator developed by Arden et al.[23] was an open design and used washers suspended on string on the open face of the simulator to hold the instruments. Finally, Horeman et al.[21] utilized commercially available single- and multi-port laparoscopic trocars, which were passed through holes with a rubber underlay, each surrounded by a specialized ring to measure the displaced force on the simulated abdominal wall.

Validation was performed for 13 of the trainers included in this systematic review (Table 3). Most studies included an assessment of face, content, and/or construct validity, and

Table 2. Summary of design elements of laparoscopic trainers.

Box trainer characteristics	Number of studies (n)
Material used to construct the outer simulator	
Plastic	18
Wood	3
Fibreboard	1
Metal	1
Not described	1
Closed versus open design	
Closed	19
Open	5
Is the simulator airtight?	
No	24
Yes	0
Number of ports	
2–4	16
5–7	6
8+	2
Port diameter (mm)	
0–5	5
5.1–10	4
10.1–20	2
Not described	13
Shape of the simulator	
Rectangular	17
Semi-cylindrical	3
Mannequin torso	2
Dome-shaped	1
House shaped	1
Opaque versus translucent	
Opaque	19
Translucent	5
Camera used	
Webcam	16
iPhone	1
Video camera	1
Bullet mini camera	1
Endoscope camera	1
Analogue camera	1
None	3
Camera fixed versus mobile ($N = 21$)	
Fixed	15
Mobile	6
Light source	
Webcam	5
Fluorescent lamp	4
LED lights	3
Non-descript light bulb/strips	3
Headlamp	1
iPhone	1
Room lighting/none	5
Not described	2
Portability of simulator	
Yes	17
No	6
Not described	1
Cost of materials ($USD)	
0–99	7
100–499	7
500+	3
Not described	7

compared experience and performance measures between novice and expert laparoscopists. One study only collected data on users' general observations after experience with the laparoscopic trainer,[22] and two other studies only collected data on users' skill acquisition.[26] Overall, the trainers that underwent validation were highly regarded and deemed useful tools for developing laparoscopic skills. Of the studies that assessed face validity, three models were noted to lack spatial and/or optical resolution and realism.[24,27,28] All six studies assessing construct validity demonstrated validity.

Discussion

First and foremost, this systematic review highlights that there has been no previously described laparoscopic trainer that is designed specifically for skill development in laser laparoscopy. This identified gap in the field of gynaecologic surgical simulation warrants attention, given the significant role of laser laparoscopy in the surgical treatment of endometriosis.[11] Second, this review highlights current design features of laparoscopic box trainers and allows readers to understand what has been done thus far, so that future trainers can build on design elements and be adapted to meet specific simulation objectives.

In performing our review, we encountered two studies that describe a simulation model for learning laser ablation of placental vessels in the treatment of TTTS.[29,30] These studies were excluded from our review as they are not laparoscopic trainers. In addition, the model by Javaux et al. was a virtual reality trainer[29] and the model constructed by Peeters et al.[30] was not thoroughly described, although we gather that a silicone interface simulated the abdominal wall and the model contained water to allow appropriate sonographic properties. While these models have been validated as good means for practicing foetoscopic laser surgery skills,[29,30] their design is limited to foetoscopic surgery (i.e. filled with water to simulate amniotic fluid)[30] and, therefore, the transferability of the design to a laser laparoscopy trainer is limited.

When considering the development of a laser laparoscopy trainer, we have identified three main design elements that require modification from the current most used methods as identified in this review: materials used in trainer construction, the need for a closed/airtight design, and camera mobility. When considering the materials used in constructing a trainer, we must assume the model will be used by novice learners and laser energy may unintentionally be applied to any area of the trainer. Most studies included in this review used various forms of plastic as the main material in

Table 3. Summary of validation data for laparoscopic trainers

Authors	Participants[a]: *n*	Validation methodology	Validation outcome
Hruby et al.[27]	Expert: 27 Intermediate: 6 Novice: 9	Content validity: Likert-scale survey; face validity: Likert-scale survey	The simulator is a useful and realistic training tool but lacks visual resolution
Hwang et al.[22]	Not described	General observations	Skilled surgeons successfully taught ventral hernia repair to resident surgeons
Lin et al.[35]	Novice: 24	Skill acquisition: skill compared at baseline and following a training course	Improved performance on both the novel trainer and FLS following the training course
Lysak et al.[36]	Novice: 35	Face validity: Likert-scale survey	All participants reported a positive experience using the simulator
Martin-Calvo et al.[28]	Expert: 19 Novice: 20	Construct validity: task completion time between groups; content validity: Likert-scale survey; face validity: Likert-scale survey	The simulator could differentiate users according to experience level and was agreed to improve dexterity and hand–eye coordination, but it was lacking spatial realism
Silveira et al.[38]	Novice: 51	Content validity: Likert-scale survey; face validity: Likert-scale survey	The simulator was felt to support the development of motor coordination and 2D perception
Soriero et al.[39]	Expert: 35 Intermediate: 40 Novice: 15	Construct validity: task completion time and number of errors between groups; content validity: Likert-scale survey; face validity: Likert-scale survey	The simulator was felt to be a realistic and useful learning tool and it was able to successfully differentiate users by experience level
Torres et al.[24]	Expert: 14 Intermediate: 16 Novice: 12	Construct validity: task completion time and number of errors between groups; face validity: Likert-scale survey	The simulator was able to differentiate users by experience level and was felt to be realistic, but it lacked optical resolution and the ability to adjust the camera's focus
Xiao et al.[41]	Expert: 12 Intermediate: 27 Novice: 14	Construct validity: number of errors between groups; content validity: Likert-scale survey; face validity: Likert-scale survey	The simulator was found to be a useful and realistic tool and was able to differentiate between users by experience level
Arden et al.[23]	Intermediate: 19 Novice: 10	Construct validity: task completion time between groups; skill acquisition: skill compared at baseline and following a training course	The simulator could differentiate users according to experience level and showed improvement in skill following 10 weeks of training (1 h/week)
Azzie et al.[25]	Expert: 45 Intermediate: 19 Novice: 20	Construct validity: FLS scores on five tasks between groups	The simulator could differentiate users according to experience level
Del Rio et al.[26]	Expert: 3 Intermediate: 3 Novice: 3	Skill acquisition: time to complete three tasks compared over three simulation sessions	Users showed improved skills follow each simulation session
Sellers et al.[43]	Novice: 17	Face validity: Likert-scale survey	The users felt the simulator was well designed and offered a high-quality learning experience

[a]Novice: medical learners or person with minimal/no previous laparoscopic experience; intermediate: medical learners with some previous laparoscopic experience or low-volume staff surgeon; expert: staff surgeon with extensive laparoscopic experience.

constructing their trainer. Although there are some laser-resistant plastics, they must be specifically designed for the type of surgical laser used and should be certified as laser proof, according to laser safety industry standards (e.g. American National Standards Institute (ANSI) Z136 Series).[31] Materials such as wood and fibreboard could catch fire with laser application and are, therefore, unsafe. The body of literature reviewed is limited in that the specific compositions of plastics and metals used in trainer construction are generally not included, so inferring laser safety is not possible. While 19 of the reviewed laparoscopic trainers described a closed configuration, none were designed to be airtight, which is needed to manage laser generated air contaminants (LGACs) and fumes. Lastly, 15 of the reviewed laparoscopic trainers employ a fixed camera design. Incorporating a mobile endoscope is fundamental to a laser laparoscopy trainer as the laser is integrated within the laparoscope via a specific coupler and adapter. Mobility of the laparoscope is required to precisely aim the laser beam, facilitating the surgery. This design would facilitate optimal transferability to in vivo conditions.

Development of a laser laparoscopy box trainer

This literature search identifies the following common design features for laparoscopy trainers: trainers are typically constructed as an enclosed box that allows the insertion of tools, a camera, and a laser beam. Should a CO_2 laser be used in the trainer, the spread of dangerous fumes and laser generated air contaminants should be managed, and the enclosure material should be chosen to be laser-safe.

Assessment of laparoscopic trainers

Only 13 of the reviewed studies included any assessment of their laparoscopic trainer. While significant heterogeneity existed between studies' assessment methods, the face, content, and construct validity were most frequently assessed. In this context, face validity evaluates the subjective realism of the laparoscopic trainer and content validity evaluates the usefulness of a laparoscopic trainer as a training tool. Across studies, the most reported critique on face validity assessment was the lack of optical resolution and spatial realism. Use of a laparoscope that allows for focus adjustment and full range mobility would likely improve the model realism. Construct validity is the degree to which a laparoscopic trainer can discern skill performance between individuals with varying levels of expertise, and all studies that included this assessment demonstrated construct validity.

Strengths, limitations, and future direction

This systematic review provides a comprehensive summary of the design features of laparoscopic trainers from a variety of surgical fields. The review was limited to studies that include a description of the design and/or construction of laparoscopic trainers; therefore, studies that have assessed commercially available or other previously designed laparoscopic trainers but did not include design descriptions were excluded. While we recognize that the exclusion of these trainers may represent a limitation, it was essential to only include trainers whose design elements could be analysed for suitability with a CO_2 laser. In addition, we recognize that a limitation to our systematic review is the lack of formal risk of bias assessment. Given the nature of the included studies, which focus on describing the development and design of laparoscopic box trainers, it was not possible to apply a consistent risk of bias assessment tool.

Looking forward, laser laparoscopic box trainer models should be designed, validated, and implemented. Virtual reality and augmented reality may have an important place in laser laparoscopy simulation in the future, given its ability to portray realistic surgical environments and provide real-time feedback. In addition, virtual reality models have the benefit of not needing to be performed in a laser-safe setting as the laser beam itself would be virtual. The simulation activities that learners perform using a laser must be validated, and we propose that a laparoscopic trainer offers a more conducive setting to validate such activities. Once we gain feedback from novices and experts on such activities, they can be adapted and translated to a virtual setting.

Conclusions

There is significant variability in the design of previously described laparoscopic trainers, and none has considered the use of laser technology for the practice of laser laparoscopy. We identify three main design elements that require modification from the current most used design methods. This includes the need for a closed and airtight design, improved laparoscope mobility, and adjustments to the materials used in construction as most box trainers are constructed using materials that would not be compatible or safe in laser laparoscopy. An assessment of content, construct, and face validity should be included in future studies describing novel laparoscopic simulation models to allow readers a thorough understanding of the trainer's efficacy.

Conflict of interest

Eliane M. Shore has received consulting fees from Bayer outside of the submitted work. Other authors have no conflicts of interest to disclose.

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Data availability

All data relevant to this study are available within the reviewed articles which have been referenced here.

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