A systematic review of low-cost laparoscopic simulators

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Abstract
Background Opportunities for surgical skills practice using high-fidelity simulation in the workplace are limited due to cost, time and geographical constraints, and accessibility to junior trainees. An alternative is needed to practise laparoscopic skills at home. Our objective was to undertake a systematic review of low-cost laparoscopic simulators.

Method A systematic review was undertaken according to PRISMA guidelines. MEDLINE/EMBASE was searched for articles between 1990 and 2014. We included articles describing portable and low-cost laparoscopic simulators that were ready-made or suitable for assembly; articles not in English, with inadequate descriptions of the simulator, and costs £1500 were excluded. Validation, equipment needed, cost, and ease of assembly were examined.

Results Seventy-three unique simulators were identified (60 non-commercial, 13 commercial); 55 % (33) of non-commercial trainers were subject to at least one type of validation compared with 92 % (12) of commercial trainers. Commercial simulators had better face validation compared with non-commercial. The cost ranged from £3 to £216 for non-commercial and £60 to £1007 for commercial simulators. Key components of simulator construction were identified as abdominal cavity and wall, port site, light source, visualisation, and camera monitor.

Conclusion The models described provide simple and affordable options for self-assembly, although a significant proportion have not been subject to any validation. Portable simulators may be the most equitable solution to allow regular basic skills practice (e.g. suturing, knot-tying) for junior surgical trainees.

Keywords Laparoscopic · Simulation · Trainer · Trainee · Model · Low-cost

The use of laparoscopic surgery has become widely established in clinical practice, with the acquisition of laparoscopic skills now essential for surgical trainees. The technical skills required are, however, distinct from those needed for open surgery; depth perception is impaired due to visualisation on a two-dimensional screen, there is limited tactile feedback, and long laparoscopic instruments create a fulcrum effect and amplify tremor. There is a significant learning curve associated with laparoscopic surgery, and these skills cannot be easily learnt using the traditional apprentice model of surgical training [1].

Simulation is widely regarded as the way forward, and its use has been shown to improve laparoscopic surgical skills in trainees [2, 3]. Simulation offers the opportunity to improve technical skills in a structured, low-pressure environment outside of the operating theatre without risk to patient safety [4]. Different methods of simulation have been described, ranging from high-fidelity virtual reality systems and animal models to low-fidelity box trainers. Box trainers generally have a less realistic interface and...
are designed for the practice of generic skills required for laparoscopic surgery, such as instrument handling, cutting, and intracorporeal suturing. Virtual reality simulation uses computer-generated graphics and tactile feedback to recreate the operating environment, facilitating practice of procedural-specific skills as well as generic laparoscopic skills [5, 6]. Virtual reality systems are, however, very cost prohibitive and may be inaccessible to many trainees for regular personal use [7]. With the implementation of the European Working Time Directive, opportunities for surgical trainees to gain operative experience in the workplace have also become more limited [8]. A low-cost alternative is needed for trainees to be able to practise and develop their laparoscopic skills outside the workplace. Our objective was to undertake a systematic review of low-cost laparoscopic simulators suitable for home use.

Methods

A systematic review was undertaken according to PRISMA guidelines [9] to define the properties of low-cost laparoscopic simulators. MEDLINE and EMBASE databases were searched for articles on low-cost laparoscopic simulators published between January 1990 and August 2014. The search terms used were (laparoscopic or thoracoscopic or urological or gynaecological or gynaecological), (simulator or simulation or trainer or training), and (low-cost or home-made or inexpensive or DIY or cheap). Relevant articles from the search were identified by their titles and abstracts; the full paper was then assessed for inclusion. Reference lists for relevant articles were also examined to identify additional studies not identified by the original search.

Articles included were those describing low-cost laparoscopic simulators, which were ready-made or suitable for self-assembly. Articles not written in English, with inadequate descriptions of the simulator, and costs of >£1500 were excluded. The simulators described were categorised into commercial (commercially available or intended for commercial use) and non-commercial (intended for self-assembly). Validation, cost, equipment required, and ease of assembly were examined. For ease of comparison, simulator prices in other currencies were converted into British Pound Sterling using the exchange rate on 16 August 2014. We examined whether any form of validation had been described by the authors. The face validity of each simulator was also rated based on predefined criteria for the abdominal cavity and visualisation, giving a score between 0 and 6 (see Table 1).

Results

The results of the search are summarised in Fig. 1. 73 unique simulators were identified from 71 articles: 60 were non-commercial (Table 2) and 13 were commercial (Table 3); 55 % (33) of non-commercial trainers were subject to at least one type of validation compared with 92 % (12) of commercial trainers (Table 4). Commercial simulators were already constructed and ready to use, whereas non-commercial simulators required sourcing and self-assembly of materials. The key components required for non-commercial simulator construction were identified as abdominal cavity and wall, laparoscopic port site, light source, visualisation, and camera monitor.

Abdominal cavity and wall

Materials used to simulate the abdominal cavity aimed to prevent direct vision of the laparoscopic instruments; 68 % (41) of non-commercial simulators utilised off-the-shelf components for the abdomen, whilst 32 % (19) required a custom-made box. The commonest off-the-shelf component was a plastic storage box for the abdominal cavity, with the box lid serving as the abdominal wall [10–23]. Cardboard boxes were also commonly utilised [24–31].

Laparoscopic port site

The majority of non-commercial simulators (97 %, 58) required creating a hole in the abdominal wall material (by cutting, drilling or piercing) for the laparoscopic port site. Instruments could then be inserted directly into the cavity or through a trocar. Use of a flexible covering material, such as neoprene [13, 18], and ring reinforcement around the port site [13, 32–35] were also described as methods to increase simulator authenticity.

Primary light source

An adequate light source was required to visualise the interior of the abdominal cavity. External lighting was used for 38 % (23) of non-commercial simulators, particularly where boxes were made from a translucent material [11, 12, 17, 21] or had open sides [36–38]. This was useful in cost reduction, as no additional equipment was required to provide lighting in these cases. The built-in light source from the laparoscope itself provided lighting for 17 % (10) of simulators, desk lamps for 13 % (8), and light-emitting diodes (LED) for 8 % (5). Other lighting methods described included fluorescent lights [18, 34, 39], webcam inbuilt [40, 41], fibre optics [42], and torchlight [30].
Visualisation and camera monitor

Visualisation for non-commercial simulators was most commonly achieved using a webcam (37%, 22) or laparoscope (22%, 13). Other cameras types described included video cameras [29, 34, 43–45], digital cameras [24, 28, 46, 47], and tablet/smartphone cameras [30, 31, 37, 38]. Direct vision (full [10, 48] or unilaterally blinded [26]) and mirrors [23, 36] were non-electronic methods of visualisation described. Where electronic visualisation was used, a laptop computer, video monitor, tablet, or smartphone were prerequisite and not included in any cost estimates; this was true of both commercial and non-commercial simulators; 40% (24) of models described use of a laptop/desktop computer screen and 38% (23) described using a television or video monitor.

Cost

Forty-six percentage (26) of non-commercial and 54% (6) of commercial simulators provided a figure for cost. For non-commercial, this was the cost of materials and assembly (e.g. custom-made parts); for commercial simulators, the cost represented the current or intended retail price. The cost ranged from £3 to £216 for non-commercial simulators and £60 to £1007 for commercial simulators.
| Paper | Cost | Undergone validation | Face validity score | Abdominal cavity | Abdominal wall | Port sites | Light source | Visualisation | Camera monitor |
|-------|------|----------------------|---------------------|-----------------|----------------|-----------|-------------|---------------|---------------|
| 1991 Sackier (USA) [32]/ 1998 Chung (USA) [56] | – | Yes | 6 (A3 B3) | Custom-made black perspex box; rubber sheet sides | Black perspex | Hole; rubber gasket; trocar | Laparoscope | Laparoscope | Unspecified |
| 1992 Majeed (UK) [33] | – | No | 5 (A2 B3) | Metal frame | Black perspex double sheet | Hole; rubber disc; trocar | External lighting | Laparoscope | Video monitor |
| 1992 Mughal (UK) [10] | £75 | No | 4 (A1 B3) | Opaque plastic storage box | Clear perspex lid | Hole; plastic floor tile; trocar | 20 W strip lamps | Laparoscope (or direct vision) | Video monitor |
| 1995 Gue (Australia/NZ) [43] | – | No | 3 (A1 B2) | Small coffee table/TV stand | Black plastic sheet; wire mesh | Hole; trocar | Table lamp | Video camera | TV screen |
| 1996 Shapiro (USA) [57] | – | Yes | 6 (A3 B3) | Custom-made plastic box | Flexible plastic covering | Hole; trocar | Laparoscope | Laparoscope | Video monitor |
| 2001 Hasson (USA) [58] | – | Yes | 6 (A3, B3) | Custom-made metal box | Rubber sheet | Hole; rubber sheet; trocar | Laparoscope | Laparoscope (or camcorder) | Video monitor |
| 2003 Lee (UK) [44] | – | No | 4 (A1 B3) | Computer game station (tiered table) | Table top | Anchored trocar | Lamp; external lighting | Camcorder | TV screen |
| 2004 Pokorny (NZ) [11] | NZ $200 (£101.69) | No | 4 (A2 B2) | Translucent plastic storage box | Rubber foam sheet over plastic lid | Hole; rubber foam sheet | External lighting | Spy cam; plastic pipe | TV screen |
| 2005 Beatty (UK) [12] | £50 | No | 2 (A1 B1) | Clear plastic storage box | Clear plastic lid | Hole | External lighting (bright room/ lamp) | Webcam | Unspecified |
| 2005 Blacker (UK) [24] | – | No | 3 (A1 B2) | Desk drawer | Cardboard | Hole | Desk lamp/strip lamps | Webcam | Desktop computer monitor |
| 2005 Chung (USA) [25] | – | Yes | 2 (A1 B1) | Cut-out cardboard box | Cardboard | Hole | External lighting | Webcam | Laptop |
| 2005 Ricchiuti (USA) [13]/ Bell (USA) [14] | US $360 (£215.70) | No | 6 (A3 B3) | Plastic storage box | Plastic lid; plastic sheet | Reinforced hole; neoprene; trocar | Laparoscope/ halogen lights | Laparoscope | TV screen |
| 2005 Sharpe (USA) [48] | US $185 (£110.84) | Yes | 0 (A0 B0) | Custom-made plastic box | Clear plastic lid | Hole | External lighting | Direct vision | N/A |
| Paper                | Cost          | Undergone validation | Face validity Score | Abdominal cavity | Abdominal wall | Port sites | Light source | Visualisation | Camera monitor |
|----------------------|---------------|-----------------------|---------------------|------------------|----------------|------------|--------------|---------------|----------------|
| Chandrasekera (UK) [26] | –             | Yes                   | 1 (A1 B0)           | Cut-out cardboard box | Cardboard       | Hole; trocar | External lighting | Direct vision (unilaterally blinded) | N/A |
| Do (USA) [59]         | –             | Yes                   | 5 (A2 B3)           | 2 large plastic basins | Plastic basin base | Hole; trocar | Lamp         | Video camera   | Laptop         |
| Griffin (UK) [45]     | –             | Yes                   | 2 (A0 B2)           | Custom-made wooden frame | Thin wooden sheet | Hole       | Desk lamp     | Camcorder     | TV screen       |
| Nataraja (UK) [60] / Nataraja (UK) [61] | –             | Yes                   | 3 (A0 B3)           | Perspex box       | Darkened perspex lid | Hole       | Laparoscope   | Laparoscope   | TV screen       |
| Robinson (USA) [36]   | US $50 (£29.96) | Yes                   | 0 (A0 B0)           | Custom-made metal box | Metal lid       | Hole; unspecified covering material | External lighting | Mirrors | Mirrors |
| Dhariwal (India) [42] | –             | Yes                   | 5 (A2 B3)           | Custom-made plastic box | Black plastic lid | Hole; rubber gasket; trocar | Fibre-optic light source | Laparoscope | Video monitor |
| Haveran (USA) [46]    | –             | Yes                   | 2 (A0 B2)           | Adjustable height posts; wooden sheet | Neoprene; plexiglass frame | Hole       | Xenon light source | Camera         | TV screen       |
| Martinez (Mexico) [34] | –             | No                    | 5 (A2 B3)           | Custom-made semi-cylindrical metal box | Metal | Hole; rubber covering | Fluorescent lamp | Video camera; mirror | TV screen |
| Clevin (Denmark) [62] | –             | Yes                   | 5 (A2 B3)           | White plastic wash tub | Plastic | Hole; trocar | Laparoscope | Laparoscope | Unspecified |
| Dennis (UK) [35]      | £150          | No                    | 4 (A2 B2)           | Custom-made wooden box | Plaster of paris | Hole; rubber grommet | Bicycle light | Camcorder | Camcorder screen |
| Mir (India) [27]      | –             | No                    | 4 (A1 B3)           | Cardboard box      | Cardboard       | Hole       | Laparoscope   | Laparoscope   | TV screen       |
| Raptis (UK) [15]      | £27           | No                    | 3 (A2 B1)           | Opaque plastic box | Plastic | Hole; trocar | Night-vision camera | Computer monitor/TV screen | |
| Sparks (USA) [39]     | US $150 (£89.87) | No                   | 3 (A1 B2)           | Plywood box; foam board; foam hinged lid | Plywood | Hole | Fluorescent light | Webcam | Laptop |
| Al-Abed (UK) [16]     | £40           | No                    | 6 (A3 B3)           | Plastic storage box | Foam; latex gloves | Hole; trocar | Halogen light | Webcam; plastic pipe | Laptop |
| Helmy (Egypt) [40]    | –             | Yes                   | 4 (A2 B2)           | White foam food storage box | Foam box lid | Hole; trocar | Webcam in-built | Webcam | Laptop |
| Pawar (India) [47]    | –             | No                    | 3 (A1 B2)           | Plywood box box    | Plywood | Hole | Tube light | Digital camera | TV screen |
| Year | Author (Country) | Cost | Undergone validation | Face validity Score | Abdominal cavity | Abdominal wall | Port sites | Light source | Visualisation | Camera monitor |
|------|------------------|------|----------------------|---------------------|-----------------|----------------|------------|-------------|--------------|---------------|
| 2009 | Jain (India) [63] | –    | Yes                  | 6 (A3 B3)           | Custom-made box  | Elastic rubber sheet | Hole; trocar | Laparoscope | Laparoscope | Video monitor |
| 2009 | Singh (UK) [28]  | –    | No                   | 4 (A2 B2)           | Shoebox         | Cardboard       | Hole; trocar | Desk lamp   | Digital camera | TV monitor/computer monitor |
| 2010 | Jaber (Saudi Arabia) [64] | US $41 (£24.57) | No                   | 2 (A1 B1)         | Metallic wire basket; acrylic sheet | Rubber mouse pad | Hole | External lighting | Webcam | Laptop |
| 2010 | Rabie (Saudi Arabia) [29] | –    | No                   | 3 (A1 B2)           | Half large plastic water container; plywood board | Plastic | Hole; trocar | Light bulb | Video camera | TV screen |
| 2010 | Rivas (Spain) [17] | –    | Yes                  | 4 (A2 B2)           | Translucent plastic storage box | Plastic | Reinforced hole; trocar | External lighting | Micro-camera; tube | TV screen |
| 2010 | Oliver (UK) [65]  | –    | Yes                  | 3 (A1 B2)           | Cardboard box   | Cardboard lid   | Hole | Desk light | Webcam | Laptop |
| 2010 | Ramalingam (India) [66] | –    | Yes                  | 5 (A2 B3)           | Custom-made white box (unspecified material) | Box lid | Hole; rubber sheet; trocar/tube | Laparoscope | Laparoscope | TV screen |
| 2011 | Alfa-Wali (UK) [30] | –    | Yes                  | 3 (A1 B2)           | Shoe box        | Cardboard       | Hole | Torch | Mobile phone camera | Phone screen |
| 2011 | Khine (UK) [18]   | £60  | No                   | 5 (A3 B2)           | Translucent plastic storage box | Foldable plastic lid | Hole; neoprene; trocar | Fluorescent light | Webcam | Laptop/desktop computer |
| 2011 | Kobayashi (USA) [20] | US $100 (£59.92) | Yes                  | 3 (A2 B1)         | Translucent plastic storage box | Plastic lid | Hole; rubber strip | External lighting | Webcam | Laptop |
| 2011 | Kiely (Canada) [19] | C $100-160 (£54.98-£87.97) | Yes                  | 3 (A2 B1)         | Translucent plastic storage box | Plastic lid | Hole; trocar | External lighting | Webcam (various brands) | Laptop/desktop computer (various brands) |
| 2012 | Afuwape (Nigeria) [67] | US $34 (£20.37) | No                   | 2 (A1 B1)         | Recycled plastic liquid container; plywood board | Plastic | Hole | External lighting | Webcam | Laptop |
| 2012 | Bahsoun (UK) [31]  | –    | Yes                  | 3 (A3 B1)           | Cut-out cardboard box; polystyrene | Cardboard | Hole; trocar | External lighting | iPad camera | iPad screen |
| 2013 | Akdemir (Turkey) [68] | –    | Yes                  | 4 (A1 B3)           | Custom-made plastic box | Plastic | Hole; trocar | Laparoscope | Laparoscope | Video monitor |
| 2013 | Hennessey (Australia) [69] | –    | No                   | 2 (A1 B1)           | None             | Laptop lid      | Trocar; string; skirt hanger | External lighting | Webcam | Laptop |
| Paper                          | Cost        | Undergone validation | Face validity Score | Abdominal cavity                | Abdominal wall                        | Port sites | Light source | Visualisation | Camera monitor |
|-------------------------------|-------------|----------------------|---------------------|----------------------------------|---------------------------------------|------------|--------------|---------------|----------------|
| Moreira-Pinto (Portugal) [21] | €33.67 (£26.99) | Yes                  | 4 (A3 B1)           | Translucent plastic storage box  | Cut-out plastic lid; rubber sheet      | Hole; trocar | External lighting | Webcam        | Laptop         |
| Omokanye (Nigeria) [41]       | –           | No                   | 4 (A2 B2)           | Plywood box                      | Box lid                               | Hole; foam piece | Camera in-built; light bulb | IR CCTV Camera | TV screen      |
| Ruparel (USA) [37]            | US $5 (£3.00)     | Yes                  | 1 (A0 B1)           | Ring binder                       | Ring binder                           | Hole       | External lighting | iPad camera     | iPad screen    |
|                               | US $5 (£3.00)     | Yes                  | 2 (A1 B1)           | Cut-out cardboard box             | Cardboard                             | Hole       | External lighting | iPad camera     | iPad screen    |
| Smith (UK) [70]               | US $100 (£59.92)    | No                   | 4 (A2 B2)           | Plastic crate, plywood and cork sheet | Plastic                              | Hole; trocar; plastic rings | LED lamp       | Webcam         | Laptop         |
|                               | US $130 (£77.89)    | No                   | 5 (A3 B2) | Upgraded version: add plywood frame and foam pads to port site | Plastic                             | Hole; trocar | LED lamp       | Webcam         | Laptop         |
| Wong (USA) [71]               | US $309 (£185.14)    | Yes                  | 4 (A2 B2)           | Custom-made hard plastic box     | Vinyl membrane glued to plastic frame | Hole; trocar | LED strip      | Miniature CCD camera | Video monitor  |
| Beard (USA) [22]              | US $85 (£50.93)     | Yes                  | 3 (A2 B1)           | Translucent plastic storage box  | Plastic lid                           | Hole; flexible material cover | External lighting | Webcam         | Laptop         |
| Escamirosa (Mexico) [38]      | –           | No                   | 2 (A1 B1)           | Clear plastic document case       | Plastic                              | Hole       | External lighting | Smartphone or tablet camera | Video monitor  |
| Walczak (Poland) [23]         | US $51 (£30.56)     | No                   | 3 (A2 B1)           | Translucent plastic storage box  | Opaque plastic lid                    | Hole; rubber sheet; metal washer; trocar | LED light bulb | Mirrors        | Mirrors        |
|                               | US $99 (£59.32)     | No                   | 5 (A3 B2) | Translucent plastic storage box | Opaque plastic lid                    | Hole; rubber sheet; metal washer; trocar | LED light bulb | Webcam        | Home computer |
The cost of laparoscopic equipment (instruments and laparoscope) was not included in cost estimates for non-commercial simulators. However, a number of articles suggested that used or expired disposable instruments could be obtained from the operating department at no cost to the trainee [16, 23–26, 39, 40, 44]. Alternatively, they could also be obtained by donation from laparoscopic equipment manufacturers [15, 20, 26]. Electronic devices for visualisation (video monitor, laptop computer, tablet/smartphone) were not included in cost estimates for non-commercial simulators. Laparoscopic equipment and visualisation monitors were also not consistently included for commercial simulator model packages [49–52].

### Face validity

Commercial simulators had better face validity than non-commercial simulators, with a median score of 5 compared to 3 (maximum 6). Commercial simulators tended to utilise higher-fidelity visualisation equipment, with a median visualisation score of B3 compared with B2 for non-commercial simulators. For the abdominal cavity, there was comparable face validity, with both groups having a median score of A2.

### Discussion

Cost will undeniably be a key factor in the accessibility of a simulator model. Many articles omitted cost estimates, so there is difficulty in making a true cost comparison between commercial and non-commercial simulators available. Although there is an overlap in the price range, non-commercial models appear to be able to achieve a lower cost than commercial ones, with the lowest reported figure being $5 (£3) compared to $100 (£60) for a commercial model [37, 53]. This difference could be due to commercial models factoring in a profit margin and assembly fee in addition to the value of the raw materials. Moreover, commercial models will usually include
expensive laparoscopic instruments in the cost, which could potentially be obtained cost-free when self-assembling [16, 23–26, 44].

Non-commercial models commonly utilised off-the-shelf components—a potentially a cost-reductive strategy, as custom-made parts could incur a greater expense. In particular, the use of a translucent plastic box provided a sturdy frame and utilised external lighting, negating the need for an additional light source inside the box [11, 12, 17, 21]. Visualisation using a webcam and computer offered an inexpensive solution, as they can be obtained cheaply. With computer ownership being widespread [54], it can be assumed that most trainees have access to a computer at home. Many trainees may also own a tablet computer. Tablet-based simulation could provide a video feed more comparable in quality to a laparoscope than a budget webcam [31]. Using a tablet or smartphone, where the screen and camera are on the same device, may also be easier to assemble. However, adjustment of camera position would be more difficult.

Commercial simulators, although seemingly costlier in comparison, do have the advantage that they come assembled and ready to use, with more models having undergone some form of validation. However, the appropriateness of the validation methods undertaken are not easily assessed, and only models from established industry suppliers appear to have undergone more extensive validation [50, 55]. In terms of face validity, commercial simulators largely seem to have better face validity, particularly as laparoscopes are more frequently used for visualisation, allowing realistic image quality and camera motion. A laparoscope may be difficult to obtain at a reasonable cost; an alternative may be to use a small camera mounted on a plastic pipe, which also allows adjustment of the operative field view [11, 16, 17]. The ideal simulator would have a highly realistic user interface and allow development of both the technical and non-technical skills required for laparoscopic surgery. The simulators examined in this review chiefly aim to develop basic laparoscopic skills such as instrument handling and cutting; therefore, a highly realistic user interface, as in virtual reality simulators, may be superfluous to requirements. However, use of lower-fidelity simulators does not preclude the development of non-technical skills. For example, the simulator could be incorporated into an operating theatre environment with other team members present, where trainees could be observed and assessed on emergency or elective scenarios.

Of course, simply having access to a simulator does not equate to improvement in surgical skill. Regular use of the trainer with feedback from a supervisor would be ideal. Simulator training could take place during the normal working day with allocated practice time, or this could be done at leisure at home.

Conclusion

The models described provide simple and affordable options for self-assembly, although a significant proportion has not been subject to any validation. Whilst simulation cannot replace operating theatre experience, portable simulators may be the most equitable solution to allow regular basic skills practice (e.g. intra-corporeal suturing, knotting) for junior surgical trainees.

Compliance with ethical standards

Disclosures Miss. Mimi M Li and Mr. Joseph George have no conflicts of interest or financial ties to disclose.

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