Chapter 1
Future Directions in Robotic Surgery

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Abstract Robotic surgery has become an established part of clinical surgery. The advantages of using a robot have been enumerated by many clinicians, however the true potential has yet to be realized. In addition, the systems available today are extraordinarily simple and cumbersome relative to the more sophisticated robotic systems used in other industries. However more important is the fact that the fundamental principles underlying robotics have yet to be exploited, such as systems integration, feedback control, automatic performance, simulation and rehearsal and integration into healthcare enterprise. By looking at robotic implementation in other industries, and exploring the new robotic technologies in the laboratories, it is possible to speculate on the future directions which would be possible in surgical robotics.

1.1 Introduction

A robot is not a machine – it is an information system. Perhaps it has arms, legs, image capture devices (eyes) or various chemical or biologic sensors. However the primary functions are threefold – to acquire information about the world, to 'process' that information and to perform an action in the world. Simply put, robotics can be reduced to input, analysis and output. Some robotic systems interpose a human (instead of a computer) between the input and output – these are tele-manipulation (or for surgery, tele-surgical) systems. The complexity (and benefits) arise as each

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component is developed. On the input side, there are an enormous number of devices, from mechanical, chemical and biologic sensors to imagers of all portions of the electromagnetic spectrum. The 'processor' or analyzer of the information from the various sensors and/or imagers can be either a human, or a computer system, the former for human control while the latter is for 'autonomous' or semi-autonomous control, depending upon the level of sophistication of 'artificial intelligence' which is incorporated. Finally, on the output side there is likewise a wide variety of devices to interact with the world, including manipulators (instruments) and directed energy devices (electrocoagulation, lasers, etc.), all of which can be on a macro-scale of organs and tissues, or micro- and nano-scale for cells and intracellular structures.

However the most important concept is that robotic systems are nothing more than tools – admittedly very sophisticated tools – but tools nevertheless. The species *Homo sapiens* began with only teeth and fingernails to manipulate the world, progressing to sticks and stones, metal and finally energy. Over hundreds of thousands of years (though recently, only a few thousand years), the ability to interact and shape our world has provided the opportunity to free us from the vagaries of nature and to actually control our environment to a greater extent than ever before. Healthcare has always been a straggler, rarely inventing a new technology, but rather succeeding by adopting technologies from other disciplines and industries. Robotics is but one of the many areas where success has been achieved – to the greater benefit of our patients.

There is a new opportunity for medical and surgical robotics, one in which healthcare (or biomedical science) can take the lead – and that is in bio-inspired (or bio-mimicry) devices, whereby observing living systems, new robotic devices and/or systems can be developed. The fertile creativity of the physical and engineering sciences will continue to provide remarkable new ideas and systems, and together with biologic systems, will take robotics well beyond any of the possible projections of today. However, it must be kept in mind that the fundamental purpose is to extend human performance beyond the limitations of the human body, just as stone ax, metal scissor or microscope extended human capabilities in the past, with the stated intent to improve the surgeon's ability to provide higher quality and safer patient care.

1.2 Systems Integration

A capability that is unique to robotic surgery systems (as opposed to open, flexible endoscopy, laparoscopy and Natural Orifice Transluminal Endoscopic Surgery (NOTES)) is systems integration, a characteristic which is emphasized in engineering science. One of the principle advantages of the robotic surgical system is the ability to integrate the many aspects of the surgical care of a patient into a single place (the surgical console) and at a single time (just before or during performing surgery) (Fig. 1.1). At the console the surgeon can perform open or minimally invasive surgery, remote tele-surgery, pre-operative planning or surgical rehearsal, pre-operative

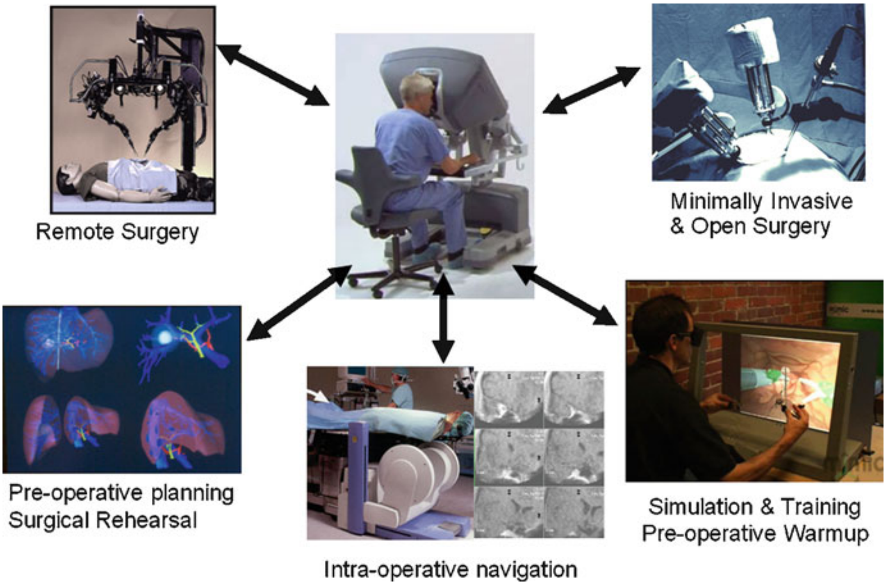

Fig. 1.1 Integration of operative procedures using the surgical work station (Courtesy of the author)

warm-up, intra-operative navigation and tele-mentoring (if a dual-console is used). In addition, training can be performed "off line" in a simulation laboratory or on the actual console.

Today's robotic surgical systems are stand alone, usually moved into the operating room (or for some image-guided systems, mounted on a boom or stationed in a part of the room with a CT or MRI scanner). Then surgeons, radiologist, cardiologists, etc. must operate together with their team of nurses, technicians, etc. When an instrument or catheter needs to be replaced, a scrub nurse is needed; when a new supply such as suture or gauze is needed, the circulation nurse is needed. This is not the case in industry – robotic systems incorporate multiple robots into a single 'robotic cell'. When a different tool is needed, the robotic tool changer performs the function; when a new supply (like a nut, bolt, etc.) needs to be inserted, this is provided by the robotic supply dispenser. The military has developed the 'Trauma Pod' surgical system [1], a prototype system of an "operating room without people' in which the scrub nurse is replaced by a robotic tool changer, and the circulation nurse is replaced with an automatic supply dispenser – modified from a standard pharmacy medication dispenser (Fig. 1.2). When the surgeon needs to change an instrument, the voice command is given (for example, scalpel for right hand) and the robotic tool changer automatically performs the function. When a supply is needed, a voice command (for example, 2–0 chromic catgut on a GI needle) is given and one of the 120 different sterile trays with supplies is chosen and 'handed' to the surgeon (robotic manipulator) to remove the supply and use it. The accuracy

Fig. 1.2 Prototype ‘surgical robotic cell’ – the ‘operating room without people’ (Courtesy of Pablo Garcia, SRI International, Menlo Park, CA 2008)

is 99% and the speed is approximately the same as the corresponding scrub or circulating nurse, which is about 17 s. The advantage is that this frees up the nurses to perform more intellectually demanding tasks, rather than standing around for hours, simply handing instruments or supplies to the surgeon.

As indicated above, because the robot is truly an information system, it can be incorporated into the entire hospital information enterprise. The information encoded into the robotic instruments or the supply trays can be collected, analyzed and distributed (in real-time) beyond the operating room to the other hospital support functions. When a disposable instrument or used supply is discarded, that information can be instantly sent to the Central Supply department, where a replacement can be automatically ordered and the inventory adjusted. This allows the hospital to not only accurately track all the instruments and supplies, but can also decrease the amount of inventory which is stored or goes out of date because of tracking and immediate re-ordering. This is standard practice in most industries, and referred to as asset-tracking and supply-chain management. Efficiency and cost savings are realized by decreased supplies on the shelf and decreased personnel needed to inventory and order all the supplies. Incorporating these capabilities directly into the robotic system functioning simply extends the efficiency and cost saving all the way into the operating room.

Another unique aspect of the robotic systems is the ability to store the video of the procedure and track hand motions [2]. These data can be stored in a ‘black box’ like the aircraft flight recorder and can lead to automatically generating the operative note (from analysis of video and hand motions) as well as mining the data for errors. As in inventory control, this data could automatically be sent to the quality improvement and risk management systems, greatly reducing the amount of time and effort to collect and analyze the data to improve patient care and safety while decreasing the time required by the surgeon to dictate operative reports, review quality assurance reports, etc. Such documentation could also be used by the hospital credentialing and privileging committee when the surgeon requests annual review of hospital operating procedures. Whether such an implementation of the robotic systems will occur is a different matter – it is no longer a technical issue but rather one of policy, privacy, cost or practicality. Thus, using the perspective that the surgical robot is just one more node of the hospital information enterprise demonstrates the value added of robotic systems beyond their mechanical and operative value.

For direct patient care, the importance of integrating the entire ‘process’ of surgery into operative procedures can be facilitated by a surgical robotic system. The current practice of surgery includes the pre-operative evaluation f the patient, with the result decision to operate and a plan for the surgical procedure. However, the ‘plan’ is in the surgeon’s head, based upon the diagnostic information which has been gathered, and must be executed in real time during the surgical procedure, without complete information about the anatomy, anatomical variations due to the disease process, congenital anomalies, or other variations from the ‘normal’ and expected anatomy. The result is that the surgeon will encounter unexpected variations, hopefully recognize them in time to modify the procedure for a successful completion. All other industries use a 3-D model of their ‘products’ (Computer Aided Design/Computer Aided Manufacturing or CAD/CAM models) to rehearse a procedure through simulation before performing the procedure. In a non-pejorative way, the patient is the ‘product’ for healthcare, so when surgical procedures are performed without previous planning or rehearsal on a model, there frequently are resultant errors. There is the beginning of computer-based pre-operative planning and surgical rehearsal on patient-specific 3-D models, derived from the patient’s own CT or MRI scan. Marescaux et al. [3] have reported pre-operative planning and surgical rehearsal for complex liver resections for hepatic cancer, with a result of a significant decrease in operating time, blood loss and errors. In the future for difficult surgical procedures, it will become commonplace for a surgeon to import the patient-specific 3-D image from the patient’s CT or MRI scan, plan and rehearse the operation directly on the surgical console, repeat the difficult parts of the operation until no mistakes are made, and thereafter conduct a near perfect performance during the procedure. In the more distant future, the operation will be recorded while being rehearsed and errors will be ‘edited out’ of the stored performance of the procedure; when the surgeon is satisfied with the edited operation, it will be sent to the robot to perform under ‘supervisory control’ of the surgeon, with many times the precision and speed, and virtually error free.

One final component that will be integrated into the surgical console will be specific exercises for pre-operative warm-up. It is a priori that all professionals (soccer, basketball, symphony, dance, etc.) improve their performance by warming up before performing their professional skill, yet surgeons have not accepted this obvious advantage. Initial data has demonstrated that performing 15 min of pre-op warm-up exercises on a virtual reality simulator is able to decrease operative time and errors [4]. Soon these exercises will be incorporated into the surgical workstation and become a required preliminary part of every operation. This is yet one more way of incorporating simulation into daily clinical practice.

1.3 Automatic and Autonomous Surgery

Surgeons pride themselves on being completely in control of a surgical procedure, being able to deal with unexpected anatomy or events during a surgical procedure in order to complete a safe operation. Yet other industries use automatic (i.e. specifically executed pre-programmed 'steps' or tasks) or autonomous (i.e., perform a task in an unstructured environment rather than according to a pre-programmed sequence) robotic systems to perform procedures. With the exception of the LASIK procedure in ophthalmology [5], there are no automatic or autonomous systems in surgery. The closest analogy would be the surgical stapling devices, which can clamp, seal (staple) and cut bowel or other structures with a single application – but these are hand held and have no sensors to detect proper position, strength of application, etc. Yet looking at the clothing industry, an automatically sewn seam is far superior to a hand-sewn garment. Likewise, autonomous sorting robotic systems (pick and place robots) far exceed human performance both in accuracy and speed in identifying objects and moving them to a specific position, such as sorting different candies into box. The basic principles behind these actions are very well known and well proven, the challenge is to be able to adapt such systems or tasks to an unstructured environment in living systems for surgical procedures. While this is very hard, due to the large variability from patient to patient, continuous motion due to heart beat, breathing, etc., the problem is not intractable. It is computationally intense and requires micro-second adaptation to the dynamic situations, including such tasks as image recognition, analysis, registration (without fiducials), adaptive control, etc., however it theoretically could be achieved with known technology. It is likely that the first steps will be automatic tasks, such as an anastomosis, in which the surgeon performs a resection and then sets up the severed ends, and issues a "connect" command for the robotic system to automatically sew the ends together. Beyond this initial task, multiple other automatic tasks could be sequenced in such a fashion to have a simple autonomous procedure. Combined with a previously 'rehearsed' and 'saved' surgical procedure, there will eventually be the option to rehearse the operative procedure, edit out the errors, and then send the completed procedure to the robotic system to complete faster and with greater accuracy.

1.4 Intelligent Instruments

Today's surgical instruments are very simple mechanical devices, controlled directly by the surgeon's unaided hand. The surgeon proceeds to dissect, transect and other maneuvers with the instruments, unaware of what may lie just below the surface and depends upon the subjective 'sense of touch' to assist when visualization of the structures is not possible. Various haptic sensors and displays have been investigated, however there are no mechanical sensors for the sense of touch that are integrated into current surgical instruments.

Using ‘information science’, instruments can become intelligent. Within the area of ‘information’ the use of energy (rather than mechanical) systems should be included, since most energy systems are reliant upon some form of information (computer) control. Both information and energy are ‘intangible’ and thus are complimentary parts of the Information Age, and the combination of the two is creating the next generation of intelligent surgical (robotic) instruments.

There are a number of prototype laparoscopic instruments with various sensors, such as force reflecting graspers [5]. But future instruments will go beyond sensing and they will be energy directed rather than mechanical instruments. The advantage of using intelligent surgical instruments is that they can provide both diagnosis and therapy, in real-time, in a single instrument. One current example is combining diagnostic ultrasound with High Intensity Focused Ultrasound (HIFU) [6], in which both Doppler imaging for diagnosis and HIFU for therapy are combined to both detect internal hemorrhage with the Doppler, and instantly stop the bleeding with the HIFU, and then recheck with the Doppler to insure hemostasis is complete. This is performed transcutaneously, without any incisions, rather than the standard method of a full surgical procedure with large (or even laparoscopic) incisions and direct control of the bleeding. By moving into the energy spectrum (rather than mechanical instruments) it is possible to move from minimally invasive to non-invasive therapies. There are many such opportunities by incorporating biophotonics, ultrasonics and other energy-based systems into the instruments of a robotic surgery system, since they can be controlled by the surgical console. Such integration goes well beyond the scope of human performance, not only physical but cognitive. Using closed loop feedback, the therapeutic modality (laser, ultrasound, etc.) can be monitored and when a specific quantitative threshold has been reached, the instrument can be shut off in milliseconds, even before the threshold is perceived by the surgeon. Healthcare has just begun to exploit the potential of the energy spectrum; in spite of having a number of different energy-based systems, such as X-ray, ultrasound, lasers, ultraviolet, near-infrared, etc., less than 5% of the electromagnetic spectrum has been investigated. The utilization of energy to diagnose, treat, and monitor with closed-loop feedback will lead to the next generation of surgical and robotic devices and systems.

1.5 Molecular Surgery (Biosurgery) with Micro-Systems and Nano-Systems

The era of molecular biology, genetic engineering and other micro/nano scale procedures has been in the laboratory for decades and is finally emerging into clinical practice. Instruments and devices have been developed to both sense/diagnose as well as manipulate/treat cellular and intracellular structures. By working at the molecular level, the results are changing the biology of the patient, but not necessarily the anatomy – changing function, not structure. Cellular biologists and other basic science researchers are now using new tools, such as femtosecond lasers, optical tweezers, micro-electro-mechanical systems (MEMS), atomic force microscopes, etc. to make incisions into individual cells, and manipulate the mitochondria, Golgi apparatus and even to into the nucleus and 'operate' upon individual chromosomes. In the future, such systems will begin performing 'genetic engineering' by directly removing specific defective genes and replacing them with normal functioning genes. Yet, manipulation at the micro and nano-scale is not possible with human hands – it requires a sophisticated tele-operated work station, which is not different from the current surgical workstation. But what the surgeon 'sees' on the monitor at the cellular level is radically different from looking at organs or tissues. In viewing cells, the structures are caused to fluoresce – auto-fluorescence, induced fluorescence, or with molecular marker fluorescent 'probes' – in order to follow the progress of the procedure. For a cellular surgical procedure, the surgeon will be looking at the colors of the individual proteins within the cell which will change as they are treated. Working on the surface of the cell membrane will present a view similar to looking at a mountain range, where large craters (ion channels) will be the entry ports for various proteins that need to be inserted into the cell. Given such powerful new tools and an unfamiliar 'landscape', the surgeon will need to retrain not only their psychomotor skills, but also need to develop new cognitive skills.

1.6 From Soldiers to Generals

All of the surgical tools and systems, including robotic systems, are designed for the surgeon to directly operate upon the organ or tissues, with an assistant or two to help retract. It is quite literally the surgeon battling the disease one-on-one. There are interesting new robotic systems being developed at the micro level. Beginning with the endoscopic capsule [7], which is a video system in a pill that is swallowed with sequential photos taken as it passively is propelled by peristalsis through the GI tract, new concepts in surgical robotics are being investigated. Micro-robots, which go beyond simple visualization systems, are attempting to add locomotion to the capsules, and include various types of micro-manipulators to perform surgery. There are a number of very difficult challenges, nevertheless progress has been made and tiny robots are in the experimental laboratory. However at this small scale, it is very difficult for a single robot to perform all of the necessary functions of light source, visualization, locomotion, manipulating, etc. The concept has been raised that this level of micro-robots may require that each robot perform a single function, such as camera, light source, grasper, scissor, etc.; therefore it will be necessary to use a group of function-specific micro-robots in order to perform an operation. After inserting many micro-robots into the abdomen (through a tiny umbilical incision), the surgeon will then need to control a dozen or so of these at a time – much like a commander controlling a squad of soldiers. The surgeon will need to radically change perspective and behavior, and will need to begin acting like a general in charge of a squad of soldiers, rather than behaving like an individual soldier attacking a specific target (disease). This would be an extremely radical way of conducting a surgical procedure, but may well provide a revolutionary new way of performing "surgery".

1.7 Conclusion

Robotic and computer aided systems have finally brought surgery into the Information Age. Current instruments will continue to evolve and new systems, especially energy based and those systems on a much smaller scale, will be added to the surgical armamentarium. In general, the instruments and systems will become more intelligent and integrated, not only in the operating room but throughout the entire hospital information enterprise. The purpose for the speculative nature of this chapter is to create a vision of what is possible, and to offer a challenge to the biomedical engineering community as a whole. Surely many of these will not be realized, others will materialize even beyond these modest predictions, and then there will be the outliers, the "unknown unknowns", that will be the game-changers to disrupt the predictable progress and take surgery into a completely new direction. However, there is one thing which is certain: The future is not what it used to be.

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