Virtual Reality (2021) 25:491–510
https://doi.org/10.1007/s10055-020-00469-z

ORIGINAL ARTICLE

Simulation-based surgical training systems in laparoscopic surgery: a current review

Minsik Hong[1] · Jerzy W. Rozenblit[1,2] · Allan J. Hamilton[2]

Received: 23 August 2019 / Accepted: 8 September 2020 / Published online: 17 September 2020

Abstract
Simulation-based training has been widely used in medical education. More specifically, various systems for minimally invasive surgery training have been proposed in the past two decades. The aim of this article is to review and summarize the existing simulation-based training systems for laparoscopic surgery in terms of their technical realizations. Forty-three training systems were found and analyzed. These training systems generally consist of training tasks, a visualization interface, and an instrument interface. Three different approaches—physical, virtual, and augmented reality—to implement visualization interfaces are discussed first. Then, haptic feedback, performance evaluation, and guidance methods are summarized. Portable devices to enable at-home training and instrument tracking technologies to support visualization, evaluation, and guidance are also presented. Based on survey of the relevant literature, we propose several recommendations to design the next-generation training systems in laparoscopic surgery. Novel guidance and assessment schemes with augmented reality visualization are recommended to design an intelligent surgical training simulator. This intelligent simulator enhances the training procedure and ultimately improves the patient safety.

Keywords Surgical training · Laparoscopy · Virtual reality · Augmented reality · Haptic guidance · Objective assessment

1 Introduction

The top priority goal of health care should be patient safety. Preventing medical errors is one of the solutions to achieve this goal. Unfortunately, Makary and Daniel estimated that medical errors were the third crucial cause of death in the USA in 2016 (Makary and Daniel 2016). Simulation-based training can be one of the effective education methods not only to promote patient safety but also to prevent medical errors. Simulation training is widely used in various fields such as aviation, military, industry, and medicine. It has become common in medical education. According to (Ziv et al. 2000; Kunkler 2006), several benefits of medical simulation are commonly accepted:

- minimize ethical issues,
- improve educational experience,
- provide learner-centered education and teacher-enabled environment,
- provide patient risk-free environment,
- enable users to learn and practice new techniques,
- enable performance assessment.

In surgery, trainees should complete training curriculums and get a certificate before performing surgery in the operating room. As an advanced technique, laparoscopic surgery started as early as in 1987 (Lau et al. 1997) requires more training. Unlike in a traditional open surgery, in laparoscopy surgeons use long and thin instruments with an endoscopic camera which displays the operating field view on a two-dimensional (2D) monitor. Due to this, issues such as the lack of depth perception, less tactile force feedback, and restricted vision require the mastery of specific skill set prior to commencing surgery on patients. Therefore, well-defined

✉ Minsik Hong
mshong@email.arizona.edu

Jerzy W. Rozenblit
jr@ece.arizona.edu

Allan J. Hamilton
allan@surgery.arizona.edu

1 Department of Electrical and Computer Engineering, University of Arizona, 1230 E. Speedway Boulevard, Tucson, AZ 85721, USA

2 Department of Surgery, University of Arizona, 1501 N. Campbell Avenue, Tucson, AZ 85724, USA

simulation training procedures such as the fundamentals of laparoscopic surgery (FLS) (Soper and Fried 2008) and corresponding physical training platforms were proposed for surgical residents and medical students. Robotically assisted minimally invasive surgery has also become common in a wide range of procedures. For robot-assisted surgery skill training, trainees can use actual robotic systems or virtual reality (VR) simulators (e.g., da Vinci skill simulator and Mimic dV-Trainer) (Abboudi et al. 2013). Here, we focus on the standard MIS surgery training systems (typically, for laparoscopy). Therefore, we refer the readers to (Abboudi et al. 2013; Bric et al. 2016; Sridhar et al. 2017) for a detailed survey on robotic surgery training systems.

Various simulation-based training systems for laparoscopic surgery were introduced by both many academic and private-sector entities. These systems range from simple and low-cost devices to sophisticated, complex but expensive devices. In this paper, a variety of existing training systems are presented mainly from an engineering perspective with clear implications on their clinical utility. We have conducted an extensive literature survey, and therefore, the articles cited represent all relevant works that contain technologies or concepts for laparoscopic surgery skill training. Based on the survey results, we present several recommendations for design and implementation of the state-of-the-art laparoscopic surgical trainers. Finally, our present research approaches in this domain are briefly introduced to elucidate the proposed recommendations.

The literature review was undertaken mainly using PubMed and Google Scholar. The search terms associated with *laparoscopic surgery*, *minimally invasive surgery*, *surgical training*, *training device*, *simulator*, *simulation*, *survey*, and *review* were firstly considered to extract key terms. The following were extracted as the key terms after the first-round survey.

- Physical reality, virtual reality, and augmented reality
- Haptic feedback, force feedback, tactile feedback, and tactile sensation
- Performance assessment, evaluation, metrics, and proficiency
- Guidance and haptic guidance
- Instrument tracking
- Portable, take home, and at home

The second-round survey was conducted to investigate existing training devices using the extracted key terms with the following keywords: laparoscopic surgery, minimally invasive surgery, and surgical training. After the two steps survey with screening, 43 training systems were found and analyzed. The survey results are discussed in the following section.

2 Technical realizations

Simulation-based training in laparoscopic surgery basically consists of training tasks, a visualization interface to display the training tasks, and an instrument interface which uses real surgical instruments or mimics the real instruments. Figure 1 illustrates this simplified model. Most of the existing training systems have these three components. Also, additional components can be added to provide a better training environment. In this section, the various technical realization methods to implement each component are presented.

2.1 Training tasks

Various simulated tasks have been proposed for a trainee to practice surgical skills effectively. They form the basis for skill acquisition. In Oropesa et al. (2011), a classification of basic tasks is presented. The existing simulation-based training systems use at least one of the tasks listed below:

- *Navigation* A surgeon can only see a limited area captured by an endoscope and displayed on a 2D monitor. The image of the anatomy through the endoscope is different than the view seen in open surgery. Therefore, in training, it is required not only to learn how to navigate an endoscope properly but also how to adapt its position and orientation to the new surgical scene. To this end, a camera navigation task was proposed as one of the fundamental exercises. In addition to camera manipulation, instrument navigation is impeded by the lack of depth perception. Moreover, the movement of the instruments is non-intuitive due to the fulcrum effect. (The camera navigation also suffers from the same issue.) Therefore, instrument navigation tasks such as touch a target point using an instrument were defined as well.

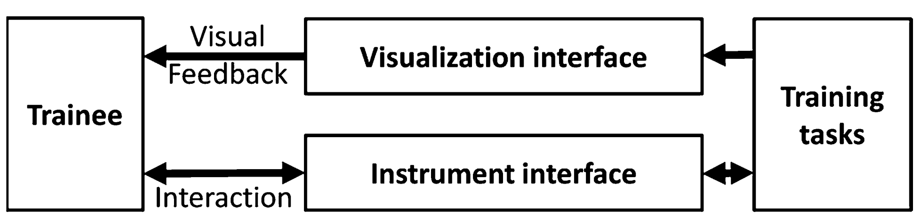

Fig. 1 Simplified model of simulation-based training in laparoscopic surgery

- *Object manipulation* To overcome hand–eye coordination issues, the tasks such as grasping an object (e.g., picking a rubber ring up) and pulling an object (e.g., stretching an elastic band) were designed. These tasks mimic grasping and pulling tissue in an actual surgery.
- *Object transfer* Tasks such as peg transfer and needle passing are designed to practice bimanual manipulation (i.e., transfer of an object from one instrument to another).
- *Cut-related* Cutting and dissecting skills are required to perform actual surgery. By using laparoscopic scissors and simulated setups such as gauze (e.g., pattern cutting), a trainee can acquire this set of fundamental surgical skills.
- *Suture-related* Due to the limited degree of freedom in the movement of the instruments with depth perception limitations, suturing and knot tying are the most difficult tasks in laparoscopy. The suture-related tasks such as intracorporeal knot tying were defined to mimic actual surgical tasks.

Based on these (and similar) basic tasks, comprehensive practice exercises can be designed to prepare standard training tasks such as fundamentals of laparoscopic surgery (FLS) or to provide simulated surgical scenarios such as cholecystectomy.

2.2 Visualization interface: Physical versus virtual, versus augmented reality to display tasks

To implement the training tasks, three different approaches are employed. Each method has its own advantages and disadvantages.

2.2.1 Physical reality (PR)

The simulated training tasks are designed using real materials such as plastic, metal, wood, and fabric. Also, actual surgical tools can be used during the training sessions. To mimic the appearance of the human abdomen, simple box trainers have been widely used (Soper and Fried 2008). The benefits of the box trainers are as follows:

- The systems provide realistic tactile feedback.
- A trainee can use real surgical instruments with an endoscope.
- Cost-effective solutions are available. (Most of such systems are relatively inexpensive.)

However, there are several disadvantages:

- The systems cannot provide objective assessment.
- The initial setup may be cost-effective. However, recurrent costs are accrued to purchase consumable training materials (e.g., fabric gauze, thread, etc.).
- It is challenging to provide realistic, simulated surgical scenarios.
- An instructor is needed to guide a trainee.

To provide a better training experience with physical reality simulators (PRSs), computer-based capabilities which provide objective assessment results were proposed (e.g., CELTS (Stylopoulos et al. 2004), EndoVis (Escamirosa et al. 2015), Blue Dragon (Rosen et al. 2002), and Chmarra et al. (Chmarra et al. 2010)). However, regardless of the objective assessment features, these computer-enhanced systems still need a human instructor to teach surgical skills. In addition, training setup replacement incurs additional costs. For the computer-enhanced systems, performance evaluation and instrument tracking methods are required. These are presented in Sects. 2.4 and 2.6, respectively.

2.2.2 Virtual reality (VR)

Instead of using real materials, training tasks can also be represented by computer graphics technologies. Virtual reality simulators (VRSs) provide various training scenarios including simulated surgical exercises. To render surgical scenarios, accurate, three-dimensional (3D) anatomical models based on medical images such as MRI and CT are used (Alcaniz et al. 2003; Cakmak et al. 2005; Moreno et al. 2012). Also, various objective assessment results are provided to a trainee after finishing a particular task. However, it is challenging to provide realistic tactile feedback when using virtual environments. The key VRSs are listed as follows:

- Commercial devices: LapMentor (Andreatta et al. 2006; Zhang et al. 2008; Salkini et al. 2010), LapSim (Duffy et al. 2005; Våpenstad et al. 2013), LapVR (Iwata et al. 2011), Lap-X (Kawaguchi et al. 2014), MIST-VR (Wilson et al. 1997), SIMENDO (Verdaasdonk et al. 2006), VSOne (Cakmak et al. 2005), and Xitact LS500 (Schijven and Jakimowicz 2002)
- Non-commercial devices: GeRTiss (Alcaniz et al. 2003), LapSkills (Acosta and Temkin 2005), SmartSIM (Khan et al. 2017), VBLaST (Maciel et al. 2008), and VESTA (Tendick et al. 2000)

To develop these sophisticated VR simulators, advanced computer graphics technologies should be applied. Given 3D anatomical models, surgical tool and soft tissue interactions should be considered based on organ-force models (Basdogan et al. 2007). Also, deformation and collision detection algorithms should be applied to provide a more realistic surgical scene representation. We refer the reader to (Jiménez et al. 2001; Meier et al. 2005; Teschner et al. 2005; Ruthenbeck and Reynolds 2013; Wu et al. 2015; Zhang et al. 2018) for technical details of deformation models for surgical simulation and its collision detection schemes with software development tools. For instance, VESTA and LapSkills used geometric surface models for 3D reconstruction. Among various deformation models, spring–mass models and finite elements methods (FEM) were applied for most of non-commercial devices. In case of commercial devices, most published papers focus only on the effectiveness of the proposed system by conducting human subject studies rather than presenting details of technical realizations.

In Maciel et al. (2008), physics-based modeling and the corresponding collision detection schemes were presented to demonstrate VR rendering of the FLS tasks (i.e., peg transfer task, pattern cutting, suturing, ligating loop). For instance, rigid body dynamics and mesh–mesh collision detection were applied for the peg transfer task. For the suturing task, needle–tissue interactions were realized by considering contact force, physics-based constraints, and the mass–spring model of deformation. The collision detection and its corresponding force model can also be used for artificial tactile feedback given a specific instrument interface.

Finally, texture mapping and lighting effects are also important consideration in order to provide more realistic visualizations of surgical scenes (e.g., bleeding). Hardware acceleration and novel algorithms will be necessary to enhance it.

2.2.3 Augmented reality (AR)

Augmented reality (AR) is a visualization technology that facilitates the overlay of computer-generated virtual objects on a live camera image. Two types of displays—head-mounted displays (HMDs) and 2D monitors—can implement AR technology (Milgram et al. 1995). In laparoscopic surgery simulators, typically, a 2D monitor with a camera is used to implement AR training environments (Van Sickle et al. 2005; Botden et al. 2008a, 2009; Loukas et al. 2013; Lahanas et al. 2015), called here augmented reality simulators (ARSs). For instance, in an ARS, a trainee may use real surgical instruments with physical materials (e.g., artificial tissue) while performing a task, for example instrument navigation, clipping, and peg transfer. In the meantime, virtual environments are overlaid to express splendid surgical scenes such as human anatomies (e.g., ProMIS Van Sickle et al. 2005; Botden et al. 2008a, 2009). Also, ProMIS can be the computer-enhanced PRS as well. The main advantage of ProMIS is to provide realistic haptic feedback (due to using real surgical instruments with physical materials) and graphical effects using AR overlays to mimic actual surgical scenes.

In Loukas et al. (2013), an instrument navigation task as well as an interaction between a real object and a virtual object was implemented using AR overlays. A virtual sphere was overlaid on a live camera image for a trainee to touch this object using a real surgical instrument. The instrument movement was traced using a vision-based instrument tracking method as presented in Sect. 2.6. In Lahanas et al. (2015), virtual training environments for instrument navigation, peg transfer, and clipping were implemented under the conventional box trainer setup. They used open source libraries—ARToolkit (https://www.artoolworks.com) for AR rendering and Bullet (https://bulletphysics.org) for simulation of physical behaviors.

In Botden and Jakimowicz (2009 and Rahman et al. (2013), the authors introduced several other computer-enhanced simulators as ARSs. However, these simulators (e.g., Blue dragon, CELTS, and LTS3e) which were already described in Lahanas et al. (2016) did not use AR technologies to represent tasks. Therefore, we conclude that these simulators are PRSs in this article.

Mixed reality (MR)—"merging of real and virtual worlds" (Milgram and Kishino 1994)—can also be used to represent training environments. We may consider MR as a superset of AR. However, there are several working definitions of MR such as "accordance with the Reality-Virtuality Continuum," "synonym for AR," "combination of AR and VR," and "a stronger version of AR" (Speicher et al. 2019). One of the key MR features is the real-time interaction between virtual and real objects. To provide a better training experience, it would be recommended to consider "degree of interaction" (e.g., manipulate MR environments, haptic tactile feedback), "level of immersion" (e.g., "how immersed the user feels"), and novel MR devices (e.g., HoloLens) based on a conceptual framework presented in Speicher et al. (2019).

2.3 Instrument interface with haptic feedback

In Westebring-van der Putten et al. (2008), the authors described "haptic perception" with three simplified models to describe the corresponding surgery types (e.g., open surgery, minimally invasive surgery, and robotic surgery). Haptic feedback generally consists of tactile feedback related to touch interaction and kinesthetic feedback related to position and movement. In laparoscopic surgery training, two different types of haptic feedback, i.e., natural and artificial, can be employed based on the task representation methods (that are PR, VR, and AR).

PRSs provide natural haptic feedback by using real or artificial tissues. However, VRSs cannot provide haptic feedback without a technical solution, specifically by designing a proper interface. Most commercial VRSs (e.g., LapMentor (Andreatta et al. 2006), LapSim (Duffy et al. 2005;

Våpenstad et al. 2013), LapVR (Iwata et al. 2011), VSOne (Cakmak et al. 2005), and Xitact LS500 (Schijven and Jakimowicz 2002)) provide this type of feedback mechanism base on their own technical realization way. For instance, VSOne has a haptic input device (5 degrees of freedom; 20 cm × 20 cm × 20 cm working range) which has a haptic grip controlled by the in-house developed force feedback software. Artificial haptic feedback is also accomplished by using commercial haptic devices such as PHANToM (Tendick et al. 2000; Maciel et al. 2008; De Luca et al. 2016). To attach surgical instrument onto the haptic devices, custom "plug-and-play" interfaces were designed. The force is generated based on collision detection results.

One of the most important technologies for the artificial haptic feedback is haptic rendering (Salisbury et al. 2004) which models reaction force exhibited by the haptic device. Examples include the knot tying model (Wang et al. 2005), models of catheter and blood vessels (Gao et al. 2012), and tool–tissue interactions described in Basdogan et al. (2004) and Chen et al. (2011) to provide more realistic haptic feedback for VRSs.

In ARSs, the two types of haptic feedback described above can be provided by using both real and virtual environments. However, both haptic interface and haptic rendering are required to generate artificial feedback for the interactions between surgical instruments (or their models) and virtual objects. Presently, there is no reported ARS that supports artificial haptic feedback.

In Westebring-van der Putten et al. (2008), Van Der Meijden and Schijven (2009) and Overtoom et al. (2018), the in-depth survey of haptic feedback was presented. We refer the reader to those publications for more technical details.

2.4 Performance evaluation

Most computer-enhanced PRSs, VRSs, and ARSs provide objective assessment methods. Based on specific surgical proficiency metrics, the simulators can evaluate trainees' performance and provide feedback. In this subsection, such evaluation methods are discussed.

2.4.1 Assessment metrics

The advantage of using a computer-based training environment is the ability to gather a set of quantitative measures based on which training outcomes and proficiency levels can be objectively established. A plethora of such metrics exist (Cotin et al. 2002; Oropesa et al. 2011, 2013; Escamirosa et al. 2015). Below, we summarize the ones which are most frequently used in computerized assessments.

- *Most commonly use metrics* completion time and path length
- *Distance-related metrics*: angular path; depth to indicate a distance traveled by an instrument along the insertion axis; orientation that represents amount of instrument rotation
- *Velocity-related metrics* idle time to indicate inactive period; average velocity; maximum velocity
- *Acceleration-related metrics* average acceleration and motion smoothness
- *Volume-related metrics* economy of volume; energy of volume
- *Area-related metrics* angular area; economy of area; energy of area
- *Force-related metrics* average force; maximum force; average torque; maximum torque
- *Collision-related metrics* the number of collisions (e.g., hitting objects by an instrument); tissue damage;
- *Error-related metrics* the number of errors; accuracy
- *Others* economy of diathermy; bimanual dexterity

Most PRSs simply show several instrument movement-related metrics such as completion time, idle time, path length, and average speed using tables or graphs. Some VRSs show more metrics such as the number of collisions. Also, most commercial VRSs provide the history of evaluation metrics for long-term assessment of each individual user with scores. The scoring methods are presented in the following section.

2.4.2 Scoring and classification

Displaying numerical values is an efficient method to represent performance. However, obtaining a "score" is often more intuitive for a trainee in assessing his or her performance than reviewing a list of evaluative numbers. The simplest, yet effective way, is to have a system (or an evaluator) provide a pass/fail grade after a task has been performed. Conventionally, human experts (supervisors) would assign a score based on assessment criteria by observing the entire training task or by using recorded videos (Fraser et al. 2003; Vassiliou et al. 2005; Andreatta et al. 2006; Botden et al. 2009; Hardon et al. 2018). Rater-based scoring (i.e., where a designated individual scores the participant's technical proficiency) was usually reserved for specific, well-described, generalized tasks such as laparoscopic skills (Hasson et al. 2001; Fraser et al. 2003; Vassiliou et al. 2005; Soyinka et al. 2008; Hardon et al. 2018) or suturing tasks (Botden et al. 2009). Even though assessment criteria are designed for "objective evaluation," the involvement of designated expert raters introduces issues of validation, intra- versus inter-rater variability, as well as more subjective issues such as bias of conflicts of interest which can all cloud validity of the scoring process.

Unlike methods that rely on human raters, computer-based methodologies can deliver more objective assessment (Cotin et al. 2002; Stylopoulos et al. 2004; Soyinka et al. 2008; Ahmad et al. 2013). Various scoring methods have been developed using metrics such we had listed above (completion time, path length, and motion smoothness) to design proper and generalizable methods of assessing proficiency. For instance, lower values of some metrics such as the path length and motion smoothness indicate a better performance. Means and standard deviations of metrics performed by experts were used as references to generate a normalized score, i.e., the z-score. The z-score allows us to provide a relative measure by comparing a trainee's values to the experts' ones (Cotin et al. 2002). Also, an artificial neural network (ANN)-based scoring system was applied to SmartSIM (Khan et al. 2017). When experts performed a specific task ("learning mode"), instrument movements and the corresponding metrics such as completion time, path length, and number of damage incidents were collected to create a benchmark. When a trainee performed ("evaluation mode"), his/her performance metrics were compared to those generated by experts. Also, instrument movements of experts were used to train the ANN and the trainee's movements were fed to the network to evaluate the movement by calculating the Euclidian distance between an estimated position of the ANN and the actual instrument position. Detailed analyses of video recordings of technical maneuvers have been proposed in Oussi et al. (2018). For this video analysis, feature detection and optical flow algorithms were applied to track instrument movements. The path length and completion time which were derived by the video analysis can be used for scoring as presented in Cotin et al. (2002).

Finally, the assessment of technical proficiency is quickly gaining importance in a number of areas of clinical undergraduate medical education (e.g., entrustable professional activities as proposed by the American Association of Medical Colleges) as well as in postgraduate medical training, where technical proficiency assessment based on medical simulations is becoming an important and requisite part of residency requirements (e.g., fundamental laparoscopic skills and fundamental endoscopic skills) for advancement or completion of residency. However, once again a number of biases are introduced when the assessment of such task-related proficiency (e.g., designations as "novice," "intermediate," and "expert") is left to human raters. Therefore, the introduction of computerized assessment allows for quantitative and reproducible parameters to be used across all medical institutions and to ensure that this designation has well-defined technical milestones. This also makes it easier to ensure the public's safety if one set of standards is used across the country. To this end of developing quantifiable determinations of proficiency levels, a machine learning-based method (e.g., ANN) and computer-driven classification methods (e.g., linear discriminant analysis (LDA), fuzzy inference system (FIS), and support vector machines (SVM)) were presented in Ahmad et al. (2013) and Oropesa et al. (2014), respectively. The classification methods could use various metrics from both experts and trainees. For instance, fuzzy rules for a FIS can be designed based on human knowledge, e.g., if a path length is short and time is short, then proficiency is expert. Using experts' generated metrics, the rules can be optimized by artificial neural networks. Given a trainee's performance metrics, the developed FIS can estimate the trainee's proficiency. The machine learning-based assessment will enable mimicking the evaluation process of a human rater.

2.5 Guidance

Any learning and skill acquisition process benefits from guidance in forms that are most appropriate for the task at hand. For instance, handwriting assistance systems (Teo et al. 2002; Kim et al. 2013) teach users how to write foreign characters by providing force guidance using a haptic interface. In simulation-based training, computer-based devices can provide instant feedback to instill proper behaviors. This can be accomplished instantly, in real time as training undertake a specific learning task, using visual, audio, force, or the combination thereof, guidance methods.

2.5.1 Visual guidance

In laparoscopic surgery, operative scenes captured by a monoscopic endoscope are transmitted to a high-definition monitor screen to provide the ability for visuospatial tracking and eye–hand coordination of instruments in real time. Most computer-enhanced PRSs and VRSs mimic this visual feedback mechanism. For the visual guidance, some simulators can augment additional information over a captured live image or a digitally generated, synthetic virtual image. In some devices, a trainee can see textual instructions while practicing (e.g., ProMIS or Lap-X). Some simulators (e.g., LapMentor and Hernansanz et al. 2012) can overlay guidance trajectories to assist a trainee in maneuvering an instrument. Similarly, useful visual cues, for instance, an arrow to indicate force direction (Horeman et al. 2012) can be rendered on the display monitor. Also, an extra display which presents a guidance information can be used to enhance visual guidance (Hardon et al. 2018).

Finally, core technologies of image-guided surgery can be applied for this visual guidance. Modern image-guided surgery schemes have been widely proposed in the last two decades. By registering preoperative data such as MRI and CT images to patient anatomy with instrument tracking, a computer-assisted system can display guidance information, e.g., instrument position, 3D virtual organs (Cleary and

Peters 2010). AR rendering schemes to overlay a 3D virtual organ as well as visual cues (e.g., arrows, trajectories) can allow trainees to enhance surgical skills given a simulated setup such as a mannequin and a box trainer (Liao et al. 2010; De Paolis and De Luca 2019). For this, it is recommended to consider the corresponding registration, localization, and tracking technologies.

2.5.2 Audio guidance

Audio alerts have been commonly used to inform potential risks in real world. Sometimes, this audio warning is more intuitive than displaying visual information. For example, modern auto vehicles generate warning sounds when a hazardous situation such as low tire pressure and low fuel is faced. In simulation-based training systems, instead of displaying guidance text, it is possible to use guidance audio. For instance, ProMIS provides audio cues as well as visual guidance information. Also, by changing sound effects, a trainee can recognize that the movement is incorrect so that the simulator teaches surgical skills (Hernansanz et al. 2012).

2.5.3 Force guidance

Several devices have been proposed to provide force-based guidance for robotic training in laparoscopic surgery. Using force generated by motors, the system can restrict an instrument motion (Shamsunder and Manivannan 2008; Chen et al. 2016) or minimize a deviation from a desired instrument trajectory (Prada and Payandeh 2005; Hernansanz et al. 2012), while a trainee practices surgical skills such as instrument navigation and needle passing. For this force guidance, virtual fixtures (Bowyer et al. 2014) which are "collaborative control strategies" to assist or regulate a motion given a constraint geometry were generally introduced. Also, vibration has been used to issue a warning whenever a trainee deviates to a predetermined threshold from a desired instrument trajectory (Howard and Szewczyk 2014). Finally, "hand-over-hand" guidance concepts have been used to mimic how an expert surgeon holds a trainee's hand to teach surgical skills. In Tagawa et al. (2013) and Yang et al. (2013), recorded experts' motions were used to provide proper force guidance given a VR training setup. The main advantage of the force guidance is to providing intuitive and active navigation. Therefore, it allows a trainee to improve surgical skills.

2.6 Instrument tracking

Instrument tracking is a means of monitoring visuospatial proficiency and data collection for objective performance assessment. In the guidance context, sensing the position of an instrument is a sine qua non condition for implementing guidance methods such as those discussed above. Tracking is also mandatory when VRSs or ARSs use the real surgical instruments. In Chmarra et al. (2007), various tracking systems for objective assessment are discussed. Here, we review the two main different ways to track instruments.

2.6.1 Vision-based tracking

Vision-based methods should be accomplished by using cameras. Using at least one camera with color marker(s), a simulator recognizes the instrument movements. One of the main benefits of using cameras is that it is possible to both track the instrument and use motion analysis software to examine instrument movements. This is possible when using real surgical instruments which have very thin and light markers without any structural modifications. This is the key reason why several PRSs and ARSs use vision-based methodologies. In Loukas et al. (2013), the authors proposed an instrument tracking method only using a standard endoscopic camera to provide AR training environment. Unlike using a single camera, multiple (e.g., two or three) cameras were used to track the instrument in Botden et al. (2008a), Chen et al. (2013), and Escamirosa et al. (2015). In this case, an extra camera is needed for visual feedback because the cameras were assigned for the tracking.

2.6.2 Sensor-based tracking

A specialized device is used for the sensor-based tracking. This device such as a light-emitting diode (LED) ball is on the instrument or by employing the tip of the instrument. A specific type of a tracking system, e.g., radio frequency, visual recognition, or LEDs, will then localize and register the position of an instrument in the three-dimensional training space, sampling at a predetermined frequency.

Generally, the vision-based tracking method only tracks the tip of the instrument. It is, however, quite challenging to detect or track states more complex that the 3D coordinates of the tip. For example, often we need to know a grasper's open/close condition and its orientations. Unlike the vision-based method, sensor-based tracking methods are "richer" in that they can monitor many more degrees of freedom. Many computer-enhanced PRSs use mechanical equipment (e.g., TrEndo (Oropesa et al. 2011)) with a couple of electromagnetic sensors to capture instrument motions (Wilson et al. 1997; Rosen et al. 2002; Debes et al. 2010; Oropesa et al. 2011; Kawaguchi et al. 2014). Also, several VRSs use commercial haptic devices with real surgical instruments (Tendick et al. 2000; Alcaniz et al. 2003; Maciel et al. 2008). Most of commercial VRSs have their own tracking methods. To detect the open/close state of the real surgical grasper, additional sensors such as an infrared (IR) and flex sensors can be installed on the handle (Chen et al. 2013; Lahanas et al. 2015). For sensor-based tracking, the most important consideration is the need to install additional physical components in the system. This should not hinder both the actual surgical instrument's movement and trainee's manipulation.

2.7 Portable versus standing trainers

Most simulation-based trainers were designed as standing devices so that it is inconvenient to relocate the trainers. Portable trainers are mainly low-cost and lightweight devices which do not provide sophisticated capabilities often found in the standing/fixed trainers. There are several ways to implement portable trainers.

- Portable box trainer platforms (Adrales et al. 2003; Debes et al. 2010, 2012; Martins et al. 2015; Yiasemidou et al. 2017) with a laptop PC
- Camera-less box trainers (Sharpe et al. 2005; Chandrasekera et al. 2006) with low-cost training materials such as sugar cube and beans
- Tablet PC-based box trainers (Ruparel et al. 2014; Thinggaard et al. 2015; Yoon et al. 2015; De Loose and Weyers 2017)
- All-in-one box trainers (Hruby et al. 2008; Korndorffer et al. 2012)
- Homemade box trainers with a web camera (Beatty 2005; Jaber 2010)
- A portable VRS (Zahiri et al. 2016)
- A commercial gamming platform to practice instrument navigation task (Bokhari et al. 2010)

Clearly, the benefit of the portable trainers is that the users can practice at home.

2.8 Summary

Various technical realization methods have been discussed for laparoscopic surgery training simulators by analyzing existed simulators. Visualization interface and instrument interface are essential components for all simulators. Additional components such as guidance and assessment interfaces can be added to provide better training experience as shown in Fig. 2. Forty-three simulators were selected to discuss each component from the key literature. Task representation, haptic feedback, guidance, performance evaluation, and instrument tracking methods of each simulator are summarized in Table 1. Only few simulators have guidance interface and use AR environments. Several enhanced simulators have an assessment interface to evaluate performance objectively. Performance evaluation metrics and scoring methods of each simulator are summarized in Table 2.

According to the type of visualization interface, PRSs, VRSs, and ARSs are classified. Figure 3 shows a comparison chart among them. The key benefit of PRSs is to provide realistic training environments with real surgical instruments. Also, computer-enhanced PRSs are good to practice fundamental surgical skills such as instrument navigation, object transfer, and suturing by providing objective assessment. VRSs can provide surgical scenarios for trainees to practice overall surgical procedures. However, it is required to enhance rendering technologies for realistic visualization and haptics to mimic natural tactile feedback. Even though there are few reported ARSs, augmented reality and mixed reality have a potential to enhance training experiences. AR rendering schemes can be applied to provide guidance and assessment information. Also, core haptic tactile feedback technologies for VRSs and ARSs can be applied for robotic surgery platforms (haptic feedback is still an open and challenging problem in robotic surgery).

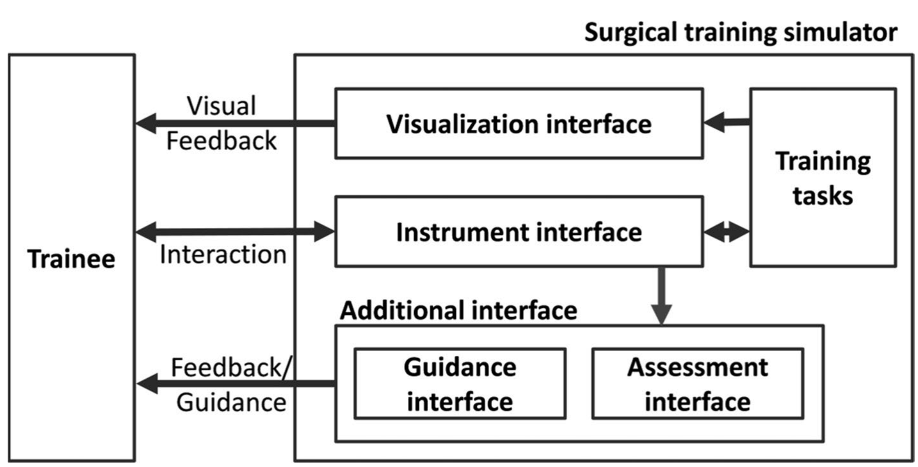

Fig. 2 Simplified model of the enhanced laparoscopic surgery training simulator

Table 1 Tabulated summary of surgical trainers from the key literature in this survey

References	System name	Tasks					PR vs. VR vs. AR	Haptic feed-back	Guidance			Perfor-mance evaluation	Instru-ment tracking	Portability
		Camera naviga-tion	Object-related	Cut-related	Suture-related	Surgical sce-narios			Visual	Audio	Force			
Botden (2008, 2009)	ProMIS		●	●	●		PR AR	NF	●	●		●	VT	
Stylopoulos (2004)	CELTS		●	●	●		PR	NF				●	ST	
Soyinka (2008)	LTS3e		●	●	●		PR	NF				●		
Escamirosa (2015)	EndoVis		●	●	●		PR	NF				●	VT	
Rosen (2002)	Blue Dragon		●	●	●		PR	NF				●	ST	
Chmarra (2010)			●	●	●		PR	NF				●	ST	
Fraser (2003)	MISTELS		●	●	●		PR	NF				●		
Hardon (2018)	ForceSense		●	●	●		PR	NF	●			●	ST	○
Horeman (2012)					●		AR	NF	●			●		
Loukas (2013), Lahanas (2015)			●	●			AR					●	VT	
Tendick (2000)	VESTA	●	●	●		●	VR	AF					ST	
Verdaasdonk (2006)	SIMENDO	●	●	●	●	●	VR					●	ST	○
Duffy (2005), Våpenstad (2013)	LapSim	●	●	●	●	●	VR	AF				●	ST	
Iwata (2011)	LapVR	●	●	●	●	●	VR	AF				●	ST	
Maciel (2008)	VBLaST		●	●	●		VR	AF					ST	
Schijven (2002)	Xitact LS500		●	●	●	●	VR	AF				●	ST	
Chen (2013)			●				VR					●	VT	
Alcaniz (2003)	GeRTiss					●	VR	AF					ST	
Acosta (2005)	LapSkills	●	●	●	●	●	VR	AF				●	ST	
Salkini (2010), Zhang (2008)	LapMentor	●	●	●	●	●	VR	AF				●	ST	
Tagawa (2013)						●	VR		●		●	●	ST	
Wilson (1997)	MIST-VR		●	●	●	●	VR					●	ST	
Moreno (2012)		●	●			●	VR						ST	
Khan (2017)	SmartSIM	●	●	●		●	VR					●	ST	
Kawaguchi (2014)	Lap-X	●	●	●	●	●	VR		●			●	ST	○
Cakmak (2005)	VSOne	●	●	●	●	●	VR	AF				●	ST	
Hernansanz (2012)							VR		●	●	●	●	ST	○
Ruparel (2014)	iTrainers		●	●	●		PR	NF						●
Yiasemidou (2017)	Pyxus		●	●	●		PR	NF						●
De Loose (2017)			●	○	○		PR	NF						●

Table 1 (continued)

References	System name	Tasks					PR vs. VR vs. AR	Haptic feed-back	Guidance			Perfor-mance evaluation	Instru-ment tracking	Portability
		Camera naviga-tion	Object-related	Cut-related	Suture-related	Surgical sce-narios			Visual	Audio	Force			
Debes (2010, 2012)	D-box		●	●	○		PR	NF						●
Chandrasekera (2006)			●	●	○		PR	NF						●
Zahiri (2016)	PortCAS		●				VR							●
Bokhari (2010)							VR							●
Yoon (2015)	iTrainer		●	○	○		PR	NF						●
Korndorffer (2012)	Joystick Simscope		●	●	●		PR	NF						●
Adrales (2003)			●	●	●		PR	NF						●
Beatty (2005)			●	●	●		PR	NF						●
Sharpe (2005)			●	○	○		PR	NF						●
Hruby (2008)	EZ trainer		○	○	○		PR	NF						●
Thinggaard (2015)	TABLT		●	●	○		PR	NF						●
Jaber (2010)			○	○	○		PR	NF						●
Martins (2015)	White box		○	○	○		PR	NF						●

●—support; ○—possible; PR—physical reality; VR—virtual reality; AR—augmented reality; NF—natural haptic feedback; AF—artificial haptic feedback; ST—sensor-based tracking; VT—vision-based tracking

Table 2 Tabulated summary of performance evaluation from the key literature in this survey

References	System name	Metrics											Scoring	Classification
		Completion time	Path length	Distance-related	Velocity-related	Acceleration-related	Area-related	Volume-related	Force-related	Collision-related	Error-related	Others		
Botden (2008, 2009)	ProMIS	●	●			●							H	
Stylopoulos (2004)	CELTS	●	●	●		●							C	
Soyinka (2008)	LTS3e	●			●						●		H	
Escamirosa (2015)	EndoVis	●	●	●	●	●	●	●						
Rosen (2002)	Blue Dragon	●	●						●					
Chmarra (2010)		●	●	●	●	●	●	●						●
Fraser (2003)	MISTELS	●			●						●		H	
Hardon (2018)	ForceSense	●	●						●		●		H	
Horeman (2012)		●							●					
Loukas (2013), Lahanas (2015)		●	●								●			
Tendick (2000)	VESTA													
Verdaasdonk (2006)	SIMENDO	●	●							●				
Duffy (2005), Våpenstad (2013)	LapSim	●	●	●							●	●	C	
Iwata (2011)	LapVR	●	●								●		C	
Maciel (2008)	VBLaST													
Schijven (2002)	Xitact LS500	●	●								●			
Chen (2013)		●												
Alcaniz (2003)	GeRTiss													
Acosta (2005)	LapSkills	●	●	●		●			●	●	●	●		
Salkini (2010), Zhang (2008)	LapMentor	●	●								●			
Tagawa (2013)		●	●											
Wilson (1997)	MIST-VR	●	●		●						●			
Moreno (2012)														

Table 2 (continued)

References	System name	Metrics											Scoring	Classification
		Completion time	Path length	Distance-related	Velocity-related	Acceleration-related	Area-related	Volume-related	Force-related	Collision-related	Error-related	Others		
Khan (2017)	SmartSIM	●	●	●						●				
Kawaguchi (2014)	Lap-X	●	●											
Cakmak (2005)	VSOne	●	●											
Hernansanz (2012)		●	●											
Ruparel (2014)	iTrainers													
Yiasemidou (2017)	Pyxus													
De Loose (2017)														
Debes (2010, 2012)	D-box													
Chandrasekera (2006)														
Zahiri (2016)	PortCAS											●		
Bokhari (2010)														
Yoon (2015)	iTrainer													
Korndorffer (2012)	Joystick Simscope													
Adrales (2003)														
Beatty (2005)														
Sharpe (2005)														
Hruby (2008)	EZ trainer													
Thinggaard (2015)	TABLT													
Jaber (2010)														
Martins (2015)	White box													

●—explicitly presented in the cited paper; H—human-involved scoring; C—computerized scoring;

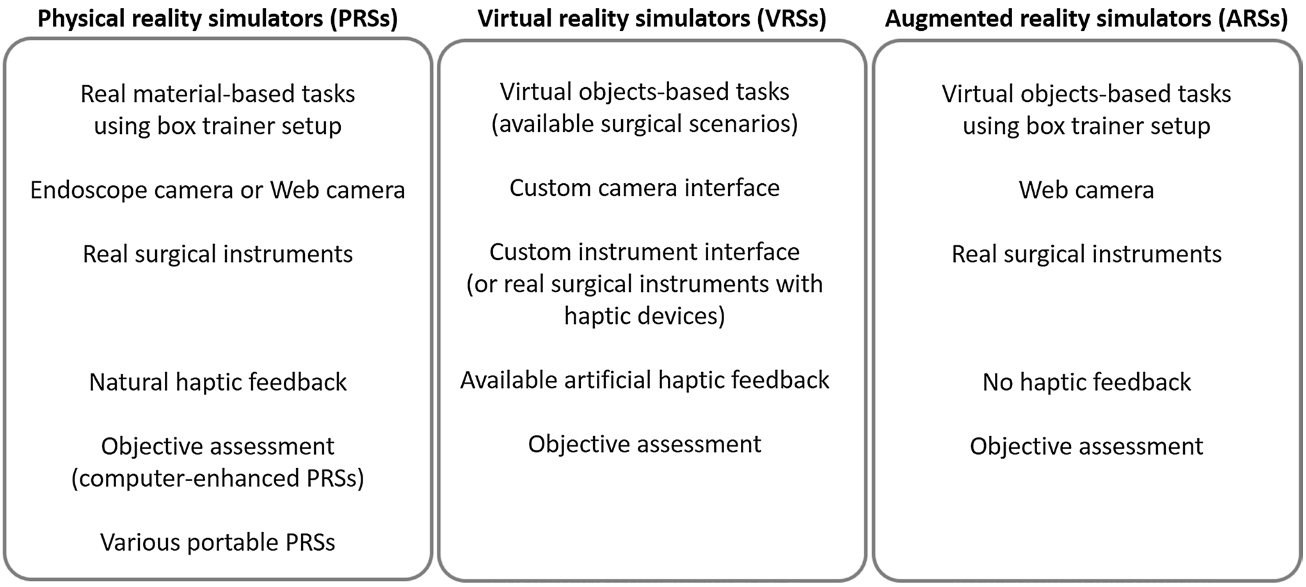

Fig. 3 Comparison chart among PRSs, VRSs, and ARSs

3 Recommendations to design better training systems

During the past two decades, various simulation-based training systems for laparoscopic surgery have been proposed, developed, and put into practice. Thanks to technological developments, additional features can now be considered to augment such trainers. In this section, several recommendations are proposed for design of the next-generation systems, based on the survey results and our own experience.

3.1 Guide a trainee like a human instructor

When a human instructor teaches a trainee in real life, he or she can provide a visual demonstration before practice, verbal instruction, while a task is being performed, and feedback after a practice session that is generated based on a set of relevant evaluation metrics. In general, an instructor can guide a trainee directly through physical contact in manual skill training (e.g., sports or handwriting/calligraphy). For instance, a human coach can grasp a trainee's hand and show how to hit a ball during a tennis lesson. This is just one kind of mentor–apprenticeship models. In this apprenticeship mode, there are typically three steps—pre-instruction session, the actual practice session with instant coaching, and post-feedback review session.

In laparoscopic surgery training, most computer-enhanced PRSs mainly focus on objective assessment to support the post-feedback session. The simulator can display an assessment report so that a trainee recognizes where his or her present performance may lie within the spectrum of proficiency, or in terms of reaching a defined endpoint in skill acquisition. Most of the commercial VRSs can provide video instructions to mimic the pre-instruction session. However, only very few systems can offer instant guidance while performing a task. We posit that to provide most effective training environments, guidance methods must be incorporated in training devices. AR rendering to overlay guidance information such as text instruction, recommended paths, and visualization effects of the progress with force feedback to teach a trainee how to manipulate surgical instruments can be one of the examples.

Most objective assessment metrics are linked directly to the basic movements of the surgical instruments. In order to evaluate more complex manipulations such as suturing or cutting, new evaluation metrics or methodologies must be developed that take into account such complex motions and output relevant measures. For instance, a machine learning technology is one of the potential candidates to mimic human experts' evaluation process. Surgical movements, particularly those of an expert surgeon are notoriously hard to calibrate. For instance, speed alone is not the key indicator. Learned smoothness of movement (or economy) of movement to avoid superfluous actions and to keep operative time to a minimum might be a better measure of performance. This is an outstanding arena in which we can apply machine learning and AI-based analysis. Just as such methods have been required to analyze in depth which baseball players have the sought after qualities and characteristics in hitting, pitching, and catching (Lewis 2004) to aid a team in addressing its weakness, so these very same methods can also be used to help identify what strengths and weakness individual surgical trainees have.

3.2 Proficiency-based learning

In Gallagher and O'Sullivan (2011) and Spruit et al. (2013), the brief concept of proficiency-based learning was presented. First, proficiency should be defined and validated to set an achievable goal. Then, adaptive training that enables a trainee to make progress according to his or her own pace is suggested based on the defined proficiency. For this adaptive training, a partial task can be provided instead of performing the entire task for a novice. Also, various training tasks can be used based on the proficiency objective (Soyinka et al. 2008). For the assessment, the actual performance and the achievable goal can be compared so that the training system could suggest a next training task.

For instance, a proficiency-based curriculum was proposed for the FLS tasks in Ritter and Scott (2007). The allowable errors and recommended completion time were stipulated based on expert surgeons' performance. Similarly to that method, a simulator can suggest achievable "mini-tasks" (e.g., completion time and path length) to guide a trainee's progress in a stepwise fashion toward the desired outcome.

3.3 Appropriate haptic feedback

According to reported studies (Botden et al. 2008b; Chmarra et al. 2008; Panait et al. 2009), haptic feedback generally allows a trainee to perform accurately and effectively in complicated tasks such as suturing and knot tying. In the basic skill training, these studies reported that haptic feedback is less important. Therefore, assessing where and when to enhance the training with haptic feedback must be determined.

In PRSs, natural and tissue-specific haptic feedback is provided without an additional expense. However, guidance and objective assessment methods should be considered to design the next-generation simulators. For instance, force sensor-based evaluation and guidance methods were presented and validated under physical reality setup in Hardon et al. (2018).

Unlike the physical reality simulators, VRSs require a method to generate artificial haptic feedback based on computational models. As discussed in the previous section, knot tying (Wang et al. 2005) and instrument–tissue interactions (Basdogan et al. 2004; Chen et al. 2011) were modeled to support VRSs. Also, several commercial training systems simulate haptic feedback using actuators with mechanical equipment. However, it is still challenging to achieve realistic tactile sensation. Therefore, the novel technologies are required to mimic natural haptic feedback. These technologies can also be applied to robotic surgery platforms.

Alternatively, a hybrid approach which switches between physical reality and virtual reality as needed may be a solution. Based on the proficiency level, if the natural reality is required, the system can use a physical reality setup. Otherwise, the system also can use a virtual reality setup for a trainee to practice required skills under a certain surgical scenario. For instance, Lap-X hybrid (Medical X, Rotterdam, the Netherlands, https://www.medical-x.com/) supports these features. Advanced ARSs can also be used as a compromise solution.

4 An example of a new-generation system: computer-assisted surgical trainer (CAST)

In our research, we are developing a next-generation surgical trainer called computer-assisted surgical trainer (CAST) for laparoscopic surgery. The CAST platform consists of two mechanical fixtures with real surgical instruments, a single web camera to imitate an endoscope camera, a physical scene box to install various training tasks, and electronics with a standard personal computer (Fig. 4). Each fixture has a gimbal that mimics trocar's functionality and enables expression of real instrument movements. The instrument tracking is accomplished by precise encoders with mathematical models (Hong et al. 2017a). Also, motors are installed to provide force guidance. Therefore, CAST has the characteristics of a computer-enhanced PRS.

CAST software consists of several modules as shown in Fig. 4. *opt*MIS generates collision-free and shortest recommended trajectories using open motion planning library (Moll et al. 2012; Jain et al. 2019). *opt*Viz provides visual guidance using AR rendering schemes. A depth map is used for accurate visual representation of virtual objects and occlusion interactions between real and virtual objects. Also, collision detection between objects (e.g., real instruments and virtual objects) is integrated to implement dynamic scenarios such as a wire cutting task using Bullet physics engine (https://bulletphysics.org). Based on these schemes, we are implementing an AR rendering engine to provide high-fidelity, semantically rich effects for visual guidance using a 2D monitor display. For instance, 3D information using simple visual cues such as cubes, arrows, and posts with text messages are overlaid on a live camera image to provide intuitive instructions to a novice trainee. The initial study indicates that providing depth information by overlaying visual cues using 3D cube and post enhances trainees' performance (Wagner and Rozenblit 2017). Figure 5 shows various training scenarios (an instrument navigation task using a heart model, object transfer tasks using a peg board and wire board, and a wire cutting task) with visual guidance. In addition, we are developing AR applications using a head-mounted display (e.g., HoloLens; Microsoft Corporation, US, https://www.microsoft.com/en-us/hololens) with the CAST hardware platform. The new AR training systems

Fig. 4 Hardware and software modules of computer-assisted surgical trainer (CAST)

will provide rich training experience by introducing novel guidance methods.

*opt*Guide provides haptic force guidance to assist a trainee how to manipulate surgical instruments in manner analogous to a human instructor teaching a trainee while performing a particular task. This force guidance module adaptively adjusts force based on human operator's performance. To accomplish this, adaptive fuzzy sliding mode controllers were designed (Hong 2019). Attractive force to minimize deviations from a desired trajectory using forbidden region virtual fixtures and assistive force to help a trainee to traverse a recommended trajectory using guidance virtual fixtures are provided to the trainee who is performing a specific task. As an active guidance scheme, this force guidance is the novel and unique feature of the CAST system given a PR/AR setup. Our preliminary pilot studies indicate the advantages of using force guidance. The force guidance reinforced proper execution of a procedure resulted in 64% improvement by the attractive force and improved 35% of the movement economy by the assistive force when trainees perform an object transfer task (Hong 2019).

*opt*Assessment (Riojas et al. 2011; Hong et al. 2017b) quantifies competency objectively with various metrics such as completion time, idle time, deviation, path length, and direction profiles. In Riojas et al. (2011), a prototype of objective assessment was implemented using a fuzzy inference system. Based on this foundation, we proposed an achievable goal-based scoring method by designing a hierarchical fuzzy inference system (Hong et al. 2017b). This scoring system allows a trainee to understand the training progress by comparing his/her outcomes with the suggested goals.

Inspired by the virtual teacher concept in Gillespie et al. (2013), CAST can provide instant coaching by restricting or promoting a movement based on a computer-generated recommended path and performance evaluation. Presently, we are refining the force guidance systems to take into account various human factors and proficiency levels. To support

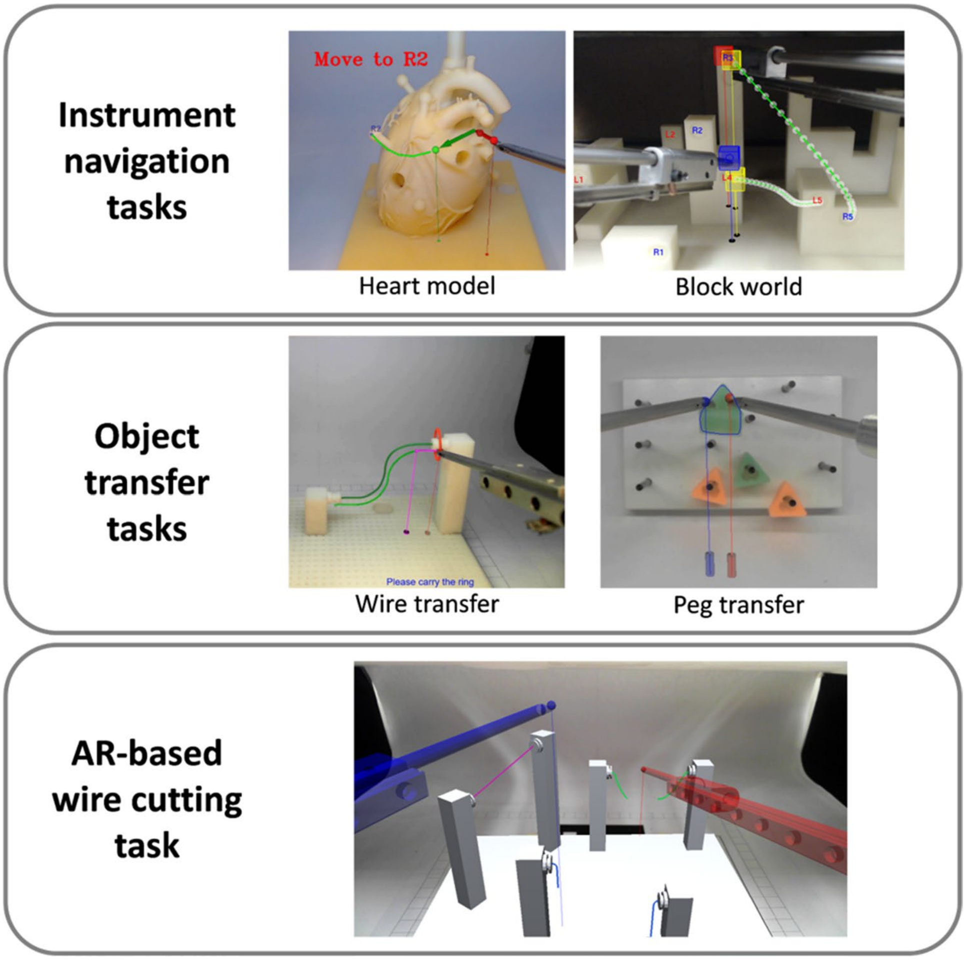

Fig. 5 Various training tasks with visual guidance information using PR and AR

proficiency-based task generation and instant coaching, we are refining the proposed assessment system as well. Also, we are developing machine learning-based task analysis methods such as a single shot state detector (Peng et al. 2017) to estimate object states such as grasping an object, transferring an object, and dropping an object using a convolutional neural network (CNN) with semantic object definitions. Figure 6 illustrates the desired system block diagram of CAST. To this end, we will conduct human subjects study for face, content, and construct validity.

5 Conclusion

In this paper, we have analyzed various surgical training simulators from the technical realization point of view. Haptic feedback, performance evaluation, guidance, and instrument tracking schemes have been discussed in the context of various visualization methods (i.e., PR, VR, and AR). To provide better training experience, we recommend to include guidance and assessment modules in addition to visualization and instrument interfaces. Intelligent guidance schemes can enhance the process of surgical skill acquisition by mimicking a human instructor. To support intelligent guidance, novel assessment schemes are also needed. These features will improve training outcomes and therefore the patients' safety as well as the quality of patient care. A natural extension of such methods will ultimately find its way into training for robotically assisted procedures and into the OR in real time.

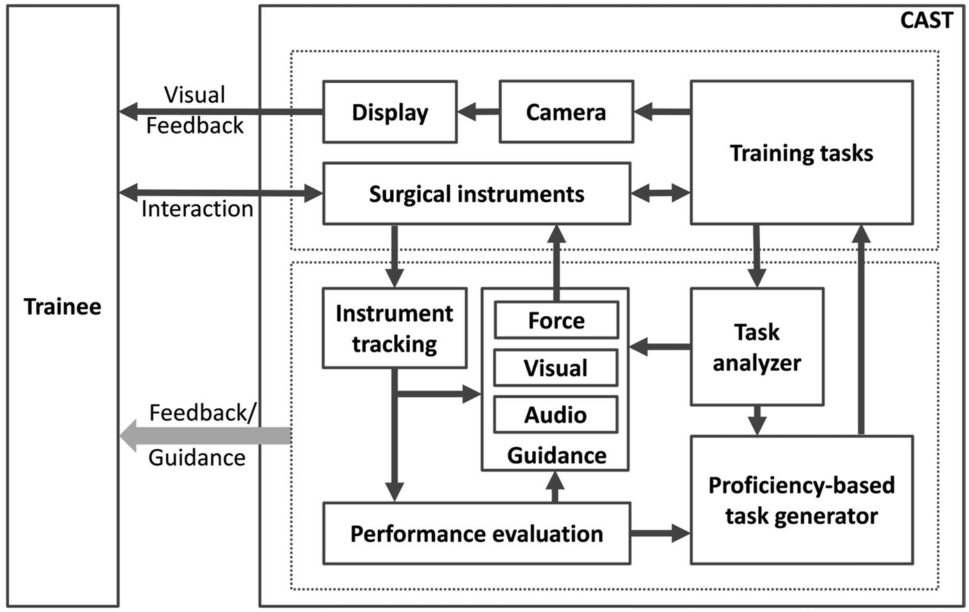

Fig. 6 System block diagram of CAST

Acknowledgements This material is based upon work supported by the National Science Foundation under Grant Number 1622589 "Computer Guided Laparoscopy Training." Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

References

Abboudi H, Khan MS, Aboumarzouk O et al (2013) Current status of validation for robotic surgery simulators a systematic review. BJU Int 111:194–205

Acosta E, Temkin B (2005) Haptic laparoscopic skills trainer with practical user evaluation metrics. Stud Health Technol Inform 111:8–11

Adrales GL, Chu UB, Witzke DB et al (2003) Evaluating minimally invasive surgery training using low-cost mechanical simulations. Surg Endosc 17:580–585

Ahmad MA, Mansoor S Bin, Khan ZA, et al (2013) Benchmarking expert surgeons' path for evaluating a trainee surgeon's performance. In: Proceedings of the 12th ACM SIGGRAPH international conference on virtual-reality continuum and its applications in industry - VRCAI '13. pp 57–62

Alcaniz M, Monserrat C, Meier U et al (2003) GeRTiSS: generic real time surgery simulation. Stud Health Technol Inform 94:16–18

Andreatta PB, Woodrum DT, Birkmeyer JD et al (2006) Laparoscopic skills are improved with LapMentor^{TM} training: results of a randomized, double-blinded study. Ann Surg 243:854–860

Basdogan C, De S, Kim J et al (2004) Haptics in minimally invasive surgical simulation and training. IEEE Comput Graph Appl 24:56–64

Basdogan C, Sedef M, Harders M, Wesarg S (2007) VR-based simulators for training in minimally invasive surgery. IEEE Comput Graph Appl 27:54–66

Beatty JD (2005) How to build an inexpensive laparoscopic webcam-based trainer. BJU Int 96:679–682

Bokhari R, Bollman-McGregor J, Kahol K et al (2010) Design, development, and validation of a take-home simulator for fundamental laparoscopic skills: using Nintendo Wii® for surgical training. Am Surg 76:583–586

Botden SMBI, Buzink SN, Schijven MP, Jakimowicz JJ (2008a) ProMIS augmented reality training of laparoscopic procedures face validity. Simul Healthc 3:97–102

Botden SMBI, De Hingh IHJT, Jakimowicz JJ (2009) Suturing training in augmented reality: gaining proficiency in suturing skills faster. Surg Endosc 23:2131–2137

Botden SMBI, Jakimowicz JJ (2009) What is going on in augmented reality simulation in laparoscopic surgery? Surg Endosc 23:1693–1700

Botden SMBI, Torab F, Buzink SN, Jakimowicz JJ (2008b) The importance of haptic feedback in laparoscopic suturing training and the additive value of virtual reality simulation. Surg Endosc 22:1214–1222

Bowyer SA, Davies BL, Rodriguez Y, Baena F (2014) Active constraints/virtual fixtures: A survey. IEEE Trans Robot 30:138–157

Bric JD, Lumbard DC, Frelich MJ, Gould JC (2016) Current state of virtual reality simulation in robotic surgery training: a review. Surg Endosc 30:2169–2178

Cakmak H, Maass H, Kühnapfel U (2005) VSOne, a virtual reality simulator for laparoscopic surgery. Minim Invasive Ther Allied Technol 14:134–144

Chandrasekera SK, Donohue JF, Orley D et al (2006) Basic laparoscopic surgical training: examination of a low-cost alternative. Eur Urol 50:1285–1291

Chen R-J, Lin H-W, Chang Y-H et al (2011) Development of an augmented reality force feedback virtual surgery training platform. Int J Autom Smart Technol 1:41–45

Chen W, Huang B, Chen S, et al (2013) FPGA and virtual reality based minimally invasive surgery training system. In: Asia-Pacific workshop on FPGA applications. pp 1–6

Chen Z, Malpani A, Chalasani P, et al (2016) Virtual fixture assistance for needle passing and knot tying. In: IEEE International conference on intelligent robots and systems. pp 2343–2350

Chmarra MK, Dankelman J, Van Den Dobbelsteen JJ, Jansen FW (2008) Force feedback and basic laparoscopic skills. Surg Endosc 22:2140–2148

Chmarra MK, Grimbergen CA, Dankelman J (2007) Systems for tracking minimally invasive surgical instruments. Minim Invasive Ther Allied Technol 16:328–340

Chmarra MK, Klein S, De Winter JCF et al (2010) Objective classification of residents based on their psychomotor laparoscopic skills. Surg Endosc 24:1031–1039

Cleary K, Peters TM (2010) Image-guided interventions: technology review and clinical applications. Annu Rev Biomed Eng 12:119–142. https://doi.org/10.1146/annurev-bioeng-070909-105249

Cotin S, Stylopoulos N, Ottensmeyer MP, et al (2002) Metrics for laparoscopic skills trainers: the weakest link! In: MICCAI - Medical image computing and computer-assisted intervention, pp 35–43

De Loose J, Weyers S (2017) A laparoscopic training model for surgical trainees. Gynecol Surg 14:24

De Luca V, Meo A, Mongelli A, et al (2016) Development of a virtual simulator for microanastomosis: new opportunities and challenges. In: International conference on augmented reality, virtual reality and computer graphics, pp 65–81

De Paolis LT, De Luca V (2019) Augmented visualization with depth perception cues to improve the surgeon's performance in minimally invasive surgery. Med Biol Eng Comput 57:995–1013. https://doi.org/10.1007/s11517-018-1929-6

Debes AJ, Aggarwal R, Balasundaram I, Jacobsen MB (2010) A tale of two trainers: virtual reality versus a video trainer for acquisition of basic laparoscopic skills. Am J Surg 199:840–845

Debes AJ, Aggarwal R, Balasundaram I, Jacobsen MBJ (2012) Construction of an evidence-based, graduated training curriculum for D-box, a webcam-based laparoscopic basic skills trainer box. Am J Surg 203:768–775

Duffy AJ, Hogle NJ, McCarthy H et al (2005) Construct validity for the LAPSIM laparoscopic surgical simulator. Surg Endosc 19:401–405

Escamirosa FP, Flores RMO, García IO et al (2015) Face, content, and construct validity of the EndoViS training system for objective assessment of psychomotor skills of laparoscopic surgeons. Surg Endosc 29:3392–3403

Fraser SA, Klassen DR, Feldman LS et al (2003) Evaluating laparoscopic skills, setting the pass/fail score for the MISTELS system. Surg Endosc 17:964–967

Gallagher AG, O'Sullivan GC (2011) Fundamentals of surgical simulation: principles and practice. Springer, New York

Gao B, Guo S, Xiao N (2012) Design of the virtual reality based robotic catheter system for minimally invasive surgery training. In: 2012 IEEE international conference on automation and logistics (ICAL), pp 611–616

Gillespie RB, O'Modhrain MS, Tang P et al (2013) The virtual teacher. J Chem Inf Model 53:1689–1699

Hardon SF, Horeman T, Bonjer HJ, Meijerink WJHJ (2018) Force-based learning curve tracking in fundamental laparoscopic skills training. Surg Endosc 32:3609–3621

Hasson HM, Aruna Kumari NV, Eekhout J et al (2001) Training simulator for developing laparoscopic skills. JSLS J Soc Laparoendosc Surg 5:255–265

Hernansanz A, Zerbato D, Gasperotti L, et al (2012) Improving the development of surgical skills with virtual fixtures in simulation. In: International conference on information processing in computer-assisted interventions, pp 157–166

Hong M (2019) An intelligent guidance system for computer-guided surgical training

Hong M, Peng KS, Lundine V, Rozenblit JW (2017a) Laparoscopic instrument tip position estimation for visual and haptic guidance in the computer assisted surgical trainer. In: 2017 IEEE international conference on systems, man, and cybernetics, SMC 2017, pp 3083–3088

Hong M, Rozenblit JW, Hamilton AJ (2017b) A simulation-based assessment system for computer assisted surgical trainer. In: Proceedings of the symposium on modeling and simulation in medicine. Society for Computer Simulation International, pp 834–844

Horeman T, Rodrigues SP, Van Den Dobbelsteen JJ et al (2012) Visual force feedback in laparoscopic training. Surg Endosc 26:242–248

Howard T, Szewczyk J (2014) Visuo-haptic feedback for 1-D guidance in laparoscopic surgery. In: 5th IEEE RAS/EMBS international conference on biomedical robotics and biomechatronics, pp 58–65

Hruby GW, Sprenkle PC, Abdelshehid C et al (2008) The EZ trainer: validation of a portable and inexpensive simulator for training basic laparoscopic skills. J Urol 179:662–666

Iwata N, Fujiwara M, Kodera Y et al (2011) Construct validity of the LapVR virtual-reality surgical simulator. Surg Endosc 25:423–428

Jaber N (2010) The basket trainer: a homemade laparoscopic trainer attainable to every resident. J Minim Access Surg 6:3–5

Jain S, Hong M, Rozenblit JW (2019) Proficiency based planner for safe path planning and applications in surgical training. Simul Ser 51:1–12

Jiménez P, Thomas F, Torras C (2001) 3D collision detection: a survey. Comput Graph 25:269–285

Kawaguchi K, Egi H, Hattori M et al (2014) Validation of a novel basic virtual reality simulator, the LAP-X, for training basic laparoscopic skills. Minim Invasive Ther Allied Technol 23:287–293

Khan ZA, Kamal N, Hameed A et al (2017) SmartSIM - a virtual reality simulator for laparoscopy training using a generic physics engine. Int J Med Robot Comput Assist Surg 13:1–16

Kim YS, Collins M, Bulmer W, et al (2013) Haptics assisted training (HAT) System for children's handwriting. In: 2013 World Haptics conference, WHC 2013, pp 559–564

Korndorffer JR, Bellows CF, Tekian A et al (2012) Effective home laparoscopic simulation training: a preliminary evaluation of an improved training paradigm. Am J Surg 203:1–7

Kunkler K (2006) The role of medical simulation: an overview. Int J Med Robit Comput Assist Surg 2:203–210

Lahanas V, Georgiou E, Loukas C (2016) Surgical simulation training systems: box trainers, virtual reality and augmented reality simulators. Int J Adv Robot Autom 1:1–9

Lahanas V, Loukas C, Smailis N, Georgiou E (2015) A novel augmented reality simulator for skills assessment in minimal invasive surgery. Surg Endosc 29:2224–2234

Lau WY, Leow CK, Li AKC (1997) History of endoscopic and laparoscopic surgery. World J Surg 21:444–453

Lewis M (2004) Moneyball: the art of winning an unfair game. WW Norton & Company

Liao H, Inomata T, Sakuma I, Dohi T (2010) 3-D augmented reality for MRI-guided surgery using integral videography autostereoscopic image overlay. IEEE Trans Biomed Eng 57:1476–1486. https://doi.org/10.1109/TBME.2010.2040278

Loukas C, Lahanas V, Georgiou E (2013) An integrated approach to endoscopic instrument tracking for augmented reality applications in surgical simulation training. Int J Med Robot Comput Assist Surg 9

Maciel A, Liu Y, Ahn W et al (2008) Development of the VBLaST^{TM}: a virtual basic laparoscopic skill trainer. Int J Med Robot Comput Assist Surg 4:131–138

Makary MA, Daniel M (2016) Medical error-the third leading cause of death in the US. BMJ 353:1–5. https://doi.org/10.1136/bmj.i2139

Martins JMP, Pinto RRV, Cavazzola LT (2015) White box: low cost box for laparoscopic training. Arq Bras Cir Dig 28:204–206

Meier U, López O, Monserrat C et al (2005) Real-time deformable models for surgery simulation: a survey. Comput Methods Programs Biomed 77:183–197

Milgram P, Kishino F (1994) A taxonomy of mixed reality visual displays. IEICE Trans Inf Syst 77:1321–1329
Milgram P, Takemura H, Utsumi A, Kishino F (1995) Augmented reality: a class of displays on the reality-virtuality continuum. Telemanipulator Telepresence Technol 2351:282–292
Moll M, Kavraki LE, Şucan IA (2012) The open motion planning library. IEEE Robot Autom Mag 19:72–82
Moreno MR, Marban A, Rojas JC, et al (2012) Simulator for laparoscopic surgery with open source approach. In: International conference on design and PROcesses for MEdical Devices, pp 207–210
Oropesa I, Chmarra MK, Sánchez-González P et al (2013) Relevance of motion-related assessment metrics in laparoscopic surgery. Surg Innov 20:299–312
Oropesa I, Sánchez-González P, Chmarra MK et al (2014) Supervised classification of psychomotor competence in minimally invasive surgery based on instruments motion analysis. Surg Endosc 28:657–670
Oropesa I, Sánchez-González P, Lamata P et al (2011) Methods and tools for objective assessment of psychomotor skills in laparoscopic surgery. J Surg Res 171:e81–e95
Oussi N, Loukas C, Kjellin A et al (2018) Video analysis in basic skills training: a way to expand the value and use of BlackBox training? Surg Endosc 32:87–95
Overtoom EM, Horeman T, Jansen FW, et al (2018) Haptic feedback, force feedback, and force-sensing in simulation training for laparoscopy: a systematic overview. J Surg Educ
Panait L, Akkary E, Bell RL et al (2009) the role of haptic feedback in laparoscopic simulation training. J Surg Res 156:312–316
Peng KS, Hong M, Rozenblit JW (2017) Learning-based object tracking for transfer tasks in laparoscopy training. EuroCast 2017:254–255
Prada R, Payandeh S (2005) A study on design and analysis of virtual fixtures for cutting in training environments. In: Proceedings - 1st Joint Eurohaptics conference and symposium on haptic interfaces for virtual environment and teleoperator systems; World Haptics conference, WHC 2005, pp 375–380
Rahman MA, Mahmud P, Mashuk MS (2013) Augmented and virtual reality based approaches in minimally invasive surgery training. In: 2013 International conference on informatics, electronics and vision (ICIEV), pp 1–4
Riojas M, Feng C, Hamilton A, Rozenblit J (2011) Knowledge elicitation for performance assessment in a computerized surgical training system. Appl Soft Comput J 11:3697–3708
Ritter ME, Scott DJ (2007) Design of a proficiency-based skills training curriculum for the fundamentals of laparoscopic Surgery. Surg Innov 14:107–112
Rosen J, Brown JD, Barreca M, et al (2002) The blue DRAGON - A system for monitoring the kinematics and the dynamics of endoscopic tools in minimally invasive surgery for objective laparoscopic skill assessment. In: Studies in Health Technology and Informatics. pp 412–418
Ruparel RK, Brahmbhatt RD, Dove JC et al (2014) "ITrainers" - Novel and inexpensive alternatives to traditional laparoscopic box trainers. Urology 83:116–120
Ruthenbeck GS, Reynolds KJ (2013) Virtual reality surgical simulator software development tools. J Simul 7:101–108
Salisbury K, Conti F, Barbagli F (2004) Haptic rendering: Introductory concepts. IEEE Comput Graph Appl 24:24–32
Salkini MW, Doarn CR, Kiehl N et al (2010) The role of haptic feedback in laparoscopic training using the LapMentor II. J Endourology 24:99–102
Schijven M, Jakimowicz J (2002) Face-, expert, and referent validity of the Xitact LS500 laparoscopy simulator. Surg Endosc 16:1764–1770
Shamsunder SC, Manivannan M (2008) Haptic guided laparoscopy simulation improves learning curve. Stud Health Technol Inform 132:454–456
Sharpe BA, Machaidze Z, Ogan K (2005) Randomized comparison of standard laparoscopic trainer to novel, at-home, low-cost, camera-less laparoscopic trainer. Urology 66:50–54. https://doi.org/10.1016/j.urology.2005.01.015
Soper NJ, Fried GM (2008) The fundamentals of laparoscopic surgery: its time has come. Bull Am Coll Surg 93:30–32
Soyinka AS, Schollmeyer T, Meinhold-Heerlein I et al (2008) Enhancing laparoscopic performance with the LTS3E: a computerized hybrid physical reality simulator. Fertil Steril 90:1988–1994
Speicher M, Hall BD, Nebeling M (2019) What is mixed reality? In: Conference on human factors in computing systems, pp 1–15
Spruit EN, Band GPH, Hamming JF, Ridderinkhof KR (2013) Optimal training design for procedural motor skills: a review and application to laparoscopic surgery. Psychol Res 78:878–891
Sridhar AN, Briggs TP, Kelly JD, Nathan S (2017) Training in robotic surgery—An overview. Curr Urol Rep 18
Stylopoulos N, Cotin S, Maithel SK et al (2004) Computer-enhanced laparoscopic training system (CELTS): bridging the gap. Surg Endosc 18:782–789
Tagawa K, Tanaka HT, Kurumi Y et al (2013) Laparoscopic surgery simulator using first person view and guidance force. Stud Health Technol Inform 184:431–435
Tendick F, Downes M, Goktekin T et al (2000) A virtual environment testbed for training laparoscopic surgical skills. Presence Teleoperators Virtual Environ 9:236–255
Teo CL, Burdet E, Lim HP (2002) A robotic teacher of Chinese handwriting. In: Proceedings - 10th symposium on haptic interfaces for virtual environment and teleoperator systems, HAPTICS 2002, pp 335–341
Teschner M, Kimmerle S, Heidelberger B et al (2005) Collision detection for deformable objects. Comput Graph Forum 24:61–81
Thinggaard E, Bjerrum F, Strandbygaard J et al (2015) Validity of a cross-specialty test in basic laparoscopic techniques (TABLT). Br J Surg 102:1106–1113. https://doi.org/10.1002/bjs.9857
Van Der Meijden OAJ, Schijven MP (2009) The value of haptic feedback in conventional and robot-assisted minimal invasive surgery and virtual reality training: a current review. Surg Endosc 23:1180–1190
Van Sickle KR, McClusky DA, Gallagher AG, Smith CD (2005) Construct validation of the ProMIS simulator using a novel laparoscopic suturing task. Surg Endosc 19:1227–1231
Våpenstad C, Hofstad EF, Bø LE et al (2013) Limitations of haptic feedback devices on construct validity of the LapSim® virtual reality simulator. Surg Endosc 27:1386–1396
Vassiliou MC, Feldman LS, Andrew CG et al (2005) A global assessment tool for evaluation of intraoperative laparoscopic skills. Am J Surg 190:107–113
Verdaasdonk EGG, Stassen LPS, Monteny LJ, Dankelman J (2006) Validation of a new basic virtual reality simulator for training of basic endoscopic skills: the SIMENDO. Surg Endosc 20:511–518. https://doi.org/10.1007/s00464-005-0230-6
Wagner A, Rozenblit JW (2017) Augmented reality visual guidance for spatial perception in the computer assisted surgical trainer. In: Proceedings of the symposium on modeling and simulation in medicine. Society for Computer Simulation International, pp 855–866
Wang F, Burdet E, Vuillemin R, Bleuler H (2005) Knot-tying with visual and force feedback for VR laparoscopic training. In: 2005 IEEE engineering in medicine and biology 27th annual conference, pp 5778–5781
Westebring – van der Putten EP, Goossens RHM, Jakimowicz JJ, Dankelman J, (2008) Haptics in minimally invasive surgery – a review. Minim Invasive Ther Allied Technol 17:3–16

Wilson MS, Middlebrook A, Sutton C et al (1997) MIST VR: A virtual reality trainer for laparoscopic surgery assesses performance. Ann R Coll Surg Engl 79:403–404

Wu J, Westermann R, Dick C (2015) A survey of physically based simulation of cuts in deformable bodies. Comput Graph Forum 34:161–187

Yang T, Liu J, Huang W et al (2013) Mechanism of a learning robot manipulator for laparoscopic surgical training. Intell Auton Syst 2:17–26

Yiasemidou M, de Siqueira J, Tomlinson J et al (2017) “Take-home” box trainers are an effective alternative to virtual reality simulators. J Surg Res 213:69–74

Yoon R, Del Junco M, Kaplan A et al (2015) Development of a novel iPad-based laparoscopic trainer and comparison with a standard laparoscopic trainer for basic laparoscopic skills testing. J Surg Educ 72:41–46

Zahiri M, Booton R, Siu K-C, Nelson CA (2016) Design and evaluation of a portable laparoscopic training system using virtual reality. J Med Device 11:011002

Zhang A, Hünerbein M, Dai Y et al (2008) Construct validity testing of a laparoscopic surgery simulator (Lap Mentor®): evaluation of surgical skill with a virtual laparoscopic training simulator. Surg Endosc 22:1440–1444

Zhang J, Zhong Y, Gu C (2018) Deformable models for surgical simulation: a survey. IEEE Rev Biomed Eng 11:143–164

Ziv A, Small SD, Wolpe PR (2000) Patient safety and simulation-based medical education. Med Teach 22:489–495