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Robotics in General Surgery

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1. Introduction

General Surgery has seen an evolution over the last several decades toward minimally invasive approaches to procedures that were classically performed though large open incisions. The former assumption in the surgical world that "a big surgery requires a big incision" is no longer true. The benefit of significant reductions in the size of incisions is clear to surgeons who appreciate fewer wound complications and to the educated public who value less post-operative pain and rapid return to normal activities. As incisions and access ports become smaller and fewer, the tools to enable complex tasks through these ports are being developed. Robotics is one of the primary tools being incorporated into the surgical environment. The term robot comes from the Czech word *robota* for "compulsory labor"[1].

While many modern definitions of 'robot' include a component of automation, such a component has yet to be significantly integrated into General Surgery machines. Thus, for the purpose of this chapter, a surgical robot is defined as a machine that performs various complex surgical tasks in a master-slave configuration.

Surgical robots offer many advantages in the area of minimally invasive General Surgery and have made significant contributions to the field in the last twenty years. Robotics was first introduced to the General Surgery operating room in the form of surgeon controlled robotic arms for laparoscopic camera manipulation. More recently, robotic surgical systems that allow the surgeon to operate from a remote console have been introduced. Significant challenges remain for the field including the cost-effectiveness, safety, training, and adoption. However, the benefits of robotics in the operating room are becoming clear and further development will see the maturation of a field with significant promise to improve patient care.

2. The Surgeon Assistant

The first surgical robot was approved by the FDA in 1994 for use in General Surgery. The Aesop® (Automatic Endoscopic System for Optimal Position, Computer Motion Inc., Goleta CA) is a system designed to assist the surgeon in the era of laparoscopy by taking control of the laparoscopic camera[2, 3]. The system is composed of an articulated, electromechanical arm mounted to the operating room table. The arm provides 7 degrees of freedom (7-DOF) that is completely controlled by the surgeon via foot control, hand control, or voice recognition[4]. Aesop® was designed to reduce the need for an assistant to operate the camera during laparoscopic procedures and was subsequently found to have benefits in reducing

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smudging, fogging, inadvertent movements and overall operative time[5, 6]. The EndoAssist (Prosurgics, High Wycombe, England) is another FDA approved laparoscopic camera control system that relies on a head mounted sensor. The system is a stand alone cart with an electro-mechanical robotic arm that is activated by a foot pedal, and moves according to the desired viewing direction of the surgeon (Figure 1). The system can be quickly learned and offers similar benefits to the Aesop® [7]. The EndoAssist and Aesop® systems were found to be equally effective in task performance in a study by Wagner and colleagues[8] while Nebot and colleagues[9] found the EndoAssist guidance more efficient than the voice commanded Aesop®. Both studies, however, noted some drawback to the size of the EndoAssist and its separation from the operating table.

3. The Teleoperator Era

Since their introduction in 1994, robotic applications in General Surgery have evolved from simple surgical assist devices, to more sophisticated systems capable of enhancing surgical performance. The primary class of robots used in General Surgery today, are "master-slave" machines, where the robot mimics the movement of the surgeon. In these units the "master" control console, from which the surgeon operates, is physically separated from the "slave" unit, composed of the robotic arms performing the surgery. As a result of this separation, these systems are also referred to as teleoperators or telemanipulators.
While the foundation of teleoperator surgical systems can be traced back to the United States National Aeronautics and Space Administration (NASA) in the 1970s, their major development was funded by DARPA (Defense Advanced Research Project Administration) as a potential military tool for remote surgical care of the injured soldier. Two main teleoperator surgical robots were developed from the research; the da Vinci® Surgical System (Intuitive Surgical, Inc., Sunnyvale, CA) described in detail below and the Zeus® system (Computer Motion, Goleta, CA). Intuitive Surgery and Computer Motion merged in 2003, resulting in a single FDA approved robotic platform on the market today that carries the name da Vinci®.

3.1 The da Vinci ® Platform

The da Vinci® surgical system (Figure 2), which obtained FDA approval in September 2001, has two main components: the surgeon's console and a patient's side cart. The surgeon's console houses the sophisticated visual display system, surgeon's control handles, and the user interface panels. The patient side cart is the actual robotic device, and electro-mechanical arms that move in response to the surgeon's motions at the console.
The surgeon console (Figure 3) consists of a workstation, which can be located up to 10 meters away from the operating table, from which the operator controls a video endoscope and two to three robotic arms. The surgeon is seated at the workstation and places his or her head inside a viewing space. The console contains the surgeon controls which act as high resolution input devices that read the position, orientation, and grip commands from the surgeon's finger tips. The surgeon's motions are relayed from the console to the robotic arms, which, in turn, manipulate the instruments (i.e. needle drivers, forceps, scissors) and the endoscope. The surgeon's console also holds commands for special enhancement functions such as motion scaling and tremor reduction.
The da Vinci® surgical system utilizes a sophisticated optic display. High-resolution images of the operative site are projected to the surgeon through a dual-lens, three-chip digital camera

system. Each camera transmits to different medical grade cathode ray tube (CRT) monitors located inside the console, which display a separate image to each eye. These are fused in the surgeon's brain, to create a three-dimensional image. In addition, the images are anatomically aligned with the position of the surgeon's hands, creating the feeling of being immersed into the surgical field—where the surgeons feels as if their hands are virtually inside the patient's body.
The da Vinci® robotic arms are attached to a patient-side cart (Figure 4) that contains the 2 to 3 arms that control the operative instruments as well as a center arm that controls the video endoscope. The cart is mobile allowing its position to be adapted to the specific operation being performed. Once locked in place and engaged within the patient, however, the cart cannot be re-positioned without entirely disengaging the system. The standard array of 8 mm da Vinci® instruments are outfitted with an EndoWrist® technology (Figure 5) with bidirectional articulation that provides 7-DOF. All instruments respond to the movement of the control handles with "wrist-like" movements that mimic the human hand. A variety of instrument tips are available including forceps, needle drivers, and scalpels, as well as both monopolar and bipolar electrocautery devices (Figure 6).

4. Advantages of Telerobotic Surgical Systems

Robotic surgery was introduced into clinical practice in the late 1990s, after conventional laparoscopic surgery had already made a significant impact on modern surgical practice. The primary advantages of the robotic surgical systems stem from their ability to address many of the limitations of conventional minimally invasive techniques. Modern laparoscopic instruments challenge the surgeon to perform manipulations with rigid shafted instruments through access ports. Undesirable effects of the current approach include counter intuitive movement at the instrument tip (fulcrum effect), reduced degrees of freedom, and the optical limitations of a 2-dimensional view through a single lens.
Telerobotic surgical systems enhance dexterity in several ways. Internal software filters out the natural tremor of a surgeon's hand, which can become particularly evident under high magnification and problematic when attempting fine maneuvers in very small fields[10]. In addition, the system can scale movements such that large movements of the control handles can be transformed into smaller movements inside the patient[10-12]. Lastly, the "wristed" 7-DOF instruments significantly enhance dexterity as compared with the 5-DOF of standard laparoscopic instruments. Robotic instruments permit a larger range of motion and rotation, similar to the natural range of articulation of the human wrist. This increased dexterity may be particularly advantageous during complex operations in limited spaces that require fine dissection and intracorporeal suturing.
During conventional minimal access surgery, instruments pivot around the fulcrum of the insertion point, thus movement in the surgical field is always opposite to the direction of motion of the surgeon's hand. In the robotic surgical systems electronic separation of the instrument tips from the handles eliminates the effects of instrument length, minimizes the fulcrum effect, and restores a more intuitive non-reversed instrument control[13].
The sophisticated vision system of the da Vinci® described above, is another significant advantage of robotic technology, adding a measure of safety and surgical control beyond what is available with traditional laparoscopy. The three dimensional display improves depth perception, and the ability to magnify images by a factor of ten allows extremely sensitive and accurate surgical manipulation. The alignment of the visual axis with the surgeon's hands in the console further enhances hand-eye coordination.

Lastly, teleoperator systems feature ergonomically designed workstations designed to minimize physical strain and fatigue associated with long minimally invasive procedures[14-16]. This may prove to become a particularly significant issue as the field of bariatric surgery expands, due to the high levels of surgeon fatigue seen when operating on the larger size and thicker body walls of bariatric patients.

5. Disadvantages of Telerobotic Surgical Systems

While robotic surgical systems have successfully provided several key advantages over standard minimal access surgery, there are a number of limitations that have prevented this technology from reaching its full potential. Foremost among these is the loss of force feedback (haptics). While such feedback is reduced in standard minimal access surgery, compared to open surgery, it is further reduced with the robotic interface. The operating surgeon must therefore rely on visual cues such as tissue compression and blanching, and suture stretch (e.g. knot deformation), to determine the tensile strength of tissue and sutures[17, 18].

Another significant limitation of robotic technology is the extremely high initial cost of purchasing a robot (~$1,200,000) as well as the relatively high recurring costs of the instruments (~$2500 per 10 usage disposable instrument) and maintenance (~$100,000 per year)[19]. A strong argument for the cost-effectiveness of robotic surgery has yet to be made with recent studies comparing robotic procedures with conventional operations revealing that the absolute cost for robotic operations is significantly higher[20].

Lastly, the robotic systems are large and bulky and have complex, time-consuming setups, requiring additional specialized training for the entire operating room team. This translates into robotic procedure times that are predictably longer when compared to conventional laparoscopic approaches, at least until the surgical team becomes facile with the use of the new technology. Even with an experienced team, setup times have been reported to require an additional 10 to 35 minutes at the beginning of each robot-assisted case[21]. Undoubtedly, many of these issues will be remedied in the next generation of equipment as the technology continues to improve. Table 1 summarizes the advantages and disadvantages of robot-assisted surgery in comparison to conventional minimal access surgery.

6. Current Applications of Robotics in General Surgery

To date, the majority of published clinical experience using robotic technology has consisted primarily of retrospective case reports and case series. Robotic surgical systems have been used in many different surgical disciplines including Urology, Cardiac Surgery, Gynecology, General Surgery and Pediatric Surgery. Despite the important role General Surgery has played in advancing minimally invasive surgical techniques, General Surgeons have been relatively slow to pick up on robotics in comparison to other surgical specialists particularly Urologists. Nonetheless, telerobotic surgical techniques have been applied to a rapidly growing list of General Surgery procedures (Table 2). Highlights of selected procedures are discussed below.

6.1 Cholecystectomy

The introduction of laparoscopy about 20 years ago revolutionized the treatment of gallbladder disease[22]. Since then the laparoscopic cholecystectomy has become the standard of care and one of the most common laparoscopic procedures performed today. It is thus no surprise that the first robotic surgical procedure performed on a human was a laparoscopic cholecystectomy in 1997 by Himpens, Leman, and Cadiere[23].

Since that time, many clinical series have been published documenting experiences with robotic-assisted cholecystectomy[10, 24-28]. All of these studies have shown few intra- or post-operative complications confirming the feasibility and safety of using the da Vinci® robotic system to perform laparoscopic cholecystectomy[29, 30]. Studies comparing totally robotic to conventional laparoscopic cholecystectomy generally demonstrate significantly longer OR times with the robotic procedures[31-34]. No clinical outcome advantage is presently apparent for robotic cholecystectomy over laparoscopic cholecystectomy. Nonetheless, robotic cholecystectomy is an excellent procedure for teaching the basics of robotic surgery, and may be useful as a training procedure.

6.2 Fundoplication

Telerobotic fundoplication, like cholecystectomy, also has been used by many centers to initiate their clinical experience with telerobotic gastrointestinal surgery. There are several series in the literature demonstrating that robotic fundoplication is feasible and safe with a low conversion rate and an acceptable morbidity rate, however similar to robotic cholecystectomy, robotic fundoplications resulted in longer operating room times[30, 35-41]. Several randomized control trials of robot-assisted versus conventional laparoscopic fundoplications have been published. Most of these show similar results to the studies mentioned above, in that the procedure is feasible, and the outcomes are similar to conventional laparoscopy. Some argue that the small field of operation and the importance of suturing for repair of the hiatus and construction of the fundoplication makes this procedure an ideal application for telerobotic surgical systems[29]. The most recent randomized control trial by Müller and colleagues[42], did in fact demonstrate shorter operative times for robotic fundoplication when performed by an experienced team. However, given the higher costs and similar clinical outcomes, the advantages of robot-assisted fundoplication over standard laparoscopic techniques are yet to be proven.

6.3 Heller Myotomy

The role of robotic technology in assisting minimally invasive Heller myotomy is more apparent. Laparoscopic Heller myotomy is a difficult operation to perform, with a steady rate of esophageal perforation occurring (approximately 7%) even for very experienced surgeons[30, 43]. The published telerobotic Heller myotomy series, in comparison, have demonstrated extremely low rates of esophageal perforation[43-45]. It is felt that the performance enhancing features of the robot such as increased dexterity, 3D imaging, and tremor filtration permit greater precision during performance of the myotomy compared to traditional laparoscopic techniques. No randomized controlled trials have been published as of yet, to validate these claims.

6.4 Bariatric Surgery

Robotic surgical systems are being used to assist in a variety of bariatric surgical procedures. Cadiere and colleagues[46] were the first to enter this area, performing a gastric banding procedure in 1999. Since then telerobotic surgical techniques have also been reported for biliary pancreatic diversion with duodenal switch, as well as various elements of laparoscopic Roux-en-Y gastric bypass procedures[47-51]. All studies demonstrate the feasibility and safety of performing robotic bariatric procedures. Mohr and colleagues[52] developed a totally robotic Roux-en Y gastric bypass technique. They reported telerobotic operations were accomplished significantly faster than the laparoscopic operations and suggest that their results point to the potential superiority of telerobotic bariatric surgery. In general, authors suggest that the robotic surgical system may enhance performance particularly in superobese patients. The strength of the robotic arms, as well as the additional degrees of freedom in motion offered by the wristed instruments appears to overcome the problems generated in these patients by their thick abdominal walls.

7. Colorectal Surgery

Given that conventional laparoscopic colorectal surgery is still in its infancy, it is not surprising that telerobotic colorectal surgery remains in an early state of development. However, one would expect the benefits of robotic surgery in other deep pelvic procedures including prostatectomy[53] and hysterectomy to translate into benefits in low anterior colon procedures. The first reported robotic colectomy was performed by Weber end colleagues in 2002[54]. Several studies have since reported safety and feasibility of a variety of colorectal procedures[55-62]. Some difficulties have been encountered in obtaining adequate excursion with the robotic arms, primarily in procedures requiring dissection both up to the splenic flexure and down to the pelvis. As is the case for many of the other procedures discussed above, robotic colorectal operations have similar clinical outcomes to conventional laparoscopic techniques along with longer operating times, and higher overall costs, and thus no demonstrable patient benefit[30, 63]. Some suggest, however, that the true benefit of robotic surgery systems may be in enabling more surgeons in the future to perform minimally invasive colorectal surgery, where they would otherwise perform open procedures[64].

7.1 Endocrine Surgery

There are published reports on a variety of telerobotic endocrine procedures including adrenalectomy, parathyroidectomy as well as pancreatic procedures[29, 41, 65-70]. While very few telerobotic pancreatic procedures have been performed to date, some argue that complex gastrointestinal surgeries such as pancreatic resections, which require fine dissection and accuracy in a small operating field may prove to benefit most from robotic technology[30, 41].

The most documented robotic endocrine procedure is the adrenalectomy. The first reported fully robotic adrenalectomy was done in 2002 by Young and colleagues from the Brody School of Medicine[71]. Since then several other case series have reported feasibility and safety of robotic adrenalectomy. One randomized control trial has been published comparing robotic to standard laparoscopic adrenalectomy[72]. However, the study concluded that the telerobotic adrenalectomy is inferior to the conventional laparoscopic procedure due to longer OR times, higher conversion rates, and higher post-operative complications.

8. Robotics in General Surgery: The Future

8.1 Remote Telesurgery

The original vision for robotic surgery—to escape the confines of operating rooms, hospitals, and even the planet and provide skilled surgical care remotely, is becoming a reality. The separation of surgeon and patient inherent to telerobotic surgical systems has been leveraged to develop remote telesurgery, the use of robotics to perform surgery at a distant location. This was first accomplished in September, 2001 by Jacques Marescaux of Strasbourg, France, with the help of sophisticated asynchronous transfer mode telecommunications technology. While sitting at the surgical console in New York City, he performed a telerobotic cholecystectomy, dubbed "operation Lindbergh" on his patient in Strasbourg, who was 4000 km away[73, 74]. This was truly a technical tour de force that required an enormous amount of planning and execution to keep the latency, time from hand motion of surgeon at console to actual response of robot at the patient's side, within acceptable limits. While this certainly was not a procedure easily reproduced for daily use, Anvari and colleagues[59] have had remarkable success in establishing an actual telesurgery program using commercial fiberoptic networks. Dr. Anvari and his group have successfully performed 22 telerobotic laparoscopic surgeries including 13 fundoplications, 3 sigmoid resections, 3 right hemicolectomies, 1 anterior resection, and 2 inguinal hernia repairs, between Hamilton, Canada and a remote hospital in North Bay, Canada (a distance of 400 km).

8.2 Augmented Reality Surgery

Digital integration is another future domain for the surgical robot. In recent years, sophisticated imaging modalities have expanded beyond their role as mere diagnostic techniques, and are now the foundation of sophisticated interactive computer applications which directly guide surgical procedures (image guided therapy-IGT). The overlaying of radiologic imaging data onto the operative visualization system, known as augmented reality, can guide the surgeon's dissection path, by demonstrating vital anatomic structures beyond the visible surface[75-77]. The immediate future promises integration of preoperative and intraoperative imaging data with the robot-assisted platform into a unified surgical delivery system. This union of image-guided therapy and robotic surgery may eventually give rise to operative techniques that truly transcend human capability.

9. Miniaturization

Advances in Micro-Electro-Mechanical-Systems (MEMS) promise the future of robotics will see smaller and smaller embodiments. MEMS are devices measured in micrometers that are built using a variety of advanced fabrication methods including electromagnetic discharge and laser micromachining[78]. MEMS technology began as electro-mechanical sensors and actuators but has grown to integrate biologic, fluid, optical and magnetic systems[79]. Miniaturized sensors and actuators will soon address the limitations of current robotic surgery through haptic feedback and advanced tracking systems. In the long term, these devices will enable complex therapeutic manipulations inside increasing small structures such as the intestinal tract, the vasculature and beyond[80].

10. Automation

As noted earlier in the chapter, surgical robotics used in General Surgery today has not included significant automation. Analogous to the airline industry, computer control of surgical robots has zero tolerance for failure. Despite the ability to automate many basic surgical tasks, the safety bar will be set high. The FDA has yet to approve an automated device for General Surgery and will undoubtedly require significant pre-market testing prior to approval. Other surgical fields have seen small inroads into automation as with the ROBODOC®, a reaming system for the femoral component of hip implants used in orthopedic surgery. The system is programmed based on pre-operative imaging and intra-operative registration to cut a precise cavity in the femoral canal[81-84]. The FDA approved the system after significant pre-market testing for failure modes[85-87]. Many believe that a fully automated surgical robot is unattainable due to subtle variations in human anatomy that demands human skills beyond the capabilities of an algorithm[88]. Although not on the immediate horizon, automation may one day meet the safety challenges it faces and become reality.

11. Conclusion

In summary, robotics has made a significant contribution to General Surgery in the past 20 years. In its infancy, surgical robotics has seen a shift from early systems that assisted the surgeon to current teleoperator systems that can enhance surgical skills. Telepresence and augmented reality surgery are being realized, while research and development into miniaturization and automation is rapidly moving forward.

The future of surgical robotics is bright. Researchers are working to address the electro-mechanical limitations of current robotic systems. Increasing utilization and competition in the marketplace should drive the cost of robotic systems down, improving their cost-effective proposition. By ultimately enabling increasingly complex interventions through minimally invasive approaches, robotics will have a significant role in the future of surgery.

	Robot-Assisted Surgery	**Conventional Minimal Access Surgery**
Advantages	Tremor Filtration	Affordable, ubiquitous
	Stereoscopic Visualization	Some haptic feedback
	Seven degrees of freedom	Well-developed, established technology
	Improved dexterity	
	Elimination of fulcrum effect	
	Motion Scaling	
	Ergonomic Positioning	
	Tele-surgery	
	Improved hand-eye coordination	
Disadvantages	Minimal haptic feedback	Two-dimensional visualization
	Expensive	Compromised dexterity
	Longer set-up times	Limited degrees of motion
	Large footprint	
	New technology	Fulcrum effect (hand-instrument motion reversal)

Table 1. Advantages and Disadvantages of Robot-Assisted Surgery vs. Conventional Minimal Access Surgery

Robotic General Surgery Procedures
Cholecystectomy
Heller Myotomy
Anti-reflux surgery
Colon Resection
Bariatric surgery
Endocrine surgery
Esophageal resection
Small bowel surgery
Liver resection
Splenectomy
Gastric Surgery

Table 2. Applications of Robotics in General Surgery

Figure 1. The EndoAssist manipulates a laparoscopic camera at the command of the surgeon. ©*[2006] Prosurgics, Limited*

Figure 2. The da Vinci® robotic surgical system comprising of a surgeon's console and a patient side cart. ©*[2007] Intuitive Surgical, Inc*

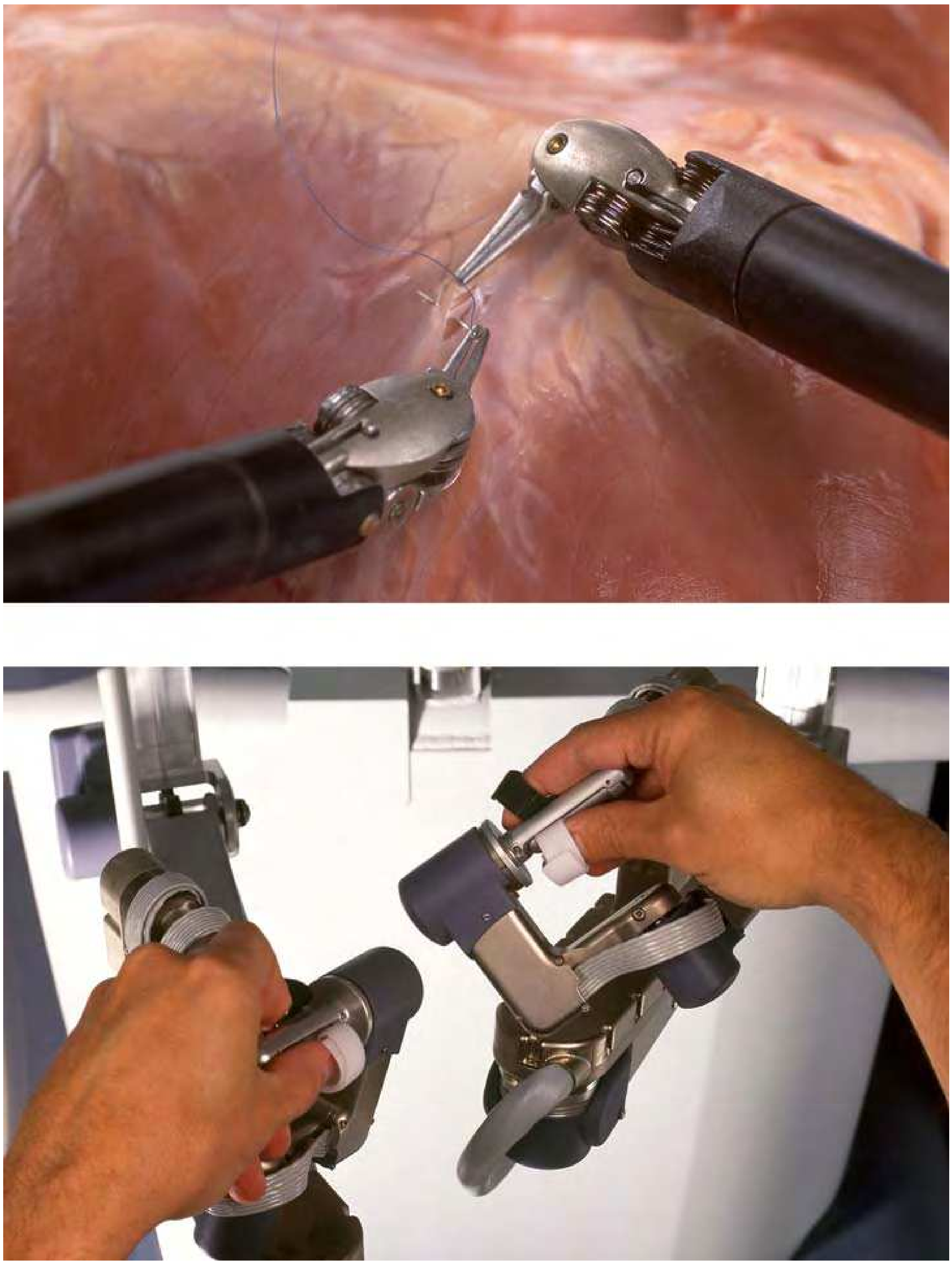

Figure 3. Surgeon’s console including operative field view (above) and master controls (below). *©[2007] Intuitive Surgical, Inc*

Figure 4. Patient side cart. ©*[2007] Intuitive Surgical, Inc*

Figure 5. Demonstration of the 7 degrees of freedom with Endowrist® technology compared to surgeon hands. ©*[2007] Intuitive Surgical, Inc*

Figure 6. Range of available “wristed” instruments. *EndoWrist® ©[2007] Intuitive Surgical, Inc*

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The first generation of surgical robots are already being installed in a number of operating rooms around the world. Robotics is being introduced to medicine because it allows for unprecedented control and precision of surgical instruments in minimally invasive procedures. So far, robots have been used to position an endoscope, perform gallbladder surgery and correct gastroesophogeal reflux and heartburn. The ultimate goal of the robotic surgery field is to design a robot that can be used to perform closed-chest, beating-heart surgery. The use of robotics in surgery will expand over the next decades without any doubt. Minimally Invasive Surgery (MIS) is a revolutionary approach in surgery. In MIS, the operation is performed with instruments and viewing equipment inserted into the body through small incisions created by the surgeon, in contrast to open surgery with large incisions. This minimizes surgical trauma and damage to healthy tissue, resulting in shorter patient recovery time. The aim of this book is to provide an overview of the state-of-art, to present new ideas, original results and practical experiences in this expanding area. Nevertheless, many chapters in the book concern advanced research on this growing area. The book provides critical analysis of clinical trials, assessment of the benefits and risks of the application of these technologies. This book is certainly a small sample of the research activity on Medical Robotics going on around the globe as you read it, but it surely covers a good deal of what has been done in the field recently, and as such it works as a valuable source for researchers interested in the involved subjects, whether they are currently “medical roboticists” or not.

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