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REVIEW ARTICLE

Low-cost simulation systems for surgical training: a narrative review

Dhananjaya Sharma,[a,*] Vikesh Agrawal,[a] Jitin Bajaj[b] and Pawan Agarwal[a]

[a]*Department of Surgery, Government NSCB Medical College, Jabalpur (MP), 482003, India;* [b]*Department of Neurosurgery, Government NSCB Medical College, Jabalpur (MP), 482003, India*

**Corresponding author at: Department of Surgery, Government NSCB Medical College, Jabalpur (MP), 482 003, India. Email: dhanshar@gmail.com*

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Abstract

This narrative review appraises low-cost simulation systems for surgical training. Low-cost simulators are needed for minimally invasive and other advanced surgeries because opportunities for practicing the necessary surgical skills using high-fidelity simulation in the workplace are limited due to cost, time and accessibility to junior trainees. A low-cost box simulator can be easily made by self-assembly of components that are available locally or online and even with used, discarded or expired disposable instruments. Skills acquired through low-cost simulations translate into improvements in operating room performance and their efficacy is on a par with expensive systems. A brief comparison of various surgical simulation models, ranging from cadaveric, animal, bench-top, virtual reality, augmented reality to robotic simulators is included in this review. In addition, these low-cost systems can result in significant savings in costs of resident training, as well as in annual running costs of skills labs. Every speciality has developed its own versions of low-cost training systems and has shown their benefits. Low-cost laparoscopic training in 3D is also possible by using visual feedback via the transparent/open top of the box trainer. However, it is important to understand the limitations of a low-cost system. It is a widely available cost-effective workhorse, which can lay the foundation of basic generic surgical skills for younger trainees. Advanced skills can then be easily constructed with high-cost high-fidelity systems.

Keywords: *surgical training; simulation; low-cost; frugal innovation*

What is simulation?

The term ‘simulation’ is defined by the Cambridge Dictionary as ‘a model of a set of problems or events that can be used to teach someone how to do something, or the process of making such a model’. According to Wikipedia, the word simulation implies an imitation of a real-life process, usually via a computer or other technological device, in order to provide a lifelike experience.[1]In simpler terms, it is ‘an imitation of some situation or process’ creating a ‘full dress rehearsal of equivalent situation’, which can be repeated again and again, for the purpose of teaching, learning, and/or training of ‘practice of skills, problem solving, and judgment’.[2–4]

How did the concept of simulation for training start?

Credit for simulation for training goes to the aviation industry with flight simulation; the first flight simulator was created in 1910. The idea gained traction during World War II, when pilots and their ground crew needed to learn how to fly in quickly changing environments. The success of this idea led to the introduction of flight simulators in civil aviation after the war. The history of medical simulation began in the late 1950s when defibrillator models and mannequins for resuscitation made their appearance.[3] The first report of using actors to simulate patients in an attempt to teach neurology was published in 1964.[5] In the 1970s, the advent of technology and processing power resulted in computer-generated simulators. However, the widespread acceptance of surgical simulation really picked up pace with the arrival of laparoscopic and other minimally invasive procedures in the early 1990s, which forced surgeons to seek simulation technology to acquire and master these new skills. The timeline of the evolution of simulation for training into medical and surgical simulation is well recorded.[2,3,6]

Is simulation a new teaching concept for surgical training?

The aviation industry was the first to start structured competency-based simulation training and assessment; however, simulation as a means of learning or rehearsing was well described in surgery by Sushruta some 2600 years ago, which has largely gone unrecognized.[7,8] Sushruta is credited with advocating the use of cadavers and synthetic models for practice before surgery and taught his technical skills using various experimental modules that included learning the art of bandaging and ligaturing by tying bandages round the corresponding limbs of a full-sized doll made of stuffed linen, suturing on pieces of cloth, skin or hides, probing on worm-eaten wood, applying enemas using tubes inserted into the mouth of a gourd, extracting by withdrawing seeds from the kernel of a jackfruit, cauterizing by applying alkali on a piece of soft meat, and incising on vegetables such as watermelon, gourd and cucumber.[9,10]

Although there are sporadic references to wooden models for learning acupuncture from China (11th to 17th century AD), wax, écorché and papier-mâché models for learning anatomy from Europe (13th to 19th century AD), varieties of obstetric mannequins or models made of various materials in Italy, France and Britain (18th to 19th century AD) for training of midwives and doctors, there are practically none for teaching surgery.[11] By practicing on both live and inanimate models or cadavers, surgeons throughout history have been able to pioneer new surgical techniques and practice operations without sacrificing patient safety; however, authentic publications about them are scarce. The first reference to training by surgical simulation (after Sushruta) comes in 1868 when a technique for hernia repair was demonstrated on a mannequin during a medical conference in New York.[12] Over the next few decades, mannequins started appearing for training of laryngoscopy, tracheal intubation, and eye surgery; the use of sheep or pig eyes was also reported for eye surgery training.[11]

William Stewart Halsted (1852–1922), an American pioneer surgeon who devised the residency training system and a doyen of modern surgical residency teaching, arrived on the scene along with his famous 'see one, do one, and teach one' adage. This learning by doing philosophy worked at that time, because it depended upon the sheer volume of exposure to caseloads as its cornerstone; however, it is no longer possible in the 21st century.[13] But surgical learning by simulation continued to be autodidactic – residents continued to practice tying knots, suturing on clothes and practicing on cadavers and/or animal organs before actually operating on patients – although there is not much published literature on this.

Why is simulation needed in surgical training and what are the current contradictions of the ideal training method?

Surgical residents must acquire a tremendous base of skills and knowledge during their training. Halstead's time-honoured surgical apprenticeship model has become unsustainable due to factors such as patient-load dependence, restricted faculty numbers and time available for teaching, restrictions in working hours for surgeons in training, reduced availability of operating time, the medico-legal and ethical issues involved in 'live' operative training, increasing complexities of operations, and increasing specialization. The contradictions of such a paradigm (requirements of 'ideal' surgical training versus clinical 'real-life' constraints) are shown in Table 1.

Any acquisition of motor skills is based on the three-stage theory of Fitts and Posner.[14] The three stages are cognition (understanding the task), integration (comprehending and performing the mechanics of the task) and automation (performing the task with speed, efficiency and precision).[14] It is obvious that the same applies to acquiring surgical skills, and simulation training is the key to this. It can be more easily explained as the phenomenon of developing appropriate 'muscle memory' for the required surgical skills by repetitive practice, i.e. simulation. Moreover, simulation also assists in mental cognitive rehearsal of the proposed surgery and has a positive and significant effect on surgical training because it leads to automaticity.[15,16]

How does simulation help in surgical training?

The skills needed to be learned by surgical trainees may be divided into three distinct areas: patient-centred skills, process-centred skills and environment-centred skills.[17] The first and last of these are considered 'soft' skills as against the actual 'hard' surgical skills.

Simulation is a valuable and necessary adjunct to learning safe surgical skills, because opportunities in the real clinical setting may be inadequate (Table 1). Simulation training has the potential and power to provide a bridge between theoretical learning and real-life clinical experience, allowing acquisition of the necessary surgical skills before the trainee gets an opportunity to operate on a real patient. It has many other advantages:[2,17,18]

- Allows trainees to become familiar with anatomy, equipment and techniques before performing procedures on patients

Table 1. The contradictions of surgical training

Ideal surgical training	Real-life barrier
Hands-on exposure to a minimum number of cases	Patient safety/quality of care/ethical issues
Repetitive practice of skills	Quality of care/ethical/medico-legal issues
Structured training programme, uniform training, defined objectives and outcome	Opportunity and duration dependent, working time restrictions/24 hours, shorter duration of higher professional training
Split-level training	Surgical hierarchy/opportunity dependent
Needs-driven training to be tailored to individuals/exposure to complex clinical/operative situations	Varied case load and heterogeneity of cases in different departments
Adoptive and adaptive to newer technology	Poor access to newer technique/technology
Objective assessment of acquired skills with necessary feedback	Traditional experience-based teaching
Accessible to trainee	Non-availability of teacher/supervisor for assessment and feedback, limited dedicated teaching time
Sustainable	Poor access/stereotyped teaching module, cost

- Allows learning in a low-pressure atmosphere, without undesired interference while training in dedicated teaching time rather than patient care time
- Increases retention and accuracy, because it allows repetitive practice of skills, and avoids the learning curve associated with real patients
- Promotes a safety-conscious culture because risks to patients and learners are avoided; therefore has potential to reduce surgical errors
- Allows creation of tasks/scenarios on demand, providing a range of difficulties, and training can be tailored to individuals
- Allows multiple learning strategies with defined outcomes
- Allows minimum standards against which to evaluate students to be set and assessed objectively
- Complex clinical situations can be practised, and rehearsal of serious/rare events/interventions is possible
- Allows induction into new clinical environments, and design, testing and use of new clinical equipment
- Permits refresher training of skills for senior surgeons
- Provides feedback and can be integrated within curricula.

Every study, without exception, shows that skills acquired through simulations translate into improvements in operating room performance. More importantly, surgical simulation allows the trainee to try and 'fail' without any consequences for patients; and learning from the cause of this 'failure' is the key to refining the skills being practised.[19,20]It is a typical win-win situation, everyone wins: surgeon (skills improve), patient (outcomes improve), and hospital (decreased operative time, improved patient care, decreased costs with fewer complications).[21–23] That is why it has become the foundation of modern surgical training and is increasingly incorporated in curricula. Its acceptance by society and authorities is based on the fact that the beneficiaries of improved performance are not only the surgical trainees themselves but also their patients and thereby society at large.[17,24] Its pre-eminence can be gauged by the fact that surgical skill acquisition by simulation and its assessment were the area of focus in most of the contemporary articles among surgical education's 100 most cited articles listed by Matthews et al. in 2016.[25]

Bruce Lee (famous martial artist) praised the significance of practice and simulation: 'I fear not the man who has practiced 10,000 kicks once, but I fear the man who has practiced one kick 10,000 times.'[26]

What are the pros and cons of currently available simulation systems for surgical training?

There are many surgical simulation models, ranging from cadaveric, animal and bench-top, to virtual reality (VR), augmented reality (AR) and robotic simulators. Their advantages and disadvantages are compared in Table 2.[27,28]

What is the need for low-cost simulation systems?

Historically, surgeons acquired their gastrointestinal and vascular anastomosing skills on goat's intestine and aorta brought from the local butcher's shop; it was simulation training in a very rudimentary wet lab. Another common

Table 2. Comparison of various simulation systems

Simulation model	Advantages	Disadvantages
Cadavers	Accurate anatomy. When fresh: gold standard for surgical simulation because of its similarity to living tissue. Perfused cadaveric tissue creates high-fidelity models	Expensive, limited availability. Requires regular maintenance and special facilities. Formalin-fixed cadavers are hard and inappropriate for coelomic simulation. Not reusable following certain procedures. Ethical/infection issues
Live animals (wet lab)	Live experience, may share some features with human surgeries. Living anatomy and physiology. Tissue feel and haptics. Requires adequate control of bleeding, thus replicating human surgery with high-fidelity. Can practice every element of an operation: technical skills, avoiding complications and their management as and when they arise	Possible structural differences between human and animal anatomy. Ethical concerns over the use of live animals as surgical simulators. Expensive, requires a big setup, large team including surgical assistants, anaesthetists, care takers for the animal lab. Only for single use. Potential to transmit lethal organisms responsible for zoonotic diseases
Animal parts (modified wet lab)	Economical. Easy availability from abattoir. Minimal ethical issues	Sterilization requirements need to be strict. Disposal has to be regulated
Bench-top and laparoscopic box simulators (low-fidelity, physical reality [PR])	Allows practice of basic individual skills/technique. Economical and simple. Portable, easy availability. Multiple uses possible. For use of novice surgeon	Teach 'only' basic surgical skills. Does not allow simulation of all steps. Limited realism. Skills difficult to assess. Lack of interactivity and automated correction advice as seen in virtual reality (VR)
Bench-top 3D printed modules and human mannequin (high-fidelity, PR)	3D printing, can accurately recreate complicated procedures under realistic condition. For advanced surgeons	More expensive than low-fidelity PR, but cheaper than animal and VR. Limited availability. Skills difficult to assess
VR simulators	Create realistic environments that capture minute anatomic details with high accuracy. Provide explanations of the tasks to be practised. Allows practice of variety of different simulations on a single unit. Interactivity. Haptic metrics enable educators to assess trainee's improvement (under research)	Lack realistic haptic feedback. Expensive. Limited availability
Patient-specific augmented reality (AR) simulators, also known as mixed reality (MR) because it is a bridge between PR and VR	Augment pre-operative patient imaging data on top of the patient's anatomic structures. Retain realistic haptic feedback. Provide objective assessment of the performance of the trainee. Allows the trainee to use the same instruments that are currently used in the operating room. Provides realistic haptic feedback	Expensive. Limited availability
Robot-assisted surgery simulators	Ease-of-use. Readily available haptic metrics for assessment	Very expensive. Limited availability. Lack of high-fidelity surgical simulations

Modified from Badash et al.[27] and Lahanas et al.[28]

sight was the whole team rehearsing the steps of a new/major operation on cadavers.

The advent of minimally invasive surgery brought this rapidly emerging technology into the equation, and its requirements became woven into the fabric of surgical simulation. It has a significant learning curve for the following reasons: impaired depth perception (as visualization is on a two-dimensional screen), impaired tactile feedback, two-handed choreography for dissection, non-dominant hand dexterity, accurate instrument targeting, intracorporeal suturing, different hand-eye coordination, familiarity with the fulcrum effect, and working in a less ergonomically friendly position leading to earlier fatigability.[29,30] This surgery also required additional technology: a camera, screen and light source. These requirements meant that these skills could not be learned solely using the traditional apprentice model or the simple economical modified wet labs of traditional surgical training.

This also meant that opportunities to practise surgical skills using high-fidelity simulation in the workplace became limited due to cost, time and geographical constraints, and accessibility to junior trainees. An alternative was needed to practise laparoscopic skills when junior trainees were away from hospitals.[30] Initially, the average cost of a commercially available simulator was ~US$5000, and the conventional training of a surgical resident in the operating room for 4 years was calculated, 2 decades ago to be ~US$50,000.[31] Costs and annual maintenance of modern surgical skills centres established by various teaching institutions and apex surgical associations run into millions of US dollars.[32,33]

As always, technology was and is commercially driven; commercially available surgical simulation systems are expensive and not easily available. This prompted legions of surgeons to innovate and devise low-cost, easily available and sustainable alternatives for simulation of surgical training.

Developing low-cost surgical simulation systems becomes even more important and needs based when institutions are held accountable but are not given or do not have adequate resources.[17] There is a pressing need for this in low- and middle-income countries. It is well known that various surgical societies have endorsed checklists to reduce errors and ensure consistency, completeness and safety in carrying out various surgical procedures. Surgeons working in resource-constrained milieu automatically develop a mental checklist to economize and safely cut down on any expenditure where possible. This is the thought process that has led to the development of low-cost surgical simulation systems.

How is a low-cost simulation system made?

Low-cost box trainers for laparoscopic surgery are the vanguard driving this ecosystem of low-cost simulation systems for surgical training. The anatomy of low-cost box trainers for laparoscopic surgery is presented in Table 3.

The secret to reducing the cost of such a box trainer lies in self-assembly of components that are locally available, off-the-shelf, or can be bought from online shopping portals, or even used, discarded or expired disposable instruments.[30,34–37]

These box trainers are the most equitable and useful solution to allow regular basic skills practice for junior surgical trainees. They are light, portable, inexpensive and easily transportable to any setting that provides a computer screen. They can be quickly and easily assembled, are immediately accessible and practical, cost-effective, inanimate models to target key skills out of hours and outside the hospital environment.[38] Their biggest advantage is their low cost, which makes them easily available to most surgical trainees. They are also easily modified and flexible, they have haptics, and they allow different or new instruments to be compared.[29]

What is the efficacy of low-cost simulation systems?

Low-cost box trainers (dry-lab training) are designed for novice surgeons for the practice of generic skills required for laparoscopic surgery, such as instrument handling, cutting, and intracorporeal suturing/knot tying.[30] The Society of American Gastrointestinal and Endoscopic Surgeons and the American College of Surgeons have designed a Fundamentals of Laparoscopic Surgery (FLS) programme to systematize training and evaluate the cognitive and psychomotor skills required to perform minimally invasive surgery. The psychomotor component of the FLS uses a trainer toolbox that allows testing of five pre-defined level-based tasks: peg transfer, pattern cutting, ligation loop and suturing with intracorporeal as well as extracorporeal knot tying.[28] Similarly, the Association of Laparoscopic Surgeons of Great Britain and Ireland offers a low-cost competency-based training curriculum and formally recognizes those trainees who are able to demonstrate proficiency in a defined set of five laparoscopic tasks by awarding a certificate called LapPass (https://www.alsgbi.org/lappass/).

All low-cost box trainers are fully capable of simulating these five tasks to achieve level-based training, which is one of the prerequisites for ideal simulation (Table 1). This shows that low-cost simulation works and can be as good as expensive delivery systems. The items used to create the simulated tasks are generally cheap and found in grocery stores and novelty shops. Common examples are transfer of small objects between the instruments or bowls; suturing a glove or chicken leg; placing polo mints onto a vertical cocktail stick; cutting a pre-drawn figure from foam/gauze/glove; peeling fruit (grapes, kiwi, and orange) or the skin of a chicken leg; suturing incisions in rubber gloves; reattaching excised fingers from gloves; arranging letters and numbers in the appropriate squares; mesh placement over a defect; and intracorporeal and extracorporeal knots on Penrose drains. etc.[29]

Table 3. Anatomy of low-cost box trainers for laparoscopic surgery

Component of simulator	Low-cost substitute[30,34–37]
Abdominal cavity and wall	Plastic/cardboard storage box/metallic basket, two acrylic plates with hinge joints, plastic document holder case
Port site	Hole in the abdominal wall material (by cutting, drilling or piercing)
Light source	External lighting (in case of transparent box), desk lamp, light-emitting diodes, fluorescent lights, inbuilt webcam, fibre optics
Visualization	Webcam, video camera, digital cameras, tablet/smartphone camera, and small camera mounted on a plastic pipe
Camera monitor	Laptop/desktop computer, TV/video monitor, tablet, or smartphone

In addition, low-cost models can and have been modified innovatively for simulation of the task the trainee needs to improve, including adapting to a 30-degree visual perspective (by emulating the angled laparoscope) and 3D video-surgery training (using virtual reality glasses).[39,40]

What does reliability and validity of surgical simulation training systems mean?

Reliability and validity are concepts used to evaluate the quality of training systems; they indicate how well a system measures something. Reliability is about the consistency of a measure, and validity is about the accuracy of a measure.[41]

Reliability or consistency of a simulator means results are consistent from one measurement to another, e.g. at different times, with different raters, or even with different (but considered equivalent) tasks.[42] It alludes to giving a similar result when two surgeons with a similar level of experience use it, or if the same surgeon uses it twice with no enhancement of skills between the two attempts.[43]

Validity or accuracy is not an inherent characteristic of a system, but it is the degree to which evidence supports the purpose of interpretation and uses of results.[42,44] Various benchmarks have been developed to assess validity:[26,43,45]

- Construct validity: the agreement between a theoretical concept and its assessment (i.e. it can differentiate between an experienced senior surgeon and one who is more junior)
- Face validity: the extent to which it resembles the real world
- Content validity: the extent to which a measurement reflects what it is supposed to measure
- Criteria validity: the extent to which the simulator correlates with the gold standard
- Predictive validity: the extent to which the simulator predicts future performance
- Transfer validity: a gauge of whether the simulator has the effect it proposes to have, i.e. will use of the simulator improve performance while operating, as a consequence of learning.

Most low-cost simulators are reliable (because they are consistent and standardized for what is being taught/practised) and valid (for most of the benchmarks), although perfectionists continue to be sceptical because many of these simulators have not been subjected to rigorous validation studies.[30,46,47]

Summary of reviews and studies of low-cost simulation systems

Simple valid low-cost box-type simulation system are easy to construct and can be made at an economical cost, as little as US$5, as against a present-day commercially available systems starting from US$100.[30,34,35,48–54] Feasibility and effectiveness of guided practice using low-cost simulating systems on the development of surgical/laparoscopic skills by surgeons in a resource-poor setting have been shown in many studies.[18,55–61] Low-fidelity locally made box trainers and high-fidelity virtual reality simulators are equally effective means of teaching basic laparoscopic skills to novice learners.[62–67] In fact, a few studies have found that for basic laparoscopic training, low-fidelity models are superior to high-fidelity models.[68,69] Laparoscopic training on such bench models has been shown to be better and more cost-effective than operating room teaching of trainees.[70,71] Makeshift low-cost simulators can also allow for judging technical skills among participants of varying expertise.[72–74] Low-cost but effective surgical skills laboratories can result in significant savings in the cost of resident training as well as in annual running costs.[37,75,76]

All reviews support the use of simulation for surgical training with the exception of one comparing 30 randomized controlled trials, which concluded that 'While there may be compelling reasons to reduce reliance on patients, cadavers, and animals for surgical training, none of the methods of simulated training has yet been shown to be better than other forms of surgical training.'[77] These authors blamed methodological flaws such as small sample size, non-blinding, confounding comparisons, and disparate interventions as reasons for failing to see a clear benefit for surgical simulation. Others have also blamed poor experimental designs of many published studies, stating that surgical simulation is a 'good idea whose time has come' but 'bad science in the field of medical simulation has become all too common'.[78]

What are the qualities of ideal low-cost simulation systems?

These are well known.[29,79,80] The ideal system should be low cost, low maintenance, small, and light enough to carry anywhere. Its construction must be easy and cheap so as to be accessible to most trainees worldwide. It can be used many times by multiple users. It must provide multiple points of entry to permit a variable distance to the target and a variable angle of action to simulate various tasks and clinical situations of real laparoscopic operations. It should permit the trainee to become familiar with anatomy (to scale, tissue texture and accurate replication of anatomy), equipment, and techniques of surgery being practised so that a learning curve can be avoided as much as possible when the trainee begins to operate on patients? It should allow a range of difficulties so training can be tailored to individuals. It should allow multiple learning strategies with defined outcomes. There should be provision for objective assessment of trainees. It should allow design, testing and use of new clinical equipment. It should permit refresher training of skills for senior trainees, It must have a facility to provide feedback. It should be reliably reproducible and valid. And finally, designing such a system should be part of the training for all surgical trainees because it allows them to better understand the science of the skills to be acquired.[29] There cannot be a more relevant quote with regard to surgical training using simulation than 'Tell me and I forget, teach me and I may remember, involve me and I learn.' (Benjamin Franklin)[81]

How do low-cost simulation systems work for different specialities?

There is more to low-cost simulation systems than developing a few home-made box trainers for laparoscopy. Every speciality has developed its own versions.

Gastrointestinal surgery

The need for simulation in training for laparoscopic abdominal surgery, and especially laparoscopic cholecystectomy, was felt almost as soon as it became popular in the early 1990s, because most general surgeons were not familiar with the required skills. This led to the development of the first training model that allowed surgeons to learn these new motor skills.[82] Almost at the same time, the need was felt for the development an inexpensive model for this purpose, which resulted in design of the first low-cost model.[83] Various surgical societies and departments designed, tested and started using their own low-cost versions of such simulators for teaching common surgeries such as laparoscopic cholecystectomy, laparoscopic appendectomy and laparoscopic inguinal hernia repair.[84] Some of the low-cost simulators in gastrointestinal surgery, using simple commonly available items to simulate these operations are described in Table 4.

Bariatric surgery

Due to the complexity of bariatric procedures, virtual reality has many technical and safety advantages over hands-on training, hence there is a scarcity of low-cost simulators in this particular field of surgery.[90] Although virtual reality simulators offer high-fidelity training replicating entire operations, most of them lack haptic feedback with the use of surgical instruments, and the initial cost of system acquisition is high. Efforts are being made to reduce the cost of bariatric surgery simulation, including the use of porcine perfused tissue models mounted in a low-cost human mannequin, which may cost as little as US$50 once the initial expenses are covered.[91] Jejuno-jejunostomy is one of the most technically demanding minimally invasive surgeries among all bariatric procedures and is deemed to be an appropriate learning model that can be practised easily using porcine tissue.[92] Relatively low-cost innovations include an instrument vibration feedback system, which allows objective assessment of a trainee's growth, and the simulation of blood and smoke while using electro-cautery, which adds to the realistic experience while training.[93,94]

Paediatric surgery

Paediatric surgical trainees need to learn fine tissue cutting and suturing because their patients and their tissues are small. Simulation is also required for rare and complex surgical procedures in paediatric surgery and in neonatal minimally invasive surgery, which require extra-ordinary skills. Two recent reviews have bemoaned the lack of easily available and validated low-cost simulators in this field.[80,95] There is a huge scope for development of low-cost simulation models in paediatric and neonatal surgery, and this need has been met to some extent by wet-lab training, involving animal organs and portable low-cost box trainers that allow real-time tissue feel while cutting and suturing. Such simulations fulfil the local need, are portable and are distributed as 'simulation on demand, made widely available wherever and whenever it is required'.[96] Such inanimate wet-lab training can overcome ethical issues and the exorbitant costs of establishing animal labs.[97,98] Furthermore, several low-cost high-fidelity 3D printed models are being used for simulation of various advanced surgeries. Some of the low-cost simulators in paediatric surgery are described in Table 5.

Plastic surgery

Plastic surgery training demands a unique set of skills in combination with acute awareness of anatomy, planes and elasticity of tissues and the tension and coverage required to close an incision. Microsurgery training demands the use of high-powered magnification, anastomosis or repair of blood vessels and nerves that are less than 1 mm in diameter, and handling of microsutures and use of simulation helps trainees master this craft.[110] A whole gamut of models ranging from bench models, cadaveric animal tissue, cadaveric human tissue, live animal models, and virtual reality

Table 4. Some low-cost simulators in gastrointestinal surgery

Surgical procedure	Simulated with the use of
Laparoscopic cholecystectomy[84]	Narrow rubber tubing and a rubber band represent the cystic duct and cystic artery
Laparoscopic appendectomy[84]	Latex, non-powdered glove, inverted so that the fingers were inside the body of the glove. The fifth finger alone protruded outward, simulating the appendix. The body of the glove, stuffed with two additional latex gloves, served as the cecum. A short length of red rubber band inserted at the base of the simulated appendix represented the appendicular artery
Laparoscopic appendectomy animal ex vivo model[85]	Porcine large and small bowel. The mesentery of the small bowel and the distal end of the lumen are attached to the side wall of the large bowel in such a way that the luminal structure (i.e. small bowel) depicts the appendix and the mesentery represents the mesoappendix
Laparoscopic inguinal hernia repair[84]	A high-resolution photo reproduction of the inguinal region from an actual laparoscopic procedure was placed on firm, foam backing. Inexpensive crinoline fabric (7.5 × 12.5 cm) served as the mesh for simulation. Spermatic cord, was simulated by white tubing that protruded anteriorly from the foam backing
Laparoscopic inguinal/femoral hernia repair[86]	Moulded rubber hernia simulator model of human pelvis
Stoma construction[87]	Tupperware box, porcine bowel and skin from a local abattoir
Abdominal wall model[88]	The model was made using different synthetic materials to represent layers (skin, vinyl sheet; subcutaneous fat, 10 mm soft foam; anterior rectus sheath and muscle, floor mat; posterior rectus sheath, masking tape; peritoneum, clear adhesive tape)
Anal sphincter injuries repair[89]	Condom simulating the rectal mucosa, cotton tissue simulating the internal anal sphincter, and bovine meat simulating the external anal sphincter

Table 5. Some low-cost simulators in paediatric surgery

Surgical procedure	Simulated with the use of
Neonatal thoracoscopic congenital diaphragmatic hernia repair*	Small food box (neonatal chest), elastic neoprene band (diaphragm), cloth (defect), balloon (spleen), cord (bowel), sponge wrapped in kitchen film (lung). All bought from a local store for < US$14
Wet-lab involving animal organs[100,*]	–
Bowel anastomosis	Sheep/goat intestine
Duodenal anastomosis for atresia with luminal discrepancy	Sheep's bladder simulating dilated duodenum and sheep's intestine simulating unused duodenum
Gastrostomy	Sheep's stomach
Emergency airway access[101]	Modified emergency airway cart
Paediatric laryngeal model[102]	Low-cost 3D printing model using silicone
Laparoscopic choledochal surgery[103]	Low-cost 3D printing model
Laparoscopic pyloromyotomy[104]	Low-cost 3D printing model
Paediatric/congenital cardiac surgery[105]	Low-cost 3D printing model
Endoscopic third ventriculostomy[106]	Low-cost 3D printing model
Minimal invasive surgery of oesophageal atresia with trachea-oesophageal fistula repair[107]	Household materials such as corrugated plastic tubes (PVC) of different sizes to simulate ribs, intercostal spaces, trachea and spine, and tubular latex balloons to simulate the oesophagus and lungs to make the basic model. This device was inserted into the thoracic cavity of a rubber dummy simulating a 3 kg new born with a work area volume of 50 mL. Cost of the materials used was US$50
Paediatric intussusception air enema reduction technology[108]	Low-cost mannequin
Laparoscopic Anderson-Hynes pyeloplasty[100,109],*	Low-cost 3D printing model. Sheep bladder (as dilated pelvis) and bowel (as ureter). Inverted oesophago-cardiac junction of goat. Porcine uterus (which is a dilated organ) and aorta

*V. Agarwal, unpublished data.

simulators are used, each with advantages and disadvantages.[111] However, the limitations of simulators for conventional plastic surgery trainees have long been known and can be summarized in one sentence: 'sophisticated haptics which can simulate living tissue are generally not available'.[112] Cost constraints with animal or cadaveric labs and virtual reality models are well known; however, several low-cost bench simulation models have been designed that allow trainees to practice basic generic skills for conventional plastic surgery and microsurgery. Some of these are described in Table 6.

Urological surgery

An erudite and comprehensive up-to-date review on urology simulators has been published recently; this includes evidence-based analysis of all varieties of simulators.[26] Many of these newer models use high-fidelity bench, virtual reality, expensive fresh or Theil embalmed cadaveric systems. Nevertheless, several innovative, hands-on interactive simulation ideas have been incorporated in successful boot camps in the UK and Africa.[134] Some of the low-cost simulators in urology are described in Table 7.

Neurosurgery

Many new approaches and procedures have become possible in neurosurgery since the advent of microscopic and endoscopic techniques. These have prompted both novice and experienced neurosurgeons to learn and master these skills by simulation. Excellent commercial neurotrainer, sinus system and endoscopic models are available; however, these are too expensive for resource-limited situations.[147] To overcome cost constraints, many low-cost neurosurgical simulation models have been built and some of these are described in Table 8. Many excellent 3D and virtual reality models for various neurosurgical (skull base, deep brain stimulation, endovascular) surgeries are increasingly being used. Their cost may be negated, to some extent, if the actual intraoperative time is reduced as a result of practicing on them.[153]

Cardiothoracic and vascular surgery

Surgical simulation is an important educational tool in training cardiothoracic surgeons because the trainees have to become familiar with many high risks and a broad range of open, minimally invasive, and endovascular techniques.[154–155] The Joint Council for Thoracic Surgery Education in the US has been responsible for starting regular boot camps for resident training as well as developing a simulation curriculum with specified modules and assessment tools specific for training programmes.[156,157] The boot camp model has been shown to be useful.[158]

Table 6. Some low-cost simulators in plastic surgery

Surgical procedure	Simulated with the use of
Common fundamental skills in plastic surgery such as suturing, excision, tendon repair, vascular anastomosis, handling of fine instruments[113–117]	Simple skin pads, latex gloves, silicone tubes, plastic/wax models. Fresh tissue surgical simulation in cadavers. Synthetic bench model, prepared with 2.5-mm-thick laminated plates composed of rubber (flattened pure poly-vinyl chloride) reinforced with mesh (polyester and cotton). Open cell/elastic foam model
Split skin graft harvesting/tangential excision of burns[118–121]	Micro-foam taped over 1-L infusion bag. Porcine belly skin taped over 1-L infusion bag kept on specially designed wooden simulator. Partly cooked lasagne sheet taped over 1-L infusion bag
Tendon repair[118]	Porcine foot tendons
Local flap[118,122,123]	Chicken skin moulded over wool/foam. Biosynthetic dressing with self-adhesive backing model of skin. Foam core base overlaid with multiple silicone layers
Basic microsurgical techniques[118,124–128]	Synthetic/bench models include rubber glove/pad model, surgical gauze model, Japanese noodle model, synthetic vessel model, and silicone-based nerve repair model. Glove/chicken thigh vessel on a bench-top microscope using expired/leftover sutures from the operating theatre. Cryo-preserved rat arteries. Model made of embroidery needles placed in clockwise pattern on a diathermy-tip cleaner pad. Polyurethane card model
Cleft lip repair[129]	Low cost 3D printing models, overall manufacturing cost is US$11.43 for the reusable moulding system and US$4.59 for the consumable models
Cleft palate repair[130–132]	Hollow plastic ball (mouth component), conical plastic surgical measuring jug with dense red foam (hard palate), and pink dyed latex (soft palate). These were mounted into the mouth component and adhered with superglue. Low-cost 3D model
Burns education[79]	The 'burn suit'
Endoscopic-assisted breast augmentation[133]	Fibreglass mannequins used for clothing display, anatomic structures such as the ribs, pectoralis major muscle, and pectoralis minor muscle were printed on a T-shirt, and elastic compression garment

Table 7. Some low-cost simulators in urology

Surgical procedure	Simulated with the use of
Adult circumcision, dorsal slit and paraphimosis reduction[135,136]	Model penis which is then covered with simulated bowel in which the two layers of the prepuce are simulated by folding the simulated bowel on itself; and corona is simulated by applying a rubber band
Medical circumcision[137]	Wooden penile model piece; different coloured cloth to simulate two layers of prepuce
Suprapubic catheter insertion[138–140]	Open wooden/plastic box/lunch box (simulating abdomen) covered with urethane foam/ abdominal open and closure pad/covered with gelatine/surgical tape (simulating abdominal skin and rectus sheath) and a party balloon, glove filled with water/3-L bag of irrigation fluid tied with two tourniquets to simulate a full bladder
Suprapubic catheter exchange[134]	Porcine abdominal wall; a segment of small bowel was stitched around a size 16F Foley catheter to form a tract that was anastomosed to a porcine urinary bladder
Open dismembered pyeloplasty[141–143]	Reconfiguring and suturing chicken skin dissected off its muscle to create a model of the ureteropelvic junction. Crop and oesophagus of a chicken. A4 Kraft envelopes, catheter tip syringe filled with 30 mL of air, tape, modelling and party balloons
Laparoscopic dismembered pyeloplasty[144]	Porcine bladder
Laparoscopic renal surgery training/difficult nephron sparing surgeries[145]	Silicone replicas of kidneys using a 3D printer
Robotic pyeloplasty[146]	Silicone cast over 3D moulds (material cost only US$1.32/model)

Table 8. Some low-cost simulators in neurosurgery

Surgical procedure	Simulated with the use of
Hand-eye coordination[148]	Indigenous clay models
Intraventricular surgeries: endoscopic third ventriculostomy, septostomy, and tumour resections[149,150]	Detachable brain models using synthetics
Endoscopic third ventriculostomy[151]	Semi-transparent synthetic cylindrical bottle, gel foam and thermacol creating a brain model, placed in a green coconut
Open/microscopic/endoscopic spinal decompression: laminectomy[148]	Model for laminectomy by sticking an ice-cream spoon, marked with lines, on a piece of foam; task can be to cut between these lines by a Kerrison's rongeur
Ligamentum flavum removal[148]	Passing a Foley catheter, which simulates the spinal cord, through a piece of foam, and the task can be to separate the foam and cut it without injuring the underlying catheter
Open/microscopic/endoscopic drilling[148]	A boiled egg is placed in a piece of foam, and the surgeon drills (with a high-speed drill) the outer shell of the egg, in a paint-brush manner
Deep microsurgical skills in the skull[152]	Mannequin head, water balloons, and clay to mimic actual deep microsurgery in the brain

The complexities of major cardiothoracic and vascular surgeries have meant that the majority of simulators are commercial, expensive virtual reality-based systems.[155] However, many simple, cost-effective, inexpensive, bench models are also available; these may be synthetic (e.g. rubber vessels to simulate coronary anastomosis, models of heart and bypass grafting) or consist of combination of synthetic and biological tissue (e.g. porcine or bovine organs to practice vascular anastomoses, valve suturing, cardiopulmonary bypass, oesophagectomy, video-assisted thoracic surgery and open pneumonectomy, bronchoscopy).[154,159–164]

Reflecting the importance of its frequency and emergency nature, several low-cost models are in use for intercostal tube drainage (ICTD).[165–167] Innovative teaching models for ICTD have also been used in trauma training courses for health workers working in sub-optimal active conflict zones.[168]

Is simulation only useful for teaching technical skills?

Non-technical skills for surgeons (NOTSS) are increasingly being incorporated in surgical training and have been endorsed by many surgical societies.[134,169] These involve situation awareness, decision making, communication and teamwork, and leadership. Previously these were referred to as 'soft skills' to be used intuitively, but the reality is that non-technical skills can enhance or undermine technical performance.[170,171] Surgery was, is and will always remain a team effort; and the importance of team work cannot be overemphasized.[172] Scenario-based low-cost simulations involving audio-visual aids for surgical ward rounds and discussions have largely been used in teaching NOTSS.[173–176] Recently, an innovative simulated functional operating room in situ approach has been found useful in teaching effective interprofessional communication and teamwork skills.[177,178]

How can the benefits of low-cost simulation be translated into good surgical practice?

Some of the flaws of the Halstedian system have been resolved with the use of simulation. However, the next challenge was and is to ensure that skills learned during simulation are translated into real clinical practice.[179] Simulation can be criticized for its inability to sync with real scenarios, low-cost trainers are too abstract, may not be related to real-life procedures and as a result, trainees may not become accustomed to the unfriendly real environment faced preoperatively, intraoperatively, and postoperatively.[180] The stark difference between simulation and an actual real-life emergency requiring an instantaneous response was shown so emphatically in the recent Hollywood movie 'Sully'.[181]

Simulation teaches only the 'how' of surgery; if it is combined with the 'why' of surgery in the form of Peyton's 'Four-Step-Approach' (demonstration, deconstruction, comprehension and performance), then it is more effective for immediate and long-term retention of skills.[182] The authors feel strongly that the best training module is the one that retains the wisdom of traditional methods and at the same time combines that with the newer technologies.

Heavy surgical workloads in developing countries mean longer working hours and more exposure for trainees, but paradoxically it also means less 'dedicated' time for acquiring skills beforehand with the use of simulators. Low-cost portable bench models that are available out of routine duty hours in a space within or near the resident work areas are of great benefit to these trainees because they can practice as and when time becomes available.[183] Low-cost simulation models are needed to provide the starting point of the cascade of surgical training. Once these are in place, further advances and refinements can be made as shown in the sequence depicted in Fig. 1.

Role and impact of 3D in laparoscopic surgery and its low-cost training

The advent of 3D laparoscopy added the dimension of depth, which was lacking in conventional 2D laparoscopy. Many studies, including randomized controlled trials, have shown the benefit of stereoscopic vision, which improves accuracy and learning time in laparoscopic skills for novices.[184,185] This led to an expansion in the use of 3D laparoscopic surgery and the European Association of Endoscopic Surgery (EAES) initiated a consensus development conference with the aim of creating evidence-based statements and recommendations for the surgical community for use of 3D vision in laparoscopy to reduce operative time.[186] More importantly, low-cost laparoscopic training in 3D can be easily provided using visual feedback via a transparent or open top on the laparoscopic box trainer. Such visual feedback helps novice surgeons become familiar with complex laparoscopic motions and helps reduce the learning time required for trainees to carry out laparoscopic surgery.[187,188]

Recent changes and the future for low-cost simulation system for surgical training

The emergence of 3D rapid prototyping, telesurgery (along with telementoring), and patient-specific virtual reality systems has revolutionized simulation-based surgical teaching in recent times. Of these, 3D printed models attracted the maximum interest because of their ability to appear similar to human anatomy.[102] However, the challenges with 3D rapid prototyping, in addition to cost, were and still are the limitations of materials used to create the correct tissue fidelity to provide the necessary accurate haptic feedback, i.e. the 'feel' of the tissues for lifelike manipulation and suture placement.[46,189] Surgeons need exact replication of the viscoelastic properties of tissues, various tissue planes and the physiological tissue response to surgical insults; this, along with cost-effectiveness has to be the future goal of 3D models for simulators.[190]

The importance of incorporation of simulation in surgical training is well accepted, and there have been increasing calls for its attainment.[191,192] However, its implementation has been mainly in the developed world due to cost constraints. Fully fledged incorporation of simulation in surgical training is only possible if its acceptance is accompanied by a paradigm shift in thinking at all levels, from the regulating and funding bodies down to the individual surgeon educators.[17]

Although the idea is a good one, a common criticism of low-cost simulators in the past has been the lack of

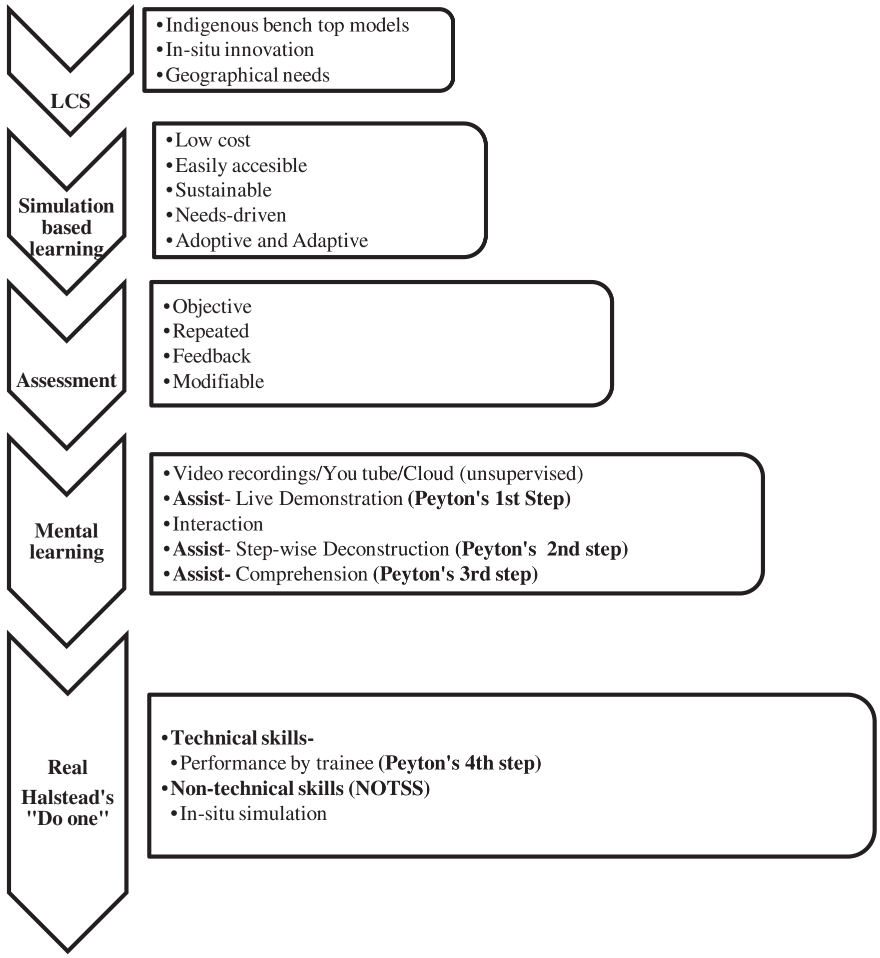

Figure 1. 'Simulation-Reality sequence' depicting the translation of low-cost simulation (LCS) into good practices in reality.

validation by rigorous scientific studies.[44,47,78] This could be easily achieved if the surgeons designing these low-cost simulators were to take the extra small step of scientifically validating them.

Satava, one of the pioneers of surgical simulation, enumerated the challenges in this field 19 years ago: 'refinement of simulation techniques leading to better fidelity, better validation, better incorporation in curriculum, better availability across the world'.[193] A lot of work has been done since then, but further improvement is possible on each of these counts.[194]

Free virtual reality apps for surgical teaching/training have been available for mobile phones for some time, even though their fidelity may be low with regard to the actual feel of the surgical experience.[195] The COVID 19 pandemic has changed the world in many ways. Prestigious universities are now offering many free online courses. More and more free virtual reality content is expected to become available in the future. At the same time, the world is becoming more egalitarian and equitable with wider grass roots access to faster internet broadband and 4G/5G networks. Cost will always be the most important determinant of access to technology, and low-cost alternatives will always be needed for those who train and work in resource-constrained settings.

So what is the final word?

Theoretically, an ideal simulation system is the cheapest model that can provide best learning and longest retention in the shortest time period.[196] However, in practice, such an ideal system cannot be cost-effective in resource-constrained situations because the costs shoot up when an attempt is made to upgrade low-cost training systems with a high-fidelity physical reality experience, augmented with virtual assessment, explanation of tasks, appropriate feedback and prompting. Hence, it is important to understand the limitations of a relatively low-fidelity, low-cost system that is basically meant for less experienced trainees to learn basic skills. After mastering the basics, they can go on to more expensive high-fidelity systems as and when needed as senior professionals to train for advanced rule- and knowledge-based skills.[2,197–199] Once it is realized that that both low-cost low-fidelity and high-cost high-fidelity systems are a continuum – two ends of the same spectrum – and not dichotomous different approaches,[2] then the science and philosophy of low-cost simulation systems becomes easier to understand. The low-cost system is the more easily and widely available cost-effective workhorse that can lay the foundation of basic generic surgical skills, on which the edifice of advanced skills can then be easily constructed with high-cost high-fidelity systems. An ode to these low-cost surgical simulators would be incomplete without saluting the surgeons' ingenuity 'inside' the box and their imaginative thinking 'outside' the box, which led to devising these systems.

Conflict of interest

None declared.

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