Surgical Simulator Showdown

Danielle Julian, Alyssa Tanaka, Patricia Mattingly, Roger Smith

Florida Hospital Nicholson Center

Celebration, FL

Danielle.Julian@flhosp.org, Alyssa.Tanaka@flhosp.org,

Patricia.Mattingly@flhosp.org, Roger.Smith@flhosp.org

ABSTRACT

The introduction of robotic technology in minimally-invasive surgery created a need to develop more efficient and effective training and assessment tools. Virtual reality simulators were introduced to the field to address this need. Currently, there are four da Vinci simulators - the dVSS, dV-Trainer, RoSS, and the RobotiX Mentor. These simulators offer basic training for novice robotic surgeons, familiarizing them with the skills needed to perform safe surgery. While there is literature available for each simulator individually, it can be difficult for a user to select the appropriate system to meet their training needs.

Thus, this paper presents the results of a comparative analysis of the system components of each device (e.g., exercises, scoring metrics, physical dimensions, and student management). Previous research has directly compared three of the four simulators, however this is the first study to compare all four. To collect the information, the team reviewed the device manuals for details on each system, contacted device company representatives, and explored the system capabilities firsthand.

While all systems offer basic skill training in highly immersive 3D environments, each device offers unique advantages and capabilities for training robotic surgeons. The dVSS creates a high-fidelity training environment by leveraging the real robotic surgeon's console for visualization and control inputs. The dV-Trainer, RoSS, and RobotiX Mentor offer simulated versions of these systems. Each includes system management services for instructors to collect, export, and analyze trainee scores. All systems have been the subject of multiple published validation studies, however these reports do not provide essential details on the nuances of each simulator. The analysis in this paper can be used to aid potential users, buyers, and trainers in identifying the features, which are more essential to their training centers.

ABOUT THE AUTHORS

Danielle Julian, M.S. is a Research Scientist at Florida Hospital's Nicholson Center. Her current research focuses on robotic surgery simulation and effective surgeon training. Her current projects include rapid prototyping of surgical education devices and the evaluation of robotic simulation systems. Her background includes research in Human Factors and learning and training to enhance the higher-order cognitive skills of military personnel. She holds a M.S.in Modeling and Simulation, Graduate Simulation Certificate in Instructional Design, and a B.S. in Psychology from the University of Central Florida.

Alyssa D.S. Tanaka, Ph.D. is a Research Scientist at Florida Hospital Nicholson Center. Her research work focuses on robotic surgery simulation and effective surgeon training. Her current projects include rapid prototyping of surgical education devices, the validation of a robotic surgical curriculum and evaluation of robotic simulation systems. She holds a Ph.D. and M.S. in Modeling and Simulation, Graduate Simulation Certificate in Instructional Design, and a B.S. in Psychology and Cognitive Sciences from the University of Central Florida. She holds a diploma in robotic surgery from the Department of Surgery, University of Nancy, France.

Patricia Mattingly, M.D. is a Research fellow at Florida Hospital's Nicholson Center. Her research focuses on robotic surgery simulation and effective surgeon training. Her current projects include the development of a robotic surgical curriculum and assessing surgical task-induced fatigue. She is a fellow in minimally invasive gynecologic surgery with Columbia University Medical Center. She completed her residency in obstetrics and gynecology at Carolinas Health Care System in Charlotte, NC and earned her M.D. from the Medical College of Georgia. She received her B.S. in Biochemistry and Molecular Biology at the University of Georgia.

Roger Smith, Ph.D. is an expert in the development of simulation devices and training programs. He has spent 25 years creating leading-edge simulators for the Department of Defense and Intelligence agencies, as well as accredited methods for training with these devices. He is currently the Chief Technology Officer for the Florida Hospital Nicholson Center where he is responsible for establishing the technology strategy and leading research experiments. He has served as the CTO for the U.S. Army PEO for Simulation, Training and Instrumentation (PEO-STRI); VP and

CTO for training systems at Titan Corp; and Vice President of Technology at BTG Inc. He holds a Ph.D. in Computer Science, a Doctorate in Management, and an M.S. in Statistics. He has published 3 professional textbooks on simulation, 10 book chapters, and over 100 journal and conference papers. His most recent book is *A CTO Thinks About Innovation*. He has served on the editorial boards of the *Transactions on Modeling and Computer Simulation* and the *Research Technology Management* journals.

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INTRODUCTION

With an increase in the number of minimally-invasive procedures, surgical education has shifted away from the traditional apprenticeship model (i.e., "See one, do one, teach one") towards an experiential framework. Surgical trainees may encounter their first surgical experience on an inanimate training model, excised tissue, or as of more recently, a virtual reality (VR) simulator. These hands-on modalities provide a trainee with the opportunity to become familiar with equipment and instruments, develop skills (e.g., improved dexterity), and increase the understanding of surgical techniques and procedures (Polavarapu, Kulaylat, Sun, & Hamed, 2013).

VR simulation was first introduced to surgical education in the late 1980s (Satava, 1993). Since implementation, VR simulators have been established as valuable training tools for the acquisition of basic surgical skills. They allow a trainee to safely overcome the learning curve associated with new techniques while providing independent and repetitive exposure in a safe and cost-efficient environment (Chou & Handa, 2006). The application of VR simulators in surgery has proven to be essential with the development and implementation of new technology and complex devices.

One such device, Intuitive's da Vinci Robotic Surgical System, introduces unique components not available in traditional surgical techniques. This system provides surgeons with 3D vision, 7 degrees of freedom of laparoscopic instruments, tremor damping, motion amplification, camera stability, and other advanced features (Palep, 2009). In a robotic procedure, the surgeon sits at the surgical console separate from the other surgical team members and patient. From this console the surgeon manipulates master controllers, which translate the surgeon's movements into the smaller, more precise movements of the robotic instruments that are attached to a separate patient cart. The surgeon also controls the camera functionality using these master controllers. The camera provides magnified, stereoscopic vision allowing for depth perception and creation of a synthetic tactile sensation (Figure 1).

While this system offers multiple benefits, it introduces a technological divide between the surgeon and patient, which can lead to usability factors and a need for a specialized skillset. Providing a trainee with experience on the actual da Vinci system can be difficult due to the associated costs and resources required. Hospitals must make a large capital investment when adopting a robotics program and subsequently must recoup their investment via robotic procedures in the operating room. This often limits access to the system for training to time outside of normal operating room working hours. Along with accessibility limitations, training with the actual system requires the use of Intuitive's surgical instruments, which incur an additional cost.

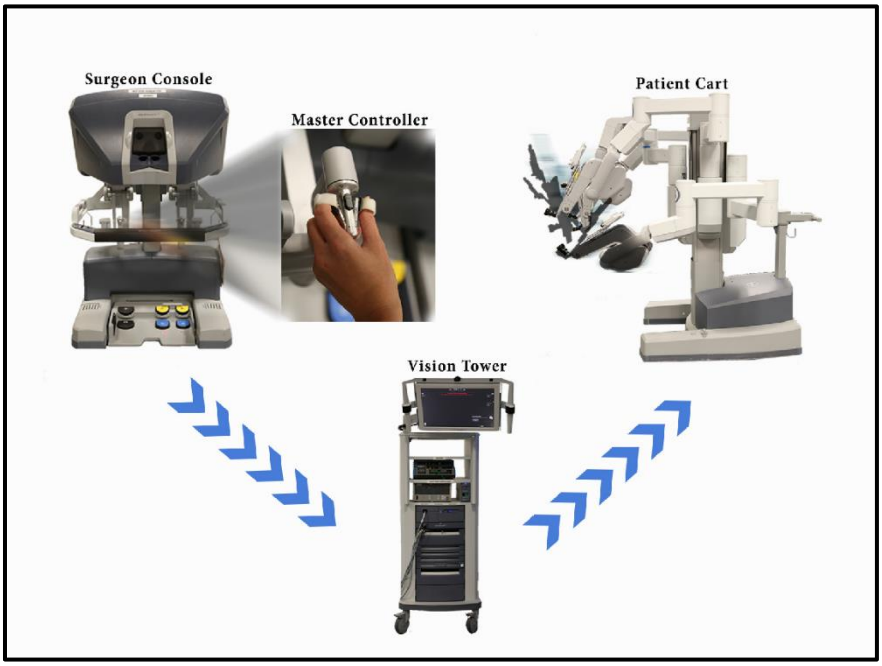


Figure 1. The da Vinci System

Over the last ten years several VR robotic simulators for the da Vinci have become available for educational and training purposes (Figure 2). Currently the commercially available simulation systems are:

- da Vinci Skills Simulator (Intuitive Surgical Inc., Sunnyvale, CA);
- dV-Trainer (Mimic Technologies, Inc., Seattle, WA);
- Robotic Surgical Simulator (Simulated Surgical Skills LLC, Williamsville, NY); and
- RobotiX Mentor (Simbionix USA Inc., Cleveland, OH).

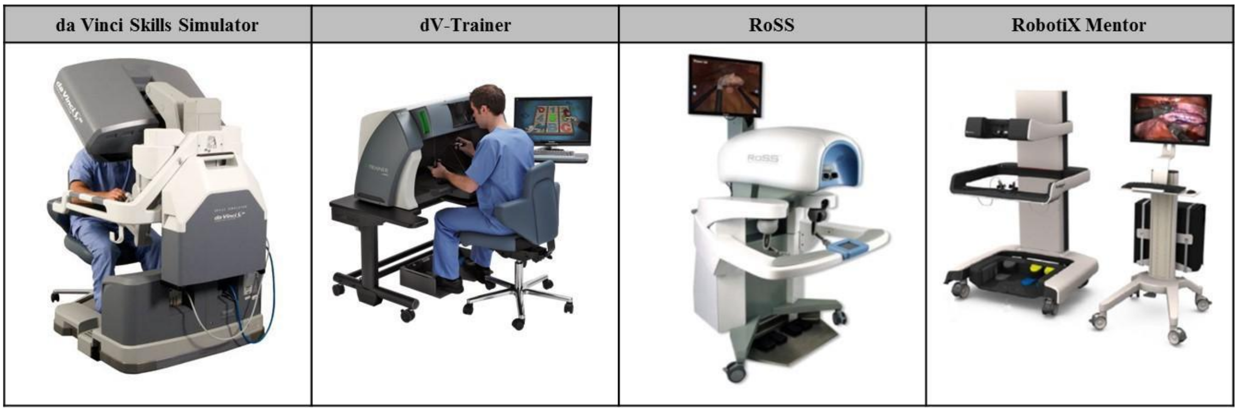


Figure 2. Simulators of the da Vinci Surgical Robot

Most hospitals or training centers will typically invest in only one type of robotic simulator. In general the systems are very similar, however each offers unique capabilities that may make it difficult for an institution to decide on which system is most appropriate for their specific training needs. Thus, there is a need for comparative evaluations of these simulators to aid potential buyers and users in selecting an appropriate device for their purposes.

The objective of this paper is two-fold: to demonstrate a framework for comparing multiple training systems and demonstrate its use by providing readers with an objective comparison of the available VR robotic surgical simulators. This comparative framework provides potential trainers, buyers, users, and instructors with the appropriate information and details needed when considering an investment in an educational training device. This process can be leveraged across various training fields when a comparison of multiple training systems is needed.

This is an extension of a previous analysis, which examined the functionality of only three of the simulators (i.e., da Vinci Skills Simulator, dV-Trainer, and Robotic Surgical Simulator) and illustrated the capabilities side-by-side (Smith, Truong, & Perez, 2014). Since the previous analysis, new technologies, exercises, and simulators have emerged. This paper provides comparative data on the functionality of the four commercially available robotic simulators.

METHODOLOGY

Before conducting the comparative analysis, the Florida Hospital Nicholson Center research department composed a catalog of the minimum system requirements needed in a robotic simulator to effectively train surgeons. These included hardware and software components, as well as aspects critical for using the system as an education and training tool. These components were identified using expert judgment on the critical aspects of the system that a novice surgeon would need to learn including system components (e.g. controls) and surgical skills that they would need to master (e.g. needle driving). Educational components were also identified to identify what components are necessary for a simulation system that is being used for education. The identified requirements from the actual da Vinci system were used as criteria for each simulation systems (Table 1). These requirements were compared across simulation systems and were used to communicate the accuracy of the simulators features to the actual system (i.e., the realism of the simulators) (Table 2).

Table 1. Selected Criterion for Simulator Comparison

Criterion	Meaning	Purpose
Hardware Components		
Accessibility	Availability of simulator. The system may be a stand-alone system (ability of operating independently of the actual da Vinci surgical system) or embedded (utilizing the da Vinci surgical console).	Provides surgeons with a convenient and easily accessible training device.
Ergonomics	The ability to adjust the stereo viewer, foot pedals, and arm rest.	Provides the surgeon with optimal positioning and maximum comfort.
Master Controllers	Naturally positioned manual manipulators attached to console within a fixed working space.	Used to translate surgeons hand movements into micro-movements of the instruments.
Stereoscopic Visual System	The visual system used in the da Vinci surgical system. This system provides two slightly separate images. When these images are viewed together it creates an impression of depth.	Visual system provides surgeons with a 3D perception to provide surgeons high definition and natural colors.
Software Components		
Exercises	Multiple levels of training scenarios for either basic robotic skills (e.g., suturing skills) or procedural skills for specific robotic procedures.	Provides training scenarios to educate user on proper use of da Vinci surgical system and to provide repeat practice, while providing assessments of user's performance.
Scoring System	Established thresholds that provide users with scoring benchmarks set by expert robotic surgeons.	Benchmarks indicate acceptable and unsatisfactory scoring. Allowing the user or administrator to track progression in each exercise.
User Management	Allows user to create personal accounts. Also, allows administrators or instructors to identify and control the state of users.	Personal accounts allow student account to track and maintain training progress Provides administrators or instructors with the ability to track and manage student accounts.
Curricula Development	Ability for administrators to create and/or assign users a course of study and specified training.	To provide an optimal training based on users experience and training needs.
Data Export	Allows administrators or instructors to pull saved data (e.g., exercise scores, attempts, etc.) for a single student or an entire group.	Exported data can be used to track user's development and progression or can be used for statistical purposes.

From this analysis, the team identified multiple physical components of the actual da Vinci robotic system that must also be present in the simulation systems. That is, each simulation system should mimic major mechanisms of the da Vinci robot including: the master controllers, visual system, foot pedals, ergonomics, and size.

The introductory skills required to use the robotic system are typically offered through basic exercises. These exercises are generally not clinically directed (i.e. require clinical decision making), but are focused on the mechanical and psychomotor skills required to drive the system. The number and types of exercises housed in the simulators were identified. For education and training purposes, it is also essential for the systems to have certain administrative capabilities relevant to the learner and the educator. Specifically, the scoring system, curricula development capabilities, user management functions, and data export process are critical for capturing and communicating learners' performance.

Table 2. Comparison of Simulator Features

Simulator	Ergonomics	Controllers	3D vision	Foot pedals	Admin control	Data export	Scoring System	Basic Robotic Skills Exercises	Total Score
DVSS	+	+	+	+	-	+	+	+	+7
dV-Trainer	+	+	+	+	+	+	+	+	+8
RoSS	-	+	+	+	+	-	+	+	+6
RobotiX Mentor	+	-	+	+	+	+	+	+	+7

The team evaluated each system for these requirements by exploring the simulators firsthand, identifying the similarities and unique characteristics across the systems. We elected to purchase all of the systems to ensure that this evaluation remained objective and without undue influence from the manufacturers. The team also reviewed the device manuals to collect additional details about each system (Simbionix RobotiX Mentor User Guide, 2015; Skills Simulator for the da Vinci Si Surgical System, 2013; dV-Trainer Robotic Simulator User's Manual, 2015; Robotic Surgery Simulator User's Manual, 2012). For further information, representatives of each of the manufacturing companies were contacted.

RESULTS

While all systems offer robotic skill training in highly immersive 3D environments, each device offers unique advantages and capabilities for training robotic surgeons. Each of these devices are manufactured by a different company and provides a unique hardware and software solution for training and surgical rehearsal. The sections below describe the different physical and software requirements of the four commercially available da Vinci robotic surgical simulators.

Hardware

Embedded vs Stand-Alone

The majority of the available robotic simulators for the da Vinci system are customized stand-alone systems built to mimic the appearance and technical aspects of the actual da Vinci robot. However, the da Vinci Skills Simulator (dVSS), also referred to as the "Backpack," is a customized computer package that attaches to the actual surgical console through a single fiber optic network cable. Currently, there are two dVSS models, one for each da Vinci Surgical System model available on the market, the da Vinci Si and Si-e surgical system and the da Vinci Xi Surgical System. Each simulator model is only compatible with the corresponding da Vinci Surgical System. In other words, the dVSS Si model is only compatible with the da Vinci Si and Si-e surgical system and the dVSS Xi model is only compatible with the Xi surgical system.

Attached simulators of this type are usually referred to as "embedded trainers" because they leverage equipment that has already been constructed, purchased, and installed for the use of the real system. Embedded trainers are popular in military facilities that may face limited space and weight constraints. These types of trainers significantly reduce the hardware needed solely for training purposes. The U.S. Navy uses embedded simulators aboard ships to reduce weight and space requirements, allowing them to train while the ship is at sea. In addition to saving space, these trainers allow trainees to use the actual controls from the real system to operate the simulator. This type of training provides a realistic experience that is almost identical in feel to the actual system, which may contribute to higher transfer of skills. The dVSS allows the trainee to use the actual surgeon console and corresponding controls that they will use in a surgery, including the master controllers, visual system, and foot pedals.

While embedded trainers offer many advantages, they also come with inherent disadvantages. The entire surgical system can be used for surgery without the simulator however, the simulator relies on access to the surgeon console. Therefore, if the surgeon console is being used in surgery, the simulator cannot be used. The surgical system is expensive and hospitals typically try to maximize the use in the operating room to recoup the investment. In a hospital with a high-volume of robotic surgery program that doesn't have a system dedicated for training, the accessibility and availability of the simulator may be limited.

In addition to availability, embedded trainers increase the amount of use on the actual system. These types of simulators put more usage hours on real controls leading to increased maintenance costs for those devices. That is, heavy use of the dVSS comes with equivalent use of the actual surgeon console, which may ultimately lead to the need for more frequent maintenance. Most maintenance costs are covered by the hospital purchased warranty for the robot, so additional maintenance is typically not a financial cost, but rather impacts the availability of the system for surgical procedures.

The remaining simulators, the dV-Trainer, Robotic Surgical Simulator (RoSS), and Robotix Mentor, are all stand-alone virtual reality simulators that mimic the hardware components of the da Vinci Surgical System. The dV-Trainer, RoSS, and Robotix Mentor are all designed to replicate the appearance of the robotic surgical console including, master controllers, visual system, and foot pedals. Unlike the dVSS, these systems provide training that is independent of the actual da Vinci Surgical System. This provides trainees with a more convenient and easily accessible training device. However, the disadvantage of these systems is that the hardware is simulated and does not exactly replicate the feel of the real robotic controls.

Technical Components

The dV-Trainer consists of three main pieces of equipment: a “Phantom” hood, foot pedals and a desktop computer. The hood replicates the stereo viewer and master controllers of the da Vinci surgeon console. The dV-Trainer foot pedals mimic those on the da Vinci surgeon console footswitch panel. This footswitch panel looks and functions almost identically to the robotic foot pedals. The high-performance desktop computer generates the 3D images and measures the movements of the master controllers. The dV-Trainer also leverages support equipment that includes a touch screen monitor, keyboard, and a mouse that enable an instructor to select exercises to build a curriculum for students and allow an administrator to manage the collected data. This simulator can be configured to imitate the S, Si, and Xi model of the da Vinci robot.

The RoSS is designed as a single piece of hardware with a similar appearance to the robotic surgical console. The hardware device includes a single 3D computer monitor, commercial force feedback devices for hand controls, foot pedals that replicate either the S or the Si model of the da Vinci robot, and an external monitor for the instructor to view. This simulator can be configured to imitate either the S or the Si model of the da Vinci robot.

The Robotix Mentor shares some similarities and differences with the dV-Trainer and RoSS. This system is composed of two mobile carts supporting the hardware equipment. One cart provides the replicated surgeon console with Sony 3D stereoscopic glasses, custom free-floating hand controls, and foot pedals. The surgeon console, controls, and vision system are mimicked in hardware, while a 3D software model replicates the functions of the robotic arms and surgical space. The second cart is connected and contains the high performance graphics computer, monitor, keyboard, and mouse. These components allow instructors to build custom curricula from the available exercises and manage collected data.

Ergonomics

It’s important that training systems provide users with an accurate ergonomic experience as compared to the real system or device. A simulation should not provide an artificially less or more comfortable experience, nor one which is less efficient and responsive than the real system (Smith, 2012). Within these guidelines, user preference and comfort are important considerations for any system. If a user feels as if the simulator is not equivalent to the real system, they may reject its value, become frustrated, and be hesitant to use it. The trainees may also become accustomed to the simulated features and lack knowledge and confidence with the real system. A major benefit to surgeons using the da Vinci surgical system is the improvement in ergonomic characteristics in comparison to traditional surgical techniques (Lux, Marshall, Erturk, & Joseph, 2010). The stereo viewer, foot pedals, and arm rest can be adjusted on the surgeon console, providing the user with maximum comfort and optimal positioning. Thus, it is important for the training systems to mimic the adjustable ergonomic components.

Since it is an embedded trainer, the dVSS allows learners to train in in the exact ergonomic positioning that they would perform surgery. The dV-Trainer provides a custom adjustable table, stereo viewer, and arm rest. While the system’s hardware differs from that of the dVSS, it still provides users with the same ergonomic settings.

Only the stereoscopic viewer can be adjusted on the RoSS, which may make it challenging for trainees of differing height to achieve optimal positioning. The RobotiX Mentor allows the trainee to adjust the arm rest, foot pedals, and the stereo viewer, but does not allow the user to change the height of the simulated console.

Master Controllers

The master controllers are the manual manipulators surgeons use to control the instruments and camera. The controllers on the actual da Vinci surgical system are attached to the surgeon console within a fixed working space. On either side of the master controllers are finger clutch buttons. These buttons allow the surgeon to adjust the positioning within the working space to prevent collisions of the master controllers and return the controllers to an ergonomically comfortable position. This functionality can also be accessed via a pedal on the footswitch panel. Each training system should provide a work space similar to the actual da Vinci system, a clutch button capability on both the master controllers and the footswitch panel, and mimic the usability components of the da Vinci's master controls. All of the simulators provide a mimicked version of the da Vinci Surgical System's hand controls, including a finger clutch component. However, the actual system provides clutch buttons on both sides of the master controllers, an aspect leveraged by the dVSS. However, the standalone trainers (i.e. dV-Trainer, RoSS, and RobotiX Mentor) only provide the clutch button on one side of their controllers. Additionally, the appearance and usability aspects of the master controls differ significantly across all the simulators (Figure 3).

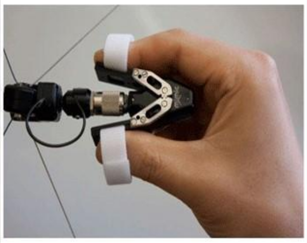
da Vinci Skills Simulator	dV-Trainer	RoSS	RobotiX Mentor
			

Figure 3. Simulator Hand Controls

The dV-Trainer has unique controls which connect to three cables that measure movement, rather than the more precise master controllers that are used in the da Vinci robot. The RoSS uses modified SensAble Omni Phantom™, force feedback, 3D space controllers (3D Systems Inc., Rock Hill, SC). These devices have a much smaller range of motion than the master controllers on the da Vinci robot and therefore require more frequent clutching than the actual robot. The RobotiX Mentor utilize innovative free-floating hand controls that are tethered to the arm rest by a bundled electronic cable. The attachment and orientation of the hand controls were designed to minimize the interference and weighted drag on hand movements. However, these controllers and mimicked console provide a much larger working space than the da Vinci surgical system, therefore trainees can perform movements in the RobotiX Mentor that cannot be replicated in the actual system.

Such high fidelity instrumentation provides the user with realistic controls in order to raise the level of immersion (Sherman & Craig, 2002). For example, military simulators have demonstrated this in the driving controllers of the Close Combat Tactical Trainer (CCTT) (Johnson, Mastaglio, & Peterson, 1993) and the recoil of simulated rifles in the small arms Engagement Skills Trainer (EST) (Platte & Powers, 2008). For the CCTT armored vehicle trainer, a great deal of effort was put into creating simulated driving controls which accurately mimicked the real vehicle, but which had longer operational life necessary for a training device (Johnson et al., 1993). When developing a surgical simulator the tactile fidelity of the hand controllers is significantly more important and of much higher resolution of control.

Visual system

The visual system in the da Vinci Surgical System provides the surgeons with a true stereoscopic image. The endoscope (i.e the camera inserted into the abdomen) records the visual scene simultaneously with two lenses. The images are transmitted to the user's left and right eye, creating one seamless image in the stereo viewer. Therefore each simulator system was assessed on their ability to mimic a stereoscopic, simulated 3D visual system closest to the real da Vinci surgical system. Each robotic surgical simulators should provide a 3D environment through a mimicked stereo viewer to provide a similar training experience to that of the actual da Vinci robot. As an embedded trainer, the dVSS leverages this hardware to create a high-definition, 3D virtual environment. The dV-Trainer, RoSS and RobotiX Mentor provide simulated technology and hardware to provide a similar experience. The dV-Trainer's visual system uses a similar system to the actual robot: individual images for the left and right eye are transmitted from the computer and into the stereo viewer. The RoSS uses a single 3D computer monitor, built into the system and polarized glasses to produce 3D images, producing a visual scene with less depth of field than the actual da Vinci system. The visual system used in the RobotiX Mentor is also much different than the actual da Vinci surgical console. This viewer uses off-the-shelf Sony 3D stereoscopic glasses. The Sony glasses must be adjusted and focused for each use. To ensure optimal focus and vision, the user must maintain their body position used when originally focusing the viewer. Often, if the user moves the glasses must be readjusted for clear vision.

Vision is often the primary sense used to immerse users into a virtual training experience (Sherman & Craig, 2002). It is imperative to present users with a graphic display that provides visual stimulus and delivers an immersive display, while accurately representing the training material. Slater et al (2009) demonstrated that subjects in a dynamic virtual environment which was created by ray tracing experienced a measurably higher level of immersion and response stress than those who experienced the same environment rendered via the less realistic ray casting method.

Software

Exercise Modules

The exercise modules in each simulator are organized into hierarchical menus according to the surgical skill being addressed and the complexity of the exercise. To ensure effective training there are multiple core skills and relevant tasks that each simulation device should provide within the exercises (Table 3). Each simulator provides on-system instructions for every exercise in the form of textual documents and narrated video demonstrations.

Table 3. Comparative Simulator Exercise Categories

dVSS	dV-Trainer	RoSS	RobotiX Mentor
Surgeon Console Overview Endowrist Manipulation 1 Camera and Clutching Endowrist Manipulation 2 Energy and Dissection Needle Control Needle Driving Games Suturing Skills	Surgeon Console Overview Endowrist Manipulation Camera and Clutching Energy and Dissection Needle Control Needle Driving Troubleshooting Games Suturing Skills	Orientation Module Motor Skills Basic Surgical Skills Intermediate Surgical Skills Hands-on Surgical Training	**Basic Robotic Skills and Tasks:** Robotic Suturing Robotic Single-Site Suturing Stapler Robotic Essential Skills **Procedural Modules:** Hysterectomy Prostatectomy Lobectomy

As described earlier, the dVSS Backpack is available in two different models which match the model of the robot to which it will be connected, either the Si (or Si-e) or the Xi model. There are differences in these two models of the simulator which should be identified. The dVSS Si contains 41 exercises organized into nine categories. Six of the 41 exercises are from the Fundamentals of Robotic Surgery (FRS), a robotic surgical skills education, training, and assessment program for novice robotic surgeons (Smith, Patel, Satava, 2014). These FRS exercises are also available in the dV-Trainer and the RobotiX Mentor. The remaining exercises provide training on many crucial technical skills required for robotic surgery, such as needle control and suturing skills. The Xi introduces 13 new exercises for a total of 47 exercises organized into eight categories. The Xi offers new games and exercises that teach the use of advanced instruments (i.e., stapler) which is a surgical skill not addressed by previous simulators. The other exercises expand on training for camera control, endowrist manipulation and needle driving. Many of the original exercises have improved graphics from recent updates created by Mimic Technologies (Skills Simulator for the da Vinci Xi Surgical System, 2015) and new exercises have been added from a third vendor, SenseGraphics AB (Stockholm,Sweden).

Mimic Technologies and SimbioniX have developed many of the simulation exercises found in both the dVSS Si and Xi. As a result, many of the exercises in the dVSS and the dV-Trainer are similar. However, the current version 3.3 of the dV-Trainer has a number of new exercises, which are not found in the dVSS, and the graphics have been upgraded so the visual presentation is no longer identical. This version of the dV-Trainer contains 65 exercises organized into ten categories. This count includes preview exercises for Maestro AR, described below, and FRS exercises described earlier.

Mimic's Maestro AR (Augmented Reality) provides procedure-specific exercises that allow 3-D interaction between the trainee's virtual robotic instruments and real surgical videos. Maestro AR was designed to train procedure-specific anatomy, procedural steps, and decision-making skills. All of the exercises give instruction and guidance to help trainees identify anatomy and improve their technical skills including grasping, retracting, cutting, and energy application. In addition, the exercises test a trainee's knowledge of the procedural steps with multiple choice questions during the exercise (dV-Trainer Robotic Simulator User's Manual, 2015; Kumar, Smith, & Patel, 2015).

The RoSS simulator contains 52 unique exercises, organized into 5 categories, and arranged from introductory to more advanced. The RoSS system has fewer exercises but most include three levels of difficulty where each level is actually a unique exercise. This company has developed a set of 3-D exercises that are unique from those found in other simulators. They also provide optional video-based surgical exercises, called Hands-on Surgical Training (HoST) modules, in which the user is guided through the movements necessary to complete an actual surgical procedure. These guided videos leverage the force feedback capabilities of the hand controllers to push and pull the student's hands to follow the simulated instruments on the screen. They require the student to perform specific movements accurately during the video before the operation will proceed.

The RobotiX Mentor organizes its' 53 exercises into eight modules which fall under one of two categories: Basic Skills or Procedural Modules. Thirty exercises fall under Basic Skills. Twenty three exercises fall under Procedural Modules which include complete procedures and procedure-specific exercises. Procedural exercises can be performed in a guided or unguided fashion. The guided version of the exercises prompts the user for each step of the surgery or task. In addition, the RobotiX Mentor has exercises that review anatomy and focus on team training. The RobotiX Mentor is the only simulator that offers complete surgeries and procedure-specific exercises in a fully simulated anatomical environment. The RoSS' HoST and the dV-Trainer's Maestro AR do have surgical exercises where the user performs procedure-specific tasks while actual surgical footage plays. However, neither of them offer those tasks in a fully simulated environment. Incorporating such exercises allows students to practice procedures in a safe and reproducible environment, while providing complications and emergent situations.

Scoring System

Upon completion of each exercise, all of the simulators automatically proceed to a scoreboard showing the student's performance on the exercise. All four simulators use the host computer to collect data on the performance of the student in multiple performance areas (i.e. metrics). Using this data, the simulator provides scores for various surgical skills and a total composite score to signifying the user's overall performance on the exercise. In addition to the metrics collected by the computer, the manufacturers of each simulator have created accompanying thresholds to indicate whether the student is attaining a specified level of proficiency for individual metrics and overall for each exercise. All four systems have identified threshold scores to indicate acceptable and unsatisfactory scoring levels. The thresholds were developed based on the performance of experienced robotic surgeons. These are commonly interpreted as "passing" and "failing" (i.e. above acceptable threshold and below unsatisfactory threshold respectively), with a "warning" area between the two levels. Together these create green, yellow, and red performance areas to visually communicate the quality of the student's performance on each metric.

All of the simulator manufacturers worked with experienced robotic surgeons to assist in establishing the relative values of each measure used in the composite score, just as they did for the threshold levels described earlier. Because these evaluations are the opinions of the specific people who collaborated with the company on the development of the system, the dV-Trainer, the RoSS, and the RobotiX Mentor provide the ability for a system administrator to adjust these levels to meet the needs of unique curriculum, courses, and students. However the dVSS is a closed, turnkey system which does not allow for threshold adjustments found in the other simulators.

Each of the four simulators provide a different scoring system. The dVSS uses the Classic System, which represents the trainees score via a percentage of combined pre-established metrics. The dV-Trainer recently shifted from this scoring system and now provides the users score as a composite of total points earned, rather than percentages. This scoring system is known as the Proficiency Scoring System. For this system, the instructor can change proficiency baselines and customize the scoring protocol to fit their needs. The RoSS scoring system follows similar principles of the dVSS and dV-Trainer's scoring systems, however the scoring system is visually communicated differently from the rest. The display presents a horizontal bar, which is colored green, yellow, or red to indicate passing or failing. The magnitude of the bar is a rough measure of the quality of performance (Figure 4). Additional displays show the numeric score and its relative position to a passing threshold.

The RobotiX Mentor scoring metrics vary between simulation modules and cases. Some metrics apply to every exercise while others are only used for exercises in which they are relevant. Due to the novelty of the RobotiX Mentor, proficiency benchmarks have not been set for all exercises yet. Similar to the RoSS' visual representation, exercises with defined proficiency levels provide a horizontal bar colored green, yellow, and red with a marker indicating passing or failing (Figure 4). For benchmarked scores, additional displays showing numeric scores can also be accessed. Exercises without set benchmarks provide a variety of exercise specific metrics divided into categories which are provided in a list format.

da Vinci Skills Simulator	dV-Trainer	RoSS	RobotiX Mentor
			

Figure 4. Example Scoreboards from Each Simulator

Progression monitoring and performance measures are two important components that should be incorporated into all educational training systems (Jones, Hennessy, & Deutsh, 1985). Therefore, each scoring systems was compared by their ability to successfully collect key metrics, present thresholds, communicate the learner's performance, and provide progression monitoring. The system should provide meaningful feedback that the trainee can use to specifically target skills that need additional attention and improve future performance. While some scoring systems may translate easily to users, others systems may be less explicit. This may make it difficult for trainees to truly understand areas that need additional training.

User management

Each simulator allows an administrator or instructor to manage and organize student performance according to the unique login credentials of the student. Additionally, all systems have a "guest" account to make the system accessible to anyone, but without the ability to uniquely identify and track individual performance under that guest account. The dV-Trainer, RoSS, and RobotiX Mentor allow the administrator to create user accounts directly from the systems, while the dVSS requires an external PC using a software program provided by Intuitive.

Curricula Development

Once a user account and login credentials have been created, administrators using the dV-Trainer, RoSS, or RobotiX Mentor can create and assign curriculum. The curriculum within the dV-Trainer and Robotix Mentor allow administrators to organize exercises into different assignments or phases. For example, a curriculum may consist of a warm-up phase with easy exercises, pre-course evaluations, and post-course evaluations. These would appear as three separate sections within the curriculum. The exercises in the RoSS simulator are organized into a hierarchical tree structure according to the skills being taught. An administrator for this system can assign a specific branch within this structure as the curriculum for a specific user. But it is not possible to reorganize any set of exercises from multiple branches into a custom curriculum as it is in the dV-Trainer and RobotiX Mentor.

The Robotix Mentor also provides administrators with the ability to add accompanying didactic material (e.g., PDF or video) into a curriculum folder, such as, video of real surgeries that are being simulated. In addition, this simulator includes an administrative management system, MentorLearn, which allows administrators to create, maintain, and assign specific curricula to specific users remotely. The dVSS does not provide administrators the ability to create or assign curriculum to users.

Data Export

All four systems allow administrators to export data as a delimited file directly from the simulators. The dV-Trainer and RobotiX Mentor administrators can export data for a single student or an entire group. Further, these system allow administrators to export data according to multiple criteria, including, all of the data on the machine, or subsets defined by the unique user ID, date range, completion status, or a specific exercise. The dVSS and RoSS administrators can export data files for each student account. While all systems render delimited files that can be removed from these systems for analysis, each system allow administrators to collect student data via different criteria. Some administrators may need to export data through a more sensitive criteria than a student account. The dV-Trainer and RobotiX mentor provide multiple ways to collect student data in comparison to the dVSS and RoSS.

DISCUSSION

Robotic surgery requires a unique set of surgical skills compared to other surgical techniques. Surgical training devices that can provide automated, objective performance assessment is desirable and useful for proficiency-based training. Robotic surgery simulators provide entry-level familiarization and skill development in a safe environment outside of the operating room.

The simulators described in this paper are complex system that are valuable training tools at a lower cost. Each device offers unique capabilities for training robotic surgeons. While each simulator generally provides a physical environment conducive to introducing user to the robotic system, the simulated hardware varies across systems and can be different than the real-world equipment. Learners may experience a trade-off between lower price and perfect accuracy of a simulator. For example, the dVSS allows user to interact with the actual da Vinci surgical console and its features, however this device requires a greater investment than the other stand-alone simulators.

Each system's software components provide trainees with the ability to practice basic robotic skills. Recent advancements in technology has introduced more procedural specific exercises to train an integration of multiple robotic skills and techniques. While all of the simulated devices provide core skills for novice robotic surgeons, more experienced surgeons may benefit most from the RobotiX Mentor’s procedure-specific exercises. In general, each system has some type of learning management system that educators can use to create curricula and track users’ performance. The dV-Trainer, RoSS, and Robotx Mentor provide multiple options for creating, customizing, and building curricula to provide optimal training.

Unfortunately, due to limited accessibility to each of these systems, potential stakeholders may not have the opportunity to experience each of the simulation systems firsthand. However, it is imperative that hospitals critically evaluate the capabilities of training systems and how those capabilities align with their training needs prior to purchasing and incorporating a system into their training curricula. The goal of this analysis is to provide potential users, buyers, instructors, and trainers who have a need for a robotic surgery simulator with the information to make an informed decision on systems that are appropriate for their needs.

It may be difficult for buyers to properly evaluate which system will meet their desired training and educational needs. Yet, if an organization or training center invests in a system that does not meet the learner and instructor needs or does not meet the environmental constraints, the system will not be valuable to the organization, underutilized, and lead to a decrease in return on investment. The process demonstrated in this paper can be leveraged into other domains, when multiple training systems exist in the market.

Prior to purchasing a simulation system, there are several critical components an investor should consider. For an education and training device, it is important to evaluate potential systems for appropriateness to the learning environment. Other factors should also be considered including, whether the system is self-guided or requires management, durability, portability, and the ability to appropriately modify system to meet learning objectives. This process and results of this study will be used to inform future use of the simulation systems at the Nicholson Center.

REFERENCES

Chou, B., & Handa, V. L. (2006). Simulators and virtual reality in surgical education. *Obstetrics and gynecology clinics of North America*, *33*(2), 283-296.

dV-Trainer Robotic Simulator User's Manual, Mimic Technologies, Inc., (2015).

Johnson, W. R., Mastaglio, T. W., & Peterson, P. D. (1993, December). The close combat tactical trainer program. In *Proceedings of the 25th conference on Winter simulation* (pp. 1021-1029). ACM.

Jones, E. R., Hennessy, R. T., & Deutsch, S. (1985). *Human factors aspects of simulation*. National Academy Press.

Kumar, A, Smith, R, Patel, V (2015) Current status of robotic simulators in acquisition of robotic surgical skills. *Current opinion in urology* 25, no. 2: 168-174.

Lux, M. M., Marshall, M., Erturk, E., & Joseph, J. V. (2010). Ergonomic evaluation and guidelines for use of the daVinci Robot system. *Journal of Endourology*, *24*(3), 371-375.

Polavarapu, H. V., Kulaylat, A. N., Sun, S., & Hamed, O. H. (2013). 100 years of surgical education: the past, present, and future. *Bulletin of the American College of Surgeons*, *98*(7), 22.

Palep, J. H. (2009). Robotic assisted minimally invasive surgery. *Journal of Minimal Access Surgery*, *5*(1), 1.

Robotic Surgery Simulator User's Manual: For Models S and Si, Simulated Surgical Systems LLC., (2012).

Platte, W. L., & Powers, J. J. (2008). *Using motion capture to determine marksmanship shooting profiles: Teaching soldiers to shoot better faster*. NAVAL POSTGRADUATE SCHOOL MONTEREY CA.

Satava, R. M. (1993). Virtual reality surgical simulator. *Surgical endoscopy*, *7*(3), 203-205.

Sherman, W. R., & Craig, A. B. (2002). *Understanding virtual reality: Interface, application, and design*. Elsevier.

Simbionix RobotiX Mentor User Guide. Simbionix USA Inc. (2015).

Skills Simulator for the da Vinci Si Surgical System (User's Manual), Intuitive Surgical Inc., (2013).

Skills Simulator for the da Vinci Xi Surgical System (User's Manual), Intuitive Surgical Inc., (2015).

Slater, M., Khanna, P., Mortensen, J., & Yu, I. (2009). Visual realism enhances realistic response in an immersive virtual environment. *Computer Graphics and Applications, IEEE*, *29*(3), 76-84.

Smith, R. D. (2012). Game technology in medical education: An inquiry into the effectiveness of new tools. Oviedo, FL: Modelbenders Press.

Smith, R, Patel, V, Satava, R (2014). Fundamentals of robotic surgery: a course of basic robotic surgery skills based upon a 14-society consensus template of outcomes measures and curriculum development." *The International Journal of Medical Robotics and Computer Assisted Surgery* 10, no. 3: 379-384.

Smith, R., Truong, M., & Perez, M. (2015). Comparative analysis of the functionality of simulators of the da Vinci surgical robot. *Surgical endoscopy*, *29*(4), 972-983.