44

Telerobotics: Its Future in Clinical Application

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Introduction

Telerobotic surgery was initially developed for the management of injured soldiers in American conflict theaters. The need was for rapidly deployable, remotely controlled, complex patient care platforms and, as the technology developed, it became clear that early research prototypes were not sufficiently portable. Further development of telesurgical systems was then left to the private sector. The initial da Vinci system was marketed to cardiac surgeons because the precise instrument movements for fine suturing and the minimally invasive nature of the access seemed ideally suited for conventionally maximally invasive open heart surgery. The size of the instruments, trocars, and robotic footprint, however, made its application challenging. Around the same time (late 1990s and early 2000s), there was a rapid upswing in the number of prostatectomies for the second most common solid organ malignancy in men. Screening modalities for prostate cancer were becoming more sensitive, and public awareness of male health disorders was growing due to high-profile celebrities publicly announcing their urologic issues. In addition, complex laparoscopy was expanding into prostate surgery, yet few surgeons were able to master the technique due to the pelvic location of the prostate gland and complex suturing required to reconnect the bladder to the urethra after the gland removal. The da Vinci system seemed ideal for this. The depth of the operative field was no longer an issue because 3D visualization and magnification coupled with fine control of seven degrees freedom of the instrument movements afforded not only improved suturing capabilities, but also visualization of the neurovascular bundles which impart potency.

Adoption of robotics for prostate cancer management boomed such that as of this writing over 50% of all prostatectomies in the United States are done robotically [1]. Observing the benefits of robotic surgery in the pelvis, gynecologists embraced its application such that in 2007, robotic hysterectomy received FDA approval. Approval for procedures in otolaryngology followed in early 2010. Currently, robotic-assisted surgery is performed in pediatric general/cardiac/urologic surgery and adult urologic/general/otolaryngologic/cardiac/gynecologic surgery. In each field, applications are being added rapidly, and just recently, articles have appeared discussing the role of robotics in open surgical applications [2,3]. This rapid increase in use has been met with some criticism as high-profile articles have questioned the comparative effectiveness of robotic surgery [4]. The common criticisms are that (1) the robotic technology is a large financial burden on the healthcare industry, (2) surgical outcomes have only been shown to be improved at high-volume centers

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and are significantly worse during a surgeon's initial learning curve, (3) marketing influences and public demand have driven robotic surgery more than sound evidence, and (4) the current iteration is still bulky, misses key feedback technologies for the surgeon, and provides only unidirectional links between surgeon and patient. The drive to improve current technology has led to many investigators around the world exploring ways to miniaturize, simplify, and expand feedback capabilities while lowering cost. Each of these endeavors can be segmented into multiple new technologies.

Efforts to improve patient outcomes cannot center only on the technology, however. The surgeon must be improved either prior to doing their first case or during surgery. There has been much discussion in the literature about the true learning curves for robotic surgery and the data clearly show that the more experience a surgeon gains (number of cases performed), the better their outcomes are. This also translates to diminished resource utilization through shorter operative times, shorter hospital lengths of stay, and decreased convalescence taking the patient out of school or the work place. Methods for accelerating the learning curves through simulation training, surgical warm-up, and patient-specific presurgical rehearsal may not only enable fledgling roboticists to perform like experienced surgeons, but also experienced surgeons in their prime to improve their abilities further.

Experimental telesurgical platforms

While users of the da Vinci robot have steadily extended the practice of robotic surgery, many research laboratories have continued to advance the technology with other systems. The worldwide surgical robotics research field is already too large to summarize here; for recent reviews, see Taylor *et al.* (2008) [5] and Speich and Rosen (2004) [6]. In this chapter, we focus on a few research thrusts of the current worldwide research efforts which are aimed at improvements in teleoperated surgical systems to reduce some of the limitations described above. Research prototype teleoperated surgical robots which are being developed around the world include the SRI M7 [7], the Tokyo Institute of Technology Robot IBIS IV [8], the DLR Miro (Figure 44.1) [9,10], and the Johns Hopkins experimental testbed based on the da Vinci mechanism. Our own system, the RAVEN surgical robot, is described below. Our group has worked to develop portable and interoperable surgical robots with emphasis on prototypes suitable for dry-laboratory and animal experiments.

Figure 44.1 The DLR Miro surgical telerobot features three seven degrees of freedom arms with both teleoperation and direct human manipulation capabilities. Image copyright Deutsches Zentrum für Luft- und Raumfahrt, used with permission.

RAVEN

The RAVEN surgical robot (Figure 44.2) was designed to meet needs of combat casualty care, but developed from a knowledge base in laparoscopic surgery [11–16]. The RAVEN is a dual-armed teleoperated surgical robot with interchangeable instruments. Each instrument can be positioned in X, Y, and Z directions and has up to four internal degrees of freedom such as jaw open–close and three wrist rotations. The two RAVEN seven degrees of freedom (DOF) surgical arms are divided into three main parts: the static base that holds all seven actuators, the spherical mechanism that positions the tool [17], and the tool interface.

The first four joint axes intersect at a single point (Figure 44.2b). In the case of laparoscopic procedures, this point is aligned with the center of the port where it traverses the abdominal wall. This property of the spherical mechanism creates a pivot for tool motion similar to manual laparoscopy. Motors mounted on the base of the manipulator actuate all motion axes.

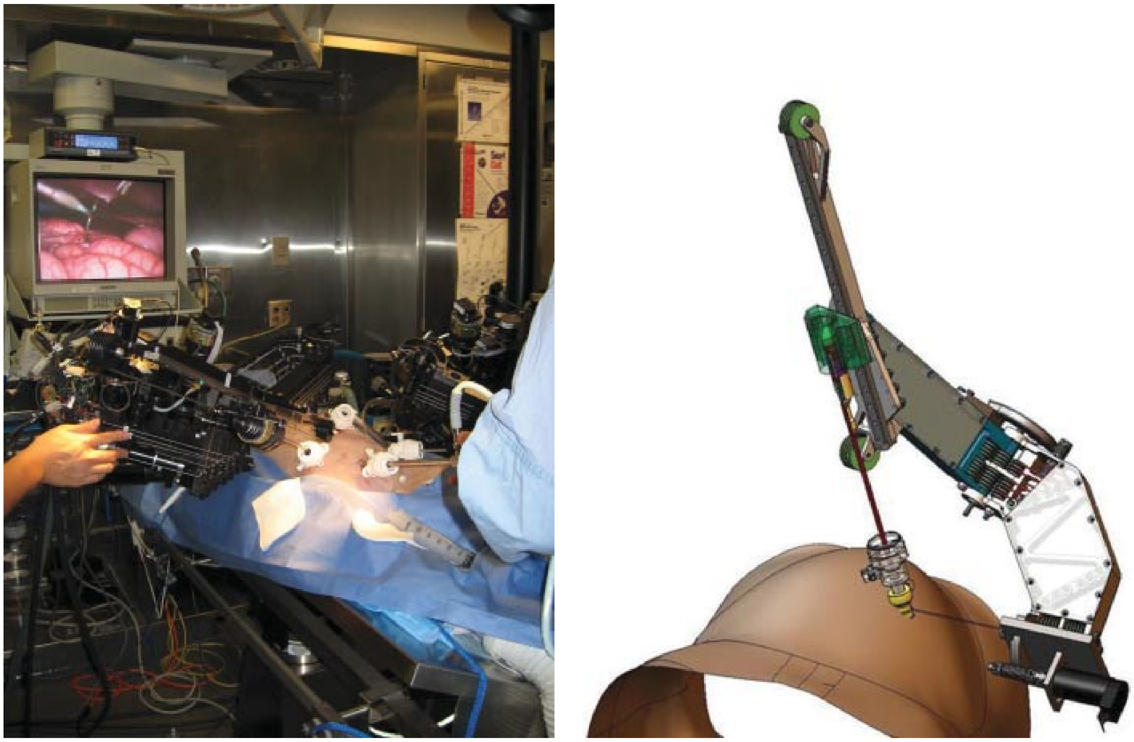
(a) (b)

Figure 44.2 (a) Dual-armed RAVEN robot used in porcine laparoscopic cholecystectomy, late 2007. (b) Illustration of links in the RAVEN spherical mechanism. All three mechanical motion axes intersect at the insertion point.

The motors of the first three axes have fail-safe brakes to prevent tool motion when "paused" and in the event of an emergency stop (E-stop) or power failure. The cable-drive system is comprised of a capstan on each motor, a pretension adjustment pulley, a pulley array to redirect the cables through the links, and attachment to each motion axis. The shoulder axis is terminated at a single partial pulley. Each axis is controlled by two cables, one for motion in each direction. The cables are pretensioned against each other and terminated at both ends to prevent slipping. The cable system geometry has constant length to maintain constant pretension on the cables through the entire range of motion; however, there are force and motion couplings between the axes, which are compensated by the control system. Laser pointers are attached to the shoulder and elbow joints to allow for visual alignment of the manipulator relative to the surgical port. When the two dots projected on the skin of the patient converge, the manipulator is positioned such that the center of rotation of the surgical manipulator is aligned with the pivot point on the abdominal wall like the remote center of the da Vinci robot. Each surgical manipulator has a mass of approximately 15 kg, which includes the motors, gear heads, and brakes.

The tool interface (Figure 44.3) allows for quick changing of instruments and couples tool roll, wrist, and grasp motions from RAVEN motors to the instrument. The original RAVEN tool interface was designed for robotic surgical instruments powered by concentric shafts. This allowed the use of instruments left over from the Zeus surgical robot commercialized in the 1990s by Computer Motion. The new version of the RAVEN (now under construction; see below) will feature a tool adapter suitable for cable-driven surgical instruments in which the concentric drive shafts are replaced by a cable–pulley system. Desirable properties of a tool interface include low insertion and extraction

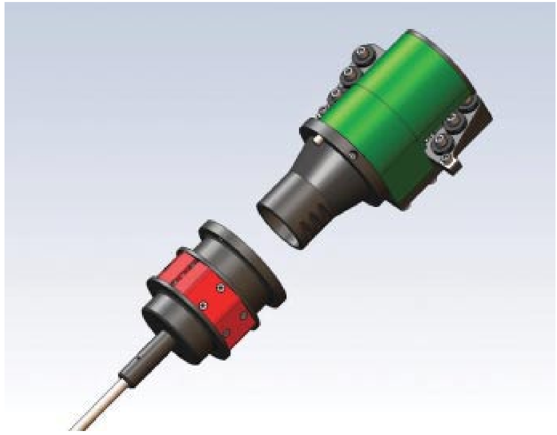

Figure 44.3 Tool interface for the RAVEN I robot can be grasped and exchanged with one hand (either human or robot hand) at the red hexagonal ring.

force, positive retention of the instrument, and a low-profile design. It should require only one hand (human or robotic) to replace tools.

The control system and supported electronic hardware were designed to incorporate safety, intelligence, modular design, and flexibility. As this is a medical device, the most critical of these aspects is safety. However, to implement a safety system to the standard required for human clinical use required an engineering effort beyond our budget. The RAVEN safety system, although not sufficient for human clinical use, meets the objectives of (1) protecting itself from software errors, (2) increasing the reliability of operation, and (3) achieving a degree of safety sufficient for ethical use of experimental animals. The RAVEN safety system includes features such as a small number of states, programmable logic controller (PLC) for state transition control (Figure 44.4), fail-safe brakes which activate on power loss, a "normally closed" E-stop circuit, and a surgeon foot pedal. With these features, implemented in a simple, robust system, outside the complex control software, we have a degree of predictability, reliability, and robustness sufficient for experimental use with large numbers of experimental subjects (such as busy surgical residents) and experimental animal surgery.

Field experiments, HapSmrt, and NEEMO

Novel future scenarios for surgical telerobotics include battlefield casualty care, remote care for victims in disaster zones, field camps in the developing world, and medical care in exotic locations such as a Mars mission or an isolated Antarctic research site. Our group participated in two field experiments to study the engineering requirements for telerobotic surgical systems capable of operating in such missions.

In 2006, Dr. Timothy Broderick, of the University of Cincinnati, organized the High Altitude Platform Mobile Robotic Telesurgery (HapSmrt) field experiment [14,18,19]. In this mission, our RAVEN surgical telerobot was deployed in a remote semi-desert area north of Simi Valley, California. Power was supplied by a basic portable generator, and Internet communication was provided by a Puma unmanned aerial vehicle

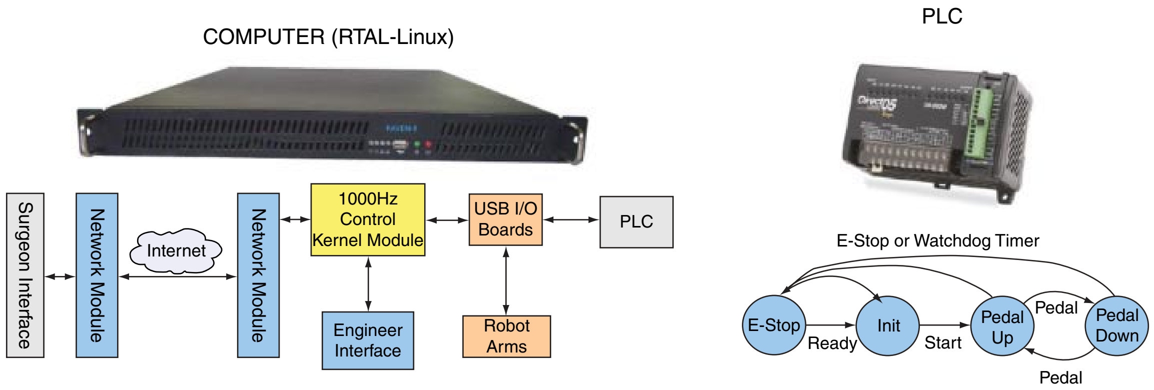

Figure 44.4 The RAVEN control system features a programmable logic controller (PLC) for reliable control of transitions between four basic safety states. Computer running a real-time variant of Linux updates RAVEN control 1000 times per second.

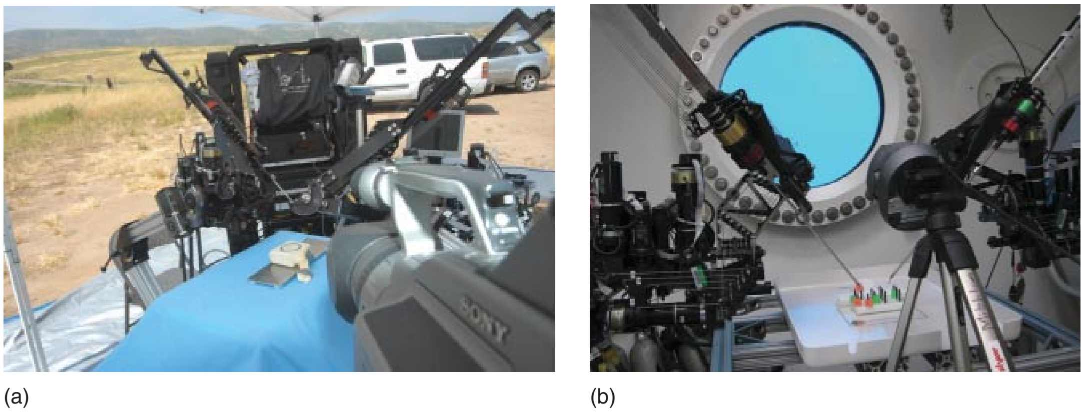

Figure 44.5 (a) RAVEN setup in a semi-desert site outside Simi Valley, CA. In this project, RAVEN was controlled by a remote surgical console via a radio link on an unmanned aerial vehicle (Aerovironment Inc.). (b) RAVEN setup in the NASA Extreme Environment Mission 12, 20 m under the ocean off Key Largo, FL. RAVEN was remotely controlled by Internet link from Seattle, WA.

(UAV) provided by Aerovironment (Simi Valley, CA). During three field days, the system was transported to the remote site and set up each day (Figure 44.5a). A 1 Mb s^{-1} data link transmitted control commands from the surgeon console to the remote robot and transmitted video from the robot site to the surgeon console. A special-purpose hardware video coder/decoder (codec) from HaiVision (Montreal, Canada) was used at each end of the video link. Surgical tasks performed included suturing on a latex glove stretched across a frame.

In 2007, Dr. Broderick organized the NASA Extreme Environment Mission Operations-12 (NEEMO-12). The goals of this mission were to advance and demonstrate technologies related to remote healthcare for astronauts on extended space missions [16], in particular, the capability of surgical intervention by remotely operated surgical robotics. The experiment took place in the Aquarius Underwater Habitat, a facility 20 m below the ocean surface about 16 km from Key Largo, Florida. Two surgical robots were deployed into the Aquarius habitat: the RAVEN (Figure 44.5b) and the SRI, International M7 robot. Control of the robots was provided over an Internet link from the University of Washington (Seattle, WA) and SRI (Palo Alto, CA), respectively. The last part of the Internet connection to the remote site was provided by a microwave link from shore to buoy and a 20 m cable down to the habitat.

Dr. Broderick, NASA flight surgeon Dr. Joseph Schmid, and geologist Dr. Mary Sue Bell came to the University of Washington for 2 days of training. They learned and practiced procedures for operation, assembly, and disassembly of RAVEN. In preparation for integration of the RAVEN into the habitat, NASA requirements necessitated the creation of extensive operational documentation for the RAVEN's startup, shutdown, and E-stop recovery procedures. RAVEN was shipped to the Aquarius operational facility. The RAVEN was then dismantled, packaged, and taken down to the Aquarius by US Navy divers. Drs. Broderick and Schmid reassembled the RAVEN in Aquarius for the teleoperation experiments. The RAVEN was controlled from three separate locations. Master consoles were set up in Seattle, WA, at the shore base in Key Largo, FL, and at Cincinnati Museum Center in Cincinnati, OH. All locations used the Phantom Omni haptic devices (SensAble, Cambridge, MA) as the input devices (Figure 44.6). Surgeons performed experimental benchmark tests drawn from the Society of American Gastrointestinal Endoscopic Surgeons (SAGES) Fundamentals of Laparoscopic Surgery (FLS) test protocol. For surgery tasks in Seattle, two different video systems were used (HaiVision to VLC and iChat V.2.1.3 on Apple Macintosh). Latency between Seattle and Florida was quite noticeable to users, on the order of 1 s. Internet round-trip latency for the command packets was measured at only 70 ms, so the

Figure 44.6 RAVEN surgical control site for the NEEMO mission (Figure 44.5). The user interface consists of two Phantom Omni haptic devices and surgical master communication software running on the laptop.

majority of this time was due to video compression and decompression.

One of our goals in the NEEMO-12 mission was characterization of the network quality between the control site at the University of Washington in Seattle and the Aquarius habitat. The observed 70 ms delay was composed of two components: (1) the regular Internet between the University of Washington and Aquarius shore base and (2) the special microwave link between the shore base and Aquarius. These links were characterized in terms of round-trip time delay. Our computers inside RAVEN contained a packet reflector program. Another program at the University of Washington sent regular streams of test packets to the packet reflector and measured the round-trip delay time for each packet. Although similar to the standard ping command measurement, this system used User Datagram Protocol (UDP) packets of the same type as used in teleoperation.

Results

Measured delay distributions are shown in Figure 44.7. The mean and standard deviation were 76.5 ms and 5.4 ms, respectively. When packet sending rates were decreased from 1000 to 10 Hz, these statistics were essentially unchanged.

Another significant result of the HapSmrt and NEEMO missions was numerous small engineering refinements and documents which have made the RAVEN a reliable and stable platform for research.

Plugfest 2009

As surgical teleoperation technology becomes mainstream, there will be a need for interoperation

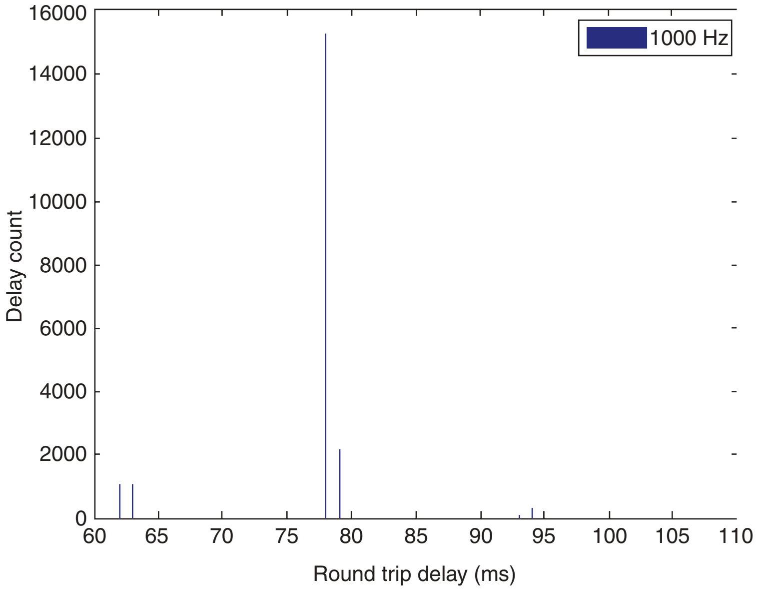

Figure 44.7 Packet delay, Seattle–NEEMO, during NEEMO-12 mission. Distribution of round-trip time delays for ITP packets sent 1000 times per second between the University of Washington in Seattle and the Aquarius habitat off the coast of Florida. The delay distribution was similar for 100 and 10 Hz packet repetition rates.

standards so that surgical consoles can control multiple surgical robot models. To demonstrate interoperable telerobotics over the global Internet, in 2009 14 unique telerobotic master and slave systems were connected by nine groups in five countries. In the context of surgical telerobotics, the master manipulator is operated by the surgeon in order to control the motions of the slave, or patient-side robot. All the connected systems used the same network data interface, which we call the Interoperable Teleoperation Protocol (ITP). ITP is a stateless data description representing commands between the master and the slave robot. Although extendable to complex functions in the future, the first data interface in the ITP is a packet of 84 bytes using the UDP network protocol for fast transmission. The small size of the ITP packet makes it suitable for high packet rates.

The ideal protocol is robust enough to work with any new teleoperators independently of their design, and flexible enough to accommodate any new data transforms or teleoperation architectures. Therefore, a mechanism is built in to ITP for designating new, numbered data specifications, extending the protocol to new innovations. Table 44.1 shows the data interface that was used in the experiments described in this chapter. The "pactyp" (packet type) and "version" fields indicate the feature set and software version in use. All motion commands are in terms of increments from the robot's current position. The ITP requires a common coordinate system (reference frame) in which to represent motion increments. From the user's perspective, facing the workstation, the right-handed frame has the positive *Y*-axis pointing right, the positive *X*-axis pointing away, and the positive *Z*-axis pointing down. Each master and slave implement transformations to convert their own coordinate systems to the common reference frame. Because the motion is well coordinated between master and slave systems, the coordinate systems are transparent to the surgical user.

During Plugfest 2009 [20], 14 research teams around the world evaluated the ability of ITP to connect their heterogeneous robots and perform a standardized task, the FLS (Fundamentals of Laparoscopic Surgery) block transfer task. Thirty trials were conducted to connect the various master and slave systems across the Internet. Of those, 29 resulted in successful task completion, 20 bi-manual telerobotic (T)FLS, five one-handed TFLS block transfer, and three bi-manual gross manipulation tasks. Plugfest 2009 showed the feasibility of interconnecting a large number of heterogeneous teleoperation systems using a common protocol. This demonstration used a simple teleoperation data interface that does not require device-specific negotiation. The great simplicity of the ITP makes it easy to incorporate into telerobotic surgical systems without requiring extensive software redesign. The ITP is extendable by defining additional packet types to support new features such as absolute motion commands. ITP's extendability allows it to be adapted to future technical and medical needs. The concepts tested in Plugfest 2009 open the way to a future where surgical consoles are developed and perfected separately from the surgical robots and thus subject to a more rapid innovation cycle. Interoperability will allow a surgeon at a single location to operate with multiple types of equipment.

Table 44.1 Data packet defining the ITP protocol. Each item is 4 bytes. Such packets of 84 bytes are sent from surgeon to patient site at 100–1000 times per second.

Name	Type	Units
Sequence	Unsigned integer	
Pactype	Unsigned integer	
Version	Unsigned integer	
Delta x (L)	Integer	Microns
Delta x (R)	Integer	Microns
Delta y (L)	Integer	Microns
Delta y (R)	Integer	Microns
Delta z (L)	Integer	Microns
Delta z (R)	Integer	Microns
Delta roll (L)	Integer	Microradians
Delta roll (R)	Integer	Microradians
Delta pitch (L)	Integer	Microradians
Delta pitch (R)	Integer	Microradians
Delta yaw (L)	Integer	Microradians
Delta yaw (R)	Integer	Microradians
Buttonstate (L)	Integer	
Buttonstate (R)	Integer	
Grasp (L)	Integer	
Grasp (L)	Integer	
Surgeon mode	Integer	
Checksum	Integer	

RAVEN II

The RAVEN II project, currently under way with National Science Foundation funding at the University of Washington and University of California Santa Cruz, is building an interoperable network of surgical telerobot systems and will deploy them at leading surgical robotics research laboratories around the United States. Based on the RAVEN design described above, the systems will be robust enough for continuous research use (up to and including animal surgery), and to enable integration of telesurgery with computation-intensive technologies such as machine vision, unsupervised learning, and motion planning. The RAVEN II system will be a stable, reliable platform upon which novel research can be performed under realistic constraints.

For RAVEN II, the RAVEN system has been redesigned, incorporating lessons learned in the development of RAVEN and its field experiments (Figure 44.8). For example, in RAVEN I, the selection of brushless DC motors over brushed motors was motivated by a better torque to weight ratio and also more efficient heat dissipation. Although the performance benefits of brushless motors were realized, they required more complex and expensive controllers and extensive wiring (14 conductors per motor). RAVEN II will replace the brushless DC motors with brushed motors and as a result simplify the amplifiers and associated wiring.

Figure 44.8 RAVEN II system, now being built by the authors at the University of California Santa Cruz and the University of Washington.

We are currently fabricating seven copies of the new RAVEN II, system, and in 2011 will deploy it in seven leading laboratories, including Harvard University, Johns Hopkins University, University of Nebraska, University of California Los Angeles, and University of California Berkeley, in addition to the University of Washington and University of California Santa Cruz. This new network will enable a diverse new set of research among a strong group of researchers at major institutions across the United States. The existing RAVEN, and indeed essentially all of today's commercial and noncommercial surgical robots, support direct teleoperation, but lack advanced computational functions. With the exception of image registration, most computational functions, such as motion planning, machine learning, stereo vision, and tactile/haptic feedback, when applied to the challenging and fresh application of surgical robotics, are explored today only in theory or simulation. RAVEN II will be a new experimental platform in surgical robotics capable of supporting both advanced software development and extended experimental testing.

Hurdles for telesurgery

Telemedicine

Major nontechnical hurdles for telesurgical practice are the legislative barriers to providing telemedical care, the credentialing and liability coverage issues, and capturing reimbursement for this care. The literature supports that telehealth practice may have a downward impact on soaring medical costs, yet legislative bodies have been slow to act [21–23]. In 2010, Virginia became the fourteenth state to pass a law (bill SB 675) requiring reimbursement for telemedicine services as the government saw telemedicine as a means to reduce healthcare costs while increasing access and improving quality [24]. Medicare and Medicaid still do not reimburse telemedicine, yet states may decide that Medicaid patients may be covered for telemedical care because individual states govern the distribution of Medicaid funds. This is the case in Virginia, where telemedicine services reimbursement does exist for Medicaid patients. Another hurdle is that currently medical staff are required to be credentialed and privileged at every remote site of practice [25]. Out-of-state practice of medicine without a license is prohibited [26] and the burden to the patient, the physician, and the medical system to mandate that each physician obtain licenses in each state where they plan to administer telemedical care is unrealistic [27]. An example of the obstructive policies to telemedicine is in Texas, where a physician can receive a $4000 fine for the first infraction of practicing telemedicine without a state medical license. In Illinois, the Medical Practice Act prohibits the practice of telemedicine without a license [28]. To encourage Congress to pass telehealth legislation, the American Bar Association has drafted a memo stating their opinion that the most formidable barrier to telemedicine is the requirement for multiple state licenses, which it feels burdens patients of lesser means most disproportionately as they cannot afford to travel long distances to obtain adequate healthcare [29].

In an effort to standardize laws for telehealth services and to expand the roles that providers can have in telehealth administration, Congress is working towards passage of the Medicare Telehealth Enhancement Act of 2009 (4/23/2009 – Introduced, HR 2068), which would amend title XVIII (Medicare) of the Social Security Act regarding telehealth services. It would remove current geographic restrictions on the provision of such services and would declare that any telemedicine practitioner credentialed by a hospital in compliance with the Joint Commission Standards for Telemedicine shall be considered in compliance with Medicare condition of participation and reimbursement credentialing requirements for telemedicine services. It would also recommend providing for separate, nonbundled Medicare payment for telehealth services [30].

Logistical hurdles

Latency

As we investigate the possibility of remote surgical operation, we must consider several considerations of the required communication networks. One very important characteristic is latency. Teleoperation latency becomes noticeable to human users above about 200 ms and annoying at about 500 ms, and significantly impacts performance of tasks at 1 s and longer [31].

The fundamental limit on communication latency is, of course, the speed of light. A round-trip message via geosynchronous communication satellite would require two trips up and two trips down of 35 200 km each, a total time at the speed of light of 469 ms. A message sent around the Earth's *surface* to the antipodes (opposite point) and sent back (for example, by optical fiber) would take only 134 ms at the speed of light. Although data routers and codecs add significant latency, our recent experiments measured the round-trip latency of the Internet between Seattle and Italy at about 220 ms. Hence teleoperation to any point on Earth without noticeable delay is theoretically possible and likely to be technically feasible.

Security

In order to provide true telesurgical care, software systems need to be in place to protect the integrity of the signal and minimize the latency of data transmission between the surgeon and the patient [32]. If general Internet connections are to be used for remote telesurgery, standard communication protocols such as the Interoperable Telesurgery Protocol (ITP) developed by the University of Washington need to be secured [33]. Authentication and authorization levels for the surgical master, surgical slave, and the patient need to be developed to prevent eavesdropping, interception, or falsification of the communication links. One way to protect remote surgery is to send information over multiple pathways of communication so that if one pathway is compromised, there are other ways in which the information can be transmitted. This also requires redundancy in signaling and research is currently ongoing to establish what portions of data are absolutely critical for the surgeon and the safety of the patient and which data are perhaps not essential in the event of data compromise [34, 5].

One of the major challenges in data transmission from surgical robots is the significant amount of video data that is captured which requires post-processing and is usually subject to latency when testing remote telesurgical procedures. In studies by Lum and coworkers, novice and experienced surgeons performed robotic surgery tasks using the RAVEN telesurgery robot and identified conditions under which effective performance was no longer achievable based on signal delay [36,37].

Anticipated advances

Augmented reality

Feedback modalities

Despite the magnified 3D visualization, tremor damping, and motion scaling that the current surgical robot offers, a major drawback to the technology is the lack of tactile feedback to the surgeon. This is particularly critical when handling delicate tissues and suturing. Other than visual cues from the patient, the surgeon does not know the magnitude of forces being applied to the tissues. In an effort to explore the role that haptics play on surgical performance, laboratories have studied visual, auditory, and mechanical feedback [38–40]. One of the engineering challenges to providing the surgeon with force feedback directly is that this requires control systems that can drive the telemanipulators with very low latency to provide an accurate sense of touch. Because this is difficult to engineer, scientists have tested auditory and visual feedback cues based on tensions applied by the robotic instruments. Both Kitagawa *et al.* [41] and Reiley *et al.* [42] studied cardiovascular surgeons tying surgical knots without any feedback and with auditory or visual feedback, or both, and observed that suture tensions were tighter without breaks in the groups with augmented feedback.

Sensing and biophotonics

It seems strange that although we have introduced advanced teleoperated robots into the operating room, most of their instruments are essentially the same graspers, needle drivers, and cauterizers that have been used for decades. A remarkable family of low-cost and miniaturized sensors are available today, driven by high-volume consumer applications such as cell phones. Integrating miniaturized sensors on to the tissue-interactive surfaces of surgical instruments raises the possibility of remarkable advances in diagnosis and targeted therapy. One possibility with great potential is the use of light emitters and detectors on surgical instruments. Such instruments, such as a prototype being developed in our laboratory [43], could stimulate and detect the response of fluorescent agents molecularly targeted to structures of interest such as tumors.

A promising direction is the use of fluorescent agents to identify surgical targets. Such targeting eliminates the need for complex registration computations between medical images and operative video. Similarly, the difficulties of compensating preoperative images for motion of soft tissues are eliminated because fluorescent labels move as the soft tissues are deformed.

Fluorescence of either normal tissues or tissues infused with a fluorescently labeled agent can be induced by pulses of ultraviolet light. Buttemere *et al.* excited unlabeled tissue with 337 nm laser light delivered by an optical-fiber instrument and analyzed the fluorescence with a bench-mounted spectrometer. Fluorescence decreased and the ratio of absorptions, in particular at 610 versus 480 nm, increased as tissue was ablated by heat from high-intensity focused ultrasound [44]. It has been established that the intrinsic fluorescence of tissue can provide a quantitative measure for evaluating the nicotinamide adenine dinucleotide phosphate (NADPH) and collagen concentrations. These concentrations in turn can be used as indicators for the degree of blood supply to the tissue under consideration. In a representative study by Georgakoudi *et al.*, esophageal varices were blocked and the connected tissue was analyzed to determine the effect of blood flow reduction [45]. Deoxygenation of the tissue was clearly detected by measuring the fluorescence and reflectance of the tissue. Although intrinsic fluorescence can identify a limited number of biomarkers, in general a fluorescence assay is needed to identify a tissue of interest. Fortunately, preliminary studies have identified groups of markers that can be used to mark tissues biochemically when they are almost impossible to distinguish with simple optical imaging or by the surgeon's eyes. For example, human erythrocyte glucose transporter type 1 (Glut1) has been shown to be detectable during the malignant progression in Barrett's metaplasia [46]. Glut1 was detected only in biopsies with carcinoma and appears to be an effective indicator of cancer. Work is in progress to produce fluorescent dyes such as a chlorotoxin:Cy5.5 bioconjugate that can delineate malignant glioma, medulloblastoma, prostate cancer, intestinal cancer, and sarcoma from adjacent tissue [47]. Such marking will allow the surgeon to remove all the cancerous tissue without damaging the nearby vital organs. The capability is critical in preventing the recurrence of cancer after surgery due to margin positivity. This biochemical technology is likely to present great opportunities to telesurgery.

Improvements in the surgeon

Comparative effectiveness

The role of robotic surgery in children and in adults has grown disproportionately with the level of evidence-based medicine to support its use [48]. It is imperative that we as adopters of robotic technologies strive to prove telesurgery's advantage over conventional surgery. The National Institutes of Health is investing $1.1 billion of research funds to support efforts to demonstrate comparative effectiveness of medical advances. Hu *et al.* recently reported on a Medicare outcomes survey of men undergoing robotic prostatectomy and found that the outcomes did not mirror those individually cited by high-volume centers [4]. This can be attributed to the variability in skill level and learning curve status of all the surgeons who contributed patients to the Medicare database. Efforts to accelerate learning curves for robotic surgeons are under way and technology noted in this chapter will be at the forefront of enabling improved surgical performance and patient outcomes.

Simulation education

The surgical education paradigm of "see one, do one, teach one" is no longer applicable in a healthcare era when patient outcomes are now at the forefront of quality control measures. As resident duty hours and access to cases diminish, thought leaders are working on new ways to train. Also, now that Maintenance of Certification requirements are being directed at not only cognitive, but also technical skills, methods to keep existing practicing surgeons up to speed in their practice and to provide fledgling surgeons with a means of exposure to multiple clinical scenarios, surgical simulation training is becoming standard. The American College of Surgeons mandated in 2009 that every general surgical resident must be provided with a simulation training element to their curriculum [49]. Literature has supported the use of simulation training to advance learners' technical proficiency and a few studies have even shown predictive validity for simulation training (performance in the laboratory correlates with performance in the operating room) [50–53]. In addition, novel training modalities to prime surgeons through surgical warm-up and patient-specific simulation procedures may prove to be beneficial for patient outcomes [54–56].

Although laparoscopic simulators have been around for over a decade, robotic simulators have only recently become available. There have been preliminary validation studies showing their utility [57–60]. The advantages of the robotic simulator are that (1) technical skills of instrument and camera clutching can be taught prior to work on the da Vinci system, (2) performance metrics can be immediately captured and fed back to the subject in a summative fashion without an instructor needing to be there, (3) as the surgical robotic instrumentation and technology update, so too can the simulator update to reflect changes, (4) access to the robot is not required as the simulator can be housed in simulation centers for continuous access, and (5) the cost of a simulator is an order of magnitude less than that of purchasing a robot for training purposes.

One new methodology for surgical preparation is surgical warm-up. Athletes, musicians, and dancers all warm up prior to their respective performances as their tasks are intensely cognitive and physical. Yet surgeons, who arguably also are in a high-stakes profession, do not do any formal warm-up to prime the centers of the brain that will be used in the case. Behavioral science theory posits that in addition to psycho-motor priming, spatial relations and memory priming are valuable in raising a subject to an "activation state" ready for the pending task [61,62]. Little literature has explored surgical warm-up, but recent reports have touted its benefits. In a study by Kahol *et al.*, a virtual reality laparoscopic simulation curriculum was created to test the performance boost of "warmed-up" subjects and observed that irrespective of the subject's level of training or even whether they were senior faculty, they consistently experienced a performance boost after warm-up [63]. This advantage was seen in the laboratory, but Calatayud *et al.* recently studied the effect that virtual reality simulation warm-up played in the operating room. Ten surgical residents who acted as their own controls were randomized to either do virtual reality laparoscopic tasks just prior to doing a laparoscopic cholecystectomy in a patient or no simulation warm-up prior to a real cholecystectomy. The data showed that when the residents warmed up on the simulator, they had statistically significantly higher objective assessment scores of their intraoperative performance [55]. It is possible that some day all surgeons will be required to do some type of warm-up, perhaps on a video game-like station, just prior to operating while the patient is being prepped.

Another simulation methodology to elevate surgical performance through preparation is patient-specific simulation training. As post-processing of high-resolution patient imaging becomes more available and importable to the robotic console or robotic simulator, surgeons will be able to survey patient anatomy in a virtual operative field and even rehearse the planned surgery prior to actually doing the surgery. To achieve this vision, the current challenges are (1) to create robust virtual reality environments based on existing patient imaging and (2) to be able to model tissue deformation adequately to give the surgeons the sense that they are really experiencing the feedback that they will experience in the actual case. Some studies have already demonstrated the ability to import existing patient imaging data and convert them into virtual reality environments [56,64]. However, modeling true tissue deformability in real time is challenging and remains the elusive goal for realizing this technology [65–67].

Conclusion

Improvements in technology and in the way surgeons prepare themselves for surgery promise to yield improved patient outcomes and decreased cost of healthcare delivery. Legal considerations specific to telemedicine and also technological impediments need to be overcome to expand access to surgical expertise in underserved and remote locations. Future robotic telesurgery platforms will be smaller, less expensive, and will provide the surgeon with more anatomic and physiologic data. The responsibility falls on us to design well-constructed comparative clinical protocols to validate clearly that telerobotic surgery goes beyond an incremental improvement over conventional surgical care, but also provides a more cost-effective health delivery platform.

References

1 Pruthi RS, Wallen EM. Current status of robotic prostatectomy: promises fulfilled. *J Urol* 2009;**181**:2420–1.

2 Casale P, Lendvay TS. Robotic hypospadias surgery: a new evolution. *J Robot Surg* 2010;**3**:239–44.

3 Parekattil SJ, Atalah HN, Cohen MS. Video technique for human robot-assisted microsurgical vasovasostomy. *J Endourol* 2010;**24**:511–4.

4 Hu JC, Gu X, Lipsitz SR, *et al.* Comparative effectiveness of minimally invasive vs. open radical prostatectomy. *JAMA* 2009;**302**:1557–64.

5 Taylor RH, Menciassi A, Fichtinger G, Dario P. Medical robotics and computer integrated surgery. In: Siciliano B, Khatib O, eds. *Springer Handbook of Robotics*. Berlin: Springer, 2008: Chapter 52.

6 Speich JE, Rosen J. Medical robotics. In: Wnek GE, Bowlin GL, eds. *Encyclopedia of Biomaterials and Biomedical Engineering*. New York: Informa Healthcare, 2004: 983–93.

7 Hill JW, Green PS, Jensen JF, *et al.* Telepresence surgery demonstration system. In: Proceedings, 1994 IEEE International Conference on Robotics and Automation, 1994: 2302–7.

8 Tadano K, Kawashima K. Development of a pneumatically driven forceps manipulator IBIS IV. In: ICROS–SICE International Joint Conference, 2009: 3815–8.

9 Konietschke R, Hagn U, Nickl M, *et al.* The DLR MiroSurge – -a robotic system for surgery. In: ICRA'09, IEEE International Conference on Robotics and Automation, 2009:1589–90.

10 Tobergte A, Konietschke R, and Hirzinger G. Planning and control of a teleoperation system for research in minimally invasive robotic surgery. In: ICRA'09, IEEE International Conference on Robotics and Automation, 2009:4225–32.

11 Rosen J, MacFarlane M, Richards C, *et al.* Surgeon/endoscopic tool force–torque signatures in the evaluation of surgical skills during minimally invasive surgery. Presented at MMVR-99 (Medicine Meets Virtual Reality), San Francisco, January 1999.

12 Richards C, Rosen J, Hannaford B, *et al.* Skills evaluation in minimally invasive surgery using force/torque signatures. *Surg Endosc* 2000;**14**(9):791–8.

13 Lum MJH, Warden D, Rosen J, *et al.* Hybrid analysis of a spherical mechanism for a minimally invasive surgical (MIS) robot – design concepts for multiple optimizations. In: *Proceedings of Medicine Meets Virtual Reality*, Long Beach, CA, January 2006:349–54.

14 Rosen J, Hannaford B. Doc at a distance. *IEEE Spectrum* 2006;October:34–9.

15 Lum M, Friedman D, Rosen J, *et al.* The RAVEN: design and validation of a telesurgery system. *Int J Robot Res* 2009;**28**:1183–97.

16 Hannaford B, Friedman D, King H, *et al* Evaluation of RAVEN surgical telerobot during the NASA extreme environment mission operations (NEEMO) 12 mission. *University of Washington Electrical Engineering Department Technical Report 2009-0002*, 2009.

17 Lum MJH, Rosen J, Sinanan MN, Hannaford B. Kinematic optimization of serial and parallel spherical mechanism for a minimally invasive surgical robot. *IEEE Trans Biomed Eng* 2006;**53**(7):1440–5.

18 Lum MH, Friedman DCW, King HH, *et al.* Field operation of a surgical robot via airborne wireless radio link. *Presented at the IEEE International Conference on Field and Service Robotics*, 2007.

19 Lum MJH Rosen J, King H, *et al.* Telesurgery via unmanned aerial vehicle (UAV) with a field deployable surgical robot. Presented at Medicine Meets Virtual Reality (MMVR), Long Beach, CA, 2007.

20 King HH, Hannaford B, Kwok K-W, *et al.* Plugfest 2009: global interoperability in telerobotics and telemedicine. Presented at the International Conference on Robotics and Automation, ICRA 2010, May 2010.

21 Boxer RJ. Telehealth can enable convenient, high-quality and affordable care for children and their families. http://www.telehealthreports.com/resources/PediatricPaper.pdf, 2009 (last accessed 18 October 2010).

22 McConnochie KM, Herendeen NE, Kitzman HJ, *et al.* Telemedicine reduces absence resulting from illness in urban child care: evaluation of an innovation. *Pediatrics* 2005;**115**:1273–82.

23 Belman S, Chandramouli V, Hegarty T, *et al.* An assessment of pediatric after-hours telephone care. *Arch Pediatr Adolesc Med* 2005;**159**:145–9.

24 Federal Telemedicine News. Telemedicine legislation passed. http://telemedicinenews.blogspot.com/2010/03/telemedicine-legislation-passed.html, 2010 (last accessed 18 October 2010).

25 iHealthBeat. Virginia bill mandates telemedicine coverage; barriers remain. http://www.ihealthbeat.org/features/2010/virginia-bill-mandates-coverage-of-telemedicine-barriers-remain.aspx, 2010 (last accessed 18 October 2010).

26 Robertson J. Physician licensure: an update of trends. http://www.connected-health.org/policy/federal-and-state/external-resources/physician-licensure-an-update-of-trends.aspx, 2005 (last accessed 18 October 2010).

27 Ackerman K. Virginia bill mandates telemedicine coverage; barriers remain. http://www.ihealthbeat.org/features/2010/virginia-bill-mandates-coverage-of-telemedicine-barriers-remain.aspx, 2010 (last accessed 18 October 2010).

28 Public Act No. 90-99, Ill. Ann. Stat. Ch. 225, §60/49.5(c).

29 Demetriou A. Health Law Section Report to ABA House of Delegates, American Bar Association, Health Law Section, Report to the House of Delegates, 2008. www.abanet.org/health/04_government_sub/media/116B_Tele_Final (last accessed 18 October 2010).

30 H.R. 2068: Medicare Telehealth Enhancement Act of 2009. http://www.govtrack.us/congress/bill.xpd?bill=h111–2068&tab=summary, 2009 (last accessed 18 October 2010).

31 Sheridan T, Ferrell W. Remote manipulative control with transmission delay. *IEEE Trans Human Factors Electron* 1963;**4**:25–9.

32 Orphanoudakis SC, Kaldoudi E, Zikos M. Telemedicine. In: Urban J, Dasgupta P, eds. *Encyclopedia of Distributed Computing*. Norwell, MA: Kluwer Academic, 1998.

33 Yang Y, Bao F, Deng R. Secure an image-based simulated telesurgery system. Presented at the International Symposium on Circuits and Systems (ISCAS), 2003.

34 Kurian J, Sarac K. A survey on the design, applications, and enhancements of application layer overlay network. *ACM Comput Surv* 2010;**43**(1):5.1–5.34.

35 Nagata H, Mizaushima H. A remote collaboration system for telemedicine using the Internet. *J. Telemed Telecare* 1998;**4**:89–94.

36 Lum MJ, Rosen J, King H, *et al.* Teleoperation in surgical robotics – network latency effects on surgical performance. *Conf Proc IEEE Eng Med Biol Soc* 2009; 6860–3.

37 Lum MJ, Rosen J, Lendvay TS. TeleRobotic fundamentals of laparoscopic surgery (FLS): effects of time delay-pilot study. *Conf Proc IEEE Eng Med Biol Soc* 2008; 597–600.

38 Vivekananda U, Henderson A, Murphy DG. The science behind haptics in robotic urological surgery. *BJU Int* 2009;**104**:33–4.

39 Okamura AM. Haptic feedback in robot-assisted minimally invasive surgery, *Curr Opin Urol* 2009;**19**:102–7.

40 van der Meijden OA, Schijven MP. The value of haptic feedback in conventional and robot-assisted minimal invasive surgery and virtual reality training: a current review. *Surg Endosc* 2009;**23**:1180–90.

41 Kitagawa M, Dokko D, Okamura AM, *et al.* Effect of sensory substitution on suture-manipulation forces for robotic surgical systems. *J Thorac Cardiovasc Surg* 2005; **129**:151–8.

42 Reiley CE, Akinbiyi T, Burschka D, *et al.* Effects of visual force feedback on robot-assisted surgical task performance, *J Thorac Cardiovasc Surg* 2008;**135**:196–202.

43 Roan P, Wright AS, Sinanan MN, Hannaford B. An instrumented minimally invasive surgical tool: design and calibration. *Appl Bionics Biomech* Special Issue on Surgical Robotics, 2010.

44 Buttemere CR, Chari RS, Anderson CD, *et al. In vivo* assessment of thermal damage in the liver using optical spectroscopy. *J Biomed Opt* 2004;**9**:1018–27.

45 Georgakoudi I, Jacobson BC, Muller MG, *et al.* NAD(P)H and collagen as *in vivo* quantitative fluorescent biomarkers of epithelial precancerous changes. *Cancer Res* 2002; **62**(3):682–7.

46 Younes M. Human erythrocyte glucose transporter (glut1) is immunohistochemically detected as a late event during malignant progression in barrett's metaplasia. *Cancer Epidemiol Biomarkers Prev* 1997;**6**(5): 303–5.

47 Veiseh M, Gabikian P, Bahrami SB, *et al.* Tumor paint: a chlorotoxin:cy5.5 bioconjugate for intraoperative visualization of cancer foci. *Cancer Res* 2007;**67**(14):6882–8.

48 van Haasteren G, Levine S, Hayes W. Pediatric robotic surgery: early assessment pediatrics. *Pediatrics* 2009; **124**:1642–9.

49 Satava RM. Emerging trends that herald the future of surgical simulation. *Surg Clin North Am* 2010;**90**: 623–33.

50 Seymour NE, Gallagher AG, Roman SA, *et al.* Virtual reality training improves operating room performance: results of a randomized, double-blinded study. *Ann Surg* 2002;**236**:458–63.

51 Watterson JD, Beiko DT, Kuan JK, *et al.* A randomized prospective blinded study validating acquisition of ureteroscopy skills using a computer based virtual reality endourological simulator. *J Urol* 2002;**168**: 1928–32.

52 Fundamentals of laparoscopic surgery. SAGES FLS program. www.flsprogram.org (last accessed 18 October 2010).

53 Peters JH, Fried GM, Swanstrom LL, et al.; SAGES FLS Committee. Development and validation of a comprehensive program of education and assessment of the basic fundamentals of laparoscopic surgery. *Surgery* 2004; **135**:21–7.

54 Kasina M, Lendvay TS. Robotic virtual reality surgical warm-up: a novel use for a simulation curriculum. Presented at the American College of Surgeons Clinical Congress, Washington, DC, 2010.

55 Calatayud D, Arora S, Aggarwal R, *et al.* Warm-up in a virtual reality environment improves performance in the operating room. *Ann Surg* 2010;**251**:1181–5.

56 Rashid HH, Berkley J, Vollenweider M, *et al.* Creating a patient specific interactive virtual reality model for robotic prostatectomy. *J Endourol* 2006;**20**: A326.

57 Lendvay T, Casale P, Sweet R, *et al.* Initial validation of a virtual-reality robotic simulator. *J Robot Surg* 2008;**2**: 145–149.

58 Sethi A, Peine W, Mohammadi Y, *et al.* Validation of a novel virtual reality robotic simulator. *J Endourol* 2009; **23**(3):503–8.

59 Kenney P, Wszolek M, Gould J, *et al.* Face, content, and construct validity of dV-Trainer, a novel virtual reality simulator for robotic surgery. *J Urol* 2009;**73**(6): 1288–92.

60 Seixas-Mikelus SA, Adal A, Kesavadas T, *et al.* Can image-based virtual reality help teach anatomy? *J Endourol* 2010;**24**(4):629–34.

61 Anshel MH, Wrisberg CA. The effect of arousal and focused attention on warm-up decrement. *J Sport Behav* 1988;**11**:18–31.

62 Hamilton CE., Mola WR. Warm-up effect in human maze learning. *J Exp Psychol* 1953;**45**:437–41.

63 Kahol K, Satava R, Smith M, *et al.* The effect of short term pre-trial practice on surgical proficiency in simulated environments: a randomized trial of "preoperative warm-up" effect. *J Am Coll Surg* 2008;**208**: 255–68.

64 Hayashibe M, Suzuki N, Hashizume M, *et al.* Preoperative planning system for surgical robotics setup with kinematics and haptics. *Int J Med Robot* 2005;**1**(2): 76–85.

65 Rosen J, Brown JD, De S, *et al.* Biomechanical properties of abdominal organs *in vivo* and postmortem under compression loads. *J Biomech Eng* 2008;**130**(2): 021020.

66 Thurfjell L, Lundin A, McLaughlin J. A medical platform for simulation of surgical procedures. *Stud Health Technol Inform* 2001;**81**:509–14.

67 Misra S, Macura KJ, Ramesh KT, Okamura AM. The importance of organ geometry and boundary constraints for planning of medical interventions. *Med Eng Phys* 2009;**31**(2):195–206.