Supplementary

Table S1 Curriculums for teaching robotic surgery

Author	Specialty or association	Curriculum focus	Curriculum components				
			Didactics	Virtual reality simulation	Dry or wet labs	Bedside assisting	Cases
Araujo & Pêgo-Fernandes, 2023 (33)	Brazilian medical association	Proposed curriculum	X	X		X	X
Baimas-George *et al.*, 2021 (34)	Hepatobiliary	Proposed curriculum	X	X		X	X
Davidson *et al.*, 2023 (64)	Transplant-donor nephrectomy	Proposed curriculum	X	X		X	
Gerull *et al.*, 2020 (70)	General surgery	Advocates for standardization		X			X
Grannan *et al.*, 2021 (77)	General surgery	Proposed curriculum	X	X		X	X
Green *et al.*, 2021 (81)	General surgery	Proposed curriculum	X	X		X	X
Ko *et al.*, 2018 (107)	Urology	Proposed curriculum		X	X		
Krause & Bird, 2019 (108)	Colorectal-total mesorectal excision	Proposed curriculum	X	X	X	X	X
Harji *et al.*, 2023 (13)	General surgery	Proposed curriculum	X	X	X	X	X
Madion *et al.*, 2022 (125)	General surgery	Advocates for standardization	X	X	X	X	X
Mark Knab *et al.*, 2018 (7)	Surgical oncology	Proposed curriculum		X	X		X
Merriman *et al.*, 2023 (130)	General surgery	Proposed curriculum	X	X		X	X
Moit *et al.*, 2019 (131)	General surgery	Advocates for standardization	X	X	X	X	X
Nathan *et al.*, 2023	–	Proposed curriculum	X	X			
Papalois *et al.*, 2022	Urology	Proposed curriculum		X			
Phé *et al.*, 2017 (146)	Urology	Impact of simulation	X	X	X		
Porterfield *et al.*, 2023 (148)	General surgery	Advocates for standardization	X	X	X	X	X
Puliatti *et al.*, 2022 (151)	Urology	Proposed curriculum	X				
Raad *et al.*, 2018 (153)	Cardiothoracic	Proposed curriculum	X	X	X	X	X
Radi *et al.*, 2022 (154)	General surgery	Impact of simulation	X	X	X		
Ramirez Barriga *et al.*, 2022 (157)	General surgery	Proposed curriculum	X	X	X	X	
Rusch *et al.*, 2017 (158)	Society of European Robotic Gynecological Surgery	Proposed curriculum	X	X	X	X	X
Satava *et al.*, 2020 (161)	Multiple	Impact of simulation	X	X	X	X	
Shaw *et al.*, 2022 (170)	General surgery	Advocates for standardization	X	X	X	X	X
Stewart *et al.*, 2023 (175)	General surgery	Advocates for standardization	X	X	X	X	X
Tam *et al.*, 2017 (8)	Surgical oncology	Advocates for standardization	X	X	X	X	
Tellez *et al.*, 2024 (177)	General surgery	Proposed curriculum		X	X		
Thomaschewski *et al.*, 2024 (178)	General surgery	Impact of simulation	X	X	X	X	X
Tom *et al.*, 2019 (181)	General surgery	Advocates for standardization		X			X
Unruh *et al.*, 2023 (186)	General surgery	Advocates for standardization	X	X		X	X
Vetter *et al.*, 2017 (190)	Gynecology	Advocates for standardization		X		X	X
Volpe *et al.*, 2020 (191)	European Association of Urology-prostatectomy	Impact of simulation	X	X	X	X	X
Winder *et al.*, 2016 (202)	General surgery	Proposed curriculum	X	X		X	X

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Table S2 Virtual reality simulations used to teach surgical residents and fellows robotic surgery

Author	Procedure	Simulator platform	Notes/useful takeaways
Abreu *et al.*, 2023 (25)	–	da Vinci Xi system; SimNow modules	Incorporation of simulation modules as part of the training curriculum showed an improvement in practice assessment scores
Abreu *et al.*, 2024 (26)	Gastrojejunal (GJ) anastomosis	da Vinci Xi system; SimNow modules	Utilized the SimNow module for virtual reality training and da Vinci Xi system for the inanimate drills training to assess transferability to operative performance
Aghazadeh *et al.*, 2016 (28)	Prostatectomy	da Vinci Skills Simulator (dVSS)	Virtual reality exercises on the dVSS correlated with positive robotic clinical performance
Ahmad *et al.*, 2021a (29)	–	da Vinci Simulation System and Mimic da Vinci Trainer	23-module mastery-based virtual reality curriculum with increasing difficulty; mastery was considered a score of 90%
Almarzouq *et al.*, 2020 (30)	Urethrovesical anastomosis and bladder mobilization for prostatectomy	da Vinci Surgical Skills Simulator	RCT to compare trainees' virtual reality simulation training schedule finding no difference between competency *vs.* 3 days of practice on future operating room performance
Berges *et al.*, 2022 (39)	Hysterectomy	da Vinci Skills Simulator	Practiced 5 simulator exercises on the da Vinci Skills Simulator at least 10 times or until they passed; then, performed each simulator exercise once an hour before doing hysterectomy in the operating room
Beulens *et al.*, 2019 (41)	–	Mimic dV-Trainer, Intuitive surgical da Vinci Xi robotic system, da Vinci skills simulator, and the 3D Systems RobotiX Mentor	1-day robotic surgery training combined e-learning module & virtual reality simulators
Beulens, Hashish *et al.*, 2021 (42)	Urethrovesical anastomosis	3D Systems Robotix Mentor Simulation System	First received training and overview of procedure and anatomy. Compared to the non-guidance and simulator-generated guidance groups, proctor-guided group showed higher satisfaction and but no significant difference in performance
Bjerrum *et al.*, 2023 (44)	–	Versius trainer	Verbally introduced to trainer, watched videos on 8 exercises selected, completed exercises twice
Brown *et al.*, 2017 (46)	–	da Vinci Surgical Skills Simulator and the standard da Vinci (SdV) robot	Overall improvement in robotic surgical skills after practicing 30 min per week over a 4-week period
Cacciatore *et al.*, 2023 (49)	–	Medtronic Hugo RAS System	Residents used a training course with introductory section and intraoperative tasks
Carneiro *et al.*, 2022 (50)	–	da Vinci Surgical Skills Simulator	Proctoring via in-person or remote mentoring showed improvement specifically with intermediate tasks
C.C.G. Chen *et al.*, 2023 (54)	Hysterectomy	da Vinci Surgical Skills Simulator	No difference in performance in the operating room regardless of warmup
Chowriappa *et al.*, 2015 (57)	Urethrovesical anastomosis	Robotic-assisted Surgical Simulator (RoSS) & Hands-on Surgical Training (HoST)	Trainees who completed HoST augmented reality training were able to complete urethrovesical anastomosis dry lab with better tissue manipulation, suture placement, and needle positioning and driving
Cope *et al.*, 2022 (61)	Hysterectomy	Surgical Science-Simbionix Hysterectomy Modules	After video on simulator modules, made attempts for ureter identification, bladder flap, and colpotomy on individual Simbionix Hysterectomy Modules
Cowan *et al.*, 2021 (62)	Urethrovesical anastomosis	da Vinci SimNow; da Vinci Xi System	A virtual reality simulation of vesicourethral anastomosis including placement of 12 stitches with life-like animations was conducted using the da Vinci SimNow
Dickinson *et al.*, 2022 (67)	–	da Vinci Xi system; SimNow modules	Residents attended multispecialty event and assigned into PGY level-specific learner groups and rotated through three simulations. First two stations were SimNow modules, and last station was mock OR with complete da Vinci Xi system with abdominal model. Increased agreement in level of confidence and knowledge improvement after multi-specialty robotics training event
Dioun *et al.*, 2017 (68)	–	da Vinci Skills Simulator	Participants performed 9 modules three times
Gerull *et al.*, 2020 (70)	–	da Vinci Skills Simulator	Subjects participated in pre-training case of robot-assisted laparoscopy and tasked to reach proficiency on da Vinci Skills Simulator
Gleason *et al.*, 2022 (73)	–	da Vinci Skills Simulator and Intuitive Learning Platform	Participants stated their improvements in robotic skills after virtual reality curriculum; set 90% as passing score
Gomez *et al.*, 2015 (75)	–	da Vinci Si surgeon's console and Skills Simulator	5-min overview and 5-min warm up given to participants before completing exercises. Training session was two individual sessions (1–2 hours) over two weeks; subjects could ask questions and receive hints
Gurung *et al.*, 2020 (83)	–	da Vinci Skills Simulator	Evaluated the role of an accelerated skill acquisition protocol (ASAP) that focused on the most difficult simulations in comparison to conventional training in terms of timing needed to obtain proficiency (defined as 90%+). While it was found that ASAP led to faster proficiency, it did not lead to less skill decay
Hertz *et al.*, 2018 (86)	–	dV-Trainer, da Vinci Skills Simulator, and RobotiX Mentor	All three virtual reality simulators, the dv-Trainer, da Vinci Skills Simulator, and RobotiX mentor, showed face and content validity
Hogg *et al.*, 2017 (6)	–	da Vinci Skills Simulator	Curriculum includes 24 virtual reality modules on Intuitive Surgical Backpack simulator using proficiency-based curriculum. Overall score improvement with mastery-based simulation curriculum
Kiely, Gotlieb, Lau, *et al.*, 2015 (103)	Suturing	da Vinci Skills Simulator	Proficiency-based robotic surgery simulation curriculum over 5 weeks with da Vinci Skills Simulator
Kim *et al.*, 2015 (104)	Urethrovesical anastomosis	Tube 3 module for Mimic da Vinci Trainer	Trainees practiced the Tube 3 module hourly for 7 days. 41 repetitions of the module were indicated to reach a stable point or predetermined proficiency level
Kim *et al.*, 2023 (106)	–	da Vinci Skills Simulator with Intuitive Learning Platform	Completed 23 exercises until achieving 90% proficiency on all exercises
Kun *et al.*, 2019 (109)	–	Mimic da Vinci Trainer	Found that sharing recording of simulation performance with trainees led to improved performance

Table S2 (*continued*)

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Table S2 (*continued*)

Author	Procedure	Simulator platform	Notes/useful takeaways
Lee & Lee, 2018 (113)	–	da Vinci Skills Simulator	Prior to the 5-week VR simulation training session on four VR training tasks, participants watched performances of four VR simulation tasks and four physical model tasks. The group who received additional mentoring improved performance more than group who reviewed their metrics
Lee *et al.*, 2019 (114)	–	da Vinci skills simulator and custom-made skills simulator (CMSS)	Students completed either CMSS or da Vinci simulator exercises; CMSS was comparable to da Vinci for training medical students in robotic surgery
Margueritte *et al.*, 2020 (126)	–	da Vinci Skills Simulator	As part of a three-day event, trainees completed skill focused virtual reality simulations
Mariani *et al.*, 2021 (127)	–	da Vinci Research Kit surgeon console and Assisted Teleoperation with Augmented Reality framework	Performance-based adaptive curriculum developed with automatic scheduling of training session based on trainee's performance
Melnyk *et al.*, 2021 (129)	–	da Vinci Skills Simulator	Gaze-augmented training with the da Vinci Skills Simulator was more efficient compared to the group of trainees using movement training
Moran *et al.*, 2022 (133)	–	da Vinci Skills Simulator	Utilized gamification to increase simulator use by implementing a simulation league in which teams of residents competed in simulation challenges over an 18-week period, with increase in self-reported simulator use and performance
Nakamoto *et al.*, 2023 (135)	–	da Vinci SimNow	Utilized gamification to increase simulator use by sending weekly leaderboards and personal progress on simulator during 4-week period, finding an increase in simulator use and scores
Newcomb *et al.*, 2018 (137)	–	da Vinci Skills Simulator	Subjects completed 5 VR tasks on da Vinci Skills Simulator and 5 R-OSATS dry lab drills. Scores from the VR drills selected statistically significant correlation with dry lab drills, demonstrating that selected VR drills can serve as supplementary training for novice surgeons
Olsen *et al.*, 2024 (141)	Prostatectomy	RobotiX MentorS	RobotiX VR-simulator for training robot-assisted radical prostatectomy was implanted
Oquendo *et al.*, 2024 (142)	–	Da Vinci Research Kit	In this study, researchers evaluated the impact of different types of haptic feedback: guidance, error enhancing, or none, finding that error enhancing initially showed enhanced skill acquisition however skill acquisition leveled out with time
Papalois *et al.*, 2022 (143)	Prostatectomy	HoloLens headset	Virtual surgical mentorship using the HoloLens was implemented for virtual reality curriculum and found to improve skills
Patel *et al.*, 2022 (144)	–	da Vinci Skills Simulator	Describe a virtual reality training used during COVID-19
Phé *et al.*, 2017 (146)	–	da Vinci Skills Simulator	dVSS training program implemented, beginning with dry lab training, then undergoing dVSS training. Junior and senior surgeons' basic surgical skills did not improve in dry lab setting after VR robotic simulation training
Radi *et al.*, 2022 (154)	–	da Vinci SimNow	Mastery-based virtual reality curriculum included 3 inanimate drills on da Vinci robotic system and 33 virtual reality tasks on SimNow with da Vinci Xi surgeon console
Sanford *et al.*, 2022 (160)	Prostatectomy	Mimic Flex VR simulator	Suturing exercise on the Mimic Flex VR simulator was completed by surgeons; significant correlation was found in technical scores between the live vesicourethral anastomosis during prostatectomy and VR exercise
Satava *et al.*, 2020 (161)	–	da Vinci Skills Simulator, Mimic da Vinci Trainer, Dome	Trainees showed improvement across simulator platforms
Scott *et al.*, 2020 (166)	–	RobotiX Mentor	6 modules on RobotiX Mentor selected to include in cross-specialty, virtual reality training program
Tillou *et al.*, 2016 (179)	–	da Vinci Skills Simulator	Required participants to obtain an 80% score before proceeding between simulator exercises
Turbati *et al.*, 2023 (183)	–	da Vinci SimNow	Participants completed 5 exercises
Turner & Kim, 2021 (185)	Hysterectomy	da Vinci Surgical System Backpack Simulator	Residents complete a virtual reality hysterectomy simulation every 4 months with coaching, finding residents' ability to complete simulation increased from 3/32 to 29/32 during final session
Valdis *et al.*, 2015 (9)	–	Mimic da Vinci Trainer	Conducted RCT with cardiac surgery trainees who were assigned virtual reality simulator practice being faster at internal thoracic artery harvest and mitral annuloplasty with higher intraoperative scores. Set proficiency level as >90%
Valdis *et al.*, 2016 (187)	Internal thoracic artery dissection and mitral valve annuloplasty	da Vinci Skills Simulator	VR exercises with a 9-exercise curriculum that is specific to skills needed for robotic cardiac surgery
Von Bechtolsheim *et al.*, 2024 (192)	–	Fundamentals of Robotic Surgery training on DaVinci Virtual Reality Simulator	Participants completed FRS training on the DaVinci Virtual Reality Simulator until reaching proficiency in 3 tasks, then took a midterm test on the DaVinci Xi system and completed 6 more tasks on the DaVinci Virtual Reality Simulator until reaching proficiency before completing a final test
Whittaker *et al.*, 2016 (197)	–	RobotiX Mentor	Construct, face, and content validity established for RobotiX Mentor
Whittaker *et al.*, 2019 (198)	–	RobotiX Mentor	Face and construct validity shown for thoracic lobectomy module on RobotiX Mentor simulator
Wiener *et al.*, 2015 (200)	–	da Vinci Skills Simulator	Conducted dry lab after achieving proficiency on the dVSS VR setting. Participants conducted bi-weekly VR training sessions over 10-week periods annually. 10 hours of training (five 2-hour sessions) found to be optimal to achieve proficiency in basic and advanced robotic skills

RCT, randomized controlled trial; PGY, postgraduate year; OR, operating room; VR, virtual reality; R-OSATS, Robotic-Objective Structured Assessment of Technical Skills; COVID-19, coronavirus disease 2019.

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Table S3 Dry lab simulations used to teach surgical residents and fellows robotic surgery

Author	Procedure(s)	Materials used	Notes/useful takeaways
Ballas *et al.*, 2019 (36)	Emergency undocking	Modified training torso	Three sessions administered: formative simulation, review simulation, and summative simulation. After formative simulation (first session), skills session was given to participants on how to properly conduct emergency docking (review session). Post-curriculum, participants showed increased knowledge score, number of critical actions during the summative simulation (third session), and confidence levels
Bendre *et al.*, 2020 (38)	Pyeloplasty	3D-printed model renal unit	3D-printed model of renal unit to simulate ureteropelvic junction obstruction, secured in laparoscopic box trainer
Brown & Kuchenbecker, 2023 (48)	–	Peg transfer	Utilized a smart task board data collection system to automate the GEARS score for a dry lab exercise—Peg transfer
Chowriappa *et al.*, 2015 (57)	Urethrovesical anastomosis	In-animate model	Dry lab used as method for assessment of skill acquisition from virtual reality curriculum
Cowan *et al.*, 2021 (62)	Urethrovesical anastomosis	3-DMed vesicourethral anastomosis kit	3-DMed vesicourethral anastomosis kit was modified so that 12 suture locations were marked to reflect virtual reality instructions to allow for comparison between two simulations
Goh *et al.*, 2015 (74)	–	Fundamental Inanimate Robotic Skills Tasks (FIRST)	Warm up exercise and instructional videos provided before completing the 4 FIRST tasks. Face, content, and construct validity were supported for the 4 FIRST exercises
Gonçalves *et al.*, 2024 (76)	Transabdominal preperitoneal inguinal hernia repair	Silicone model in endotrainer/box	Participants received instructions on steps of the procedure, including criteria for errors and goals before playing role of console surgeon on da Vinci Xi system. This study showed evidence of face, content, and construct validity of the robotic transabdominal preperitoneal inguinal hernia repair model using the da Vinci Xi system for training residents on inguinal hernia repair
Green, O'Sullivan, *et al.*, 2019 (79)	Instrument collisions	Modified training torso	Trainings working in pairs—one at bedside and one at console—trouble shot how to fix instrument collisions
Hoogenes *et al.*, 2018 (89)	Urethrovesical anastomosis	3D-printed bladder model	Participants completed online tutorial, virtual reality curriculum, warm-up, then completed exercise
Johnson *et al.*, 2019 (99)	Urethrovesical anastomosis	3D-printed model of male bony pelvis and silicone molds	Participants were given 12 minutes to complete simulation with 3D-printed model
Kiely, Gotlieb, Jardon, *et al.*, 2015 (102)	Pelvic lymphadenectomy	Pelvic lymphadenectomy model with rubber tubing, wire, cotton balls, plastic wrap, and gelatin solution	Model of pelvic lymphadenectomy was developed using rubber tubing, wire, cotton balls, and gelatin solution. This model was dissected by fellows and gynecologic oncologists sing the da Vinci Si Surgical system and was rated highly as a useful training tool. Face and content validity was received for the pelvic lymphadenectomy model using the da Vinci Si Surgical system
Laverty *et al.*, 2023 (111)	Enterotomy repair	Inanimate biotissue bowel model with cleaning sponge and hydrogel bowl	Biotissue bowel model on da Vinci Xi robotic console was developed for electrocautery and suturing simulation training. Participants received narrated video of the exercise being performed before simulation. Content, construct, response process and internal structure validity was established for an inanimate bowel model exercise with the da Vinci Xi robotic console
Lee *et al.*, 2022 (115)	Enterotomy with Repair	Inanimate bowel model with cleaning sponge	Inanimate bowel tissue model with cleaning sponge on da Vinci Xi robotic console was developed to improve trainees' robotic surgical skills
Lee *et al.*, 2024 (116)	Pancreatojejunostomy	Double-layer intestine and pancreatic silicone model	Fellows were provided with a master video on how to perform pancreatojejunostomy simulation with a modified Blumgart method by an experienced pancreatobiliary professor before simulation. Then, fellows performed 9 pancreatojejunostomy simulations, showing improved skills by the end of simulation training
Lyman *et al.*, 2021 (123)	Hepaticojejunostomy	LifeLike BioTissue Model for hepaticojejunostomy	Fellows completed 40 hepaticojejunostomy dry labs, with improvement in performance beginning at trial 16
Melich *et al.*, 2018 (128)	Total mesorectal excision	Pelvic model	Subjects completed a simulated total mesorectal excision dissection using the pelvic model and da Vinci robotic system. Total time and effectiveness of model was recorded. Pelvic model demonstrated face, content, and construct validity, supporting its use as a training platform for residents
Monda *et al.*, 2018 (132)	Partial nephrectomy	3D-printed silicone renal tumor models	Subjects received same instructions before the procedure and completed tumor excision from renal tumor model. Renal artery clamp time, preserved renal parenchyma, and surgical margins were assessed. Silicone renal tumor model confirmed face, content, and construct validity, supporting use as training tool for novice surgeons
Premyodhin *et al.*, 2018 (10)	Mitral valve replacement	3D-printed mitral valve	Mitral valve model developed from customizable 3D printing to be used as a training tool and evaluated by fellow and surgeons. Evaluators of the 3D-printed mitral valve displayed positive perception of the model for producing suture feel, tensile strength, and anatomic realism, supporting its use in training applications
Schneyer *et al.*, 2024 (164)	Myomectomy	Myomectomy model made of foam cylinder & stress ball	Robotic myomectomy simulation model created and subjects' simulation tasks were fibroid dissection/enucleation and closure of hysterectomy. Model demonstrated content and internal structure validity, supporting its usefulness for robotic myomectomy training
Scott *et al.*, 2023 (167)	Partial nephrectomy	3D-printed renal model	3D-printed renal model developed to improve understanding of renal anatomy and confidence of surgical trainees. Trainees reported significant increase in confidence on their surgical approach to robot-assisted partial nephrectomy after viewing the 3D-printed renal model
Shee *et al.*, 2020 (171)	Vesicourethral anastomosis	3D-printed bladder and urethra model	3D-printed *ex vivo* trainer of bladder and urethra with da Vinci Xi Surgical System developed to train residents on robotic vesicourethral anastomosis. Trained group of residents underwent dVSS curriculum training before performing vesicourethral anastomosis on model. Face, content, and construct validity of 3D-printed model demonstrated
Tam *et al.*, 2017 (8)	Hepaticojejunostomy, gastrojejunostomy, & pancreatojejunostomy	LifeLike BioTissue models of stomach, jejunum, and use of large vessel tissue model as hepatic duct	Proficiency-based robotic curriculum using a biotissue model. Subjects performed on Si da Vinci robot once a week with one-hour blocks to practice anastomoses. Curriculum with biotissue model demonstrated face and construct validity for training robotic pancreatoduodenectomies

Table S3 (*continued*)

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Table S3 (*continued*)

Author	Procedure(s)	Materials used	Notes/useful takeaways
Tarr *et al.*, 2022 (176)	Sacrocolpopexy	Pelvic model combined with custom silicone components	Participants watched instructional video on the multistep simulation model before performing a robotic sacrocolpopexy with the training model and da Vinci Surgical system. The developed simulation model demonstrated face and construct validity and high interrater reliability
Timberlake *et al.*, 2020 (180)	Pyeloplasty	Pyeloplasty models with Dragon Skin FX-Pro tissue-mimicking silicone	Participants watched an instructional video and then performed a dismembered pyeloplasty on the model created with the da Vinci robotic surgical system. Pyeloplasty model demonstrated preliminary content and construct validity
Towner *et al.*, 2019 (182)	Myomectomy	3D-printed model for myomectomy	3D-printed simulation model for myomectomy with da Vinci Xi surgical system was developed for usage as training tool for minimally invasive myomectomy outside the OR
Valdis *et al.*, 2016 (187)	Internal thoracic artery dissection and sutures of a mitral valve annuloplasty	Peg transfer, intracorporeal knot tying, and predrawn template with numbered boxes for movement and clutch of camera	Participants underwent dry lab training to complete 3 tasks which addressed camera movement and clutching, transferring and manipulation of Endowrist, needle control and driving, suturing, and intracorporeal knot tying
Von Bechtolsheim *et al.*, 2024 (192)	–	Fundamentals of robotic surgery training on da Vinci robotic system	Participants completed FRS training on the da Vinci Xi system until reaching proficiency in 3 tasks, then took a midterm test on the da Vinci Xi system and completed 6 more tasks on the robot until reaching proficiency before completing a final test
Walker *et al.*, 2017 (194)	Tumor resection	Pelvic tumor model with unexpected bleeding simulation	Subjects were given brief scenario of pelvic mass and were tasked with mass resection in 20 minutes. Once designated part of tumor was resected, bleeding complication was activated. Bleeding pelvic model was rated to have high realism and useful training tool
Wile *et al.*,2023 (201)	–	Low-cost home simulation model	Home simulation kits were developed for participants to use, though there was no significant difference in performance of robotic surgery simulators between those who did and did not receive the kits. Home simulation models were created to mimic the master tool manipulators on the da Vinci Skills Simulator
Witthaus *et al.*, 2020 (203)	Nerve-sparing radical prostatectomy	3D-printed model for nerve-sparing radical prostatectomy with hydrogel	Inanimate nerve-sparing robot-assisted radical prostatectomy model was developed using 3D-printing and hydrogel with the da Vinci Surgical system to be used as a training tool. Clinically relevant performance metrics of simulation incorporated into the simulation model and construct validity demonstrated for the model

GEARS, Global Evaluative Assessment of Robotic Skills; OR, operating room.

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Table S4 Wet lab simulations used to teach surgical residents and fellows robotic surgery

Author	Procedure(s)	Materials used	Notes/useful takeaways
Aghazadeh *et al.*, 2015 (27)	Enteropexy	Porcine model	da Vinci surgical robot used on a porcine model to locate a defined section of small bowel, maneuver it to a marked area, and suture it in place with a knot
Ballesta Martinez *et al.*, 2023 (37)	Vesicourethral anastomosis, pyeloplasty, and radical nephrectomy	Live porcine model under general anesthesia	All participants underwent 10–14 hours of dry lab practice for acquiring basic surgical skills before conducting the procedures on the live porcine models; dry lab training before procedure showed successful completion in vesicourethral anastomosis, pyeloplasty, and radical nephrectomy by subjects
Bertolo *et al.*, 2018 (40)	Pelvic and kidney robotic procedures via transperitoneal approach	Human cadaver	After residents underwent a single 1-day robotic human cadaver session led by supervisors, they reported perceived improvement in da Vinci VR simulator components and robotic skills. Furthermore, residents and supervisors recommended the robotic human cadaver training over the VR simulator and pig laboratory for improving residents' robotic skills
Boitano *et al.*, 2021 (45)	–	Human cadavers	After attending a 2-day curriculum with interactive didactic sessions with video, dry labs, and wet labs, participants reported increased confidence levels in most of the procedures in gynecologic oncology
Chow *et al.*, 2021 (56)	Partial nephrectomy	Ex vivo porcine kidney with marked tumor	Developed an *ex vivo* porcine model for partial nephrectomy in which residents had the chance to complete the wet lab four times over the course of a year, with decreases in time and improvement in GEARS score with progressive iterations
Clanahan, Han *et al.*, 2024 (59)	Right hemicolectomy	Human cadavers	15-minute didactic presentation on key steps and operative pitfalls with troubleshooting techniques was presented to residents then 3 hours of dissection and anastomosis in pairs on individual human cadaver models was completed
Croghan *et al.*, 2024 (63)	Partial nephrectomy	Porcine kidneys with either synthetic or biologic tumor (gonad or thymus)	A model was created using porcine kidneys for trainees to practice performing partial nephrectomy with the biologic tumors scored higher than the biologic tumor models (7.5–8 out of 10 *vs.* 6 out of 10 with 10 being 'perfect')
De Groote *et al.*, 2023 (66)	Vesicourethral Anastomosis	Chicken model	Used chicken model for vesicourethral anastomosis
Gheza *et al.*, 2023 (72)	Vaginal Cuff Closure	Vaginal cuff closure (VC) model with porcine heart	Vaginal cuff model created from porcine heart, and participants performed robotic suturing simulation. Subjects showed preference for the vaginal cuff closure (VC) model compared to the dV-trainer for practicing VC
Han *et al.*, 2023 (84)	Hiatal Hernia Repair	Porcine model	Three simulation sessions led by attending and fellow. Started with 15-min interactive didactic, including goals and objectives, then completed hands-on station. Subjects alternated between roles of surgeon and assistant; had one animate and robotic console. Confidence of residents increased on ability to operate independently
Hoffman *et al.*, 2020 (87)	Inferior vena cava injury repair	Porcine model	A porcine model for simulation of inferior vena cava injury during robotically assisted paraaortic lymphadenectomy was developed
Iqbal *et al.*, 2017 (91)	Hemicolectomy & low anterior resection	Human cadaver	After attending a structured 2-day robotic cadaver training lab, residents who previously responded they felt inadequately trained for robotic surgery felt significant increase in perceived knowledge on robotic surgery and increased preparedness to operate robotically
Jacob *et al.*, 2023 (94)	Advanced minimally invasive abdominal wall dissection	Porcine model	A porcine model was developed to teach advanced minimally invasive abdominal wall dissection techniques
Jarc *et al.*, 2017 (96)	–	Live porcine model under general anesthesia	Found that both trainees and teachers found a 3D ghost tool to facilitate coaching useful during procedures on a live porcine model
Lazar *et al.*, 2023 (112)	Lobectomy	Perfused porcine tissue model	As a part of a four-day bootcamp, trainees watched a video of an expert performing a robotic lobectomy using a perfused porcine tissue model in advance. Then at the station, trainees did a virtual reality simulation to function as a review and warm up. During the procedure the trainee received coaching from an expert surgeon in the form of both verbal advice and telestration
Mouraviev *et al,* 2016 (134)	–	Live porcine model under general anesthesia	Found that frustration was higher during simulation exercises than wet lab with live anesthetized pig during two-day robotic training course hosted by the Southeast Section of the American Urologic Association
Oh *et al.*, 2023 (138)	Lobectomy	Ex vivo porcine left lung-heart block with artificial blood	Performance on a perfused porcine tissue model for robotic lobectomies as part of a four-day bootcamp; subjects watched video of robotic lobectomy on porcine model and performed VR simulation exercises for warm up. Trainee performed lobectomy with verbal coaching and telestration
Puliatti *et al.*, 2021 (150)	Vesicourethral anastomosis	Chicken model	Used chicken model for vesicourethral anastomosis
Raison *et al.*, 2021 (156)	–	Porcine model	2-day simulation course with live porcine robotic training was developed
Schlottmann & Patti, 2017 (162)	Nissen fundoplication, Heller myotomy sleeve gastrectomy, colectomy, and lobectomy	Porcine tissue blocks with artificial blood in human mannequin	3-day robotic simulation course; each day was focused on a different sub-specialty (thoracic, colorectal, and foregut) and residents performed various procedures on porcine tissue model. Confidence in robotic surgical steps increased in residents after robotic simulation training with perfused porcine tissue blocks
Schlottmann *et al.*, 2019 (163)	Nissen fundoplication	Modified porcine tissue blocks which include lungs, heart, aorta, esophagus, diaphragm, stomach, duodenum, liver, and spleen	3-day robotic simulation course with modified porcine tissue block to increase familiarity of robotic console and controls, including port placement and docking process in procedures

Table S4 (*continued*)

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Table S4 (*continued*)

Author	Procedure(s)	Materials used	Notes/useful takeaways
Schommer *et al.*, 2017 (165)	–	Live porcine model under general anesthesia	During two-day robotic training course hosted by the Southeast Section of the American Urologic Association, which starts with 10 hours of didactics followed by virtual reality simulation tasks and wet lab with live anesthetized pig
Valdis *et al.*, 2016 (187)	Internal thoracic artery dissection and sutures of a mitral valve annuloplasty	Porcine model	Trainees harvested segment of internal thoracic artery pedicle off porcine chest wall and also placed a third suture of a mitral valve annuloplastic in porcine heart model
Von Rundstedt *et al.*, 2018 (193)	Intracorporeal bowel anastomosis	Porcine bowel	Bowel anastomosis training model created with porcine bowel and abdominal trainer; this model also showed face, content, and construct validity

VR, virtual reality; GEARS, Global Evaluative Assessment of Robotic Skills.

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Table S5 Approaches for assessment of trainee robotic surgical skill

Author	Setting	Level of automation	Name of assessment	Relevant findings
Abreu *et al.*, 2023 (25)	General surgery	Automatic	Kinematics	Utilized kinematic data from simulator including composite score, economy of motion, and errors
Abreu *et al.*, 2024 (26)	General surgery	Automatic	OSATS	Operative performance was evaluated using OSATS score
Aghazadeh *et al.*, 2015 (27)	Urology	Manual	GEARS	GEARS evaluated by two expert surgeons and the operator itself
Almarzouq *et al.*, 2020 (30)	Urology	Mixed	Kinematics & Crowdsourced GEARS (C-SATS)	Some virtual reality simulation scores correlated with GEARS score during cases in the operating room
Altok *et al.*, 2018 (31)	Prostatectomy	Manual	–	Time and quality-based evaluation after breaking the procedure into 11 steps
Anand *et al.*, 2024 (32)	Interdisciplinary	Manual	GEARS	Faculty members evaluated resident performance using GEARS
Baldea *et al.*, 2017 (35)	Urology	Manual	RoboLog	Trainees log which steps they performed and receive feedback from attendings
Bendre *et al.*, 2020 (38)	Urology	Mixed	Crowdsourced GEARS (C-SATS)	C-SATS used to evaluate 3D-printed silicone model for pyeloplasty
Berges *et al.*, 2022 (39)	Ob/Gyn	Mixed	Kinematics & GEARS	Did not find correlation between virtual reality simulation performance and intraoperative performance per GEARS
Brown *et al.*, 2020 (47)	Dry lab	Automatic	Kinematics	Analyzed kinematic and event data to estimate values of use of robotic instruments. Only a small subset of OPIs was needed to reach the highest model accuracies in estimating technical skills on a porcine model
Brown & Kuchenbecker, 2023 (48)	Dry lab	Automated	GEARS	Sharing score did not accelerate skill acquisition but did improve self-awareness of performance
Carter *et al.*, 2015 (51)	Virtual reality	Manual	GEARS & Crowdsourced	Open ended peer feedback on digital platform resulted in faster improvement on virtual reality simulation
Chen *et al.*, 2021 (53)	Vesicourethral anastomosis	Mixed	Kinematics	Used machine learning to compare kinematic data from novices & experts during key vesicourethral anastomosis stitches
C. C. G. Chen *et al.*, 2023 (54)	Hysterectomy	Manual	GEARS & R-OSATS	Used GEARS & R-OSATS to evaluate performance in operating room
G. Chen *et al.*, 2023 (55)	–	Automated	Kinematics	Used kinematic data captured by the surgeon trajectory optical monitoring system (STROMS) to evaluate accuracy during dry labs
Chowriappa *et al.*, 2015 (57)	Urology	Manual	GEARS	Used GEARS assessment to assess performance of dry lab urethrovesical anastomosis after completing augmented reality Hands-on Surgical Training (HoST)
Clanahan, Han *et al.*, 2024 (59)	Colorectal—right hemicolectomy	Manual	–	Experienced colorectal surgeons developed 10 question performance rubric for colorectal surgeries being evaluated based on OSATS and GEARS
Clanahan, Awad & Dimou, 2024 (60)	MIS	Automated	Active control time	Proportion of active control time consistent with hypothesis that this is a reflection of trainee skill
Cope *et al.*, 2022 (61)	Gynecology	Manual	GEARS	GEARS assessment used to assess virtual reality simulations
Cowan *et al.*, 2021 (62)	Urology	Automated	Kinematics & Mental Workload	Biometric data of cognitive mental workload was combined with OPIs for a virtual reality and dry lab simulation, finding that automated performance indicators were similar across platforms and that trainees had elevated cognitive workload for both simulation types
Davidson *et al.*, 2023 (64)	Abdominal transplant-donor nephrectomy	Mixed	RO-SCORE & Kinematics	Combined RO-SCORE, assessment of individual steps, active control time & number of handoffs to determine anticipated operative independence
De Groote *et al.*, 2023 (66)	Urology—vesicourethral anastomosis; wet lab	Manual	GEARS & Binary Metric Checklist	Checklist better differentiated performance than GEARS
Dubin *et al.*, 2018 (69)	–	Mixed	GEARS	Used linear regression equation with virtual reality simulator score and GEARS score, finding that simulator score does predict GEARS score
Gerull *et al.*, 2020 (70)	Virtual reality	Manual	RO-SCORE	Simulator skills curriculum evaluated with RO-SCORE
Gerull *et al.*, 2024 (71)	MIS—hiatal hernia repair	Mixed	Active Control Time	Determined Active Control Time percentage for individual procedural steps
Guni *et al.*, 2018 (82)	Urology—vesicourethral anastomosis dry lab	Manual	GEARS	A suturing checklist for needle driving and knot tying was created after assessing videos of participants completing robotic urethrovesical anastomosis on a dry lab model, with checklist validated with GEARS
Han *et al.*, 2023 (84)	MIS—hiatal hernia repair	Manual	RO-SCORE & GRS	Used GRS and O-SCORE for assessing hiatal hernia repair
Haque *et al.*, 2024 (85)	Urology—vesicourethral anastomosis	Manual	EASE	Utilized EASE to use an absolute standard of trainee performance during dry lab of vesicourethral anastomosis
Harji *et al.*, 2023 (13)	Colorectal—total mesorectal excision	Manual	GEARS	Used GEARS to score videos of trainees learning total mesorectal excision along with procedure specific assessment of steps
Holst *et al.*, 2015 (88)	Urology—dry lab	Manual	Crowdsourced GEARS (C-SATS)	Compared GEARS scores from experts *vs.* crowdsourced

Table S5 (*continued*)

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Table S5 (*continued*)

Author	Setting	Level of automation	Name of assessment	Relevant findings
Hoogenes *et al.*, 2018 (89)	Urology	Manual	GEARS & RACE	Utilized both GEARS and RACE to evaluate trainee performance of urethrovesical anastomosis dry lab
Hung *et al.*, 2017 (90)	Urology—prostatectomy & partial nephrectomy	Manual	GEARS	Utilized GEARS to assess performance in OR as trainees learned progressive operative steps
Iqbal *et al.*, 2022 (92)	Urology—partial nephrectomy	Manual	Scoring for Partial Nephrectomy (SPaN)	In this study, the Delphi method was used to develop SPaN, a procedure-focused assessment with likert scoring for individual steps of a partial nephrectomy
Jarc *et al.*, 2017 (96)	–	Manual	GEARS	Used GEARS to assess wet lab performance with 3D ghost coaching tool
Jiang *et al.*, 2017 (97)	–	Automated	Kinematics	Trajectories of instrument tip were used to create dynamic time warping algorithms to offer trainees both real-time and summative feedback
Khan *et al.*, 2019 (101)	Urology—vesicourethral anastomosis	Manual	RACE	The study showed that RACE scores can be used as an objective metric for assessing surgical performance in training
Kiely, Gotlieb, Lau *et al.*, 2015 (103)	–	Manual	GEARS	Showed improvement in training group for the GEARS score
Kim *et al.*, 2023 (106)	Multiple—suturing dry lab	Manual	GEARS & R-OSATS	Used GEARS & R-OSATS to evaluate trainee simulation performance
Laca *et al.*, 2022 (110)	Dry lab	Manual	GEARS	Real-time feedback during a training task with a surgical robot enhanced trainees' performance when they repeated the task
Laverty *et al.*, 2023 (111)	Enterotomy dry lab	Manual	GEARS	GEARS score used for dry lab assessment
Lazar *et al.*, 2023 (112)	Lobectomy wet lab	Mixed	Kinematics	Linked OPIs to bleeding during perfused lobectomy
Liang *et al.*, 2018 (118)	Dry lab	Automated	Kinematics	Measured movement metrics from MicroHand S robotic system
Liu *et al.*, 2017 (119)	Wet lab	Manual	ARCS	Developed ARCS which assesses six domains: energy pedal skills, dexterity with wristed instruments, instrument visualization, force sensitivity, optimizing view, and clutch efficiency
Lovegrove *et al.*, 2016 (121)	Urology—prostatectomy	Manual	RARP Assessment Score	An RARP score based on Healthcare Failure Mode and Effect Analysis methodology was developed to assess trainees performing robotic prostatectomy
Lyman *et al.*, 2021 (123)	Hepaticojejunostomy dry lab	Mixed	Kinematics	Synthesized OPIs to generate an operative robotic index
Ma *et al.*, 2024 (124)	Urethrovesical anastomosis	Mixed	EASE & AI	Used a combination of EASE and AI automated feedback, finding that this feedback resulted in large improvement in needle handling score
Monda *et al.*, 2018 (132)	Urology wet lab	Manual	GEARS	Used GEARS to evaluate wet lab model
Nathan *et al.*, 2023 (136)	Virtual reality curriculum comparison	Manual	R-OSATS	Found that adjuvant virtual classroom training led to a greater proficiency score as measured by R-OSATS compared to Fundamentals of Robotic Surgery curriculum
Newcomb *et al.*, 2018 (137)	Virtual reality & dry labs	Manual	R-OSATS & OPIs	Compared virtual reality & dry ab performance using R-OSATS & simulator score
Oh *et al.*, 2023 (138)	Cardiothoracic—lobectomy wet lab	Automated	Kinematics	Compared OPIs to between trainees & attending during perfused lobectomy
Olsen *et al.*, 2023 (139)	Urology—prostatectomy	Manual	GEARS	Assessment of robotic prostatectomy between crowd workers and experienced surgeons showed low agreement
Olsen *et al.*, 2024 (140)	Urology—prostatectomy virtual reality	Mixed	Kinematics	Linked surgical gestures (e.g., dissection) with active and idle time
Polin *et al.*, 2016 (147)	Dry lab	Manual	Crowdsourced R-OSATS	Crowdsourced R-OSATS scores of dry lab drills were highly correlated with expert surgeon R-OSAT scores
Powers *et al.*, 2016 (149)	Urology—partial nephrectomy	Manual	Crowdsourced GEARS	Compared GEARS scores from experts *vs.* crowdsourced
Puliatti *et al.*, 2021 (150)	Urology—wet lab	Manual	–	Defined steps and types of errors for wet lab
Quinn *et al.*, 2023 (152)	Mis—inguinal hernia	Mixed	Active control time	Robotic metrics consistent with those measured by research personnel.
Rahimi *et al.*, 2023 (155)	Dry lab	Automated	ForceSense	ForceSense measuring system was utilized to provide feedback on maximum force, impulse, and force volume and time
Ramirez-Barriga *et al.*, 2022 (157)	General Surgery—multiple procedure	Manual	R-OSATS	R-OSATS used to evaluate trainee performance during dry labs
Schneyer *et al.*, 2024 (164)	Gynecology—myomectomy	Manual	GEARS	Used GEARS assessment in robotic myomectomy simulation
Shafiei *et al.*, 2023 (168)	Multiple—wet lab	Mixed	GEARS, EEG & Eye Tracking	Linked GEARS assessment of surgical procedures with EEG and eye tracking data
Shafiei *et al.*, 2024 (169)	Multiple—Wet and dry lab	Mixed	RACE, EEG & Eye tracking	EEG and eye tracking data were extracted to predict RACE scores
Siddiqui *et al.*, 2016 (172)	Multiple—dry lab	Manual	R-OSATS	Determined R-OSATS scores that reflect competency in dry lab exercises

Table S5 (*continued*)

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Table S5 (*continued*)

Author	Setting	Level of automation	Name of assessment	Relevant findings
Simmonds *et al.*, 2021 (173)	Multiple—virtual reality	Automated	MScore Proficiency Index	Developed the MScore Proficiency Index based on virtual reality simulation performance
Soangra *et al.*, 2022 (174)	Urology—dry lab	Automated	EMG	Linked EMG with training level and time to complete dry lab
Tarr *et al.*, 2022 (176)	Urology—sacrocolpopexy	Manual	GEARS	Used GEARS assessment in robotic sacrocolpopexy simulation
Thomaschewski *et al.*, 2024 (178)	Gastroenterostomy—dry lab	Manual	GEARS	Used GEARS assessment to assess performance during wet lab portion of curriculum
Timberlake *et al.*, 2020 (180)	Pyeloplasty	Manual	GEARS	Used GEARS assessment in pyeloplasty simulation
Turner & Kim, 2021 (185)	Ob/Gyn—virtual reality hysterectomy	Automated	Kinematics	Used kinematic information and procedural steps to assess trainee completion of virtual reality hysterectomy
Vanstrum *et al.*, 2021 (188)	Urology—prostatectomy	Manual	DART	DART was developed as an objective 3-point surgical assessment to evaluate tissue dissection
Volpe *et al.*, 2015 (191)	Urology—prostatectomy	Manual	GEARS	GEARS assessment to assess prostatectomy performance in OR
Von Rundstedt *et al.*, 2018 (193)	Intracorporeal bowel anastomosis—wet Lab	Manual	GEARS	GEARS assessment to assess construct validity of bowel anastomosis wet lab
Walker *et al.*, 2017 (194)	Pelvic tumor	Automated	Kinematics	Idle time, path length, and bimanual dexterity used for assessment of pelvic tumor resection
Wang *et al.*, 2021 (195)	MIS—cholecystectomy & inguinal hernia repair	Automated	Active control time	Linked active control time with resident reported autonomy
Wang *et al.*, 2023 (196)	MIS—cholecystectomy & inguinal hernia repair	Automated	Active control time	Linked active control time with resident reported autonomy
White *et al.*, 2015 (199)	Multiple	Manual	Crowdsourced GEARS (C-SATS)	Compared GEARS scores from experts *vs.* crowdsourced of dry lab exercises
Witthaus *et al.*, 2020 (203)	Urology—prostatectomy	Manual	GEARS & RACE	Used RACE and GEARS assessment for nerve-sparing radical prostatectomy model
Wong *et al.*, 2023 (204)	Urology	Manual	Qualitative	Identified types of feedback given during case through qualitative analysis
Zia and Essa, 2018 (205)	MIS	Automated	Kinematics	Holistic features, such as sequential motion texture, discrete Fourier transform, and approximate entropy, can successfully be used for skill score predictions and skill classification

C-SATS, Crowd Sourced Assessment of Technical Skill via GEARS; DART, Dissection Assessment for Robotic Technique; EASE, End-to-End Assessment of Suturing Expertise; EMG, electromyography; GEARS, Global Evaluative Assessment of Robotic Skills; GOALS, Global Operative Assessment of Laparoscopic Skills; GRS, Global Rating Scale; RACE, Robotic Anastomosis Competence Evaluation; RARP Assessment Score, Robot-Assisted Radical Prostatectomy Assessment Score; R-OSATS, Robotic-Objective Structured Assessment of Technical Skills; RSA-Score, Robotic Skills Assessment Score; RO-SCORE, Robotic Ottawa Surgical Competency Evaluation; SPaN, Scoring for Partial Nephrectomy.

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