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Innovations in Urologic Surgical Training

Runzhuo Ma, M.D.[1], **Sharath Reddy, B.A.**[1], **Erik B. Vanstrum, B.A.**[1], **Andrew J. Hung, M.D.**[1]

[1]Center for Robotic Simulation & Education, Catherine & Joseph Aresty Department of Urology, USC Institute of Urology, University of Southern California, Los Angeles, California

Abstract

Purpose of the Review—This review aims to summarize innovations in urologic surgical training in the past five years.

Recent Findings—Many assessment tools have been developed to objectively evaluate surgical skills and provide structured feedback to urologic trainees. A variety of simulation modalities (i.e., virtual/augmented reality, dry-lab, animal, and cadaver) have been utilized to facilitate the acquisition of surgical skills outside the high-stakes operating room environment. Three-dimensional printing has been used to create high-fidelity, immersive dry-lab models at a reasonable cost. Non-technical skills such as teamwork and decision-making have gained more attention. Structured surgical video review has been shown to improve surgical skills not only for trainees, but also for qualified surgeons.

Summary—Research and development in urologic surgical training has been active in the past five years. Despite these advances, there is still an unfulfilled need for a standardized surgical training program covering both technical and non-technical skills.

Keywords

Surgical training; Surgical education; Assessment; Simulation; Urology; Robotic surgery

Introduction

Surgical training is currently transitioning from Halstead's apprenticeship model to more standardized assessments of clinical competence. Influenced by other high-stakes fields such as aviation and the military, where simulation plays an essential role before real-life exposure, surgical training has incorporated various simulation models to shorten the learning curve. Recent studies have demonstrated surgeon skills impact patient outcomes,

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Corresponding Author: Andrew J. Hung, MD, University of Southern California Institute of Urology, 1441 Eastlake Avenue Suite 7416, Los Angeles, California 90089, Phone number: (+1) 323-865-3700, Fax number: (+1) 323-865-0120.

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such as length of hospital stay, duration of postoperative catheterization time, and urinary continence recovery after robotic-assisted radical prostatectomy (RARP) [1,2], which underscores the importance of careerlong surgical skill enhancement. In addition to technical ability, the development of strong non-technical skills, such as decision-making and interpersonal communication, are also critical to surgical competence.

This review explores recent innovations in open, endoscopic, laparoscopic, and robotic-assisted surgery in the urologic field. We also summarize recent developments in non-technical skills training and surgical skill assessment. Finally, we discuss current challenges and future directions in urologic surgical training.

Material and Methods

A broad search was performed on PubMed and Medline to identify English language articles between 2016–2020. Search terms included: ‘training’, ‘simulation’, ‘curriculum’, ‘e-learning’, ‘urology’ and ‘surgery’. Reference lists of the identified articles were screened for further relevant studies. Articles were selected based on innovation, with an emphasis on more contemporary works within the past three years.

Definitions of validity adopted in this article are based on previous reviews [3,4], originally coming from Cronbach’s test validity theory. *Face validity* is a measure of participants’ subjective assessments of simulator realism; *content validity* measures expert subjective assessments of the simulator’s appropriateness for training; *construct validity* is the ability of the simulator to distinguish between different levels of experience; *concurrent validity* is the comparison of the training model against the gold standard simulation; *predictive validity* is the ability for simulated performance to accurately predict operating room performance. A new definition of validity based on Messick’s Conceptual Framework was introduced into urologic surgical training in recent years, which shifts the concept of validity from a fixed property of the simulator to emphasizing its specific assessment context [5]. The new system consists of five sources of validity: test content, response processes, internal structure, relationships to other variables, and consequences of testing. As few articles have adopted this novel schema, we used the conventional definitions of validity in this review; however, we encourage future studies to adopt the new validity framework.

Surgical Assessment

One crucial component of high-quality surgical training programs that transcends any surgical approach is objective and structured feedback [6,7]. The research community has recently developed an abundance of tools to assess technical skills. In a systematic review, Vaidya et al. identified 76 unique evaluation tools across surgical specialties, with the most frequently used being the Objective Structured Assessment of Technical Skills (OSATS) [8].

While past tools have focused on global skills assessment (e.g., OSATS), recent evaluations have been developed and validated for specific procedures. Hussein et al. developed the Prostatectomy Assessment and Competency Evaluation (PACE) to assess the quality of robot-assisted radical prostatectomy [9]. Similar assessments have been developed for partial nephrectomy (SPaN) [10], radical cystectomy (CASE) [11], and lymphadenectomy

(PLACE) [12]. These tools not only supply general feedback but can also provide evaluation of specific tasks and steps for trainees to focus on improvement. Other evaluations have been developed to assess specific tasks, including laparoscopic suturing (LS-CAT) [13] and surgical assistant skills [14].

Conventionally, these tools require review of surgical footage by specialists, which is time-consuming, limiting their extensive use in training programs. Alternative methods to assess surgery in a scalable manner have been investigated. Recent studies have utilized crowd-sourced evaluations to streamline this process, which achieved comparable results to expert assessment and is more efficient and cost-effective [15–17]. Another way to streamline this process is by automation. Data captured during surgery, such as video, instrument kinematics, and system events (e.g., camera movement), can be used to train computer algorithms on how to distinguish good vs. bad-quality surgical performance. Hung et al. developed and validated automated performance metrics (APMs), which directly quantify surgeon performance [18,19]. Baghdadi et al. use a combination of video data and machine learning to automate the evaluation of lymph node dissection thoroughness [20]. The algorithm achieved 83.3% accuracy compared to manually scored PLACE ratings.

Currently, most of the aforementioned assessment tools are utilized under research settings. How to incorporate these structured assessment tools into standardized surgical training still needs exploration. Harriman et al. reported the use of an online program, namely, Resident Report Card (RRC) to provide structured feedback to trainees after multiple types of urologic procedures [21]. Over a 5-year period, RRC records showed a steady improvement of trainees' surgical skills across procedures. Surveyed residents were overwhelmingly positive about the use of RRC in their residency training period. As an initial trial, this study sheds light on the logistics of providing timely, structured feedback.

Innovations in Open Surgical Training

Although minimally invasive and endoscopic approaches have gradually replaced standard of care for many urologic diseases, competency in open surgery remains a core objective for urologic training programs. Merrill et al. reported a decline in open surgical case volume coupled with a rise in robotic cases for residents at US teaching hospitals [22]. Variation in training environments has led to disparities in urologic resident and fellow access to open procedural training. Simulator-based modalities can help bridge this gap in open surgery training opportunities.

Past open surgical training simulations consisted primarily of realistic benchtop models for instruction of basic procedures, including the open prostatectomy, vasectomy, circumcision, and suprapubic tube (SPT) placement [3,23].

Open surgical training has continued to rely on benchtop models and cadaveric simulation. As these options have historically been expensive and difficult to procure, several cost-effective training models relying on 3D printing and cheaper materials have been developed (Table 1) [24–28]. One study showed that using household items to create models for open prostatectomy (using an orange placed in a cut-off plastic gallon container, representing prostate in the deep pelvis) was well-received and improved trainee skills [24]. An inexpensive model for ischemic priapism utilizing a hot-dog and Red Vines candy demonstrated face and content validity [25]. Trainees who completed vasectomy reversal training on 3D-printed silicone benchtop models reported improved microsurgical skills [26]. A urogynecologic simulation of trans-obturator sling procedure for stress urinary incontinence was developed using a 3D-printed model of the female pelvis, allowing for trainees to visualize and practice proper sling placement [27]. Residents also received training on penile implant surgery using a 3D-printed model, demonstrating significant skill improvement [28]. SPT placement is an open urologic procedure with a wealth of training options available. While many are commercial models [29], several low-cost simulators have been recently developed for training. One study used a water bladder surrounded by Styrofoam in a plastic container; another utilized a latex glove filled with water along with other common emergency room items [29,30]. Both were assessed as realistic and valuable training tools by experts and trainees.

Cadaveric simulation remains the most comprehensive option for open surgical training. The British Association of Urological Surgeons (BAUS) and Thiel embalmed cadavers (TEC) continue to offer courses on procedures ranging from artificial urinary sphincter to radical orchiectomy [31]. Renal transplant simulation has been particularly difficult to realistically mimic in a simulated or benchtop model, explaining the continued appeal of cadaveric training [32]. Lentz et al. also showed that cadaveric penile implant training improved resident skill and confidence in prosthesis placement [33].

Recent advances have made open surgical simulation cheaper and more accessible for trainees. An exciting direction involves the use of augmented reality (AR), in which annotations can be digitally superimposed on the surgical field. One study utilized the HoloLens AR headset to mentor residents on abdominal incisions, demonstrating improved trainee surgical performance [34]. Thus, procedures once reliant on cadaveric training may well be displaced by models utilizing 3D-printing and AR technologies.

Innovations in Endoscopic Surgical Training

Endourologic surgeries have experienced rapid adoption in recent decades, now utilized for several fundamental diagnostic and therapeutic procedures. As many of these procedures utilize proprietary medical technologies, a number of commercial endoscopic training models are available. Past simulations rely heavily on benchtop training but also utilize virtual reality (VR) and animal models for a range of procedures, including transurethral resections of the prostate (TURP) and bladder tumors (TURBT), percutaneous nephrolithotomy (PCNL), and ureteroscopy (URS) [35]. In recent years, endoscopic training has continued to build on these existing modalities and expanded the variety of procedures with validated simulations (Table 1 and Table 2).

Numerous benchtop, VR, animal, and cadaveric cystoscopy/URS models are available to simulate stones and strictures, as well as provide a realistic practice environment for trainees to improve manual dexterity [35]. For URS training, one group developed a simulation utilizing the HoloLens VR headset to perform mid-ureteric stone removal with basket, with trainees reporting greater procedure realism compared to benchtop simulation [36]. Recent studies have adapted existing cystoscopy models for new pathologies, with a particular focus in urogynecology. Al-Jabir et al. used benchtop and cadaveric models to simulate intravesical botulinum toxin injection for overactive bladder with urge incontinence, demonstrating face and content validity [37]. A separate team demonstrated face, content, and construct validity for endoscopic needle injection of bulking agents for stress urinary incontinence using porcine bladders mounted in a hysteroscopy trainer [38].

TURP and TURBT simulators have increasingly relied on VR and 3D-printed benchtop models for training. One group simulated Holmium Laser Enucleation of the Prostate (HoLEP) utilizing real endoscopic tools on synthetic prostate models [39], while another developed a comprehensive TURP curriculum with benchtop resectoscope and clot evacuation training [40]. Choi et al. developed a 3D-printed biomimetic prostate “phantom” based on MRI images, which demonstrated tissue electrocautery scarring during TURP [41]. These new models were universally rated as highly realistic and allowed for real-time skills assessment. Several VR-based TURBT simulators have recently been developed, showing measurable reductions in intraoperative blood loss and bladder injury [42,43]. Lastly, a virtual transrectal ultrasound (TRUS) prostate biopsy simulator demonstrated skills transfer to cadaveric TRUS in trainees [44]. VR-based simulators allow for the objective assessment of select competencies, and possibly can be utilized for accreditation [45].

PCNL simulation offers a variety of modalities for training, with new technologies slowly displacing the current gold standard, high-fidelity TEC. Multiple studies created reusable, low-cost models for percutaneous renal access, using ballistic gel and 3D-printed rubber collecting systems [46, 47]. An objective of PCNL training is proficiency using the fluoroscopic C-arm for intraoperative imaging. Several studies piloted high-fidelity synthetic and ex vivo porcine models to assess resident competency with C-arm use before and after training, demonstrating improvements in trainee performance [48,49].

Despite an abundance of commercial benchtop simulators available for endourologic training, significant improvements in 3D-printing and VR technologies have led to the development of highly realistic, reusable models for a wide array of procedures. Coupled with a shift towards objective, competency-based assessments, these novel simulators are gradually being adopted for standardized endoscopic training.

Innovations in Laparoscopic Surgical Training

Owing to its technically demanding nature, laparoscopic surgery is associated with a steeper learning curve than robotic-assisted surgery (RAS) [50]. A recently published systematic review on surgical training in the US and Europe found that most residents considered their laparoscopic training inadequate [51]. With the rapid growth of RAS, the opportunity for sufficient laparoscopic exposure during residency is decreasing. Simulated training can augment the acquisition of laparoscopic skills outside the operating room.

Several dry-lab models have been developed for specific laparoscopic procedures, including partial nephrectomy, pyeloplasty, ureteral reimplantation, and urethrovesical anastomosis

[3]. . Most recently developed urethrovesical anastomosis models demonstrate construct/concurrent validity (Table 1) [52], but none have demonstrated predictive validity [21]. Besides dry-lab models, several VR simulators have been commercially available for more than ten years [3]. They can be used to train basic laparoscopic skills such as camera navigation, bimanual coordination, dissection, suturing, and clip application; they also provide procedure-specific training, such as laparoscopic-assisted radical nephrectomy (LARN).

A trend in recent years favors less-expensive, more accessible laparoscopic training models. Kailavasan et al. designed a low-cost (£2.5 each) abdominal wall model, which can be used for laparoscopic port incision training [53]. The model has multiple layers, simulating the abdominal wall from skin to peritoneum. Travassos et al. published a tutorial for a homemade laparoscopic simulation box costing less than $75 [54]. Parkhomenko et al. invented several 3D-printed laparoscopic training models for basic skills training, costing $26.50 each [55]. Though the experience reported by trainees was significantly worse than expensive conventional models, the training value was comparable, suggesting 3D-printed models can be used as an economical way for laparoscopic skills acquisition.

Other studies compared simulators head-to-head to determine efficacy and cost-effectiveness. Oussi et al. compared a cheap, low-fidelity simulator (Blackbox) with an expensive, high-fidelity simulator (LapMentor) to determine if the added cost translated into better training [56]. They found that the cheaper Blackbox also yielded better skill transferability to a VR simulator, suggesting the high cost-effectiveness of low-fidelity models. Another study examined the added value of “take-home” laparoscopic training, but found no significant improvement in training efficiency or efficacy [57]. Montanari et al. investigated if the use of a 3D training box could improve the efficiency of conventional 2D laparoscopic training, but found regular 2D training is non-inferior to 3D training [58].

Despite the development of numerous training models, a recent survey found a decrease in laparoscopic training during urologic residency [59]. Attention should be drawn to incorporate laparoscopic simulation training into current residency programs in a structured and efficient way.

Innovations in Robotic Surgical Training

The number of robotic-assisted surgeries (RAS) has grown exponentially in recent years. In 2019 approximately 1.2 million RAS were performed worldwide, the largest part of which were urologic, involving urologic oncology, reconstruction, pediatrics, and female urology [60]. Thus, a high-quality robotic surgical training program is essential for trainee accreditation. A number of simulation models can facilitate the acquisition of robotic surgical skills.

Dry-lab models published in recent years were summarized in Table 1, including basic skills training and procedure-specific models (urethrovesical anastomosis, pyeloplasty, partial nephrectomy, and radical prostatectomy). Novel dry-lab simulations have utilized 3D-printing technology to create realistic, personalized models [61,62]. Melnyk et al. developed a robotic-assisted partial nephrectomy (RAPN) model using 3D-printing to create a poly-vinyl alcohol (PVA) kidney cast from patient imaging [63]. The mechanical and functional properties of the model proved to be similar to fresh porcine kidney in terms of compression, elasticity, and suture tension during renorrhaphy. This is one of the first synthetic kidney models that achieved mechanical realism and functional similarity (perfused renal hilum) to in vivo kidney models. The same team applied a similar method to create a high-fidelity, full-immersion prostate model, which can be used to simulate four critical steps of RARP (bladder neck dissection, seminal vesicle mobilization, neuro-vascular bundle dissection, and vesicourethral anastomosis) [64]. Construct validity was shown between novices and experts. Of note, clinically relevant outcomes (i.e., positive margin and VUA leakage) can also be assessed, enabling meaningful feedback to trainees.

A summary of VR/AR simulators for robotic surgery is presented in Table 2 [21]. Besides basic surgical skills, most simulators also provide procedure-specific training, including RARP, RAPN, robotic-assisted radical cystectomy (RARC) and pelvic lymph node dissection (PLND). Most of these simulators demonstrate construct or concurrent validity, while dV-Trainer® (Mimic Technologies, USA), da Vinci Skills Simulator (dVSS, Intuitive Surgical, Inc., USA) and Robotic Surgery Simulator (RoSS®, Simulated Surgical Systems LLC, USA) have shown predictive validity in animals or actual patients [21,65]. Nevertheless, the evidence level for these studies is limited due to the small numbers of participants and predominance of single-center studies. Large, multicenter, randomized controlled trials are needed to robustly support the transferability of robotic surgical skills from simulators to the operating room [65].

Novel computational technologies have been explored in robotic surgical training. A pilot study combined a machine-learning algorithm with dry-lab simulation [66]. The algorithm can learn from expert demonstrations, and then give feedback to trainees autonomously. This technology shows promise as an interactive training system that can provide real-time feedback to improve efficiency of surgical skills acquisition. Another study created a video and hand-motion playback system [67]. By synchronously recording intraoperative videos, robotic arm joint angles, and surgeon-console interaction, the system can replay the entire surgery video with corresponding expert surgeon hand-motions.

Apart from high-validity simulations, trainees' involvement in real robotic surgery is also essential for robotic skills acquisition. Cimen et al. found that simple bedside assistance experience can help trainees shorten the learning curve of robotic surgery [68,69]. Compared to novice surgeons who had no prior RARP bedside assistance experience, the group with bedside experience showed better surgical performance in their first 50 RARP cases [68].

Another factor that may impact robotic training quality is trainers' teaching ability. In order to maximize the quality of robotic training programs, a "train the trainer (TTT)" course was developed by experts from the USA and Europe [70]. A consensus was reached on a standardized TTT course design, though further validation is needed to prove its efficacy.

Multiple advances in robotic surgery training have been achieved in recent years. However, there is still a lack of standardized and validated robotic surgery curricula incorporated into residency training. Furthermore, the emergence of several novel robotic systems in recent years raises a new question about the transferability of surgical skills between different systems [71]. Further studies are required before high-level evidencebased robotic training can be carried out.

Non-technical Skill Training

Surgical competency can be defined as a collective assessment of surgical technical and non-technical skills [72]. Non-technical skills (NTS) are defined as the social (teamwork, communication, leadership), cognitive (decision making, situational awareness), and personal resources (resilience) that are important in the surgical setting [73]. While technical skills training and evaluation have historically gained more attention, there is a recent movement toward the recognition and development of NTS. Indeed, there is evidence that surgical incidents may more commonly be caused by lapses in NTS than due to deficient technical skills [74]. While robust data is scarce, a recent meta-analysis suggests that NTS training may reduce patient mortality [75].

There are a number of assessment tools to evaluate NTS that have been validated in surgical education, including Non-Technical Skills for Surgeons (NOTSS), NOn-TECHnical Skills (NOTECHS), and Observational Teamwork Assessment for Surgery (OTAS) [76]. In a systematic review of NTS assessments, Wood et al. [77] concluded that NOTSS is the best scale for individual use, while NOTECHS is best for team assessment. This highlights the idea that NTS assessment is dependent on context. In recognition that generalized assessment scales may be less applicable in specialized circumstances, Raison et al. developed an NTS assessment specific to robotic surgery [78]. The Interpersonal and Cognitive Assessment for Robotic Surgery (ICARS) includes unique behaviors (e.g., awareness of equipment failure) as compared with generic assessment tools.

Simulation is regarded as the most effective method to train NTS [79]. Somasundram et al. incorporated NTS training into a 5-day surgical boot camp simulating a number of events on the hospital ward [80]. Mean NOTSS scores were used to evaluate baseline NTS and to inform future camps. Goldenberg et al. simulated laparoscopic IVC injury and assessed NTS by NOTSS [81]. They show that NTS is greater among more senior residents, suggesting that NTS develops over the course of training. While these studies evaluate NTS, they do not show that their respective simulations increase NTS. Nelson et al. showed that general surgery residents that role-played the position of surgical technologist during live surgeries improved self-rated metrics of situational awareness, communication, teamwork, and professionalism in pre- and post-operative questionnaires [82]. Liao et al. showed that a video coaching intervention (review of surgical video with an expert) improved NOTSS scores as compared to those that did not receive video coaching [83].

Despite the recognition of NTS as important for clinical outcomes, there is still a lack of NTS training across all surgical specialties [79]. As assessment tools and training modalities are validated and become more established, it will be essential to integrate them into surgical curricula.

Video Review to Improve Surgical Skills

The aforementioned training modalities mainly involve residents/fellows focusing on the acquisition of necessary cognitive knowledge and basic psychomotor ability to perform a surgery. However, the improvement of surgical skills does not end with residency/fellowship programs; it continues throughout the career. As elite athletes review videos of their own performance to improve, surgeons can adopt the same method [84,85].

Several studies have established that by the utilization of video workshops, surgeons can improve their surgical skills and the actual patient outcomes [84]. Cathcart et al. found that following the adoption of peer-video review after RARP, surgeons used the learning points gained to modify their techniques, and the patient-reported continence recovery rate at 3 months increased from 57% to 67% ($p = 0.02$) [86]. Another study by Michigan Urological Surgery Improvement Collaborative (MUSIC) showed that by reviewing each other’s surgical videos in pairs and providing feedback in a structured format, surgeons could identify potentially beneficial changes in technique [87]. Another study found that by self-debriefing on their own simulation videos, a trainee can maintain their surgical skills over the gap period to the next training session [88].

Open Resources of Surgical Education

A survey conducted in the United Kingdom showed that 86.7% of surgical trainees routinely watched online surgical videos, i.e., on YouTube.com or Websurg.com, with most preferring videos with supplemental information such as commentary, snapshots, and diagrams [89]. Arslan et al. assessed the quality of 1,688 videos of laparoscopic and robotic-assisted radical prostatectomy on YouTube [90]. They found that the website includes high-quality videos for both procedures, but there is a lack of objective parameters to predict the educational quality of the video.

Challenges and Future Directions

Currently, one concern that limits residents’ exposure to surgery is the belief that extensive involvement of trainees in procedures may impact surgical quality. Studies regarding this question have conflicting results: most have suggested that under the appropriate supervision, resident involvement has minimal impacts on surgical quality and safety, solely lengthening operation time [91–94]. However, another study found that resident involvement increases patient complication rates (OR=1.61, $p<0.001$) [95]. Higher-level evidence is needed to resolve this question.

Secondly, there is a need for objective and structured feedback following surgery. Work hour limitations and more diverse surgical techniques make it difficult for current urologic residents to gain as much procedural exposure as prior generations. Kim et al. demonstrated that early, standardized feedback is more effective than later feedback [96]. Though an abundance of assessment methods exists, how to efficiently incorporate them into the current training system remains to be explored.

Finally, as suggested by multiple surveys [97,98], there is a dire need for incorporation of standardized, structured surgical training programs that encompass both technical and non-technical skills. One barrier is the lack of high-level evidence supporting such programs. Though several randomized controlled trials have evidenced that skills acquired by simulation curricula can be transferred to the operating room [38,99], most of them are small, single-center studies. As an initial step, an ongoing international randomized controlled trial, namely SIMULATE, aims to inspect whether a standardized URS curriculum combining theoretic knowledge, VR, and cadaveric simulation can reduce complication rates of the first 25 URS cases performed by novices [100]. Such international collaboration should be encouraged to provide critical evidence that may change current training paradigms.

Conclusions

A multitude of assessment tools have been developed to provide structured feedback to surgical trainees. Various simulators exist across diverse surgical procedures to provide technical exposure outside the operating room. Newer technology, such as machine learning, virtual reality, and 3D-printing, has advanced surgical training by providing interactive training systems and high-fidelity simulations. Despite these advancements, there is still a gap of high-level evidence supporting the role of a structured simulation curriculum in surgical training. A dire need exists for a standardized surgical training program covering both technical and non-technical skills.

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Table 1.

Dry lab trainers for open, endoscopic, laparoscopic and robotic urologic procedures (published from Jan, 2016 – June, 2020)

Surgical approach	Name of model	Training procedures	Features	Cost (US $)	Manufacturer/Institution	Debut	Relevant publications *validity*
Open	Ultrasound-guided suprapubic catheter insertion trainer (US-SCIT)	US-Guided SPT Insertion	Materials available in any ED unit, 8 minutes to construct	$1.71	University of the Witwatersrand, Johannesburg, South Africa	2018	Nonde et al. 2018 *Face, Content*
	SPT Insertion Model	SPT insertion	-	$2	Xuanwu Hospital, Beijing, China	2019	Gao et al. 2018 *Face, Content*
	Vasectomy Reversal Model	Vasovasostomy	3D-printed silicone model	NA	State University of Pará, Belem, Brazil	2019	Pinto et al. 2019 *Face*
	3D-Printed Female Anatomical Model	Trans-obturator tape and tension free vaginal tape sling procedures	Allows for anatomic education, surgical planning, and simulation of proper needle placement	NA	MedTRain3DModSim, Erasmus+ European Union	2020	Tatar et al. 2020 *Face, Content, Construct*
	3D-Pelvic Cadaver	Penile prosthesis placement	Platform can demonstrate perforation of the corporal bodies, injury to iliac vessels, and injury to urethra	NA	Jessa Hospital, Hasselt, Belgium	2019	VanRent et al. 2019 *Face*
Endo	Percutaneous renal puncture model	Percutaneous nephrostomy/ nephrolithotomy, C-arm use	3D-printed rubber renal pelvis models	$25	Uludag University, Turkey	2018	Akgul et al. 2018 *Face*
	ETXY Multifunctional trainer	Cystoscopy, Intravesical Botox injection	-	$4,500	ProDelphus, Brazil	2015	Al-jabir et al. 2019 *Face, Content*
	Ballistic Gel Collecting System	Percutaneous renal access, C-arm use	Reusable greater than 200 times	$60	Loma Linda University, CA, USA	2019	Ewald et al. 2019 *Face, Content*
	Endoscopic Needle Injection Simulator	Transurethral bulking agent injection for stress urinary incontinence	Porcine bladder placed in hysteroscopy simulator	NA	UC Irvine, USA	2018	Farhan et al. 2018 *Face, Content, Construct*
	Biopsym Simulator	12-core US-guided TRUS Biopsy	Utilizes benchtop simulator along with real TRUS biopsy tools, depicts locations of core biopsies on overlaid prostate MRI	NA	Agence Nationale de la Recherche, France	2008	Fiard et al. 2020 *Face, Content, Construct, Concurrent*
	Advanced Scope trainer	URS	-	NA	Mediskills, UK	2017	Al-jabir et al. 2017 *Face, Content, Construct, Concurrent*
	SIM-PCNL model	PCNL	High-fidelity model which can be used in full-immersion simulation	NA	University of Rochester, USA	2017	Ghazi et al. 2017 *Face, Content, Construct*

Surgical approach	Name of model	Training procedures	Features	Cost (US $)	Manufacturer/Institution	Debut	Relevant publications *validity*
	Fluoroscopy-less C-Arm Trainer (CAT)	C-Arm use, PCNL	-	NA	University of Minnesota, USA	2015	Noureldin et al. 2020 *Face*
Laparoscopic/ robotic	Urethrovesical model	Laparoscopic UVA	-	NA	Minimally Invasive Center of Surgery Jesus Uson, Spain	2019	Fernández-Tomé et al. 2019 *Face, Content, Construct*
	Urethrovesical model	Robotic-assisted UVA	Model has layers to simulate urethral mucosal layer and periurethral tissue	NA	University of Texas, USA	2019	Johnson et al. 2018 *Face, Content, Construct*
	Urethrovesical model	Robotic-assisted UVA	Model was created by 3D printing	$195	Geisel School of Medicine at Dartmouth, USA	2019	Shee et al. 2020 *Face, Content, Construct*
	Pyeloplasty model	Robotic pyeloplasty	A low cost, high-fidelity model	$1.32	University of Texas Southwestern Medical School, USA	2020	Timberlake et al. 2020 *Face, Content, Construct*
	SIMPLE-PN	RAPN	High-fidelity model with a realistic perfused renal hilum	$185	University of Rochester, USA	2016	Melnyk et al. 2020 *Face, Content, Construct, Concurrent*
	NS-RARP	RARP	High-fidelity, anatomical-correct model can be used in full-immersion simulation	$295	University of Rochester, USA	2020	Witthaus et al. 2020 *Face, Content, Construct*

LAPN, laparoscopic-assisted partial nephrectomy; NA, not available; RAPN, robotic-assisted partial nephrectomy; RARP, robotic-assisted radical prostatectomy; SPT, suprapubic tube; URS, ureteroscope; UVA, urethrovesical anastomosis.

Table 2.

Virtual reality/augmented reality simulators for open, endoscopic, and robotic urologic procedures (published from Jan, 2016 – June, 2020)

Surgical approach	Name of model	Manufacturer/ Institution	Training procedures	Features	Cost (US $)	Debut	Relevant Publication *Validity*
Open	System for Telementoring with Augmented Reality	Purdue University, USA	Abdominal incision	Augmented reality head-mounted display with Hololens VR	NA	2016	Rojas et al. 2019 *Face, Content, Construct, Concurrent*
Endo	HoLEP Synthetic Prostate Model	University of Sao Paulo, Brazil	Holmium Laser Enucleation of the Prostate	Included training curriculum, utilized real HoLEP endoscopes	NA	2014	Antunes et al. 2019 *Face, Content*
	TURP Mentor™	3D Systems/Simbionix	TURBT, TURP	Validated assessment using simulator metrics to distinguish experts and novices	NA	2019	Bube et al. 2019 *Face, Content, Construct*
	3D-Printed Digital Prostate Phantom	Max Planck Institute, Germany	TURP	Biomimetic hydrogel material allows for realistic electrocautery scarring during simulated TURP	NA	2020	Choi et al. 2020 *Face*
	HoloLens URS Simulator	Guy’s Hospital, London, UK	Ureteroscopy, PCNL	Developed Using: Uro-Scopic Trainer (Limbs and Things, Bristol, UK), and the Endo-Uro Trainer (Samed, Dresden, Germany). Training occurred within a previously validated Full Immersion Simulation “Igloo” environment	NA	2018	Janabi et al. 2018 *Face, Content, Construct*
	Uro-Trainer	Karl Storz, Germany	Cystoscopy, TURBT	VR-based tutorial on resectoscope handling, along with bleeding control and tumor excision	NA	2018	Neumann et al. 2018 *Face, Content*
Robotic	dV-Trainer®	Mimic Technologies, USA	Basic skills, RAPN, RARP	Provide haptic feedback	$158,000	2007	Moglia et al. 2016 *Face, Content, Construct, Concurrent, Predictive*
	Xperience Team Trainer™	Mimic Technologies, USA	Assistant skills	-	NA	2014	Xu et al. 2016 *Face, Content, Construct, Concurrent*
	da Vinci Skills Simulator (dVSS)	Intuitive Surgical, Inc., USA	Basic skills; Full simulated procedures	Hangs on the back of da Vinci® Surgeon Console	$89,000	2011	Moglia et al. 2016 *Face, Content, Construct, Concurrent, Predictive*
	RobotiX Mentor (RM)	3D Systems/Simbionix, USA	Basic skills, RARP	-	$137,000	2016	Harrison et al. 2018 *Face, Content, Construct*
	Robotic Surgery Simulator (RoSS®)	Simulated Surgical Systems LLC, USA	Basic skills, UVA, RARP, RARC, LND	-	$120,000	2010	Hertz et al. 2018 *Face, Content, Construct, Concurrent*

CYS, cystoscopy; HoLEP, holmium laser enucleation of the prostate; LARN, laparoscopic-assisted radical nephrectomy; LND, lymph node dissection; NA, not available; RAPN, robotic-assisted partial nephrectomy; RARC, robotic-assisted radical cystectomy; RARP, robotic-assisted radical prostatectomy; SPT, suprapubic tube; TURBT, transurethral resection of bladder tumor; TURP, transurethral resection of prostate; UVA, urethrovesical anastomosis.