Robotic Technology in Surgery: Past, Present and Future

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Abstract

Background: It has been nearly twenty years now since the first appearance of robotics in the operating room. In that time, much progress has been made in integrating robotic technologies with surgical instrumentation as evidenced by the many thousands of successful robot assisted cases. However, in order to build upon past success and to fully leverage the potential of surgical robotics in the future, it is essential to maximize a shared understanding and communication among surgeons, engineers, entrepreneurs, and health care administrators. This article should serve as an introduction to medical robotic technologies, develop one possible taxonomy, review the evolution of a surgical robot, and discuss future prospects for innovation. [Data Sources: Medline, SciSearch, IEEE Xplore as well as previously written articles by the present authors **[1,2,3]**]

Conclusions: Robotic surgery has demonstrated some clear benefits. It remains to be seen where these benefits will outweigh the associated costs over the long-term. In the future, surgical robots should be smaller, less expensive, easier to operate, and should seamlessly integrate emerging technologies from a number of different fields. Such advances will enable continued progress in surgical instrumentation and ultimately surgical care.

Key Words

robotic surgery, minimally invasive surgery, surgical technology, innovation, future of surgery, taxonomy

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This review of robotic surgery focuses on technology developments that have been applied to improving surgical care. The article should serve as an introduction to robotic technologies, as well as an outlook on present and future clinical opportunities.

Introduction

Karel Capek, a Czech playwright in the 1920's, coined the term robot in his satirical drama entitled "Rossum's Universal Robots." **[4]** He derived the word robot from the Czech word robota -- slave labor. In this play, machines were created to do mundane work so that people would be free to pursue more creative interests. One of the characters finds a more sinister use and soon the machines are employed for destructive rather than constructive uses. As the robotic technology improved, these machines developed an increasing amount of "intelligence". Ultimately, the robots became stronger and smarter than their human masters and, believing that mankind was a nuisance, began to exterminate the human population! The play caused an uproar; people at the time were afraid that robots might replace them on the assembly line. Some interpreted Capek's play as a warning, concluding that robots, as a "cure" for human work, would be worse than the original disease.

Science fiction has since popularized Capek's notion of robots as fully autonomous, anthropomorphic machines in several famous works. In the 1950's, it was the classic novels of Isaac Asimov including "I, Robot" and in the 70's and 80's it was George Lucas' "Star Wars" films with characters R2D2 and C3PO. More recently, it has been the "Terminator" series with now California governor Arnold Schwarzenegger. **[5]** Isaac Asimov's influence has left us with many probing questions as to the role robots should play in society. In his short story, "Runaround," Asimov described "The Three Rules of Robotics:"

1. A robot may not injure a human being, or, through inaction, allow one to come to harm.
2. A robot must obey all orders given to it from humans, except where such orders would contradict the First Law.

3. A robot must protect its own existence, except when to do so would contradict the First Law or the Second Law **[6]**

These rules remain a reasonable ethical framework upon which robot development may be applied to surgical care.

Although these so-called cyborgs, R2D2, The Terminator and I, Robot, have caricatured our popular conception of a robot, a less glamorous, scientific definition of a robot may be stated as follows: *a re-programmable, computer controlled mechanical device equipped with sensors and actuators.* **[7,8]** Moreover, very few robots in development are designed to be anthropomorphic. Under this definition there lies a range of robots from the simplest, single axis manipulator, up through the most complicated, highly autonomous cyborg. For the moment, the state-of-the-art in artificial intelligence is such that most robots have either a limited level of autonomy, or they are relegated to perform highly structured, low risk tasks. Thus, the current generation of robotic devices have little in common with those of science fiction. One is, however, reminded of Steven Spielberg’s concept “There is no such thing as ‘science fiction’ – only scientific eventuality”.

The actual development of practical robots has focused on non-anthropomorphic manipulators, and has been a recent phenomenon. The first programmable industrial manipulators were developed in the 1940’s. George Devol, credited as being the father of the robot, developed a magnetic process controller that could be used to control these first robotic machines. **[9]** As computer technology began to develop, so did the field of robotics. In 1954, Devol patented the first manipulator with playback memory. This event may well mark the beginning of the robot age. His device was capable of point-to-point motion and was the forerunner of devices used by industry today. In 1961, Joseph F. Engelberger formed a company called Unimation and began the commercial production of robots for industry. **[9]**

Robotic development has been frequently motivated by the need to manipulate hazardous items such as poisonous and radioactive materials. In the 1940's remote manipulators or teleoperator systems began to emerge to serve these needs. Faced with the need to get complex jobs done with existing technology, these devices were human controlled. Using visual and haptic (touch and kinesthetic) display devices to enable humans to see and feel the remote tasks they performed, these systems provided human operators with "master" input devices (glorified joysticks) to enable them to perform complex tasks from a safe distance. **[10]** Since then, robots have been used in industry for everything from arc welding to assembling complex electronic devices. Applications for these devices have reached beyond the industrial arena, into areas such as agriculture, space exploration, military, oceanographic exploration, education, and now, into Surgery**.**

With the development of minimally invasive surgical techniques in the late 1980's, surgeons no longer needed to physically place their hands within the body to perform an operation. Minimally Invasive Surgery (MIS) or minimal access surgery (MAS) thus revolutionized the concept of surgical procedures. In MIS, instruments and viewing equipment are inserted into the body through small incisions. Long manipulators are used to perform operations under manual guidance. This minimizes the collateral surgical trauma of an access incision and results in quicker recovery. These procedures have many advantages, but with conventional endoscopic instrumentation, there are substantial difficulties. The loss of wrist articulation, poor touch feedback, the fulcrum effect, the loss of three dimensional vision, and poor ergonomics of the tools make only relatively simple procedures truly widespread.**[11,12]**

The promise of robotic assistance is to eliminate many of these impediments, with the concurrent enhancements of motion scaling and tremor filtration. The surgeon may now remotely teleoperate a robot in a comfortable, dexterous, and intuitive manner. In fact, both Moll and Satava have suggested that laparoscopic surgery is a “transitional” technology in the history of surgical evolution which next leads to robotic surgery. **[13,14]**

Robots have a number of advantages over humans in performing rote manipulation tasks. Their accuracy and repeatability allowed for robots to penetrate the market in the industrial sector in the 70’s with a clear economic benefit. **[15]** However, in surgery, the environment is often far less structured, therefore some of the weaknesses in current robotic devices become apparent, such as substantial loss of force feedback (haptics) and a lack of adaptability. Using Robodoc® to mill a femur shaft to accept the femoral component of a total hip joint is an ideal robotic tool, as is a stereotactic biopsy. However, it is currently not possible to “program” a robot to autonomously perform a splenectomy. These current limitations don’t prevent robots from being useful in the operating room, rather considerable human input and guidance are needed. Surgical robots can then be viewed as “extending or enhancing human capabilities” rather than replacing humans, in contrast to the example of industrial automation. **[16]** Table I summarizes the strengths and weaknesses of robots compared with humans as relates to surgery. **[17,18]**

A convincing illustration of how humans and robots can work together to improve surgery is that of retinal repair. Retinal surgery requires precise positioning of a laser, within 25 microns of a target, in order to avoid damaging retinal blood vessels. If a retinal vessel is damaged, a retinal hematoma and subsequent blindness may occur. The unaided human hand cannot reliably direct a surgical instrument to within less than 100 microns of its target. **[19]**

Furthermore, as the surgeon becomes fatigued, an intention tremor develops that further decreases accuracy. Finally, the eye itself has a natural motion of 200 Hz and acts as a moving target. **[5]** The combination of these factors creates an operative situation that lacks the precision needed, but is well within the capabilities of current robotic technology. Robotic systems have been developed for this application to overcome human limitations. Using computer integration, the motion of the eye can be tracked and the eye made to appear stationary; the surgeon's tremor can be filtered. The end result is a system that can position a laser to within 10 microns of a target, thus making it ten times more accurate than an unaided human hand. **[18]** This scenario demonstrates the synergies of the robot and the surgeon which results in improved task performance.

In order to fully leverage this promising technology for surgical intervention, and to continue relevant innovation, it is essential that there be communication and mutual understanding among surgeons, engineers, entrepreneurs and health care administrators. On the clinical side, this starts with an open mind towards the unmet clinical need, or the unsolved clinical problem, and a willingness to evaluate promising technologies as means to an end of meeting the need or solving the problem. **[5]**

The balance of this paper is organized as follows: 1) we develop a taxonomy for surgical robots, 2) robot characterization is explained to provide a background as to how clinical requirements translate into technical specifications, 3) the historical evolution and current implementation of the da Vinci® robot is detailed to serve as case-study of innovation in the field, 4) several research frontiers are surveyed as to current developments, and we speculate on a framework for the future role of robotics in surgery.

Taxonomy

Robot assisted surgery, as a new and emerging field, has fallen loosely under the category of computer-aided surgery**. [8,20]** This distinction comes from the use of a microprocessor which controls movement and processes sensory data. The landscape of computer-aided surgery is not yet concretely defined, and there are some related sub-fields which should be distinguished. Each field may be characterized by the devices and systems which it employs.

Medical imaging is an exceptional example of a field which has been greatly augmented by the now wide-spread availability of fast and cheap computing. MRI scans generate 3-dimensional models of soft-tissue anatomy which can be integrated with various technologies for image-guidance. MRI is a pillar in image-guided surgery, but MRI-based systems for computer aided surgery are not particularly robotic and do not rely significantly on computer-controlled motions. CT, however, is an imaging modality that uses a manipulator to articulate a scanner by means of actuators, sensors, and a processor. Therefore, any surgical application which uses CT is considered a robot-assisted system, many of which are used for image-guidance. CT scans are ubiquitous in many surgical applications, but it requires closer attention to the technology itself to realize that this is an exemplary application of robotics to surgery.

Another closely related field is that of motion tracking. Motion tracking is used to obtain a precise quantitative measure for the spatial location of surgical instruments, and/or anatomy. Opto-electronic tracking systems which use light emitting diodes (LEDs) fastened to surgical instruments and cameras to monitor the LEDs are hybrid imaging/tracking systems. There also exist purely mechanical tracking systems in which a mechanical linkage is equipped with joint angle sensors (encoders), so the location of the tool end-point (*end-effector*) of the linkage may be calculated. Neither of these types of systems are mechanically powered, so they are not considered robots. Figure 1 illustrates the space of computer-aided surgery most relevant to robotics in a Venn Diagram and is not meant to be an exhaustive list of sub-fields. Robotics has found its place within the domain of computer-aided surgery.

Over the past twenty years, a wide array of surgical robots have been developed and implemented clinically at varying scales. These developments have been widespread enough to warrant an organization of the different varieties of robots into a taxonomy. Several authors have touched on this subject. **[17,8,21]** Taylor mentions that robot classification in general can be based on *technology*, *application,* or *role*. A technology-based taxonomy might have categories such as autonomous and tele-operatred robots, whereas an application-based taxonomy might have the categories cardiology and urology, etc.

The problem with these two approaches is that on either side, classifications may become quite esoteric and lose meaning for the uninvolved community. Furthermore, this is an artificial decoupling since the application, which defines the problem, is divorced from the technology, which provides the solution. Role based classifications can be more useful as they are far-reaching and speak to both technology developers, and end-users. Such a taxonomy can be a means of communication among all interested groups in describing needs, requirements, performance, and specifications.

We define our role-based taxonomy, *procedural role,* which can be divided into three discrete categories.

1. *Passive role*: The role of the robot is limited in scope, or its involvement is largely low risk.
2. *Restricted role*: The robot is responsible for more invasive tasks with higher risk, but is still restricted from essential portions of the procedure

3. *Active role*: The robot is intimately involved in the procedure, and carries high responsibility and risk.

To better understand this classification, consider the analogy of a surgeon evolving over a career. As a medical student during clinical training, one has a relatively passive role on low risk tasks such as camera operation or skin closure. As a surgical resident, one is progressively given broader responsibility and will often carry out higher risk tasks. There may still be other portions of the procedure that are critical or more difficult which the attending surgeon would perform. Once the surgeon has completed residency and fellowship, responsibility is total. This comparison should not suggest that more sophisticated or useful robots tend towards an active role, as this is presently not the case.

Based on this procedural role classification, we would suggest that researchers aim to develop robots moving toward an active role since they carry more responsibility and can reduce the burden on the surgeon. This, however, is not a necessary conclusion as it ignores the present limitations in artificial intelligence and robot autonomy. The manifestation of these shortcomings is that robots with a relatively active role require much more surgeon interaction than do passive role robots. Therefore, the level of autonomy scales down with increasing robot role, which is an important trade-off to recognize. Figure 2 illustrates this trend with robot role as a continuum rather than a discrete classification for several surgical robots. A brief description of each of these robots, and how they fit in this space is given as follows.

- *CT scan*: a familiar imaging modality in which a manipulator articulates a scanner to different locations to obtain various cross-sectional images. The robotic component of the CT is completely autonomous as it scans the relevant anatomy, and has no interaction with the patient other than a very small dose of radiation.

- *Cyberknife®*: Accuray has developed the first stereotactic image-guided system that performs real-time registration (Figure 3). Cyberknife can be used to radiate a variety of tumors, even in deformable organs such as the lungs by tracking the motion of the chest and oscillating the robot synchronously. The treatment process begins with preoperative CT images of the tumor that are input to a path-planning algorithm which generates the spatial path for the linear accelerator carried on the robot. At procedure-time, it automatically registers the pre-operative path by correlating real-time radiographic images with the pre-operative CT images to locate and eliminate the tumor in the patient [www.accuray.com]. The Cyberknife is completely autonomous during the procedure while it manipulates the linear accelerator directed towards the tumor. However, before the procedure, the computer-generated path must be carefully reviewed and potentially edited by the surgeon or radiotherapist which diminishes the autonomy. The level of radiation is enough to destroy cancerous cells so the Cyberknife assumes a more active role than CT. While engaging in a highly energetic interaction, the robot does not make actual physical contact with the patient so the scope of its involvement with the patient is still constrained.
- *Aesop®*: Computer Motion began to market Aesop in the United States in 1994 as the first FDA approved surgical robot. Aesop is a voice-controlled robot that positions an endoscope. **[7]** Aesop is fairly autonomous in that it controls its own motion with only a few simple voice commands. Its role is not passive since it is in constant contact with tissue throughout the entire procedure. However, it is only used for imaging, which is low risk and does not involve any invasive manipulations, therefore its role is considered restricted.
- *RoboDoc®*: Orthopedics was an early area of success in surgical robotics due to the rigid and predictable behavior of bone. RoboDoc is used for the bone-milling portion of total hip

arthroplasty. It is an image-guided system which preoperatively requires the surgeon to view CT images and select the appropriate implant and its placement. The system then generates the cutting path so that it may do this portion of the procedure autonomously. The surgeon must participate in the registration of the pre-operative images by locating anatomical landmarks to synchronize the CT images with the physical patient. The pre-operative setup and manual registration process decreases the level of autonomy. **[17]** Milling is a very invasive and risky portion of the procedure, yet total hip arthroplasty is a long and complex procedure, for which bone drilling is only one step, so the robot's role is still considered restricted.

- *Acrobot*®: Developed for total knee arthroplasty, the Acrobot (Figure 4) derives its name from its description, "active constraint robot," and is simply a bone-drilling instrument with motors to constrain its motions to a region defined by pre-operative images. This "hands-on" approach allows the surgeon to directly feel the forces of cutting, but ensures that certain regions are protected from the drill. **[8]** This is a lower level of autonomy for the robot, and its role is similar to RoboDoc. However, since the surgeon is in direct control, only under the influence of small motors, the system is inherently safer. It has been used on the technically challenging total knee arthroplasty so it has a more active role. **[22]**
- *NeuroMate*®: Stereotactic needle placement was the earliest recorded application of surgical robotics dating back to 1985. NeuroMate is a present day version used in stereotactic neurosurgery. This is another image-guided system which uses anatomical landmarks for manual registration. The function of NeuroMate is to determine the location of insertion for a drill, probe, or electrode based on the pre-operative images. NeuroMate then positions the instrument at the correct location for insertion, locks its joints, and thereafter acts as a guide

allowing the surgeon to carry out the procedure**. [15]** While the robot is not powered as the instruments are introduced into the surgical field, it still passively constrains the motion of the surgeon significantly. NeuroMate can then be considered to have a moderate level of autonomy. **[23]**

- *da Vinci*®: The da Vinci® system from the Intuitive Surgical (Figure 5) Corporation will be described in more detail later on. It is a teleoperated system in which the surgeon sits at a remote console on one side of the operating room, and directly controls the motion of instrumnts in the surgical field on the other side the room. The surgeon is provided with a stereoscopic visual display that is co-located with master control handles (haptic interfaces) that direct movements of the slave instruments inside the patient's body. Since the robot closely mimics the hand motions of the surgeon, the level of autonomy is very low. da Vinci® has been used for a number of types of minimally invasive procedures including cardiac, abdominal and urologic procedures. Under human control, the robot engages in sustained physical contact with the patient's tissues using a range of instruments from simple forceps, to scissors and scalpels, to complex cautury and stapling tools. Therefore, da Vinci® assumes an active role.
- *Manual instruments*: It is obvious that traditional surgical instruments have no autonomy (they are not actually robots). Since the surgeon has complete control over the instruments, he uses them for the majority of his manipulation tasks. Manual surgical instruments are used in highly active roles in most all surgical procedures.

Robot Characterization

If you could shop for a surgical robot on the internet, in deciding which robot to buy, you would want to be able to open up a web page and read about the robot's performance and specifications to make sure it fits your application. We are still years away from that possibility; it is difficult today to even get a good data-sheet from a vendor. Here, we aim to provide some brief explanations of robot characteristics so that the reader will know enough to be able to ask the right questions in communicating with a robot manufacturer, or provide meaningful requirements when participating in the process of innovation. On the highest level, understanding taxonomy is the first step, and then here are some of the more significant details:

- Degrees of Freedom: The term degrees-of-freedom, or *DOF*, is an important one in robotics in that it defines the number of independent motions of which a robot is capable. Alternatively, how many “knobs” one can turn to control the tool tip, which is usually equal to the number of motors used to drive the robot. The number of degrees of freedom is important because it describes how constrained the motion at the end-effector of the instrument will be. For example, a 6-degree of freedom robot should allow for motion of the end-effector in the x, y, and z directions, as well as to have any desired rotation in pitch, yaw, and roll (see Figure 6). A 3-degree of freedom robot often does not allow for choice in rotation, and only allows choice of motion in the x, y, and z directions.
- Workspace and Resolution: *Workspace* is a simple concept, and it is loosely defined as all of the space that the end-effector can reach. Typically, one might give a rough estimate saying that a robot has a 1 cubic meter workspace which can be imagined as a box with 1 meter sides centered on the robot. The robot would be able to reach all space within this box. A robot’s workspace is obviously limited by the length of its links, but is also constrained by joint limits, and collisions with its own links or other obstructions such as anatomy. *Resolution* is related to workspace in that it defines the smallest incremental movement the robot can make or measure (these can be different). It is often specified as a length, i.e.

cholecystectomy requires only 2 mm resolution and would never require accuracy less than 2 mm.

- Mechanism Type: There are traditionally two broad categories of robot mechanical designs, *serial* and *parallel*. Serial linkages are the most common and are characterized by links that are connected in series, one after the other, like a modern desk lamp. A parallel linkage has multiple links that run parallel to one another which meet at a common point. A simple one-degree of freedom example is a scissor car jack which has two parallel links to lift the car in one direction. The major difference is that serial linkages have a larger workspace which is required to move a lamp over any region of a large desk. A parallel linkage, on the other hand, is stiffer because it has multiple links supporting each joint which is necessary to carry the weight of a car. This increased stiffness also improves accuracy.
- Inertia and Stiffness: Inertia and stiffness are both related to material properties. The inertia of a robot is determined by its size, and the density of material. Higher inertia leads to a more sluggish robot since it is difficult to accelerate and decelerate a large mass (or, larger more powerful motors will be required, which inevitably drive up the cost). In addition, having large inertia makes safety a more critical concern since the robot will have more kinetic energy as it moves. Robot stiffness is determined by the stiffness of the material, and the geometry. If a push is given to the end-effector of the robot as it attempts to maintain a certain position, the robot will always give somewhat according to its stiffness. The stiffer the robot is, the less it gives, and the easier it is to control since it won’t bounce like a spring and can be more accurate. However, high stiffness also increases safety concerns in case of inadvertent impact.

- Speed, Force, and Backdrivability: Every robot has a transmission system to deliver force from its actuators to its end-effector. The gearing of a transmission might take fifty revolutions of the motor to result in only a tiny motion at the end-effector. This scaling down of velocity allows for forces to be scaled up. The force-speed tradeoff is an important one to keep in mind for particular applications, as it is expensive to achieve both. An additional effect from a high gear ratio is that it becomes more difficult for the surgeon to manually grab hold and "backdrive" the end-effector due to the force scaling. This is the same effect one would experience while trying to push a car while it was still in first gear. *Backdrivability* is essential if the surgeon will ever want to move the robot about by hand while it is un-powered.
- Dynamic Range: In a particular surgical procedure, there may be some portion of the procedure that requires a high force such as in bone drilling. In the same procedure, there may also be some portion that requires a small, fine resolution force such as in suturing. The ratio between this highest and lowest force is known as the *force dynamic range*. This is an important specification to know early on, as it can be difficult to design a robot with high dynamic range like that of a human. As one NASA administrator has commented, "Man is the lowest cost, 150 pound, nonlinear, all-purpose computer system/robot that can be mass produced by unskilled labor."
- Force vs. Position Control: These terms are commonplace in the robotics world, and deserve some attention. In position control, the robot attempts to follow some desired trajectory in space. This type of scheme would clearly be appropriate for a robot delivering radiation therapy according to some path in free space. Force control, on the other hand, can be used when the robot is in contact with some surface since it is often important to control the

amount of force it exerts on that surface. A bone-drilling robot might use a force control scheme to ensure smooth cutting, combined with position control to stay within some region. A hybrid approach such as this is most likely what the surgeon actually does. For example, a surgeon is careful to accurately position his knife and cut say 3mm deep into the tissue, which is a position control scheme. However, if the surgeon feels a significantly high force, he may abandon his goal of 3mm depth and instead modulate the force to a few ounces to avoid damaging some unanticipated structure.

- Bandwidth: *Bandwidth* is an important system specification. It is best understood by a simple experiment that is used to measure bandwidth. If an input signal is given to the robot to move back and forth very rapidly, the robot will attempt to execute this instruction and move at this desired rate. As the input frequency is increased, the robot eventually will not be able to keep up due to limits in stiffness and inertia (i.e., the robot is too heavy and floppy so it falls behind the command). This limiting frequency is known as bandwidth. One can easily see the importance of bandwidth in a tele-operated system. As the surgeon moves his hands very quickly, the robot's bandwidth must be higher than the frequency with which the surgeon is moving his hands, or the robot will not be able to keep up and track. We can more precisely speak of *bandwidth of motion* (how fast can we follow a commanded position with good fidelity) as well as *bandwidth in force control* (how fast can the robot accurately exert commanded forces, or comply to disturbances).

Historical Case Study: da Vinci®

The concept of telepresence surgery has been of interest for some time. For example, it was proposed by the National Aeronautics and Space Administration in 1972 as a method for providing remote surgical care to orbiting astronauts. **[24]** At that time, the limitations of robotic and computer systems made the development of such a system impossible. Furthermore, time delay is a substantial problem. Subsequent advances in computing power and component miniaturization, coupled with the emergence of minimally invasive surgical techniques for the performance of complex operative procedures, have led to renewed interest in the application of telepresence surgery. Telepresence surgery refers to the remote operation of a robot to perform a surgical procedure. **[19]** This occurs by placing an electro-mechanical system between the surgeon and the patient which converts physical motion into electrical signals with a computer. This signal is sent from the surgeon's "master" robot to the "slave" robot at the operating table on the other side of the room, or beyond.

In the late 1980s, motivated by the rapid growth of minimally invasive surgery and the shortcomings of existing surgical instruments, researchers at SRI International in Menlo Park, CA, began to look for ways to enhance surgeons' skills in MIS and microsurgery. Beginning with funding from the National Institutes of Health in 1990, SRI's team developed a successful prototype system that soon became known as the "SRI system." This seminal work combined advances in remote manipulation with force feedback, stereoscopic imaging, multimodal sensory feedback, and ergonomic design, and enabled enhanced performance of minimally invasive surgery and remote surgical tasks.

The early success of the SRI system caught the attention of the Defense Advanced Research Projects Administration, or DARPA. DARPA planners led by Dr. Richard Satava envisioned telesurgery being used by military surgeons to perform life-saving surgery on wounded soldiers on the battlefield to preserve life until they could be evacuated to a military hospital. It was theorized that, performing telesurgery via satellite, the military's best trauma surgeons could treat wounded soldiers at multiple locations from hundreds of miles away, removed from the hazards of the battlefield.

In 1995, the Intuitive Surgical Corporation was formed to develop the commercial technology required to bring telerobotic capabilities to minimally invasive surgery. Using technology developed at SRI, IBM, and the Massachusetts Institute of Technology, Intuitive's engineers developed robotic arms and instruments with the number of degrees of freedom required for complex reconstructive surgery through one-centimeter incisions. At the same time, the Intuitive team was designing a 3-D video camera and stereo viewer to provide more immersive visualization. The name of the company derives from one of telesurgery's primary goals: creation of a surgeon-robot interface so transparent to the surgeon that he can use his full set of skills in a natural and instinctive manner.

When performing telesurgery, the surgeon sits at the surgeon control console, head tilted forward and eyes peering down. During the procedure, the surgeon's hands are held in a comfortable position and inserted into the system's master interfaces. A computer monitors hand position which is sampled at over 1,300 times per second as the case proceeds. Using motion sensor information and kinematic models of the master and slave, the computer system computes, the actuator drive commands necessary to move the robot arms and provide feedback. The position of the camera, mounted on a robotic arm, can be adjusted by the surgeon for the best view of the surgical site. Accurate visualization is critical because visual cues are used to compensate for the loss of haptic feedback. Magnification is also possible at 2X-10X. This visual magnification is matched by hand motion scaling capabilities. This increases surgical precision and fine motor control by reducing the surgeon's large hand movements to the scale of the camera view. Normal hand tremors may filtered simultaneously, while permitting natural hand movements, much like open surgery.

When viewing the surgical field through the console, the surgeon can see the end-effectors of the robotic arms (the instrument tips) as they move under direction. The surgeon receives some force sensation, or haptic feedback, from the instruments. This haptic feedback is currently limited to interaction with rigid structures such as tool on tool collisions, and not soft tissues. This requires the surgeon to rely on visual feedback in tasks such as suturing. Careful attention must be paid to visual cues when pulling on a suture, or it will easily break before the surgeon feels the excessive tension.

From a clinical point of view, a small mechanical joint called the EndoWrist® is a key component of the Intuitive system. The highly mobile EndoWrist® gives the surgeon the ability to reach around, beyond, and behind. The motion of the EndoWrist® is monitored by the computer so that the control algorithms can translate the surgeon's motions to the robot's wrist. The computer translates the surgeon's hand movements into the same movements of the instruments (Figure 7), avoiding the reverse fulcrum induced movements of traditional MIS. The wrist can roll, pitch, yaw, and grip, allowing the surgeon a total of seven degrees of freedom of freedom for each hand. Moreover, the system can apply a fraction of an ounce of force for delicate suturing, or several pounds of force necessary to retract large tissue structures.

The instrument tips, or end effectors, are a combination of standard surgical instruments and novel mechanism designs. Surgeons want to have the same interaction with the tissue they have always had. Conventional surgical instruments are the result of 150 years of surgical experience in manipulating and cutting various types of human tissue. Therefore, the very ends of the instrument tips are made to resemble conventional instruments used in open surgery, while the rest of the design is entirely new. The instruments are sterilizable, and interchangeable during surgery. Central to achieving adoption of a technology is that the instruments provide surgeons with a feeling and performance similar to their traditional instruments.

In its current configuration this surgical device is unlike most industrial telemanipulators. Recall that an important driver of industrial devices was the essential need to separate the “master” controller from the “slave’ end effector for safety reasons (toxic or radioactive environments). Current conventional surgical applications find distance separation a distinct disadvantage. The surgeon at the controller console, assisting surgeon and the nurses at the patient’s side interact frequently with the slaves, removing and changing surgical instruments. This requires very safe and human friendly engineering in the tool interface. Telerobotic surgery also requires a radically different priority. Most industrial telerobots have simple safety systems that protect themselves in the event of failure. In less complex applications, the robot is the high-value item. A telesurgical system has to protect the patient first. During a procedure, all FDA-approved systems monitor themselves continuously, and will shut down and alert the surgeon if a problem arises.

The Future of Robotics in Surgery

New applications of the technology are beginning to emerge as creative surgeons work; unpredicted use in areas such as urology, bariatric and plastic surgery have been found. Giving the surgeon the ability to control more than two arms has proven to be unexpectedly useful, essentially allowing the surgeon to become their own assistant. Nevertheless, present day robotic surgery systems have limitations that have slowed the widespread introduction of the technology. A major barrier is cost. As an example, the da Vinci system is priced at nearly one million dollars. A second major concern is the cumbersome and unwieldy nature of present robotic systems which require a considerable amount of space, and additional time for setup. In the time pressed operating room, compact functionality is highly desirable, and current robotic systems have yet to deliver this.

Another area that will require optimization is the process of FDA approved safety and regulatory issues. It has been a challenge for robot manufacturers to convince the FDA that these systems acceptably safe, but progress has been made, and as time passes, credibility will build with experience. Progress needs to be made, for example, in defining what does it mean to be safe with highly mobile electromechanical devices. This is difficult enough when real-time human judgment is still in the loop, but when progressively more autonomous capabilities are introduced even more difficulties will arise in setting standards of acceptable risk.

Emerging Technologies

We can expect that soon-to-arrive robotic surgical systems will begin to provide a centralized platform within which existing and emerging technologies can be utilized. It is quite easy to imagine integrated imaging, navigation, and enhanced sensory capabilities being available in the next generation of telesurgical systems. Equally plausible will be the introduction of general skill training simulations and patient specific rehearsal capabilities.

Another major advancement in robotic technology will be a reduction in the scale at which these systems operate. Present day systems have augmented surgeon performance in existing procedures, however, the physical scale is largely unchanged from conventional manual procedures. Robotics has the potential to greatly scale down a surgeon’s motions so that, in cooperation with the computer, surgical manipulations at a sub micro scale would be possible. This would enable procedures, previously impossible given human force and position resolution.

Advancement in miniaturization of robotic mechanisms will most likely require entirely new materials and manufacturing processes combined with scalable designs to ensure performance and ease of assembly.

Smaller mechanisms will lead to many new applications for robotics in medicine. Catheter based treatments could benefit substantially by integrating robotic technologies to create “active catheters” with a high degree of control. An active catheter could be steered with much greater accuracy than that of a passive, under-controlled catheter. Such a device might be useful in minimally invasive diagnosis and/or treatment of deeply remote anatomy that would be otherwise impossible to reach. This trend toward less invasive, more specifically targeted surgical treatments has been in motion for some time. As one looks back on the “saw-bones” surgeons of the civil war, surgical treatments have progressively become more focused and, smaller robots are just the next step in that journey.

In order to operate a miniature robotic device, sensors and actuators on an even smaller scale will be necessary. Recent advances in the area of micro-electrical mechanical systems (MEMS) appear promising for this need. MEMS are integrated micro devices that combine electrical and mechanical components. **[3,19]** These working machines have gears no bigger than a grain of pollen and current technology permits these machines to be batch fabricated, tens of thousands at a time, at a cost of only a few pennies for each device. **[25]** These systems can sense, control and actuate on the micro scale, and function individually or in arrays to generate effects on the macro scale. **[25]** This technology has been used to build devices such as microengines, microtransmissions, microlocks, and micromirrors. Current applications in industry also include accelerometers, pressure, chemical and flow sensors, micro-optics, optical scanners, and fluid pumps. **[3,26]** It is clear that these types of sensors could have important medical uses, from providing force feedback with a micro-force sensor, to measuring biochemical data and overlaying it on a visual image to identify hidden infection.

With regard to force-feedback, the inclusion of high fidelity force sensors has the potential to improve force sensation beyond what the human hand can sense on its own. This improvement would be similar to the use of microphones and microscopes to enhance hearing and vision. For example, surgical ablation of larger tumors in the abdomen or lungs is often performed with an ultrasonic cutting instrument or radio frequency ablation. A force feedback type probe would be beneficial here in identifying the edge of the tumor to ensure complete ablation, and to protect healthy tissue.

MEMS devices, and their nano-scale counterparts, may do more than just act in support of macroscopic instruments, they can actually be self-contained structures which function independently. Imagine robots so small that they could actually fit inside a single living cell, or travel around the body in the bloodstream, navigating through the use of on board computers. At its most microscopic level, robots could be designed to repair damaged DNA. Some researchers have suggested that robots could be designed specifically to act as antibodies against viruses and resistant strains of bacteria that defy biologists' attempts to find cures. **[9]** Systems for precise delivery of medication will be developed. At a slightly larger level, an implantable device, capable of functioning as a miniature lab, will be placed into diabetics to measure glucose levels continuously and deliver insulin as needed.

These micro-robots are not as far off as one might think, as there is at least one similar technology which is presently in clinical use, known as the capsule colonoscopy, by Givens^{tm} Technology. Contained in a one-inch package, are two silver oxide batteries, white light emitting diodes to illuminate the camera, and a metal oxide detector array with 256x256 bits.

The capsule transmits 50,000 images over the 7 hours in which it passes through the GI tract . The images are transmitted externally via a radiofrequency communicator to a receiver belt which is worn by the patient. A physician then downloads the pictures for review **[27,28].** This device is a revolutionary advance and truly deserves to be called a “BioMEMS” device.

An important component to any robotic system is its computational capabilities. Much research effort has been put forth in using computation to give artificial intelligence (AI) behaviors to robots. Humans learn through their experiences and, most importantly, by making mistakes. Each year, physicians learn by repeating the mistakes of those who have gone before them. Yet mistakes are costly in many currencies. One of the primary motivations for developing artificial intelligence (AI) applications for medicine is to keep physicians from having to learn through making mistakes while performing critical tasks. Heuristic knowledge, or the ability of a machine to learn based on real life experiences, is the basis for AI. The rigid design of computer logic makes this very difficult to achieve.

Future directions for AI include neuromorphic engineering, genetic algorithms, and artificial evolution. The goal of neuromorphic engineering is to transform microcircuitry into an analog computing medium that resembles neural tissue. **[29]** The resulting structure captures the essence of neurons in hardware (i.e., the transistors, capacitors, and resistors of a silicon chip), generating hardware that can reliably store analog information as an electrical charge. Current research is working to mimic the dense interconnections of the human brain. Genetic algorithms and artificial evolution attempt to apply Darwin’s theory of evolution to AI. The artificial evolution approach maintains a population of viable genotypes (chromosomes), coding for control architecture. **[30]** The genotypes are interbred according to a selection pressure, much as in standard genetics, with a gradual emergence of the more evolutionarily favored control architecture. The combination of these three techniques holds promise for developing robots that learn, remember, and even evolve.

In the more near term, computer control may provide for some other interesting functionality in enhanced immersion, and virtual constraints. Virtual constraints could be used to create a no-fly zone during surgery based on pre-operative or intra-operative imaging data of protected structures such as arteries. This would reduce the risk of complication due to surgeon error, and would build on the related work from the Acrobot.

Virtual constraints could be one step in creating a more immersive experience for the surgeon. The goal would be to create a cockpit-like environment where the surgeon is surrounded by all of the tools he needed to "fly," or carry out the procedure. In the ideal case, the surgeon's console would contain complete data fusion in the workspace. This might include superimposed image overlay of pre-operative MRI data, with real-time biochemical data, and visual images so that the surgeon sees the "whole picture." In this environment, the surgeon would never need to disengage to look at MRI images. When a virtual-limit boundary has been contacted in the surgical workspace, the surgeon would "see" the corresponding contrast in biochemical composition between the tumor being excised and the surrounding tissue. The surgical workstation may also be augmented with audio capabilities to alert the surgeon to data coming from outside of the camera field of view. Seamlessly connected via high-speed, low-latency networks, to other experts in the field, a surgeon might call in special assistance or advice when a critical or unexpected situation occurs.

Clinical Outlook

The discovery of new opportunities requires the constant interplay between an unsolved problem and a new or emerging technology. One might characterize such solutions as the development of surgical tools that would allow the same operation to be done in a better fashion, or for the performance of a new operation with a better result (decreased mortality, decreased morbidity, more reversible).

Next generation surgical systems should be explored that either enhance imaging or manipulation which are the two fundamental components of a surgical procedure. Table II illustrates the parallel historical developments of imaging and manipulation technologies. The potential for new and improved imaging seems inevitable since these technologies are so widely embraced. It is important that robotic technology continues to advance in order to keep pace on the manipulation side.

Finally, when one looks back at Figure 2, the notion of the development of active and autonomous tools deserves exploration. Developments in this area may be far off, but would revolutionize surgery by using a robot to autonomously perform intricate but widely varying tasks, carrying a high level of responsibility. This will require considerable algorithm development and expansion of computing power, but given the progress in the past fifty years this does not seem unreasonable. New issues in terms of ethics and standards would then become even more relevant as Isaac Asimov predicted.

Many of these emerging technologies have dedicated research and development groups working feverishly on the next stage of development. For these developments to be truly relevant in surgery, however, they will require input and guidance from the clinical community. The surgeons' role in this technology is then two-fold, one to educate and collaborate with technical developers, and secondly to find and refine areas in their own specialties where these technologies will be useful. There are even some institutional programs that are currently being built on this premise such as the "Surgical Innovation Program at Stanford." (website:

surgery.stanford.edu/innovation/) We believe it is possible to provide an orderly framework for clinical needs assessment, technology evaluation and the blurring of the interface between clinical medicine and engineering to create the next generation of surgical innovations and innovators, following in the footsteps at Stanford of Dr. Thomas Fogarty, Dr. William New, Dr. Rodney Perkins, Dr. John Simpson, Dr. Paul Yock and others.

On the other end of the spectrum, there are now a group of engineers coming to be known as “clinical engineers” who have a technical background but are also educated in clinical applications. They may serve as the intermediary between surgeons and other engineers. This educational cross-pollination must continue, even at an increased rate and in a more structured manner. Only then will each community be able to respond to one another’s needs, requirements, constraints, and philosophies which will pave the path towards advancing the state-of-the-art of surgical intervention, and ultimately enhancing patient care

In some sense, we probably should think of medical robotic technology much like the Wright brother's first aircraft. Today's medical robots already do work in surprisingly useful ways, and yet comprise a technology only in its infancy. We have every reason to believe that the future of robotics in medicine will be full of surprises, and we should be prepared to notice them and capitalize on the opportunities. Much as airplanes now perform tasks never imagined by the Wright's, it is likely that tomorrow's medical robots will deliver functionality and breadth of utility not yet even imagined.

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Legends

Figure 1.

Title: Sub-spaces of Computer Aided Surgery Relevant to Robotics.

Legend: Depiction of sub-fields relevant to robotics. Some technologies are overlapping between sub-fields. Categorization as “Robot Assisted Computer Aided Surgery” requires processing capabilities with sensors and actuators for controlled motion.

Figure 2.

Title: Tradeoff between “Procedural Role” and Autonomy

Legend: Procedural Role indicates the level of responsibility and involvement the robot has with the patient during a procedure. Robot role in a procedure scales up with greater duration, scope, invasiveness and risk, which decreases the level of autonomy in current systems.

Figure 3.

Title: Cyberknife Stereotactic Radiosurgery System

Legend: Photograph courtesy of Accuray Incorporated

Figure 4.

Title: Acrobot Active Constraint Knee Arthroplasty System

Legend: Photograph courtesy of The Acrobot Company Limited

Figure 5.

Title: da Vinci Telerobotic Surgery System

Legend: Photograph courtesy of Intuitive Surgical Incorporated

Figure 6.

Title: Degrees of Freedom

Legend: Illustration of a 6-degree of freedom robotic instrument. First two degrees of freedom are the ability to pivot about the entry port in two planes. Next two are the ability to move in-and-out, and the ability to roll the instrument. The last two are the ability to pitch and yaw the wrist. These six allow for an arbitrary choice of position and orientation of the jaws, which is not possible with conventional endoscopic instruments. Photograph courtesy of Intuitive Surgical Incorporated.

Figure 7.

Title: da Vinci Console Masters and EndoWrist

Legend: Illustration of wristed slave instruments exactly tracking the surgeon's master controllers. Photograph courtesy of Intuitive Surgical Incorporated.

Table I.

Title: Summary of Advantages and Disadvantages of both Surgeons and Robots

Legend: There exist both advantages and disadvantages to the capabilities of both human and robot as relates to surgery. It is a balance of these elements that results in the most useful and effective technologies.

Table II.

Title: Evolution of Surgical Procedures – Image and Manipulation

Legend: The two essential elements of surgery have evolved in parallel. Imaging is a hot area of development, and robotics must help to keep pace on the manipulation side.

Table 1

	Surgeons	**Robots**
Advantages	Task versatility	Repeatability
	Judgement, experience	Stability and accuracy
	Hand-eye coordination	Tolerant of ionizing radiation
	Dexterity at mm to cm scale	Diverse sensors
	Many sensors with seemless data fusion	Optimized for particular environment
	Quickly process extensive and diverse qualitative information	Spatial hand-eye transformations handled with ease
		Real-time image association
		Manage multiple simulatenous tasks
Drawbacks	Tremors	Expensive
	Fatigue	Cumbersome
	Imprecision	Large
	Variability in skill, age, state of mind	Inability to process qualitative information
	Inability to process quantitative information easily	Not versatile
	Ineffective at sub mm scale	Technology still in infancy

Table II.

SURGICAL OPERATION

IMAGE	**MANIPULATION**
Direct Visual	Two hands direct
Camera/Magnification	Two hands long tools
Flexible Scope	Two hands long tools with an enable wrist
3-D Camera	Eletrical energy, radiofrequency energy
Ultrasound	Cryo or Thermal ablation
CT, MR, or PET Scan	Chemical energy, Photodynamic therapy

Figure 1

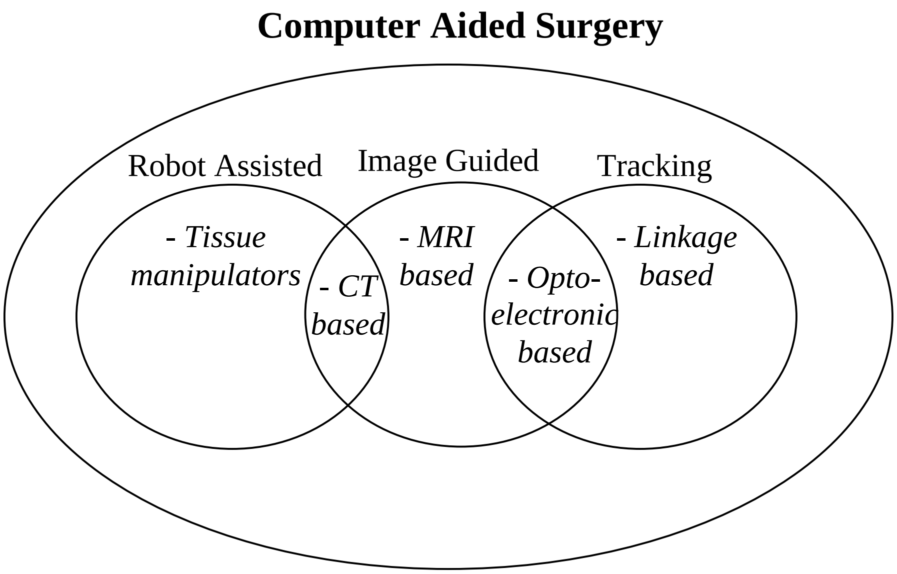
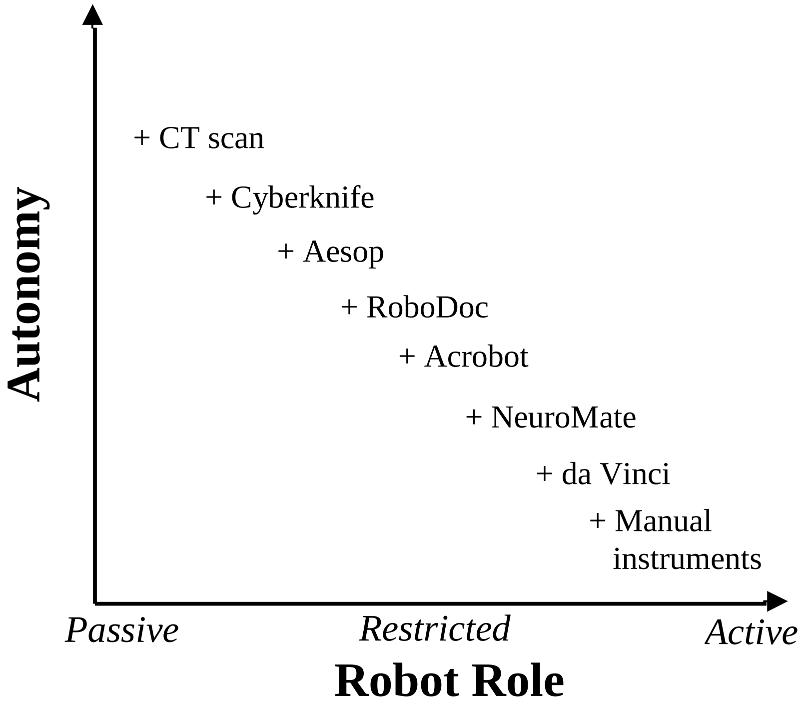

Computer Aided Surgery
Robot Assisted
Image Guided
Tracking
- Tissue manipulators
- CT based
- MRI based
- Opto-electronic based
- Linkage based

Figure 2



Autonomy
+ CT scan
+ Cyberknife
+ Aesop
+ RoboDoc
+ Acrobot
+ NeuroMate
+ da Vinci
+ Manual instruments
Passive
Restricted
Active
Robot Role

Figure 3

Figure 4

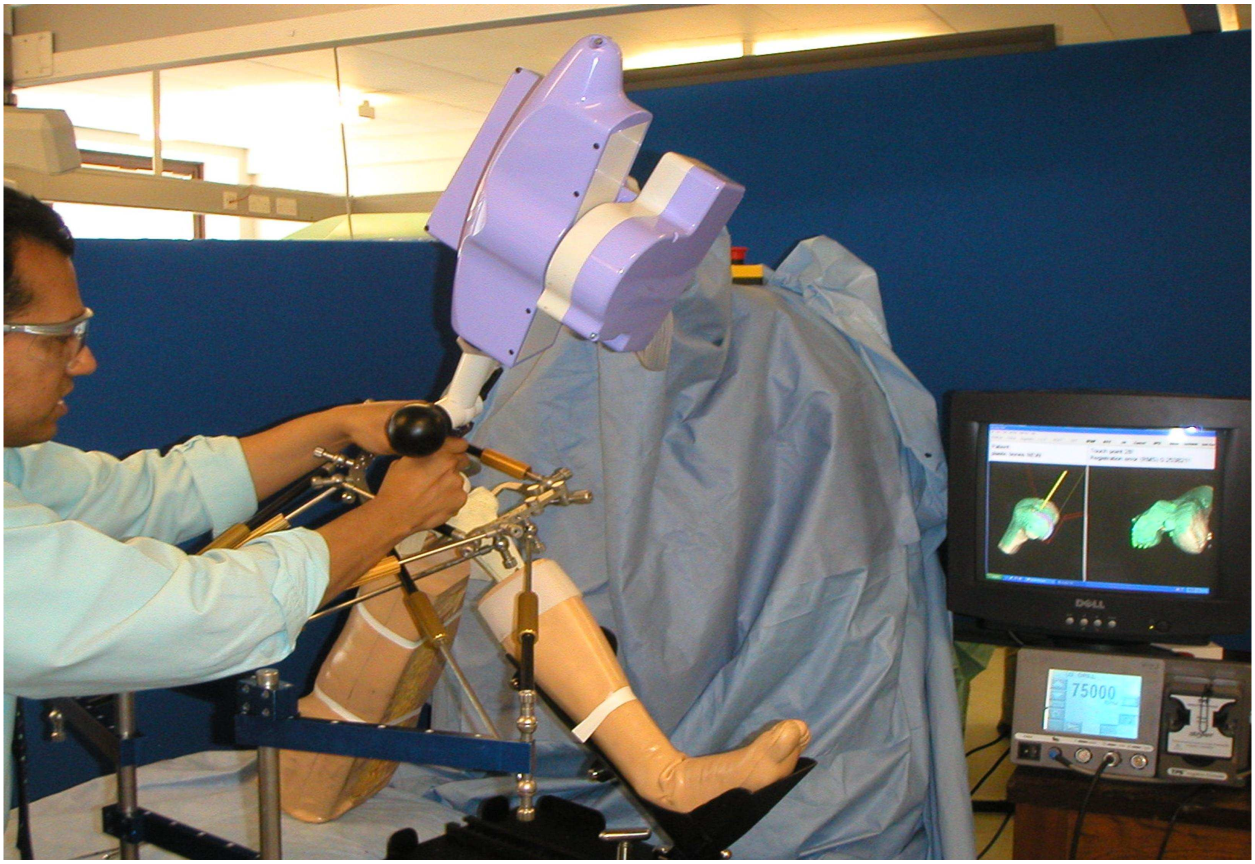


Figure 5

Figure 6

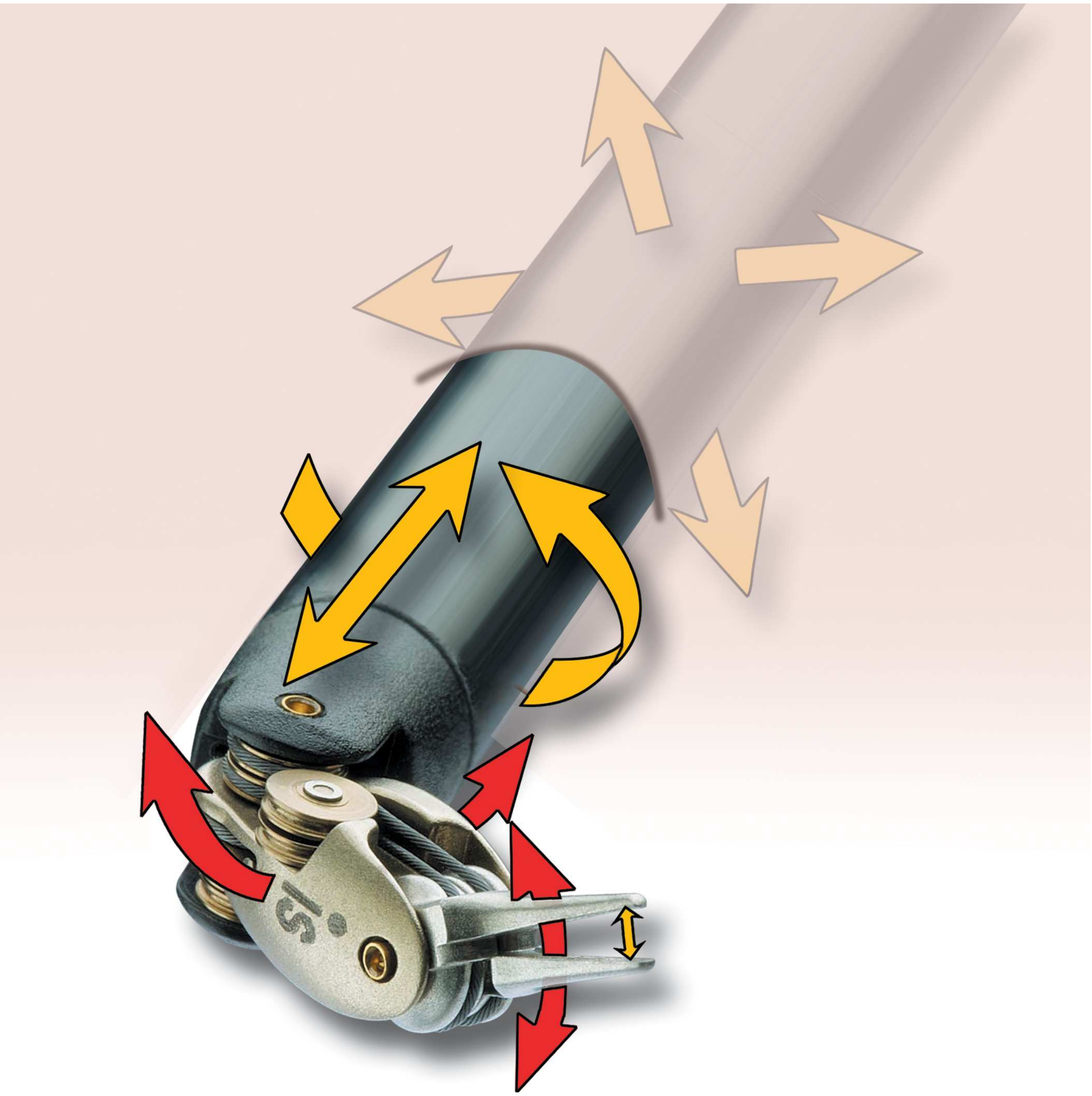


Figure 7