Medical Robotics

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INTRODUCTION

Today, robotic devices are used to replace missing limbs, perform delicate surgical procedures, deliver neuro-rehabilitation therapy to stroke patients, teach children with learning disabilities, and perform a growing number of other health related tasks. According to the Robot Institute of America, a robot is ''a reprogrammable, multifunctional manipulator designed to move material, parts, tools, or specialized devices through various programmed motions for the performance of a variety of tasks'' (1979). Given this definition, medical robotics includes a number of devices used for surgery, medical training, rehabilitation therapy, prosthetics, and assisting people with disabilities.

REHABILITATION ROBOTICS

The most extensive use of robotic technology for medical applications has been in rehabilitation robotics, which traditionally includes assistive robots, prosthetics, orthotics, and therapeutic robots. Assistive robots provide greater independence to people with disabilities by helping them perform activities of daily living. For example, robot manipulators can assist individuals who have impaired arm or hand function with basic tasks such as eating and drinking, or with vocational tasks such as opening a filing cabinet. Assistive robotics also includes mobility aides such as wheelchairs and walkers with intelligent navigation and control systems, for individuals with impaired lower-limb function. Robotic prosthetics and orthotics have been developed to replace lost arms, hands, and legs and to provide assistance to weak or impaired limbs. Therapeutic robots are valuable tools for delivering neuro-rehabilitation to the limbs of individuals with disabilities following stroke. An insightful summary of rehabilitation robotics from the 1960s to 2003, can be found in the commentary by Hillman.[1]

Assistive Robots

A number of robotic systems for assisting individuals with severe disabilities are commercially available. The most widely used is the Handy 1 (Rehab Robotics Limited, UK), which was developed by Topping in 1987.[2,3] This device enables people with little or no hand function to independently complete everyday functions such as eating, drinking, washing, shaving, and teeth cleaning. MANUS (Exact Dynamics, Netherlands) is a wheelchair-mounted, general-purpose manipulator with six degrees of freedom (DOF) and a two-fingered gripper. It was also designed to assist people with disabilities in completing tasks of daily living.[4] More than 100 people have used MANUS in their homes in the Netherlands, France, and other countries. The Raptor (Applied Resources Corporation, U.S.A.) is a 4-DOF wheelchair-mounted robot that allows individuals with disabilities to feed themselves and reach objects on the floor, on a table, or above their heads.[5]

Mobility assistance devices

Robotic technology can be used to equip mobility aides such as wheelchairs and walkers with intelligent navigation and control systems. Such mobility aides are commonly used by the elderly and people with impaired lower limb function or impaired vision. For example, Wasson et al. at the University of Virginia Medical Automation Research Center have developed an intelligent wheeled walker that can assist the user with obstacle avoidance and drop-off detection, and provide minor corrections to the user's steering input.[6,7] Prassler et al. at the University of Ulm (Germany) have designed a robotic wheelchair called MAid (Mobility Aid for Elderly and Disabled People) with an intelligent navigation and control system for people with limited motor skills.[8,9]

Vocational assistance devices

Recent studies have shown that robotic technology can greatly benefit motion-impaired individuals during the

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performance of vocational tasks. In one study, nine people with manipulation disabilities used a robotic workstation to perform manipulation tasks that they would have been unable to perform otherwise.[10] In another study, impaired individuals used a force-reflecting PHANToM (SensAble Technologies, Inc., U.S.A.) haptic interface to control a robot manipulator and to perform occupational tasks used in manual dexterity tests.[11] The results showed that the assistance provided by the force-feedback device improved task performance and decreased task completion time. These studies show that robotic technology has the potential to provide people with disabilities with much greater access to vocational opportunities. ProVAR (Professional Vocational Assistant Robot) is a 7-DOF desktop robot system, currently being developed by Van der Loos et al. at Stanford University and the Veterans Affairs Palo Alto Health Care System, that will be used in vocational environments by individuals with high-level spinal cord injuries.[12]

Prosthetics

A prosthetic is a mechanical device that substitutes for a missing part of the human body. These devices are often used to provide mobility or manipulation abilities when a limb is lost. The Utah Arm (Motion Control, Inc., U.S.A.) is a computer-controlled, above-the-elbow prosthesis developed by Jacobsen at the University of Utah in the 1980s.[13] This commercially available arm is controlled using feedback from electromyography (EMG) sensors that measure the response of a muscle to nervous stimulation (electrical activity within muscle fibers). Motion Control, Inc. also makes a two-fingered prosthetic hand that is controlled using myoelectric signals from the remnant limb. Another prosthetic hand is currently being developed at the Scuola Superiore Sant'Anna, Italy,[14] and Rutgers University[15] is creating a robotic prosthetic hand with five fingers and twenty DOF using shape-memory alloys as artificial muscles (Fig. 1).

Robotic prosthetics can also be used to replace lower limbs. The MIT LegLab is testing an intelligent prosthetic knee that enables above-the-knee amputees to walk and climb stairs more naturally by adapting the swing rate of the knee accordingly.[16]

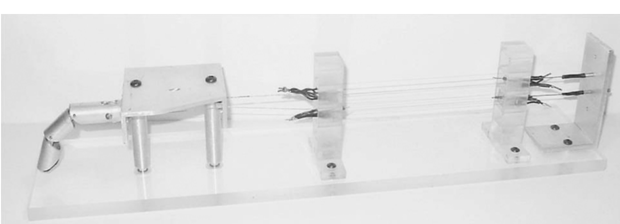


Fig. 1 Photograph of a robotic prosthetic hand under development at Rutgers University. (Photo courtesy of Kathryn De Laurentis and Constantinos Mavroidis, Rutgers University.) (*View this art in color at www.dekker.com.*)

One challenging area of prosthetics research is determining the intended action of the human so that the prosthetic device can be properly controlled. Mussa-Ivaldi at Northwestern University has developed a fish–machine interface that allows a robot to be controlled by the brain of a fish.[17] Nicolelis et al. at Duke University Medical Center have developed a system that uses implanted electrodes to measure the brain signals in an owl monkey and enables the monkey to control a robot arm to reach for a piece of food.[18] This research may eventually lead to brain–machine interfaces that can control prosthetic limbs.

Orthotics

An orthotic is a mechanism used to assist or support a weak or ineffective joint, muscle, or limb. Many orthotics utilize robotic technology, and they often take the form of an exoskeleton—a powered anthropomorphic suit that is worn by the patient. Exoskeletons have links and joints that correspond to those of the human and actuators that assist the patient with moving his or her limb or lifting external loads. For example, the Wrist-Hand Orthosis (WHO) uses shape memory alloy actuators to provide a grasping function for quadriplegic patients.[19] In ongoing research, Rosen et al. at the University of Washington are developing the exoskeleton shown in Fig. 2, which can be controlled by myosignals from the wearer's arm.[20]

Robot-Assisted Rehabilitation Therapy

Robots have the potential to be valuable tools for rehabilitation therapy. They may enhance traditional treatment techniques by enabling more precise and consistent therapy, especially in therapies that involve highly repetitive movement training. New therapy techniques may be developed using robotic devices that can actively assist and/or resist the motion of the patient. Therapeutic robots can also continuously collect data that can be used to quantitatively measure the patient's progress throughout the recovery process, enabling therapists to optimize treatment techniques. In addition, robot-assisted therapy systems have the potential to provide extended periods of unsupervised therapy, which could increase efficiency and reduce cost by decreasing the amount of one-on-one time that a therapist must spend with a patient.

Upper-limb devices

Preliminary research indicates that robotic devices have the potential to greatly enhance the neuro-rehabilitation

Fig. 2 Photograph of an exoskeleton for assisting arm movement under development at the University of Washington. (*View this art in color at www.dekker.com.*)

therapy of stroke patients.[21–27] Burgar, Lum et al.,[21,22] Krebs et al.,[23–25] and Reinkensmeyer et al.[26,27] have demonstrated that the use of robot-aided therapy can yield positive results in the rehabilitation of forearm movement in stroke patients.

Burgar, Lum et al. at Stanford University and the Veterans Affairs Palo Alto Health Care System have conducted clinical trials using the Mirror-Image Motion Enabler (MIME) robot system shown in Fig. 3, which uses a 6-DOF PUMA 560 robot to interact with the impaired arm.[21,22] This system can operate in three unilateral modes and one bilateral mode. The unilateral modes are passive, in which the patient remains passive while the robot moves the arm along a preprogrammed path; active-assisted, in which the patient initiates movement and the robot assists and guides the motion along the desired path; and active-constrained, in which the robot resists motion along the path and provides a restoring force in all other directions. This system was used in clinical trials to compare robot-assisted therapy to traditional therapy in stroke patients, and the results showed greater improvements in the robot group than in the control group.[21,22]

Krebs et al. at MIT and the Burke Medical Research Institute have conducted clinical trials with the MIT-MANUS, a backdrivable robotic system for delivering upper-extremity neuro-rehabilitation therapy.[23–25] This system can move and/or guide a patient's arm within a horizontal planar workspace, while recording the motion and applied forces. Clinical trials conducted with the MIT-MANUS have found who patients who underwent robot-aided rehabilitation improved more than patients in the control group.[24]

In other research, Reinkensmeyer et al. at the University of California at Irvine developed the ARM Guide (Assisted Rehabilitation and Measurement Guide) to evaluate and treat arm impairment following stroke, using linear reaching movements.[27] The ARM Guide has a single actuator, and the motion of the patient's arm is constrained to a linear path that can be oriented within the horizontal and vertical planes. Initial results with the ARM Guide show that the system produces quantifiable benefits in the neuro-rehabilitation of stroke patients.[27]

Robotic therapy devices have also been developed for rehabilitating the hand and fingers. Jack et al. have performed preliminary tests indicating that rehabilitation of the hand and fingers may be enhanced using the Rutgers Master II-ND (RMII) force-feedback glove.[28] This glove has four pneumatic actuators, located in its palm, which interact independently with the index, middle, and ring fingers and the thumb of the right hand. This system provides force feedback and allows the user to interact with a virtual environment. In a pilot clinical trial, three stroke patients used the system daily for two weeks and showed improved hand parameters at the end of the study.

Lower-limb devices

The NASA Jet Propulsion Laboratory and UCLA are developing a robotic stepper for lower-limb rehabilitation.[29] This device uses a pair of robotic arms that

Fig. 3 Photograph of the MIME robotic system for delivering rehabilitation therapy to patients with arm impairment following stroke. (Photo courtesy of Peter Lum, Virginia Commonwealth University.) (*View this art in color at www.dekker.com.*)

resemble knee braces to guide the patient's legs while they move on a treadmill. The system uses a harness to support the patient's weight and several sensors to measure the patient's force, speed, acceleration, and resistance. Astronauts may eventually use this system in microgravity as they exercise to help maintain normal locomotion skills, muscle mass, and calcium levels in bones. In other research, Colombo et al. at the University Hospital Balgrist (Switzerland) have implemented a robotic orthosis to move the legs of spinal cord injury patients during rehabilitation training on a treadmill.[30] Reinkensmeyer et al. at the University of California at Irvine have also developed a robotic device for measuring and manipulating stepping on a treadmill.[31] Van Der Loos et al. at the Veterans Affairs Palo Alto Health Care System are studying lower-limb biomechanics using a servomotor-controlled bicycle that can provide both assistance and resistance independently to each leg.[32]

SURGICAL ROBOTICS

In the last decade, surgery and robotics have reached a maturity that has allowed them to be safely assimilated to create a new kind of operating room. This new environment includes robots for local surgery and telesurgery, audiovisual telecommunication for telemedicine and teleconsultation, robotic systems with integrated imaging for computer-enhanced surgery, and virtual reality (VR) simulators enhanced with haptic feedback, for surgical training. According to Satava, ''the operating room of the future will be a sophisticated mix of stereo imaging systems, microbots, robotic manipulators, virtual reality/telepresence workstations, and computer integrated surgery.''[33]

Human–Machine Interfaces in Surgery

Performing a surgical task involves three primary entities: the surgeon, the medium, and the patient. The medium is the means through which the surgeon sees, interacts, and communicates with the patient. It may include standard surgical instruments, an endoscopic camera system, laparoscopic instruments, a robotic surgery system, and/or various other technologies. Figure 4 schematically depicts the human–machine interfaces for various surgical setups. As the physician is moved farther away from the patient, the medium introduced between the surgeon and the patient becomes more complex and places more constraints into the audio, visual, and physical communication/interaction channels between the surgeon and patient. Nevertheless, in some setups this complex medium may introduce valuable information by providing force feedback, enhancing vision, or enhancing the surgeon's kinematic capabilities by scaling down motion and filtering out hand tremor.

In conventional open surgery, the surgeon interacts with the internal tissues through a relatively large open incision, using direct hand contact or surgical instruments (Fig. 4a). There is no mediator in any of the communication channels: audio, visual, motion, or haptic (force feedback). In the absence of constraints on the surgical tool, the surgeon can translate and orient it anywhere in the surgical scene, using six DOF. In a minimally invasive surgery (MIS) setup, the tools and endoscopic camera are inserted through ports into the body's cavity (Fig. 4b). The port/tool and port/camera interfaces introduce a fulcrum, while decreasing the number of available DOF from six in open surgery to four in MIS, allowing only one (in/out) tool translation. The MIS setup requires at least two operators: the surgeon who is controlling the endoscopic tools and an assistant who is manipulating and positioning the endoscopic camera. The human assistant can anticipate the surgeon's intentions and reposition or track the surgical tools with the endoscopic camera, using minimal directions from the surgeon. However, the assistant is subject to fatigue from holding the camera in one position for long time segments. The assistant can be replaced by AESOP (Computer Motion Inc., U.S.A.), a voice-activated 7-DOF robotic arm that automates the critical task of endoscopic camera positioning and provides the surgeon with direct control over a smooth, precise, and stable view of the internal surgical field.[34] Broderick, Merrell, et al. have demonstrated that AESOP can also provide improved visibility during open surgery.[35]

In the United States, robotic surgery can now be performed by the two commercially available systems shown in Fig. 5: ZEUS by Computer Motion[34] and da Vinci by Intuitive Surgical,[36,37] which are FDA (Food and Drug Administration) approved for specific cardiac and thoracic surgical procedures. As of July 2003, these two companies have merged into a single company known as Intuitive Surgical. The typical surgical robot architecture follows a classical master/slave teleoperation setup (Fig. 4c,d). This setup consists of two modules: the surgeon console (master) and the robot (slave). The surgeon console includes a set of handles, a vision system, and in some cases voice command components. The robotic system interacting with the patient includes at least three robotic arms: two to manipulate the surgical instruments and a third to control the endoscopic camera. The surgeon controls the position of the robot arms by manipulating the two handles at the console. The endoscopic camera arm is controlled by voice commands from the surgeon, and the view is transmitted back to the surgeon console. None of the currently available surgical systems incorporate force feedback, but the Black Falcon,[38] which was used in part as the foundation for

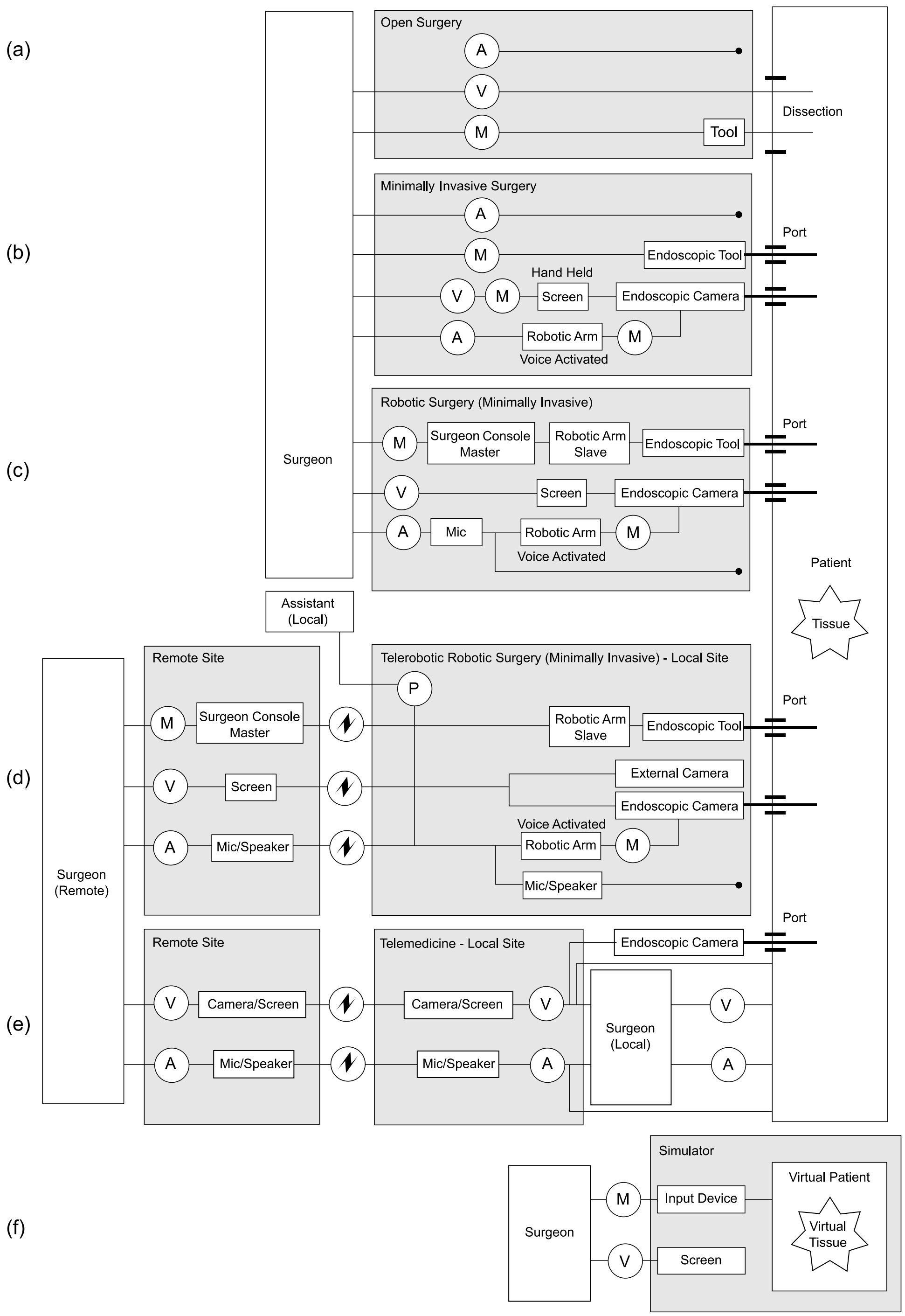
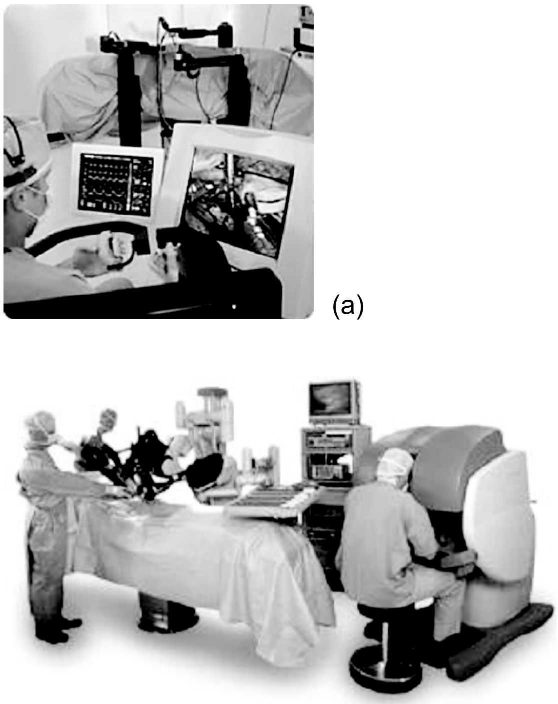


Fig. 4 Modalities used in different configurations for performing surgery: (a) open surgery; (b) minimally invasive surgery; (c) robotic surgery; (d) telerobotic surgery; (e) telemedicine or teleconsultation during surgery; (f) surgical simulation. The type of information being transferred is denoted by (A)–Audio; (M)–Motion, Haptics or Force Feedback; (V)–Vision; and (P)–Positioning.

the da Vinci system, and other surgical systems[39] have experimentally tested force feedback. This feedback allows the surgeon to feel the forces generated as the surgical tools interact with the tissue, using a bilateral (position and force) teleoperation mode. Currently, the FDA has approved only robot-assisted surgical procedures in which the entire robotic system (master/slave) is located in the operating room. However, the same robotic system has been used to perform a surgery telerobotically across the Atlantic Ocean.[40]



(a)

(b)

Fig. 5 Commercially available surgical robots: (a) ZEUS by Computer Motion (www.computermotion.com) and (b) da Vinci by Intuitive Surgical (www.intuitivesurgical.com). (*View this art in color at www.dekker.com.*)

In telemedicine and teleconsultation (Fig. 4e), the remote physician communicates with either the local physician or the patient through audiovisual telecommunication channels. Using systems like SOCRATES and HERMES by Computer Motion, the remote surgeon can control an external camera, share the view from the endoscopic camera with the local surgeon, and use it as a whiteboard to draw graphics on the image seen by both surgeons.[34]

For training purposes, the patient, tissue, instruments, and robotic arms can be replaced using computerized simulations (Fig. 4f). The surgeon can practice specific surgical tasks or full clinical procedures by interacting with virtual tissue. Haptic technology can be used to allow the physician to feel the forces generated as a result of the interaction between the virtual tools and the virtual tissue.

One element that all the modalities in Fig. 4 have in common is a human–machine interface, in which visual, kinematic, dynamic, and haptic information are shared between the surgeon and the various modalities. This interface, rich with multidimensional data, is a valuable source of information that can be used to objectively assess technical surgical skills. Algorithms that are developed for objective skill assessment are independent from the modality being used; therefore, the same algorithms can be incorporated into any of these technologies.[41–44]

Surgical Robots

The recent evolution of surgical robotics is the result of profound research in the field of robotics and telerobotics over the past four decades.[45] By examining the list of strengths and weaknesses of humans and robots in Table 1, it is apparent that combining them into a single system may benefit the level of health care delivered during surgery. The combined system allows the human to provide high-level strategic thinking and decision making while allowing the robot to deliver the actual tool/tissue interaction, using its high precision and accuracy. Because of these characteristics, robots have emerged in the field of surgery and other fields of medicine almost naturally. A number of authors have written reviews of the state of the art in surgical robotics, including Green et al.,[46] Taylor et al.,[47,48] Howe,[49] Buess et al.,[50] Cleary et al.,[51] Ballantyne,[52] and Li et al.[53]

Surgical robots can be classified into three categories: class i)—semi-autonomous systems; class ii)—guided systems; and class iii)—teleoperation systems. Special robotic arms have been designed in one or more of these categories to meet the requirements of various surgical specialties, including neurological, orthopedic, urological, maxillofacial, ophthalmological, cardiac, and general surgery. Each discipline in surgery has a special set of requirements, dictated by the anatomical structure and the surgical procedure, that necessitate special design and configuration of the robotic system. However, some robotic arm configurations (e.g., ZEUS and da Vinci) are equipped with specially designed sets of tools and may be used for various types of procedures across different surgical disciplines.

Similar to industrial robotics, the tool path of a surgical robot operating in a semi-autonomous mode (class i) is predefined based on a visual representation of the anatomy acquired by an imaging device (e.g., CT, MRI) and preoperative planning. Once the path is defined, the relative locations of the anatomical structure and the robot are registered, and the robot executes the task using position commands without any further intervention on behalf of the surgeon. For obvious safety reasons, the surgeon can stop the action, but altering the path requires replanning. Semi-autonomous robotic systems are suitable for orthopedic or neurological surgical procedures with well-constrained anatomical structures such as hard tissues and bones or with soft tissue such as the brain, confined by the skull.

Table 1 Characteristics of human and robotic systems

Characteristic	Human	Rank	Robot	Rank
Coordination	Visual/Motor—limited	–	Geometry—Highly accurate	+
Dexterity	High within the range of sensor information	+	Limited by the number and types of sensors—Range exceeds human perception	+
Info. integration	High level—High capacity	+	High level—Limited by AI algorithms	–
	Low level—Limited (info. overload)	–	Low level—High capacity	+
Adaptability	High	+	Limited by design	–
Stable performance	Degrades fast as a function of time	–	Degrades slowly as a function of time	+
Scalability	Inherently limited	–	Limited by design	+
Sterilization	Acceptable	+	Acceptable	+
Accuracy	Inherently limited	–	Designed to exceed human capacity	+
Space occupation	Limited to the human body space	+	Currently exceeds the volume needed to replace the human operator (surgeon)	–
Exposure	Susceptible to radiation and infection	–	Unsusceptible to environmental hazards	+
Specialty	Generic	+	Specialized	–

Surgical robots can be used as guided systems (class ii) in cases where high precision is required, such as in microsurgery, microvascular reconstruction, ophthalmology, or urology. The surgeon interacts directly with the robotic arm and moves the tool in space. The surgical arm provides stable, steady, and precise tool movements, using an impedance control. Forces and torques applied on the system by the surgeon's hand are sensed by a force/torque sensor and translated into a velocity command to the robot.

The architecture of a teleoperated surgical robot (class iii), as previously explained, consists of three fundamental components: the surgical console, the robotic arms, and the vision system. Using the bilateral (motion and force) mode of operation depicted in Fig. 6, the surgeon generates position commands to the robot by moving the input devices (the master) located at the surgeon's console. The position commands are transferred through a controller to the surgical robotic arms (the slave), which have actuators that move the arms and the surgical tools to the proper positions. In some systems, force feedback may be generated by actuators attached to the master input device, enabling the surgeon to feel the forces between the tool and the tissue. The force-feedback command in a bilateral mode of operation is defined as the difference between the position command generated by the operator and the actual position achieved by the robot.[37,38] As the difference between the position command and the actual position increases, the force feedback to the operator increases proportionally. Although the bilateral mode of operation does not require additional sensors for generating the force feedback, the high level of friction due to the use of non-direct-drive actuators and the high inertia due to large robotic arms impair the quality of the force-feedback signal using this algorithm. A different approach for incorporating force feedback requires the use of force/torque sensors as close as possible to the end-effector to diminish the mechanical and dynamic interference. Given the harsh environments associated with the tool sterilization and operation, attaching force

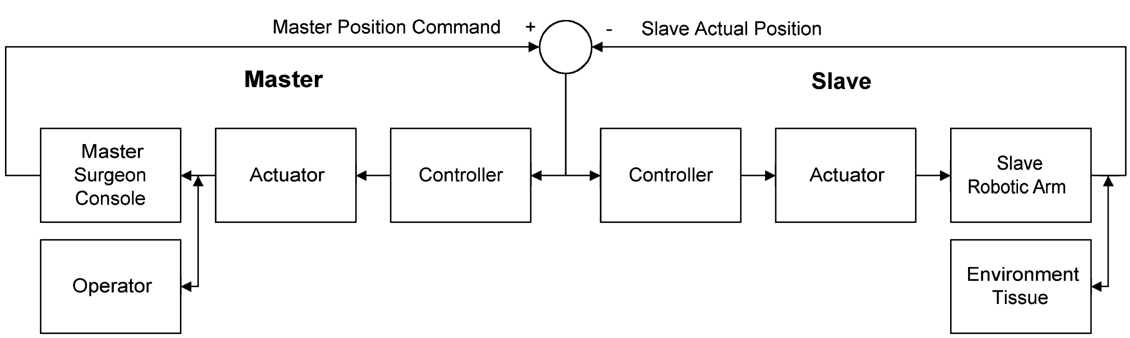


Fig. 6 A block diagram of a typical bilateral teleoperation system used in class iii robotic systems. The actuators and controllers on the master console are eliminated if force feedback is not incorporated into the system.

sensors to the tool and protecting them is still a technological challenge. For MIS, placing force sensors at the distal end of the tool is further limited by the 5–10 mm diameter of the port.

Surgical Training Simulators and Haptics

Training surgical residents adds substantial cost to medical care, including costs associated with inefficient use of operating room time and equipment. Residents are currently trained on a variety of modalities, from using plastic models to operating on live animals and human patients. A resident is more likely to make a mistake than an expert surgeon, and these mistakes can have dire economic, legal, and societal impacts. Ever-increasing costs and louder demands for efficiency have brought surgical simulators to the forefront of training options as a cost-effective and efficacious methodology. Medical simulators are inspired by the aviation simulators used by airline and military pilots to train in virtual reality. Realistic virtual reality surgical simulators allow more comprehensive training without endangering patients' lives. Residents can train for difficult scenarios or anatomy, and they can practice repairing mistakes. In addition, simulators also reduce the need to use animals and cadavers, with obvious ethical and financial benefits.

A typical virtual reality surgical simulator includes both hardware and software. Some input devices include only position sensors and thus provide only the positions of the tools as inputs to the simulator. More advanced input devices, called haptic interfaces, incorporate actuators in addition to position sensors. These actuators generate the appropriate force feedback as the tools are interacting with the virtual medium. Due to the wide variety of surgical procedures, there is no generic input device. Specific input devices are usually developed to match the actual human–machine interface associated with a specific medical procedure as realistically as possible. However, some generic input devices do exist for MIS, including the Laparoscopic Surgical Workstation by Immersion[54] or a modified version of the PHANToM by SensAble Technologies.[55] For an extensive review of medical input devices, see the reference by Chen.[56] In addition to input devices that are specifically designed for surgical simulators, any surgeon console (master) of a robotic system can be used as an input device, while the patient is replaced by a virtual model. Connecting two or more consoles together may allow two surgeons to share both the visual view and the haptic sensation of the surgical scene, either in real surgery or in a VR simulation. This will allow the surgeons to regain the collaborative capability that exists in open surgery, but is somewhat lost in MIS. The ability to collaborate may enable a local surgeon to assist an expert surgeon operating from a remote location. In addition, this mode of collaboration may be used during training sessions, where the same tool is controlled by both a trainee and a senior surgeon with overruling authority.

A variety of simulators for surgical training and preoperative planning have been developed by the National Capital Area Medical Simulation Center at the Uniformed Services University of the Health Sciences,[57] and by the National Center for Biocomputation, a collaboration between Stanford University and the NASA Ames Research Center.[58] At the heart of a simulator is its computational engine, which accepts the tool positions as inputs and is responsible for presenting the graphical representation of the surgical scene along with generating force feedback as outputs based on a model of the virtual material. Both mass-spring and finite element models are in use for simulating soft tissues. These models are considered to be an oversimplification of real soft tissue, which exhibits nonlinear, heterogeneous, viscoelastic behavior. Measuring the biomechanical characteristics of soft tissue in vivo is the subject of active research.[39,59] Most of the data currently available were acquired in situ or under postmortem conditions, which alters the fundamental characteristics of the tissue.

Developing objective methodologies for surgical competence and performance is of paramount importance to superior surgical training. The methodology for assessing surgical skill as a subset of surgical ability has gradually shifted from subjective scoring, based on expert and certainly biased opinion using fuzzy criteria, toward more objective, quantitative analysis. This shift has been enabled by the incorporation of surgical simulators and robots into the surgical training curriculum, in addition to using these tools for demonstrating continued competency among practicing surgeons. The kinematics and dynamics of the surgical tools are fundamental sources of data for objective assessment of surgical skill, regardless of the modality being used. Simple measures like completion time, tool tip path, forces, and torques are currently used as objective criteria, but they fail to provide an integrated approach for analyzing surgery as a multidimensional process. Markov modeling can be used to decompose the surgical task and analyze its internal hierarchy, using the kinematics and dynamics of the tools. This technique holds the promise of providing an integrated approach and objective means for quantifying training and skills acquisition prior to clinical implementation.[43,44]

The Future of Robot-Assisted Surgery

Analysis of the surgical robot's role in the currently available operating room (OR) setup demonstrates that the surgeon can be safely removed from the immediate surgical scene and still maintain interaction with the patient in a teleoperational mode. Although this revolutionary mode of operation may have benefits for the patient, it is far from being efficient because of the lack of supporting technologies. The increased setup and operational time of the current robotic systems is due to lack of automation and the presence of sophisticated interfaces. As a result, the simple act of changing tools or readjusting the robot's position produces inefficient interactions between the clinical staff and the technology. These examples demonstrate the incomplete integration of surgical robotic systems into the OR.

The OR of the future has been envisioned as an integrated information system.[60] Figure 7 shows a futuristic rendering of some of the subsystems that may be combined within the OR of the future. Much of the medical staff may be removed from the OR and replaced during surgery, in part by hardware in the form of supportive electromechanical devices and in part by software for documenting, assisting, and assessing the operation. The patient may be scanned by an imaging device, which will allow the surgeon to practice critical steps of the operation using the robotic console within a virtual reality environment based on patient-specific data. Then, the operation will be conducted by the surgeon utilizing the robot, tool changer, and equipment dispenser in an OR similar to a class 100 clean room. Smart tags will be incorporated into tools and equipment, and once they are used, the billing process and the inventory updates will be executed immediately. Surgical performance will be monitored in the background, and critical decisions may be made through consultation with an expert system incorporated into the system. Much of the core technology for materializing this vision already exists, but whether this vision will become common practice in the next few decades is still an open question.

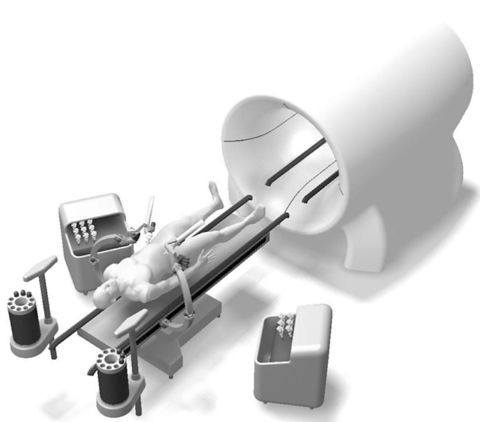


Fig. 7 A futuristic rendering of some of the subsystems that might be incorporated into the operating room of the future, including a modular operating table, surgical robotic arms, a tools changer, an equipment dispenser, and an imaging device. (*View this art in color at www.dekker.com.*)

OTHER MEDICAL ROBOTICS APPLICATIONS

Training

Robotic mannequins have been developed for simulated medical training. The commercially available Medsim-Eagle Patient Simulator developed at Stanford University and the Veterans Affairs Palo Alto Health Care System has several computer-controlled electromechanical features, including eyes that open and close, arms that move, arms and legs that swell, and lungs embedded in the chest that breathe spontaneously.[61]

Tele-echography

A French consortium has developed a telerobotic echography system consisting of a slave robot, with a real probe as its end-effector, and a master interface with a virtual probe.[62] This system transmits motion and force information bidirectionally, allowing an expert interacting with the master interface to perform an examination at a remote location, using the slave robot.

Robots for Special Education

AnthroTronix has developed JesterBot™ and CosmoBot™ for the rehabilitation and special education of children.[63] These robots combine therapy, education, and recreation and can be controlled using body movements, voice commands, or an interactive control station.

Robots for the Deaf and Blind

Dexter, a robotic hand communication aid for people who are both deaf and blind, uses fingerspelling to communicate information typed on a keyboard, stored in a computer, or received from a special telephone.[64,65]

CONCLUSION

Robotic technology has successfully produced valuable tools for rehabilitation, surgery, and medical training, as well as new and improved prosthetics and assistive devices for people with disabilities. Future applications of robotic technology will continue to provide advances in these and other areas of medicine. The most significant role of medical robots will most likely be to perform tasks that are otherwise impossible, such as enabling new microsurgery procedures by providing high-dexterity access to small anatomical structures, integrating imaging modalities into the OR, providing functional replacements for lost limbs, and enabling new human–machine interfaces and techniques for delivering neuro-rehabilitation therapy.

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ARTICLES OF FURTHER INTEREST

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Microelectromechanical Systems (MEMS) Manufacturing, p. 1004
Telemedicine, p. 1449

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