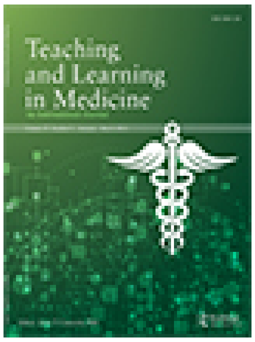

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A Review of Training Research and Virtual Reality Simulators for the da Vinci Surgical System

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***Phenomenon*: Virtual reality simulators are the subject of several recent studies of skills training for robot-assisted surgery. Yet no consensus exists regarding what a core skill set comprises or how to measure skill performance. Defining a core skill set and relevant metrics would help surgical educators evaluate different simulators. *Approach*: This review draws from published research to propose a core technical skill set for using the da Vinci surgeon console. Publications on three commercial simulators were used to evaluate the simulators' content addressing these skills and associated metrics. *Findings*: An analysis of published research suggests that a core technical skill set for operating the surgeon console includes bimanual wristed manipulation, camera control, master clutching to manage hand position, use of third instrument arm, activating energy sources, appropriate depth perception, and awareness of forces applied by instruments. Validity studies of three commercial virtual reality simulators for robot-assisted surgery suggest that all three have comparable content and metrics. However, none have comprehensive content and metrics for all core skills. *Insights*: Virtual reality simulation remains a promising tool to support skill training for robot-assisted surgery, yet existing commercial simulator content is inadequate for performing and assessing a comprehensive basic skill set. The results of this evaluation help identify opportunities and challenges that exist for future developments in virtual reality simulation for robot-assisted surgery. Specifically, the inclusion of educational experts in the development cycle alongside clinical and technological experts is recommended.**

Keywords virtual reality simulation, skills assessment, robotics, surgery, training

INTRODUCTION

Since its introduction to the United States in 1999, the *da Vinci® Surgical System* has been used for minimally invasive procedures in multiple specialties, including urologic,[1,2] gynecologic,[3,4] cardiothoracic,[5,6] otorhinolaryngologic,[7] and general surgery.[8,9] The system is now in its third generation—the da Vinci Si System (Figure 1)—yet retains its unique core components: a surgeon console from which the surgeon views the operative field and maneuvers the endoscope and instruments, a patient-side cart with three or four articulated arms to hold the endoscope and instruments, a set of wristed minimally invasive instruments that feature up to seven degrees of freedom, and a 3D vision system. These components were designed to enhance laparoscopic minimally invasive surgery by restoring to the surgeon some advantages of open surgery, such as articulated motion, 3D vision, and natural hand movement without a fulcrum effect. Most of the surgeon's interactions with the da Vinci System occur at the surgeon console (Figure 1 and Appendix in the supplemental online file), which is a surgeon-device interface significantly different from either laparoscopic or open surgery. The skillful use of its many features requires training and practice.

With successes in virtual reality (VR) simulation for learning laparoscopic skills, a natural progression is to investigate VR simulation for learning how to use the da Vinci console safely and effectively to perform surgical tasks (e.g., suturing, dissection, etc.). The teleoperated design of the robotic system provides a logical access point to present the surgeon with a virtual environment instead of a live endoscopic camera feed. Because the da Vinci System does not rely on tactile feedback to the surgeon, the development of da Vinci simulators is freed from a major challenge to creating high-fidelity laparoscopic simulators: the replication of tactile feedback to the surgeon. These aspects of the da Vinci System make it particularly amenable to VR simulation.

In recent years, multiple companies have released simulators to address the need for a safe and cost-conscious environment in which residents and surgeons can learn console skills. As with the laparoscopic simulators that preceded them, these da Vinci simulators have been scrutinized in validity studies. In general, these studies suggest that the simulators are promising tools to accelerate the initial training for console skills, as is discussed next. However, a "core" set of the skills related to a surgeon's technical proficiency with the da Vinci console controls, independent from skills related to performing specific surgical tasks, has not been well defined or broadly accepted. Associated metrics to assess proficiency in such skills are similarly lacking.

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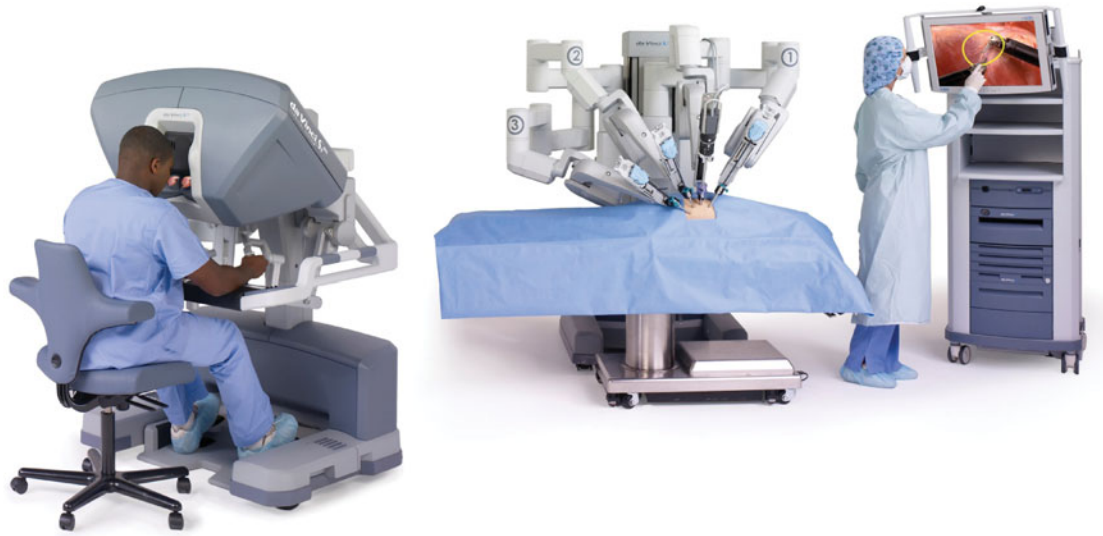

FIG. 1. The da Vinci Si Surgical System. Image courtesy of Intuitive Surgical, Inc., ©2014 Intuitive Surgical, Inc.

The purpose here is to examine the research associated with skills training, assessment, and VR simulation for the da Vinci Surgical System and attempt to answer the following questions: What are the essential skills needed to operate the da Vinci Si surgeon console (core technical skill set)? How well do existing commercial VR simulators support and measure these skills? The answers to this question set the stage to examine a final question: What gaps remain in functionality that could be addressed by future VR simulation platforms?

SELECTION OF PUBLISHED LITERATURE

In June 2013, we conducted at Scopus database search for English-language journal articles that contained the keywords *surgery* or *surgical* or *surgeon*, along with *skills* or *simulation* or *simulator*, and either *robot* or *da Vinci*. The search was limited to articles in the Scopus subject area "medicine" published since 1998—the year prior to the United States launch of the da Vinci Surgical System—and excluded review articles and conference proceedings. Articles related to neurosurgery, microsurgery, endovascular surgery, orthopedic surgery, imaging, image-guided surgery, or telemedicine were excluded. This initial search yielded 421 articles (Figure 2).

The next step was to manually identify articles pertaining to learning the da Vinci surgeon console (Figure 2). Nineteen articles were discarded because they had no abstract, whereas 179 articles were not primarily about the da Vinci platform. Twenty-two articles were high-level reviews, speculation on future technologies, or cost analyses that did not introduce novel findings on console use. The remaining 201 articles represented new research about the da Vinci System, but 26 articles focused on comparison between surgical modalities and 18 articles analyzed technology design (e.g., opportunities for haptic feedback or intraoperative navigation). Removing these left 157 articles about use of the commercially available da Vinci technology. Thirteen articles were surveys to assess surgeons' actual or anticipated adoption of robot-assisted surgery and thus provided no insight into console use. Twenty-eight articles were case reports of first-time or unusual surgical cases, or descriptions of how surgeons adapted their open or laparoscopic surgical approach to a robot-assisted approach; such articles focused more on port placement, instrumentation, and patient outcome than console utilization. Similarly, three articles focused on how to train patient-side assistant skills or port placement skills. The remaining 113 articles were about understanding surgeon proficiency at the da Vinci console. However, 40 of these articles used time spent at the console and patient outcomes of case series as indirect indicators of the console learning curve. Such articles did not focus on how, specifically, the surgeon used the console controls, and were thus eliminated, leaving 73 articles on learning the da Vinci surgeon console. This set of articles was further reduced to focus on either (a) a core technical skill set or (b) VR simulators, as described next.

WHAT CORE TECHNICAL SKILLS DO SURGEONS NEED TO USE THE DA VINCI CONSOLE?

To identify a core technical skill set, the group of 73 articles was further limited. Six articles about creating procedure-specific training models were excluded because these were primarily concerned with assessing the properties of the models (Figure 2). The remaining 67 articles were then limited to those that included specific technical console skills as determined by a consensus opinion of surgeons with expertise in robot-assisted surgery. Thirty-five studies did not identify specific console skills under consideration, so were removed. Because many studies focused on using inanimate models or VR

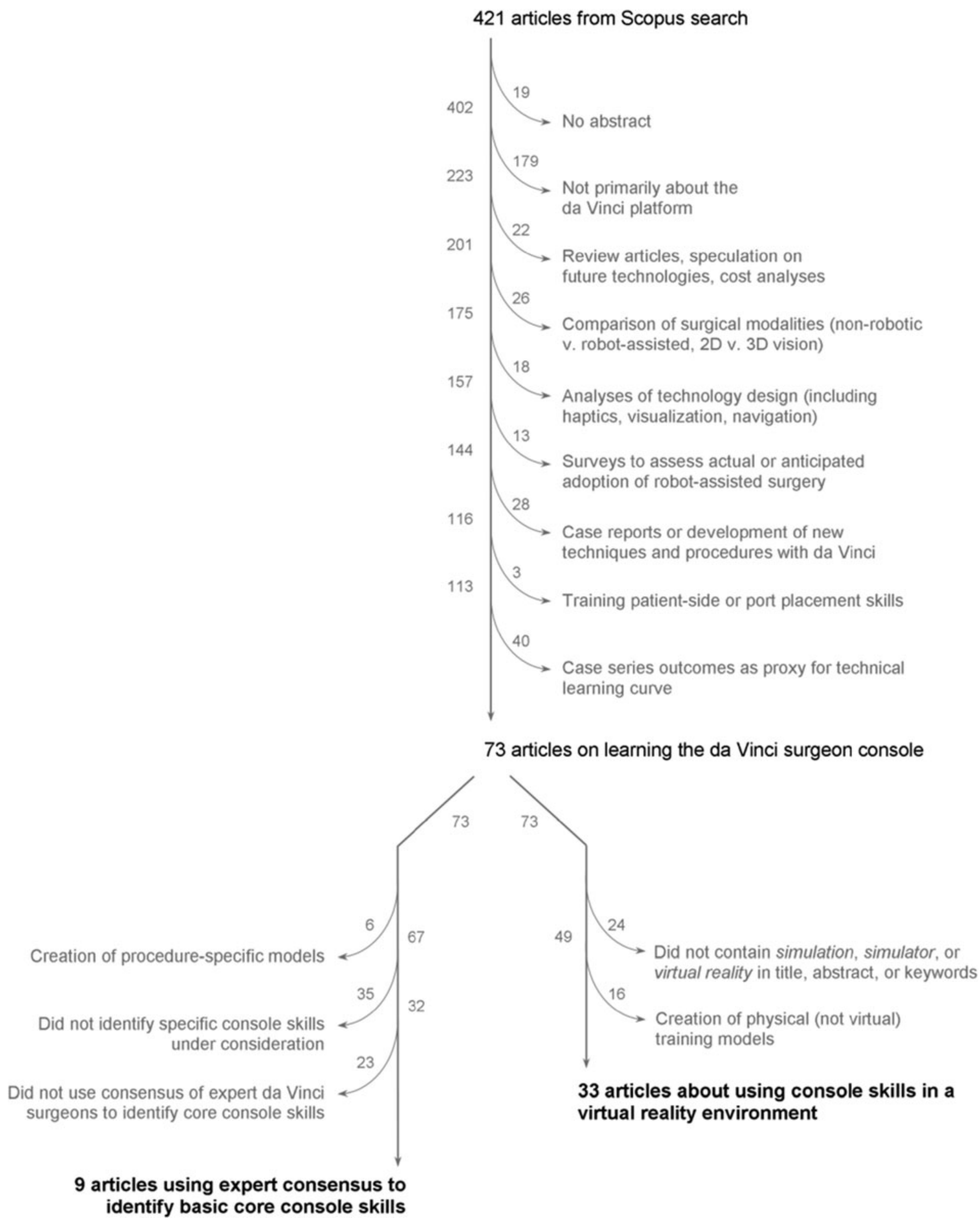

FIG. 2. Process by which literature review and reduction was performed to identify articles relevant to core technical skill set and to virtual reality simulators.

training tasks, the inclusion criterion requiring expert consensus on key skills prior to the selection or testing of these tasks was applied to ensure that the "skills" identified in such studies were not influenced by the manufacturers' description of the tasks' relevance.

This final exclusion criterion resulted in the removal of 23 articles, leaving a final list of nine articles for consideration (Figure 2, Table 1).[10–18] Four of the nine articles were from Dulan and colleagues[10–13] and represent a series of analyses based on an initial expert consensus.[13] Their expert group comprised six surgeons with robot-assisted surgical expertise in general surgery, urology, obstetrics and gynecology, and otolaryngology. Expert consensus in Stegemann et al.'s[18] analysis included surgeons from unspecified specialties who had performed more than 1,000 robot-assisted procedures. Hung et al.'s[17] study was included because the inanimate tasks they used were designed based on the consensus of surgeons with expertise with the da Vinci System;[19] neither these authors nor Goh et al.,[14] Lyons et al.,[15] or Perrenot et al.[16] described the compositions of their expert surgeon cohorts.

Surgical tasks such as needle manipulation,[18] knot tying,[18] suturing,[13,15,18] dissection,[13,18] cutting,[13,18] and retraction[13] (Table 1) were not included in this analysis because these tasks are independent of surgical modality (i.e., open, laparoscopic, or robot-assisted). The current investigation is instead focused on identifying what technical skills must be used at the da Vinci console—such as instrument manipulation, camera control, and energy control—to perform such surgical tasks. Goh et al.[14] identified skills related to movement efficiency and path planning (avoiding instrument collisions or assistant obstruction) as well as knowledge of procedural flow (autonomy); these were excluded because they suggest an integration of strategy and cognitive skills beyond the level of basic console interface skills. Dulan et al.[13] reported a number of skills required for successful use of the patient-side cart and team communication; although these are certainly important basic skills, we excluded them here because they do not involve the surgeon console interface. The same authors also included setup and adjustment of console settings as an important skill.

Aggregating the remaining skills from these studies suggests a core set of seven skills that are specific to the da Vinci console and independent of surgical specialty: bimanual wristed manipulation, camera control, master clutching to manage hand position, use of third instrument arm, activating energy sources, appropriate depth perception, and awareness of forces applied by instruments. Each skill maps directly to the console functions required to perform it (Table 2). The first five skills logically map to use of the console interface components, whereas the remaining two skills merit additional discussion. The inclusion of depth perception was unexpected because the console provides a 3D viewing environment that should minimize depth perception challenges. It is possible that this domain represents a holdover from traditional laparoscopy skills, which require the surgeon to appreciate 3D spatial relationships using a 2D endoscopic view. For example, Goh et al.'s[14] assessment of da Vinci skills was developed around an existing global assessment of laparoscopic skills,[20] which included depth perception. Notably, the laparoscopic skills assessment was itself based on an older assessment of technical skills for open surgery[21] that did not include depth perception, suggesting that depth perception skill may not be a significant issue when 3D vision is available, as it is on the da Vinci System. The final skill—the awareness of forces applied by instruments—is an important adaptation for robot-assisted surgery. Unlike open surgery or laparoscopic surgery, robot-assisted surgery does not allow a surgeon to manually feel the instrument–tissue interactions; there is no tactile feedback. In the absence of tactile feedback, it is critical for the surgeon to heed visual cues, such as tissue stretching or knot tightening, that result from instrument-tissue interactions.[22–26] For example, many surgical tasks—such as suturing, cutting, dissection, and retraction—require attention to visual cues related to tissue or suture tension when using the da Vinci System.

VIRTUAL REALITY SIMULATORS FOR THE DA VINCI SURGICAL SYSTEM

To find relevant publications about virtual reality simulators for the da Vinci System, we again examined the 73 articles identified previously (Figure 2). Of these, 33 related to console skills and virtual reality simulation. Six of the 33 articles were about noncommercial simulators under development;[27–32] because these simulators are in early development and not widely available, they were excluded from additional consideration.

Currently there are four commercially available VR simulators for the da Vinci System: the *SEP®-Robot* (SimSurgery AS, Oslo, Norway), the *RoSS™* (Simulated Surgical Systems, Williamsville, NY), the *dV-Trainer®* (Mimic Technologies, Seattle, WA), and the *da Vinci Skills Simulator™* (Intuitive Surgical, Sunnyvale, CA). As with laparoscopic VR simulators,[33–36] these da Vinci simulators have been analyzed for validity as skill assessment tools, as summarized in recent review articles by Abboudi et al.[37] and Lallas et al.[38] The purpose of the present literature review is not to evaluate the strength of validity evidence presented in previous studies but rather to determine whether the da Vinci simulators have training material that spans the core technical skill set just identified.

How Well Does Each Simulator Represent the da Vinci Si Surgeon Console User Controls and Functions?

The SEP (SimSurgery Education Platform)-Robot[39–42] emulates very few surgeon console components or functions (Appendix, Tables 1 and 2 in the supplemental online file)—it does not support 3D camera control,[39–41] and no publication suggests that it supports swapping to the third instrument arm or selecting energy sources—so it will be excluded from additional

TABLE 1
Summary of key skills required for robot-assisted surgery, as identified by expert cohorts in training research studies

Reference	Purpose of Study	Specialties Considered	Criteria for Expert Cohort	Skills Identified by Authors	
Dulan et al.[13]	Define a proficiency-based robotic curriculum	General surgery Gynecology Otolaryngology Urology	Institutional privileges to perform robot-assisted operations, an active da Vinci surgical practice, completed at least 10 robot-assisted procedures in career (6 experts)	· Adjusting console settings · Docking patient side cart · Placing trocars · Positioning patient side cart · Team communication · Using energy sources · Knowledge of component names · Maneuvering camera · Clutching · Knowledge of instrument names · Performing instrument exchange	· Controlling 4th arm[a] · Instrument manipulation · Wrist articulation · Depth perception · Passing objects between instruments · Atraumatic handling · Blunt dissection · Fine dissection · Retraction · Cutting · Interrupted suturing · Running suturing
Dulan et al.[11]	Face and content validity of curriculum from Dulan et al.[13]	General surgery Gynecology Otolaryngology Urology	Fellows and faculty members with active da Vinci practices from multiple specialties (12 experts)	Same as Dulan et al.[13]	
Dulan et al.[12]	Construct validity, cognitive workload, and expert benchmarks for tasks defined in Dulan et al.[11,13]	General surgery Gynecology Urology	Based on input from experts in Dulan et al.[11,13]	· Maneuvering camera · Clutching · 4th arm control[a] · Eye-hand coordination · Wrist articulation · Depth perception · Instrument to instrument transfer	· Atraumatic handling · Blunt dissection · Fine dissection · Retraction · Cutting · Interrupted suturing · Running suturing
Arain et al.[10]	Evaluate metric reliability, implementation feasibility, and educational benefit of curriculum in Dulan et al.[11–13]	General surgery Gynecology Urology	Based on input from experts in Dulan et al.[11,13]	Same as Dulan et al.[12]	
Goh et al.[14]	Creation and construct validity of global rating scale to assess robotic surgical skills	Urology	Not described	· Depth perception · Bimanual dexterity · Efficiency · Force sensitivity · Autonomy	· Optimizing camera view · Optimizing hand position · Minimization of instrument collisions

(*Continued on next page*)

TABLE 1
Summary of key skills required for robot-assisted surgery, as identified by expert cohorts in training research studies (*Continued*)

Reference	Purpose of Study	Specialties Considered	Criteria for Expert Cohort	Skills Identified by Authors	
Lyons et al.[15]	Face, content, and construct validity of da Vinci Skills Simulator	General surgery Urology	Not described	· Pick and place · Two-handed transfer · Wrist manipulation · Camera control	· Clutching · 3rd arm use[a] · Suturing · Energy use
Perrenot et al.[16]	Face, content, construct, and concurrent validity as well as reliability for the dV-Trainer	Not described	Not described	· 3D perception · Clutching · Visual force feedback	· Endowrist manipulation · Camera control
Hung et al.[17]	Construct and cross-method validity of inanimate, VR, and animate task assessment	Urology	Animate task assessment based on input from experts in Goh et al.[14]	Same as in Goh et al.[14] for animate tasks, not described for inanimate or virtual reality tasks	
Stegemann et al.[18]	Evaluate effectiveness, impact of a curriculum on the Robotic Surgical Simulator (RoSS)	Not described	Completed more than 1000 robot-assisted procedures (number of experts not described)	· Proper camera utilization · Instrument orientation · Coordination and depth perception · Foot control for clutching · Foot control for instrument swapping (e.g., swap to and from 4th arm[a])· · Needle manipulation	· Respect for operative space · Dissection · Knot tying · Suture transfer and handling with assistant · Cutting · Manipulating multiple instruments safely

[a] The terms "4th arm" and "3rd arm" are both used in the literature to refer to the same da Vinci component: the robotic arm of the patient-side cart that holds a 3rd instrument for the surgeon. More precisely, it is the "3rd instrument arm." It is sometimes called the "4th arm" when it is considered in addition to the three robotic arms that hold the camera and two other instruments.

discussion here. The three remaining simulators have distinctly different hardware and user controls, with varying fidelity to the actual console components (Appendix, Table 1 in the supplemental online file). The da Vinci Skills Simulator[15,17,43–48] is a hardware pack that streams a VR environment into an actual da Vinci Si surgeon console, so the console components and functions are exactly the same use as in surgery except that the Skills Simulator supports a limited set of touchpad functions. The RoSS (Robotic Surgery Simulator)[18,49–51] hardware platform is a console emulator similar in size and shape to a da Vinci surgeon console, with master controllers mounted on mechanical linkages, whereas the dV-Trainer[16,46,52–61] features a tabletop hardware platform in its console emulator, with master controllers suspended in the console emulator by wires. Both the RoSS and dV-Trainer emulate the da Vinci console stereo viewer, instrument clutches on the master controllers, and foot pedals. They have some ergonomic adjustment options.

The surgical instruments and endoscopic field of view are digitally rendered in all three simulators. Each manufacturer uses different software to model the instruments and other objects, lighting, physical interactions between objects, and other visual features. Each software platform has its own set of simulated tasks and associated metrics. However, until late 2012 the da Vinci Skills Simulator used only a large subset of the exercises developed by Mimic Technologies for the dV-Trainer.

The level of realism that a user experiences on a simulator—compared to using an actual da Vinci Surgical System—is determined by the interactions of simulator's hardware and software. For example, the quality of a function like

TABLE 2
Overlap of technical skills identified by published studies with the surgeon console functions

Technical Skills	Console Functions[a]: Control Instrument Position, Tip Angle, Grip Closure	Control Endoscope Position, Rotation, Insertion, Focus	Disengage Master Controllers to Reposition Hands	Swap Master Controller to Another Instrument	Select and Activate Energy Sources
Bimanual manipulation[13–15] with wristed instruments[13,15,16]	√				
Maneuver camera for optimal view[13–18]		√			
Manage hand position with master controller clutching[13–18]			√		
Use of third instrument arm[13,15,18]	√			√	
Use of energy sources[13,15]	√				√
Depth[13,14,18] or 3D[16] perception	√				
Atraumatic handling[13] or awareness of applied instrument force[14,16,18]	√				

[a]See the Appendix in the supplemental online file for detailed description of console functions and components.

endoscope control (Appendix, Table 2 in the supplemental online file) is determined by how the virtual field of view (software) responds to the user's depression of the camera pedal and movement of the master controllers (hardware). Multiple researchers have assessed users' perceived realism of several console functions featured in these simulators. Regarding instrument and camera control, Seixas-Mikelus et al.[49] surveyed 30 surgeons, most of whom who rated the "movement of the arms and tool control" in the RoSS as somewhat close (13/30) or very close (12/30) to an actual da Vinci System. Most of the surgeons also rated the "camera movement and clutch functions" as somewhat close (17/30) or very close (9/30) to those functions on an actual da Vinci System. Korets et al.[56] similarly surveyed a small cohort of subjects experienced with the da Vinci System, who generally rated the dV-Trainer's manipulation and camera movement functions as either "somewhat realistic" or "very realistic." In another survey of seven expert da Vinci surgeons a majority rated the realism of the dV-Trainer foot controls and 3D vision as "above average," but a minority of them rated the movement of the master controllers as above average.[58] Hung et al. reported that the median rankings from 15 expert da Vinci surgeons for "visual field, movement, and precision" were 9/10 (on 10-point scale with 10 being best) for the da Vinci Skills Simulator.[43] Similarly, most of the subjects in Foell et al.'s[48] study reported that this simulator provided a good experience of camera control, master controller clutching, and wristed manipulation. In general, the authors of these studies conclude that the three simulators seem to provide users with an adequately realistic experience of the basic console functions for the various tasks presented.

Which Core Console Skills Are Represented in Each Simulator's Tasks?

All three simulators have tasks that require some of the core technical skills for completion (Table 3). Validity studies for all three simulators have included multiple tasks requiring precise bimanual manipulation and placement of objects or needles.[15,16,43–45,48–51,56,58] Tasks designed for camera control skills have been analyzed for the dV-Trainer and da Vinci Skills Simulator,[16,43–45,48,56] although Colaco et al.[51] stated that the RoSS also has exercises focused on camera control. The RoSS appears to be the only simulator with an exercise specifically designed for master controller clutching,[50] although completion of advanced manipulation exercises in the Mimic software suite is likely to require master controller clutching. RoSS and da Vinci Skills Simulator tasks requiring use of the third instrument arm have also been included in validity studies;[15,50] such tasks are also on the dV-Trainer because it shares software with the da Vinci Skills Simulator. Tasks requiring energy selection have been reported only in validity studies for the da Vinci Skills Simulator;[15,43–45] again, the same tasks exist on the dV-Trainer, and Colaco et al.[51] state that electrocautery tasks are available on the RoSS.

None of the validity studies indicated that the simulators have tasks created primarily to address skills related to depth perception or visual cues of applied force. Perrenot et al.[16] selected a dV-Trainer pick-and-place task to satisfy a training objective for 3D perception in their study, but it is not clear whether improving depth perception skill was the manufacturer's original training intent for that task. Although none of the simulators have tasks focused on developing the situational awareness skills needed

TABLE 3
Overlap of core technical skills with virtual reality simulator content and metrics

Core Skills	Content	Content Included in Simulator?[a]		
		dV-Trainer	*RoSS*	*da Vinci Skills Simulator*
Wristed bimanual manipulation	Tasks?	Yes[16,54,56,58,59]	Yes[47–49]	Yes[15,41–43,46]
	Metrics?	No	No	No
Maneuver camera	Tasks?	Yes[16,54,59]	Yes[49]	Yes[41–43,46]
	Metrics?	No	No	No
Master controller clutching	Tasks?	No	Yes[48]	No
	Metrics?	Master workspace range[16,54]	No	Master workspace range[15,41–43]
Use third instrument arm	Tasks?	Yes[b]	Yes[48]	Yes[15]
	Metrics?	No	No	No
Use energy sources	Tasks?	Yes[b]	Yes[49]	Yes[15,41–43]
	Metrics?	Misapplied energy time[b]	No	Misapplied energy time[15,41–43]
Depth or 3D perception	Tasks?	No	No	No
	Metrics?	No	No	No
Awareness of instrument force	Tasks?	No	No	No
	Metrics?	Excessive instrument force[54,56]	No	Excessive instrument force[15,41–43]
Additional metrics reported in the literature		· Task completion time[16,54,56] · Economy of motion[16,54] · Object drops[16,54,56] · Instrument collisions[16,54,56] · Instrument out of view[16,54] · Missed targets[54] · Blood loss[b] · Broken vessels[b]	· Task completion time[49] · Instrument-instrument collisions[49] · Instrument-tissue collisions[49] · Tool tip path[81]	· Task completion time[15,41–43] · Economy of motion[15,41–43] · Object drops[15,41–43] · Instrument collisions[15,41–43] · Instrument out of view[15,41–43] · Missed targets[15,41–43] · Blood loss[41,42] · Broken vessels[41,42]

[a]Only simulator content cited in reviewed literature is included here.
[b]No reference is made in the literature to the dV-Trainer having this content but its presence is implied, because the dV-Trainer shared significant software content with the da Vinci Skills Simulator at the time these studies were performed.

to assess the level of instrument force by visual cues, some have metrics related to this skill, as is discussed next.

In summary, a comparison of the published validity studies to the core technical skill set indicates that these simulators' task content appears to be strongest in the bimanual wristed manipulation skill domain. All simulators enable use of camera control and master controller clutching during tasks, but validity studies identified specific tasks on the dV-Trainer and da Vinci Skills Simulator that focus on camera control, while the RoSS has content focusing on master clutching. All three simulators have tasks designed to use the third instrument arm and energy sources, whereas none appear to have tasks intended to develop depth perception or visual assessment of applied force.

What Metrics Does Each Simulator Use to Measure Skill Performance?

A powerful opportunity in virtual reality simulation lies in the potential to automate performance evaluation using objective metrics. Such metrics and evaluations should be supported by strong validity and reliability evidence, concepts that are thoroughly discussed elsewhere.[33–36,62–72] The simplicity and discretization of task execution or error checklists[13,73,74] make them good candidates for automation, as are metrics based on high-precision motion analysis[75–82] and task completion time. The question then becomes, How do the three simulators apply such metrics to assess performance of the core technical skill set?

All three platforms measure performance with metrics based on completion time, error measures, and motion analysis (Table 3). The metrics Colaco et al.[51] considered for the RoSS validity analysis were completion time and error measures (instrument-instrument collisions and instrument-tissue collisions), although they reference an earlier study[83] reporting that RoSS computes a number of additional metrics including motion-based measurement of tool tip path. The metrics analyzed in dV-Trainer validity studies included completion time, motion-based measures of economy of motion and master workspace volume, and error measures (object drops, instrument collisions, excessive instrument force, instrument out of view, missed targets, misapplied energy).[16,56,58] These metrics were also considered in da Vinci Skills Simulator validity studies,[15,43–45] along with error measures related to simulated blood loss and broken blood vessels.[43,44]

Unfortunately, none of the studies examined these simulators' capability to gauge users' estimation of instrument force through visual cues related to tissue stretch. The software on the dV-Trainer and da Vinci Skills Simulator will change the color of the virtual instrument shafts to red if "excessive force" is applied. However, it is not known if learning from this cue transfers to accurate force assessment during actual tissue manipulation, during which the relevant visual cues occur in the tissue instead of the instrument shaft.

Additional investigation into the details of existing simulator metrics is still needed. For example, Lyons et al.[15] and Hung et al.[43] found that even though some da Vinci Skills Simulator metrics on an energy selection task differentiated between experienced and novice robot operators, the metric specific to "misapplied energy" did not, so this metric may not provide meaningful information. Brinkman et al.[47] and Perrenot et al.'s[16] findings also suggest that certain metrics, such as "instruments out of view," may become less meaningful as robotic expertise grows and surgeons gain confidence in awareness of instrument placement. Comparison of metrics across simulator platforms requires careful consideration; for example, a da Vinci console has a larger available workspace volume for the master controllers than the dV-Trainer has, so any comparison of scores from the "master workspace range" metric on the da Vinci Skills Simulator and dV-Trainer should consider this difference. Furthermore, although the simulators include tasks requiring use of the third instrument arm, none appear to have metrics that measure how skillfully a user does this. Similarly, none have metrics that address how skillfully a user exploits the wristed degrees of freedom in the master controllers and instruments or how efficiently a user moves the camera for optimal viewing. Such metrics would provide a better basis for developing more focused training materials around the core technical skill set.

Summary of Current da Vinci VR Simulator Performance

A user's experience on a virtual reality simulator for the da Vinci System is determined by its representation of the console controls and functions (Appendix, Tables 1 and 2 in the supplemental online file), the scope of core skills addressed by its simulated tasks (Table 3), and the usefulness of its metrics or other automated feedback on user performance (Table 3). Certainly additional studies are required to determine how well skills learned in a VR simulator transfer to actual system use: without strong evidence that skills learned on a VR simulator result in improved intraoperative performance and patient care, it is weak proposition to urge widespread adoption of VR simulation for training. Nonetheless, the published data indicate that these simulators can support the basic execution and some assessment of most core skills. It is compelling to consider the possibility that novices could learn core console skills on a simulator even if the simulator's console emulator (e.g., dV-Trainer and RoSS) is less technologically sophisticated than an actual da Vinci console. On the other hand, expert da Vinci surgeons may find less value for themselves in current simulation tasks.[43] If advanced simulation tasks were created to support the continued learning needs of such experienced da Vinci surgeons, it is possible that these users might feel frustrated or hindered by a console emulator because they are accustomed to using an actual da Vinci console.

FUTURE OPPORTUNITIES FOR DA VINCI VR SIMULATION

It seems that VR simulators could bring significant value to the process of learning robot-assisted console skills. However, the current VR simulators for robot-assisted surgery have been criticized for both high cost and insufficient content beyond very basic tasks,[37,38] implying that they actually represent relatively low value for many users. To better understand how the value of future simulators could be improved, it is helpful to consider what potential users need, the scope of relevant content, how educational design expertise could enhance simulator-based learning, and the contributions of technology.

What Do Users Need From da Vinci Virtual Reality Simulators?

A da Vinci simulator should enable a user to learn and practice the skills he or she needs for surgical use. The fact that simulator design should be driven by user needs and relevant content cannot be overemphasized, yet little attention has been given to what this means. For example, users have limited time, possibly limited access to a simulator, and potentially different goals for using a simulator. Although it is often assumed that most users are novices who want structured coaching and assessment on skills, other users—particularly highly skilled surgeons—may prefer an unstructured, nonassessed environment for self-directed exploration, surgical warmup,[59,84–88] or even procedural rehearsal if the simulator content were sufficiently robust.[27,89–92] Eventually, still other users may need to use the simulator to complete high-stakes assessments such as for credentialing and maintenance of certification, as has been suggested by several researchers.[38,44,58,93] It should also be acknowledged that motivation to learn and practice new skills varies among individuals.[94,95] Although institutional or academic mandates may compel users to use a simulator, it would be preferable if the design of the simulator itself encouraged user engagement with the curriculum material and facilitated an understanding of the connection between simulator tasks and real-world clinical experience.

Who Are the Stakeholders in the Content of Virtual Reality Surgical Simulators?

Certainly, the real-world clinical content should be the primary driver for simulation design along with user goals. An exemplar clinical knowledge scope and skill set should be determined by experienced surgeons, and then education experts and technology experts can be consulted to develop a training solution, which might include VR simulators. Ongoing collaboration among subject matter experts from clinical, educational, and technological domains is essential to ensuring that simulator features remain in service of educational and user needs (Figure 3). Educational[96] and clinical expertise are both needed to choose appropriate task scope, instructional material, formative and summative assessment,[97] curriculum integration,[35,98–101] and proficiency standards.[102–105] Collaboration between technological and educational stakeholders could drive novel features such as multimodal feedback,[106–108] distance coaching via networked environments,[109] integrated support for appropriate practice schedules,[110–112] and intelligent tutoring systems[113] that provide coaching and adjust curricular content to an optimal level for individual learners.[114] Indeed, the most powerful feature of VR simulators may not be high-fidelity, immersive virtual environments: it may be that built-in curriculum support could enable learners to progress on their own, without faculty supervision. This assertion is supported by Benson et al.,[115] who compared formal and informal learning approaches and concluded that "surgeons may know the technology and surgical steps, but their skill acquisition may be limited without guidance on using the technology to complete the steps" (p. 1353). Conversely, users who desire unguided exploration and unstructured interactions—perhaps for presurgery warmup or procedure rehearsal—need scenarios built on a strong integration of clinical needs and technological capabilities.

Some fundamental properties of a simulator are best defined according to input from all three stakeholder areas. These

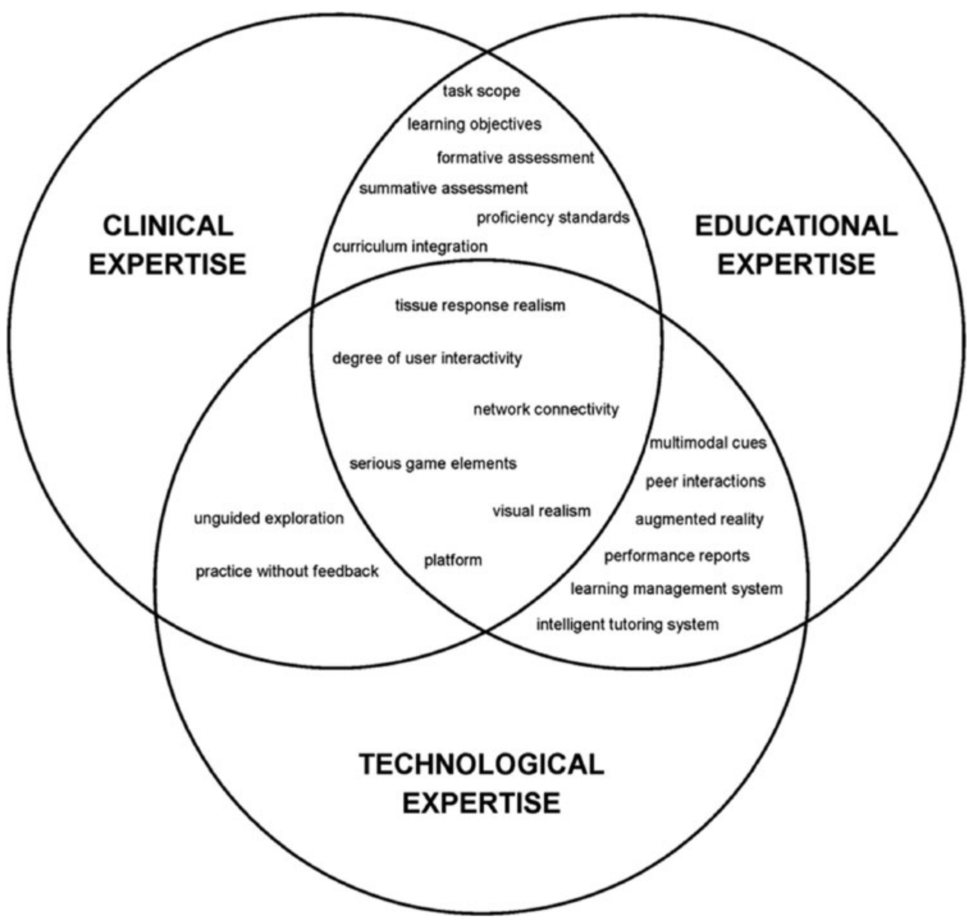

FIG. 3. Expertise from fields of medicine, education, and technology can contribute to improved simulation platforms for skills training.

properties—such as high visual fidelity with extremely realistic tissue responsiveness to handling—typically push the limits of available technology. Although clinical users would certainly prefer a very high degree of visual realism in a simulator task, the limitations on current visualization technology may oblige the clinical content and educational experts to reconsider the task scope or design other tasks that accommodate the learning objectives with less visual or tissue interaction complexity. Selection of a simulator platform (e.g., surgeon console, console emulator, website, mobile application, etc.) also requires consideration of user needs, educational goals, and available technology. An exciting opportunity for collaboration is the inclusion of features to enhance user engagement. The fast-growing field of serious games research explores ways to engage learners in educational activities by including game elements[116–119] such as storylines (e.g., a patient care reason to complete the suturing task at hand), interactive feedback (a virtual mentor surgeon providing tips for suture management), consequences of actions (dehiscence after poor suturing), and meaningful rewards for demonstration of proficiency (the virtual patient "goes home" a day early and the learner moves on to a more challenging task).

What Lies Beyond Console-Based Virtual Reality Simulation?

The potential features just described could be implemented in a variety of simulation formats to support training for robot-assisted surgery. Cognitive simulators or serious games could teach OR teams efficient workflow patterns for setting up the robotic system and turning over a room. Some companies, such as Red Llama (Seattle, WA), are pursuing this strategy for reinforcing surgeon procedural knowledge[120] and decision-making skills. Educational research in motor learning theory could contribute to improved instructional material for console skills.[112,121,122] Promising research with the use of augmented reality cues in the RoSS indicates that it may be a useful platform for learning relevant anatomy,[123] perhaps suggesting a hybrid platform for integrating motor and cognitive skills. Bringing the technology available for dual console surgery on the da Vinci Si Surgical System into a simulated environment could facilitate training for collaborative surgery.

To date, all simulators for robot-assisted surgery have focused on using VR technology for surgeon console skill acquisition, but surgical team members also need proficiency in relevant knowledge, cognitive skills, and communication skills related to using the full da Vinci System. Notably, only three articles were found in the current literature review that focused on training the skills needed at the patient's bed during a robot-assisted procedure.[124–126] Furthermore, the team members need to progress from proficiency with relatively simple cases to handling complex cases with efficacy and efficiency, including system troubleshooting. Indeed, some surgeons have reported that port placement and robot setup—not operating the console—were the most challenging aspects of learning to use the robotic system.[11] Introduction of these concepts could potentially be done in an entirely virtual world.[127] Alternatively, much as the da Vinci Skills Simulator uses an actual surgeon console to deliver a simulated experience, perhaps a da Vinci vision cart could be programmed in a "training mode" that would step a learner through different scenarios requiring interaction with the vision cart. Perhaps a da Vinci patient-side cart could be instrumented to provide real-time feedback to an individual or team for practicing different instrument arm joint configurations for various procedures. A combination of these last two training scenarios with a da Vinci Skills Simulator and surgeon console could serve as a simulation platform for full team training and practice.

What Are the Challenges to Broader Adoption of da Vinci Virtual Reality Simulation?

The opportunities are abundant yet challenges remain. The most significant technological deficiency in all existing simulators for robot-assisted surgery is probably insufficiently realistic behavior of suture and of instrument interaction with soft tissue. Robotic simulators have yet to deliver validated modules for knot tying or complex tissue handling. To be fair, the same challenge exists for laparoscopic simulators. However, the surgeon's dependence on visual cues in lieu of tactile cues in robot-assisted surgery means that the bar for visual fidelity may be higher in robotic simulators than in laparoscopic simulators. This will require considerable improvements in the underlying computational models used to represent tissues and other deformable objects in VR simulators for robot-assisted surgery. Another significant barrier to the widespread acceptance of robotic simulators is the argument that the purchase price is too high and the relevant content is too low. In general, however, the extent of clinical, educational, and technological features is proportional to the development effort and thus cost of purchase. As VR simulation gains more exposure,[128] it will be up to the clinical community to determine what the balance between features and cost should be, in light of alternative training approaches such as inanimate models, cadavers, or on the job training in the operating room. This means overcoming potential misperceptions that VR simulation is merely au courant hype and video games[129] or, conversely, that it is a panacea for every training challenge when in fact VR technology is a tool, not a solution. It will be up to the developers and researchers involved with simulation for robot-assisted surgery to help the clinical community understand simulation's potential strengths as well as limitations, in light of what must remain the central focus:[130] providing surgical personnel with the skills to deliver the best possible patient care.

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SUPPLEMENTAL DATA

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