Surgical Robotics
Surgical Robotics

Systems Applications and Visions
Preface

The dictum *Primum non nocere* (First, do no harm) and the dictum “Primum Succurrere” (First, hasten to help) as the prime directives of ethics in medicine may dictate two orthogonal approaches of practicing medicine, both of which are aimed to provide the best health care to the patient. The conservative approach relies on decades of evidence-based practice and clinical experience with a specific medical or surgical approach. However, every now and then, a scientific, technological, or clinical breakthrough occurs (alone or in combination) which leads to a paradigm shift along with disruptive new approach to health care. To some extent, this progressive approach is regulated by rigorous clinical trials as dictated by the Federal and Drug Administration (FDA) aimed at demonstration of safety and effectiveness. Although the progressive treatment approach results in a relatively high risk, there is a concomitant high reward in terms of healing and regaining a high quality of life.

Surgical robotics is a recent and very significant breakthrough in surgery. The introduction of a surgical robot into the operating room (OR) combines a technological breakthrough with a clinical breakthrough in developing new surgical techniques and approaches to improve the quality and outcome of surgery. As significant as these breakthroughs are, it is not surprising that they occurred because they are based on more than a decade of innovation in field of robotics in both academia and industry. The promise of surgical robotics is to deliver high levels of dexterity and vision to anatomical structures that cannot be approached by the surgeon’s fingers and viewed directly by the surgeon’s eyes. Making this technology available to surgeons has led to new surgical techniques that could not be accomplished previously. It is likely that clinical knowledge accumulated using these new systems or even by simply realizing their capabilities will lead to the development of new surgical robotic systems in the future. The surgical robot and various imaging modalities may be viewed as mediators between the surgeon’s hands and eyes and the surgical site, respectively; however, these two elements are part of a larger information system that will continue to evolve and affect every aspect of surgery and healthcare in general. Archived medical history, preoperative
scans, preplanning, quantitative recording of the surgical execution, follow-up and outcome assessment are all part of feed forward and feedback mechanisms that will improve the quality of healthcare.

As product of a rapidly evolving research field, this assembly of monographs aimed to capture a wide spectrum of topics spanning from ambitious visions for the future down to today’s clinical practice. The book is divided into four sections:

1. **The vision and overviews section** reviews the field from the civilian and military perspectives. It includes chapters discussing the Trauma Pod concept – a vision of an OR without humans. The importance of the trauma pod project was that it demonstrated the capability of automating all the services in the OR – services that are currently provided today by a scrub nurse and a circulation nurse that have been demonstrated to be translates to services by a robotic cell – robotic arms and information systems. Whether this concept of automation will be extended into clinical practice and thereby emphasizing even more the role of a surgeon as a decision maker while the operation is executed by the surgical robot automatically is yet to be seen.

2. **The systems section** is divided into two subsections including chapters describing key efforts in systems development and integration of macro- (first section) and micro- (second section) surgical robots in both academia and industry. Developing a macro-surgical robotic system is challenging in part due to the difficulties in translating qualitative clinical requirements into quantitative engineering specifications. Moreover, a successful system development as a whole is often a result of multidisciplinary and interdisciplinary efforts including all the subdisciplines of engineering and surgery – efforts that should not be taken lightly. In addition to challenges of macro-systems development, developing surgical robotics on a micro-system level introduces a significant reduction in scale. Forces, torques, pressures, and stresses do not scale down linearly with the geometrical dimensions. These interesting scaling properties challenge many engineering and surgical concepts. Inspired by the film “Fantastic Voyage,” the promise of a micro-robotic system is the capability to travel in the human body and provide local treatment. This concept is still in its infancy, and the academic research currently conducted in this field is focused on fundamental aspects of the system such as propulsion, navigation, energy source, manipulation, and control.

3. **The engineering developments section** covers technologies, algorithms, and experimental data to enhance and improve the current capabilities of surgical robotics. Topics of chapters in this section include tactile and force feedback, motion tracking, needle steering, soft tissue biomechanics of internal organs, and objective assessment of surgical skill. All of these will be incorporated into different layers of the surgical robotic systems in the future and will eventually put a superior robotic system in the hands of the surgeon for improving the outcome.

4. **The clinical applications section** includes chapters authored by surgeons who use surgical robotic systems clinically and describe the current clinical
applications of surgical robotics in several subdisciplines of surgery including urology, cardiology, neurosurgery, pediatric surgery gynecology, and general surgery as well as telesurgery. Most of these chapters also provide some thoughts about future applications of surgical robots in surgery. The generic nature of the surgical robotic system allows the surgeon to explore many surgical procedures that were not targeted by the robot’s original developers. Moreover, today’s growing vast array of clinical applications of surgical robotics demonstrates that the clinical community can adopt new surgical approaches once a capable tool such as a robot is made available.

Jacob Rosen
Blake Hannaford
Richard M. Satava
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Part I
Visions and Overviews
Chapter 1
Future Directions in Robotic Surgery

Richard M. Satava

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
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
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, radiologists, 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. 1.1 Integration of operative procedures using the surgical work station (Courtesy of the author)
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 of 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 perfor-
mance 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