52. Medical Robotics and Computer-Integrated Surgery

Russell H. Taylor, Arianna Menciassi, Gabor Fichtinger, Paolo Dario

The growth of medical robotics since the mid-1980s has been striking. From a few initial efforts in stereotactic brain surgery, orthopaedics, endoscopic surgery, microsurgery, and other areas, the field has expanded to include commercially marketed, clinically deployed systems, and a robust and exponentially expanding research community. This chapter will discuss some major themes and illustrate them with examples from current and past research. Further reading providing a more comprehensive review of this rapidly expanding field is suggested in Sect. 52.4.

Medical robots may be classified in many ways: by manipulator design (e.g., kinematics, actuation); by level of autonomy (e.g., preprogrammed versus teleoperation versus constrained cooperative control), by targeted anatomy or technique (e.g., cardiac, intravascular, percutaneous, laparoscopic, microsurgical); or intended operating environment (e.g., in-scanner, conventional operating room). In this chapter, we have chosen to focus on the role of medical robots within the context of larger computer-integrated systems including presurgical planning, intraoperative execution, and postoperative assessment and follow-up.

First, we introduce basic concepts of computer-integrated surgery, discuss critical factors affecting the eventual deployment and acceptance of medical robots, and introduce the basic system paradigms of surgical computer-assisted planning, registration, execution, monitoring, and assessment (CAD/CAM) and surgical assistance. In subsequent sections, we provide an overview of the technology of medical robot systems and discuss examples of our basic system paradigms, with brief additional discussion topics of remote telesurgery and robotic surgical simulators. We conclude with some thoughts on future research directions and provide suggested further reading.

52.1 Core Concepts

52.1.1 Medical Robotics, Computer-Integrated Surgery, and Closed-Loop Interventions

A fundamental property of robotic systems is their ability to couple complex information to physical action in order to perform a useful task. This ability to replace, supplement, or transcend human performance has had a profound influence on many fields of our society, including industrial production, exploration, quality control, and laboratory processes. Although robots have often been first introduced to automate or improve discrete processes such as welding or test probe placement or to provide access to environments where humans cannot safely go, their greater long-term impact has often come indirectly as essential enablers of computer integration of entire production or service processes.

Medical robots have a similar potential to fundamentally change surgery and interventional medicine as part of a broader, information-intensive environment that exploits the complementary strengths of humans and computer-based technology. The robots may be thought of as information-driven surgical tools that enable human surgeons to treat individual patients with greater safety, improved efficacy, and reduced morbidity than would otherwise be possible. Further, the consistency and information infrastructure associated with medical robotic and computer-assisted surgery systems have the potential to make *computer-integrated surgery* as important to health care as computer-integrated manufacturing is to industrial production.

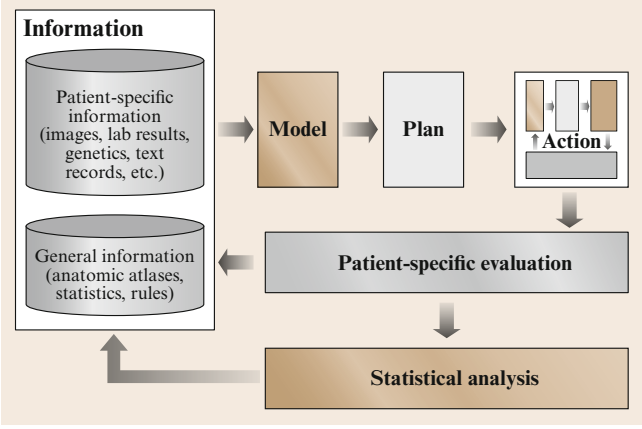

Fig. 52.1 Fundamental information flow in computer-integrated surgery

Figure 52.1 illustrates this view of computer-integrated surgery (CIS). The process starts with information about the patient, which can include medical images [computed tomography (CT), magnetic resonance imaging (MRI), positron emission tomography (PET), etc.], lab test results, and other information. This patient-specific information is combined with statistical information about human anatomy, physiology, and disease to produce a comprehensive computer representation of the patient, which can then be used to produce an optimized interventional plan. In the operating room, the preoperative patient model and plan must be *registered* to the actual patient. Typically, this is done by identifying corresponding landmarks or structures on the preoperative model and the patient, either by means of additional imaging (X-ray, ultrasound, video), by the use of a tracked pointing device, or by the robot itself. If the patient's anatomy has changed, then the model and plan are updated appropriately, and the planned procedure is carried out with assistance of the robot. As the intervention continues, additional imaging or other sensing is used to monitor the progress of the procedure, to update the patient model, and to verify that the planned procedure has been successfully executed. After the procedure is complete, further imaging, modeling, and computer-assisted assessment is performed for patient follow-up and to plan subsequent interventions, if any should be required. Further, all the patient-specific data generated during the planning, execution, and follow-up phases can be retained. These data can subsequently be analyzed statistically to improve the rules and methods used to plan future procedures.

52.1.2 Factors Affecting the Acceptance of Medical Robots

Medical robotics is ultimately an application-driven research field. Although the development of medical robotic systems requires significant innovation and can lead to very real, fundamental advances in technology, medical robots must provide measurable and significant advantages if they are to be widely accepted and deployed. The situation is complicated by the fact that these advantages are often difficult to measure, can take an extended period to assess, and may be of varying importance to different groups. Table 52.1 lists some of the more important factors that researchers contemplating the development of a new medical robot system should consider in assessing their proposed approach.

Table 52.1 Assessment factors for medical robots or computer-integrated surgery systems [52.1]

Assessment factor	Important to whom	Assessment method	Summary of key leverage
New treatment options	Clinical researchers, patients	Clinical and trials preclinical	Transcend human sensory-motor limits (e.g., in microsurgery). Enable less invasive procedures with real-time image feedback (e.g., fluoroscopic or MRI-guided liver or prostate therapy). Speed up clinical research through greater consistency and data gathering
Quality	Surgeons, patients	Clinician judgment; revision rates	Significantly improve the quality of surgical technique (e.g., in microvascular anastomosis), thus improving results and reducing the need for revision surgery
Time and cost	Surgeons, hospitals, insurers	Hours, hospital charges	Speed operating room (OR) time for some interventions. Reduce costs from healing time and revision surgery. Provide effective intervention to treat patient condition
Less invasiveness	Surgeons, patients	Qualitative judgment; recovery times	Provide crucial information and feedback needed to reduce the invasiveness of surgical procedures, thus reducing infection risk, recovery times, and costs (e.g., percutaneous spine surgery)
Safety	Surgeons, patients	Complication and revision surgery rates	Reduce surgical complications and errors, again lowering costs, improving outcomes and shortening hospital stays (e.g., robotic total hip replacement (THR), steady-hand brain surgery)
Real-time feedback	Surgeons	Qualitative assessment, quantitative comparison of plan to observation, revision surgery rates	Integrate preoperative models and intraoperative images to give surgeon timely and accurate information about the patient and intervention (e.g., fluoroscopic X-rays without surgeon exposure, percutaneous therapy in conventional MRI scanners). Assure that the planned intervention has in fact been accomplished
Accuracy or precision	Surgeons	Quantitative comparison of plan to actual	Significantly improve the accuracy of therapy dose pattern delivery and tissue manipulation tasks (e.g., solid organ therapy, microsurgery, robotic bone machining)
Enhanced documentation and follow-up	Surgeons, clinical researchers	Databases, anatomical atlases, images, and clinical observations	Exploit CIS systems' ability to log more varied and detailed information about each surgical case than is practical in conventional manual surgery. Over time, this ability, coupled with CIS systems' consistency, has the potential to significantly improve surgical practice and shorten research trials

Broadly, the advantages offered by medical robots may be grouped into three areas. The first is the potential of a medical robot to *significantly improve surgeons' technical capability* to perform procedures by exploiting the complementary strengths of humans and robots summarized in Table 52.2. Medical robots can be constructed to be more precise and geometrically accurate than an unaided human. They can operate in hostile radiological environments and can provide great dexterity for minimally invasive procedures inside the patient's body. These capabilities can both enhance the ability of an *average* surgeon to perform procedures that only a few exceptionally gifted surgeons can perform unassisted and can also make it possible to perform interventions that would otherwise be completely infeasible.

A second, closely related capability is the potential of medical robots to *promote surgical safety* both by improving a surgeon's technical performance and by means of active assists such as *no-fly zones* or *virtual fixtures* (Sect. 52.2.3) to prevent surgical instruments

Table 52.2 Complementary strengths of human surgeons and robots [52.1]

	Strengths	Limitations
Humans	Excellent judgment Excellent hand–eye coordination Excellent dexterity (at natural *human* scale) Able to integrate and act on multiple information sources Easily trained Versatile and able to improvise	Prone to fatigue and inattention Limited fine motion control due to tremor Limited manipulation ability and dexterity outside natural scale Cannot see through tissue Bulky end-effectors (hands) Limited geometric accuracy Hard to keep sterile Affected by radiation, infection
Robots	Excellent geometric accuracy Untiring and stable Immune to ionizing radiation Can be designed to operate at many different scales of motion and payload Able to integrate multiple sources of numerical and sensor data	Poor judgment Hard to adapt to new situations Limited dexterity Limited hand–eye coordination Limited haptic sensing (today) Limited ability to integrate and interpret complex information

from causing unintentional damage to delicate structures. Furthermore, the integration of medical robots within the information infrastructure of a larger CIS system can provide the surgeon with significantly improved monitoring and online decision supports, thus further improving safety.

A third advantage is the inherent ability of medical robots and CIS systems to *promote consistency* while *capturing detailed online information* for every procedure. Consistent execution (e.g., in spacing and tensioning of sutures or in placing of components in joint reconstructions) is itself an important quality factor. If saved and routinely analyzed, the *flight data recorder* information inherently available with a medical robot can be used both in *morbidity and mortality* assessments of serious surgical incidents and, potentially, in statistical analyses examining many cases to develop better surgical plans. Furthermore, such data can provide valuable input for surgical simulators, as well as a database for developing skill assessment and certification tools for surgeons.

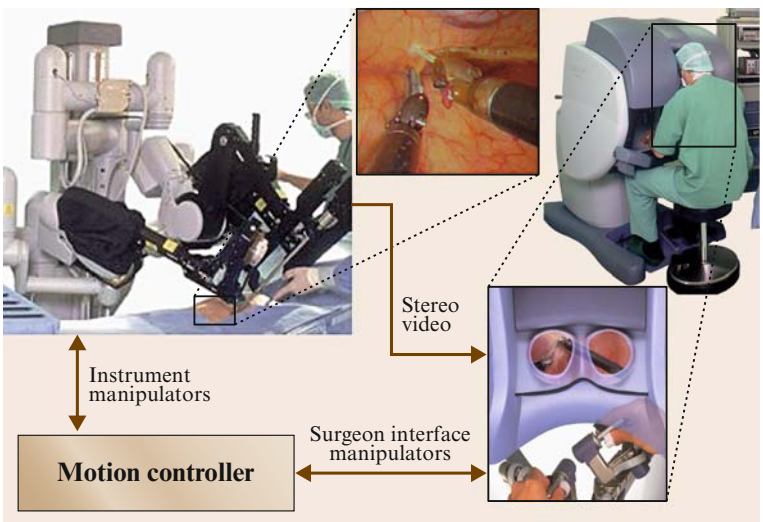

Fig. 52.2 The daVinci telesurgical robot [52.2] extends a surgeon's capabilities by providing the immediacy and dexterity of *open* surgery in a minimally invasive surgical environment. (Photos: Intuitive Surgical, Sunnyvale)

52.1.3 Medical Robotics System Paradigms: Surgical CAD/CAM and Surgical Assistance

We call the process of computer-assisted planning, registration, execution, monitoring, and assessment *surgical CAD/CAM*, emphasizing the analogy to manufacturing CAD/CAM. Just as with manufacturing, robots can be critical in this CAD/CAM process by enhancing the surgeon's ability to execute surgical plans. The specific role played by the robot depends somewhat on the application, but current systems tend to exploit the geometric accuracy of the robot and/or its ability to function concurrently with X-ray or other imaging devices. Typical examples include radiation therapy delivery robots such as Accuray's CyberKnife [52.5] (Accuray, Inc., Sunnyvale, CA.), shaping of bone in orthopaedic joint reconstructions (discussed further in Sect. 52.3.2) and image-guided placement of therapy needles (Sect. 52.3.3).

Surgery is often highly interactive; many decisions are made by the surgeon in the operating room and executed immediately, usually with direct visual or haptic feedback. Generally, the goal of surgical robotics is not to replace the surgeon so much as to improve his or her ability to treat the patient. The robot is thus a computer-controlled surgical tool in which control of the robot is often shared in one way or another between the human surgeon and a computer. We thus often speak of medical robots as *surgical assistants*.

Broadly, robotic surgical assistants may be broken into two subcategories. The first category, *surgeon extender robots*, manipulate surgical instruments under the direct control of the surgeon, usually through a teleop-

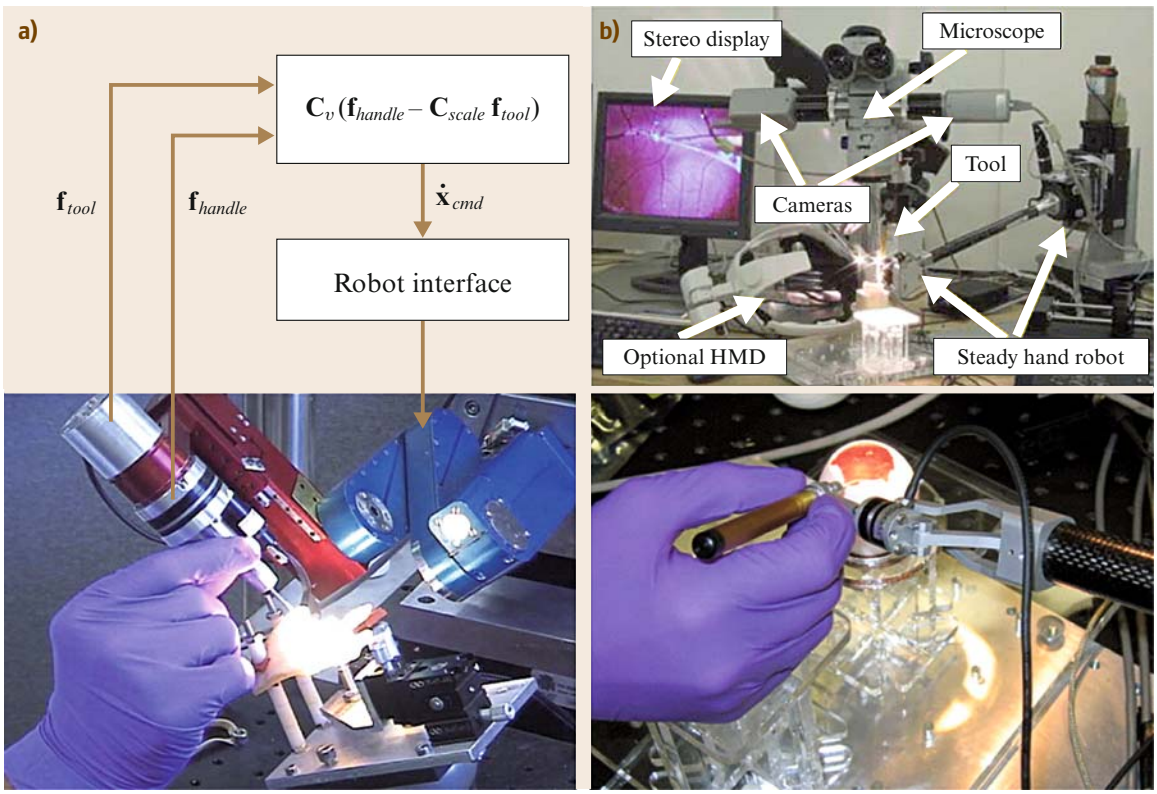

Fig. 52.3a,b The Johns Hopkins *Steady Hand* microsurgical robot [52.3,4] extends a surgeon's capabilities by providing the ability to manipulate surgical instruments with very high precision while still exploiting the surgeon's natural hand–eye coordination. **(a)** The basic paradigm of hands-on compliant guiding. The commanded velocity of the robot is proportional to a scaled difference between the forces exerted by the surgeon on the tool handle and (optionally) sensed tool-to-tissue forces. **(b)** A more recent version of the Steady Hand robot currently being used for experiments in microcannulation of 100 μm blood vessels

eration or *hands-on* cooperative control interface. The primary value of these systems is that they can overcome some of the perception and manipulation limitations of the surgeon. Examples include the ability to manipulate surgical instruments with superhuman precision by eliminating hand tremor, the ability to perform highly dexterous tasks inside the patient's body, or the ability to perform surgery on a patient who is physically remote from the surgeon. Although setup time is still a serious concern with most surgeon extender systems, the greater ease of manipulation that such systems offer has the potential to reduce operative times. One widely deployed example of a surgeon extender is the daVinci system [52.2] (Intuitive Surgical Systems, Sunnyvale, CA) shown in Fig. 52.2. Other examples include the Sensei catheter system [52.6] (Hansen Medical Systems, Mountain View, CA.) and the experimental Johns Hopkins University (JHU) *Steady Hand* microsurgery robot shown in Fig. 52.3. Further examples are discussed in Sect. 52.3.

A second category, *auxiliary surgical support robots*, generally work alongside the surgeon and perform such routine tasks as tissue retraction, limb positioning, or endoscope holding. One primary advantage of such systems is their potential to reduce the number of people required in the operating room, although that advantage can only be achieved if *all* the tasks routinely performed by an assisting individual can be automated. Other advantages can include improved task performance (e.g., a steadier endoscopic view), safety (e.g., elimination of excessive retraction forces), or simply giving the surgeon a greater feeling of control over the procedure. One of the key challenges in these systems is providing the required assistance without posing an undue burden on the surgeon's attention. A variety of control interfaces are common, including joysticks, head tracking, voice recognition systems, and visual tracking of the surgeon and surgical instruments, for example, the Aesop endoscope positioner [52.7] used both a foot-actuated joystick and a very effective voice recognition system. Again, further examples are discussed in Sect. 52.3.

It is important to realize that *surgical CAD/CAM* and *surgical assistance* are complementary concepts. They are not at all incompatible, and many systems have aspects of both.

52.2 Technology

52.2.1 Mechanical Design Considerations

The mechanical design of a surgical robot depends crucially on its intended application. For example, robots with high precision, stiffness and (possibly) limited dexterity are often very suitable for orthopaedic bone shaping or stereotactic needle placement, and medical robots for these applications [52.8–11] frequently have high gear ratios and consequently, low back-drivability, high stiffness, and low speed. On the other hand, robots for complex, minimally invasive surgery (MIS) on soft tissues require compactness, dexterity, and responsiveness. These systems [52.2, 12] frequently have relatively high speed, low stiffness, and highly back-drivable mechanisms.

Many early medical robots [52.8, 11, 13] were essentially modified industrial robots. This approach has many advantages, including low cost, high reliability, and shortened development times. If suitable modifications are made to ensure safety and sterility, such systems can be very successful clinically [52.9], and they can also be invaluable for rapid prototyping and research use.

However, the specialized requirements of surgical applications have tended to encourage more specialized designs. For example, laparoscopic surgery and percutaneous needle placement procedures typically involve the passage or manipulation of instruments about a common entry point into the patient's body. There are two basic design approaches. The first approach uses a passive wrist to allow the instrument to pivot about the insertion point and has been used in the commercial Aesop and Zeus robots [52.12, 14] as well as several research systems. The second approach mechanically constrains the motion of the surgical tool to rotate about a *remote center of motion* (RCM) distal to the robot's structure. In surgery, the robot is positioned so that the RCM point coincides with the entry point into the patient's body. This approach has been used by the commercially developed daVinci robot [52.2], as well as by numerous research groups, using a variety of kinematic designs [52.15–17].

The emergence of minimally invasive surgery has created a need for robotic systems that can provide high degrees of dexterity in very constrained spaces inside the patient's body, and at smaller and smaller scales. Figure 52.4 shows several typical examples of current approaches. One common response has been to develop cable-actuated wrists [52.2]. However, a num-

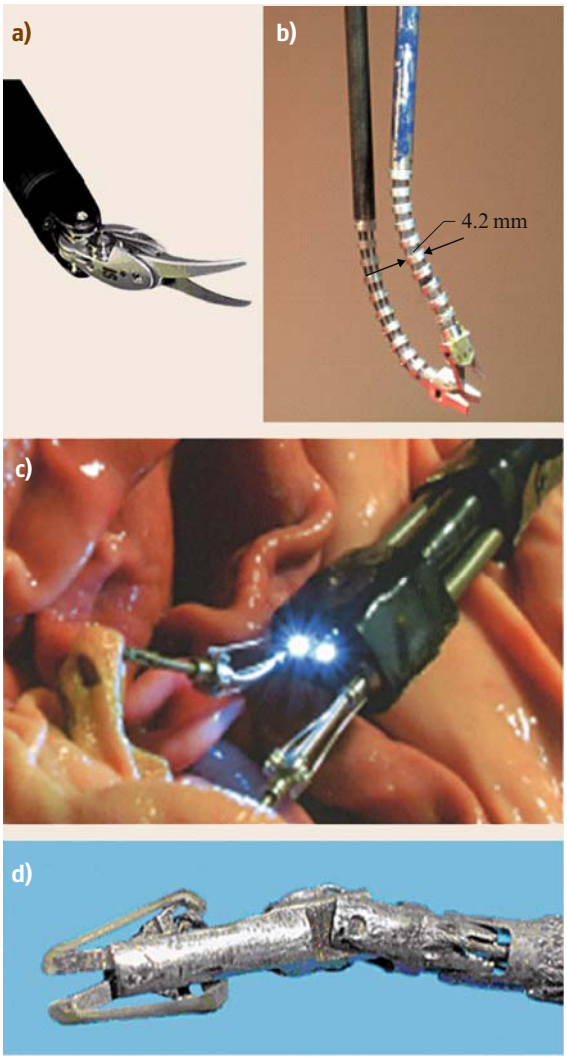

Fig. 52.4a–d Dexterity enhancement inside a patient's body: **(a)** The daVinci *wrist* with a typical surgical instrument (here, scissors) [52.2]; **(b)** The end-effectors of the JHU/Columbia *snake* telesurgical system [52.18]; **(c)** Two-handed manipulation system for use in endogastric surgery [52.26]; **(d)** five-degree-of-freedom 3 mm wrist and gripper [52.27] for microsurgery in deep and narrow spaces

ber of investigators have investigated other approaches, including bending structural elements [52.18], shape-memory alloy actuators [52.19, 20], microhydraulic systems [52.21], and electroactive polymers [52.22]. Similarly, the problem of providing access to surgical sites inside the body has led several groups to develop semiautonomously moving robots for epicardial [52.23] or endoluminal applications [52.24, 25].

Although most surgical robots are mounted to the surgical table, to the operating room ceiling, or to the floor, there has been some interest in developing systems that directly attach to the patient [52.28, 29]. The main advantage of this approach is that the relative position of the robot and patient is unaffected if the patient moves. The challenges are that the robot must be smaller and that relatively nonintrusive means for mounting it must be developed.

Finally, robotic systems intended for use in specific imaging environments pose additional design challenges. First, there is the geometric constraint that the robot (or at least its end-effector) must fit within the scanner along with the patient. Second, the robot's mechanical structure and actuators must not interfere with the image formation process. In the case of X-ray and CT, satisfying these constraints is relatively straightforward. The constraints for MRI are more challenging [52.30].

52.2.2 Control Paradigms

Surgical robots assist surgeons in treating patients by moving surgical instruments, sensors, or other devices in relation to the patient. Generally, these motions are controlled by the surgeon in one of three ways:

- *Preprogrammed, semi-autonomous motion:* The desired behavior of the robot's tools is specified interactively by the surgeon, usually based on medical images. The computer fills in the details and obtains the surgeon's concurrence before the robot is moved. Examples include the selection of needle target and insertion points for percutaneous therapy and tool cutter paths for orthopaedic bone machining.
- *Teleoperator control:* The surgeon specifies the desired motions directly through a separate human interface device and the robot moves immediately. Examples include common telesurgery systems such as the daVinci [52.2]. Although physical *master* manipulators are the most common input devices, other human interfaces are also used, notably voice control [52.12].
- *Hands-on compliant control:* The surgeon grasps the surgical tool held by the robot or a control handle on the robot's end-effector. A force sensor senses the direction that the surgeon wishes to move the tool and the computer moves the robot to comply. Early experiences with Robodoc [52.8] and other

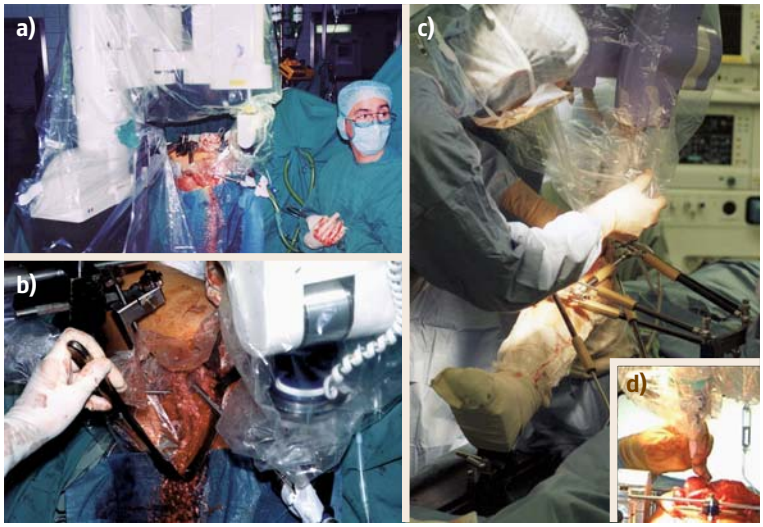

Fig. 52.5a–d Clinically deployed robots for orthopaedic surgery. **(a,b)** The Robodoc system [52.8, 9] represents the first clinically applied robot for joint reconstruction surgery and has been used for both primary and revision hip replacement surgery as well as knee replacement surgery. **(c,d)** The Acrobot system of *Davies* et al. [52.31] uses hands-on compliant guiding together with a form of virtual fixtures to prepare the femur and tibia for knee replacement surgery

surgical robots [52.16] showed that surgeons found this form of control to be very convenient and natural for surgical tasks. Subsequently, a number of groups have exploited this idea for precise surgical tasks, notably the JHU *Steady Hand* microsurgical robot [52.3] shown in Fig. 52.3 and the Imperial College Acrobot orthopaedic system [52.31] shown in Figs. 52.5c,d.

These control modes are not mutually exclusive and are frequently mixed. For example, the Robodoc system [52.8, 9] uses hands-on control to position the robot close to the patient's femur or knee and preprogrammed motions for bone machining. Similarly, the IBM/JHU LARS robot. [52.16] used both cooperative and telerobotic control modes. The cooperatively controlled Acrobot [52.31] uses preprogrammed virtual fixtures Sect. 52.1.3 derived from the implant shape and its planned position relative to medical images.

Each mode has advantages and limitations, depending on the task. Preprogrammed motions permit complex paths to be generated from relatively simple specifications of the specific task to be performed. They are most often encountered in surgical CAD/CAM applications where the planning uses two- (2-D) or three-dimensional (3-D) medical images. However, they can also provide useful *macro* motions combining sensory feedback in teleoperated or hands-on systems. Examples might include passing a suture or inserting a needle into a vessel after the surgeon has prepositioned the tip. On the other hand, interactive specification of motions based on real-time visual appreciation of deforming anatomy would be very difficult.

Teleoperated control provides the greatest versatility for interactive surgery applications, such as dexterous MIS [52.2, 12, 17, 32] or remote surgery [52.33, 34]. It permits motions to be scaled, and (in some research systems) facilitates haptic feedback between master and slave systems. The main drawbacks are complexity, cost, and disruption to standard operating room work flow associated with having separate master and slave robots.

Hands-on control combines the precision, strength, and tremor-free motion of robotic devices with some of the immediacy of freehand surgical manipulation. These systems tend to be less expensive than telesurgical systems, since there is less hardware, and they can be easier to introduce into existing surgical settings. They exploit a surgeon's natural eye–hand coordination in an intuitively appealing way, and they can be adapted to provide force scaling [52.3, 4]. Although direct motion scaling is not possible, the fact that the tool moves in the direction that the surgeon pulls it makes this limitation relatively unimportant when working with a surgical microscope. The biggest drawbacks are that hands-on control is inherently incompatible with any degree of remoteness between the surgeon and the surgical tool and that it is not practical to provide hands-on control of instruments with distal dexterity.

Teleoperation and hands-on control are both compatible with *shared control modes* in which the robot controller constrains or augments the motions specified by the surgeon, as discussed in Sect. 52.2.3.

52.2.3 Virtual Fixtures and Human–Machine Cooperative Systems

Although one goal of both teleoperation and hands-on control is often *transparency*, i. e., the ability to move an instrument with the freedom and dexterity ne might expect with a handheld tool, the fact that a computer is actually controlling the robot's motion creates many more possibilities. The simplest is a safety barrier or *no-fly zone*, in which the robot's tool is constrained from entering certain portions of its workspace. More sophisticated versions include virtual springs, dampers, or complex kinematic constraints that help a surgeon align a tool, maintain a desired force, or maintain a desired anatomical relationship. The Acrobot system shown in Figs. 52.5c,d represents a successful clinical application of the concept, which has many names, of which *virtual fixtures* seems to be the most popular [52.35, 36]. A number of groups are exploring extensions of the concept to active cooperative control, in which the surgeon and robot share or trade off control of the robot during a surgical task or subtask. As the ability of computers to model and follow along surgical tasks improves, these modes will become more and more important in surgical assistant applications. Figure 52.6 illustrates the overall concept of human–machine cooperative systems in surgery, and Fig. 52.7 illustrates the use of registered anatomical models to generate constraint-based virtual fixtures. These approaches are equally valid whether the surgeon interacts with the system through classical teleoperation or through hands-on compliant control. See also Chap. 31.

Both teleoperation and hands-on control are likewise used in human–machine cooperative systems for rehabilitation and disability assistance systems. Constrained hands-on systems offer special importance for rehabilitation applications and for helping people with movement disorders. Similarly, teleoperation and intelligent task following and control are likely to be vital for further advances in assistive systems for people with severe physical disabilities. See Chap. 53 for a further discussion of human–machine cooperation in assistive systems.

52.2.4 Safety and Sterility

Medical robots are safety-critical systems, and safety should be considered from the very beginning of the design process [52.37, 38]. Although there is some difference in detail, government regulatory bodies require a careful and rigorous development process with extensive documentation at all stages of design, implementation, testing, manufacturing, and field support. Generally, systems should have extensive redundancy built into hardware and control software, with multiple consistency conditions constantly enforced. The basic consideration is that no single point of failure should cause the robot to go out of control or to injure a patient. Although there is some difference of opinion as to the best way to make trade-offs, medical manipulators are usually equipped with redundant position encoders and ways to mechanically limit the speed and/or force that the robot can exert. If a consistency check failure is detected, two common approaches are to *freeze* robot motion or to cause the manipulator to go limp. Which is better depends strongly on the particular application.

Sterilizability and biocompatibility are also crucial considerations. Again, the details are application de-

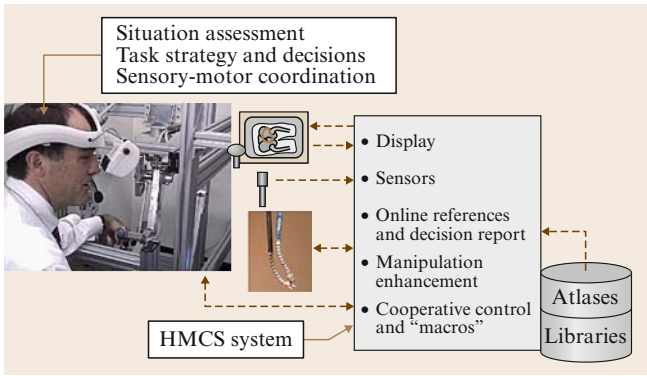

Fig. 52.6 Human–machine cooperative systems (HMCS) in surgery

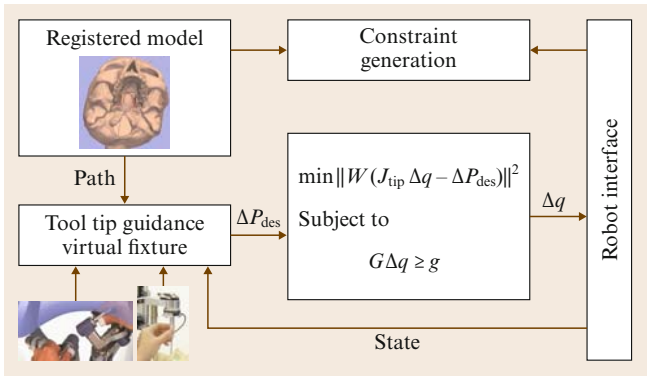

Fig. 52.7 Human–machine cooperative manipulation using constraint-based virtual fixtures, in which patient-specific constraints are derived from registered anatomical models [52.35]

pendent. Common sterilization methods include gamma rays (for disposable tools), autoclaving, soaking or gas sterilization, and the use of sterile drapes to cover unsterile components. Soaking or gas sterilization are less likely to damage robot components, but very rigorous cleaning is required to prevent extraneous foreign matter from shielding microbes from the sterilizing agent.

Careful attention to higher levels of application protocols is also essential. Just like any other tool, surgical robots must be used correctly by surgeons, and careful training is essential for safe practice. Surgeons must understand both the capabilities and limitations of the system. In surgical CAD/CAM applications, the surgeon must understand how the robot will execute the plan and be able to verify that the plan is being followed. If the surgeon is interactively commanding the robot, it is essential that the robot interpret these commands correctly. Similarly, it is essential that the robot's model of its task environment correspond correctly to the actual environment. Although careful design and implementation can practically eliminate the likelihood of a runaway condition by the manipulator, this will do little good if the robot is badly registered to the patient images used to control the procedure. If the robot fails for any reason, there must be well-documented and planned procedures for recovery (and possibly continuing the procedure manually).

Finally, it is important to remember that a well-designed robot system can actually *enhance* patient safety. The robot is not subject to fatigue or momentary lapses of attention. Its motions can be more precise and there is less chance that a slip of the scalpel may damage some delicate structure. In fact, the system can be programmed to provide *virtual fixtures* (Sect. 52.2.3) preventing a tool from entering a forbidden region unless the surgeon explicitly overrides the system.

52.2.5 Imaging and Modeling of Patients

As the capabilities of medical robots continue to evolve, the use of computer systems to model dynamically changing patient-specific anatomy will become increasingly important. There is a robust and diverse research community addressing a very broad range of research topics, including the creation of patient-specific models from medical images, techniques for updating these models based upon real-time image and other sensor data, and the use of these models for planning and monitoring of surgical procedures. Some of the pertinent research topics include the following:

- Medical image segmentation and image fusion to construct and update patient-specific anatomic models
- Biomechanical modeling for analyzing and predicting tissue deformations and functional factors affecting surgical planning, control, and rehabilitation
- Optimization methods for treatment planning and interactive control of systems
- Methods for registering the *virtual reality* of images and computational models to the *physical reality* of an actual patient
- Methods for characterizing treatment plans and individual task steps such as suturing, needle insertion, or limb manipulation for purposes of planning, monitoring, control, and intelligent assistance
- Real-time data fusion for such purposes as updating models from intraoperative images
- Methods for human–machine communication, including real-time visualization of data models, natural language understanding, gesture recognition, etc.
- Methods for characterizing uncertainties in data, models, and systems and for using this information in developing robust planning and control methods

An in-depth examination of this research is beyond the scope of this article. A more complete discussion of these topics may be found in the suggested further reading in Sect. 52.4.

52.2.6 Registration

Geometric relationships are fundamental in medical robotics, especially in surgical CAD/CAM. There is an extensive literature on techniques for coregistering coordinate systems associated with robots, sensors, images, and the patient [52.39, 40]. Following [52.40], we briefly summarize the main concepts here. Suppose that we have coordinates

$$\boldsymbol{v}_{\mathrm{A}}^{\mathrm{r}} = (x_{\mathrm{A}}, y_{\mathrm{A}}, z_{\mathrm{A}})$$
$$\boldsymbol{v}_{\mathrm{B}}^{\mathrm{r}} = (x_{\mathrm{B}}, y_{\mathrm{B}}, z_{\mathrm{B}}) ,$$

corresponding to comparable locations in two coordinate systems $\mathrm{Ref}_{\mathrm{A}}$ and $\mathrm{Ref}_{\mathrm{B}}$. Then the process of registration is simply that of finding a function $\boldsymbol{T}_{\mathrm{AB}}(\cdots)$ such that

$$\boldsymbol{v}_{\mathrm{B}} = \boldsymbol{T}_{\mathrm{AB}}(\boldsymbol{v}_{\mathrm{A}}) .$$

Generally, $\boldsymbol{T}_{\mathrm{AB}}(\cdots)$ is assumed to be a rigid transformation of the form

$$\boldsymbol{T}_{\mathrm{AB}}\left(\boldsymbol{v}_{\mathrm{A}}^{\mathrm{r}}\right) = \boldsymbol{R}_{\mathrm{AB}}\boldsymbol{v}_{\mathrm{A}}^{\mathrm{r}} + \boldsymbol{p}_{\mathrm{AB}}^{\mathrm{r}} ,$$

where $\boldsymbol{R}_{\mathrm{AB}}$ represents a rotation and $\boldsymbol{p}_{\mathrm{AB}}$ represents a translation, but nonrigid transformations are becoming increasingly common. There are hundreds of methods for computing $\boldsymbol{T}_{\mathrm{AB}}(\cdots)$. The most common for medical robotics involve finding a set of corresponding geometric features Γ_{A} and Γ_{B} whose coordinates can be determined in both coordinate systems and then finding a transformation that minimizes some distance function $d_{\mathrm{AB}} = \mathit{distance}\,[\Gamma_{\mathrm{B}}, \boldsymbol{T}_{\mathrm{AB}}(\Gamma_{\mathrm{A}})]$. Typical features can include artificial fiducial objects (pins, implanted spheres, rods, etc.) or anatomical features such as point landmarks, ridge curves, or surfaces.

One common class of methods is based on the iterated closest-point algorithm of *Besl* and *McKay* [52.41], for example, 3-D robot coordinates $\boldsymbol{a}_j$ may be found for a collection of points known to be on the surface of an anatomical structure that can also be found in a segmented 3-D image. Given an estimate $\boldsymbol{T}_k$ of the transformation between image and robot coordinates, the method iteratively finds corresponding points $\boldsymbol{b}_j$ on the surface that are closest to $\boldsymbol{T}_k\,\boldsymbol{a}_j$ and then finds a new transformation

$$\boldsymbol{T}_{k+1} = \arg\min_{T} \sum_{j} (\boldsymbol{b}_j - \boldsymbol{T}\boldsymbol{a}_j)^2 .$$

The process is repeated until some suitable termination condition is reached.

52.3 Systems, Research Areas, and Applications

52.3.1 Nonrobotic Computer-Assisted Surgery: Navigation and Image Overlay Devices

Medical robots are not ends in themselves. As the late Hap Paul often remarked, "the robot is a surgical tool designed to improve the efficacy of a procedure". (Dr Paul was the founder of Integrated Surgical Systems. Along with William Bargar, he was one of the first people to recognize the potential of robots to fundamentally improve the precision of orthopaedic surgery.) In cases where the role of the robot is placing instruments on targets determined from medical images, *surgical navigation* is often a superior alternative. In surgical navigation [52.42], the positions of instruments relative to the reference markers on the patient are tracked using specialized electromechanical, optical, electromagnetic, or sonic digitizers or by more general computer vision techniques. After the relationships between key coordinate systems (patient anatomy, images, surgical tools, etc.) are determined through a registration process (Sect. 52.2.6), a computer workstation provides graphical feedback to the surgeon to assist in performing the planned task, usually by displaying instrument positions relative to medical images, as shown in Fig. 52.8a. Although the registration is usually performed computationally, a simple mechanical alignment of an image display with an imaging device can be surprisingly effective in some cases. One example [52.27] is shown in Fig. 52.8b.

The main advantages of surgical navigation systems are their versatility, their relative simplicity, and their ability to exploit the surgeon's natural dexterity and haptic sensitivity. They are readily combined with *passive* fixtures and manipulation aids [52.43, 44]. The main drawbacks, compared to active robots, are those associated with human limitations in accuracy, strength, ability to work in certain imaging environments, and dexterity inside the patient's body (Table 52.2).

Because these advantages often outweigh the limitations, surgical navigation systems are achieving widespread and increasing acceptance in such fields as neurosurgery, otolaryngology, and orthopaedics. Since much of the technology of these systems is compatible with surgical robots and since technical problems such as registration are common among all these systems, we may expect to see a growing number of hybrid applications combining medical robots and navigation.

52.3.2 Orthopaedic Systems

Orthopaedic surgery represents a natural surgical CAD/CAM application, and both surgical navigation systems and medical robots have been applied to orthopaedics. Bone is rigid and is easily imaged in CT and intraoperative X-rays, and surgeons are accustomed to doing at least some preplanning based on these images. Geometric accuracy in executing surgical plans is very important, for example, bones must be shaped accurately to ensure proper fit and positioning of components in

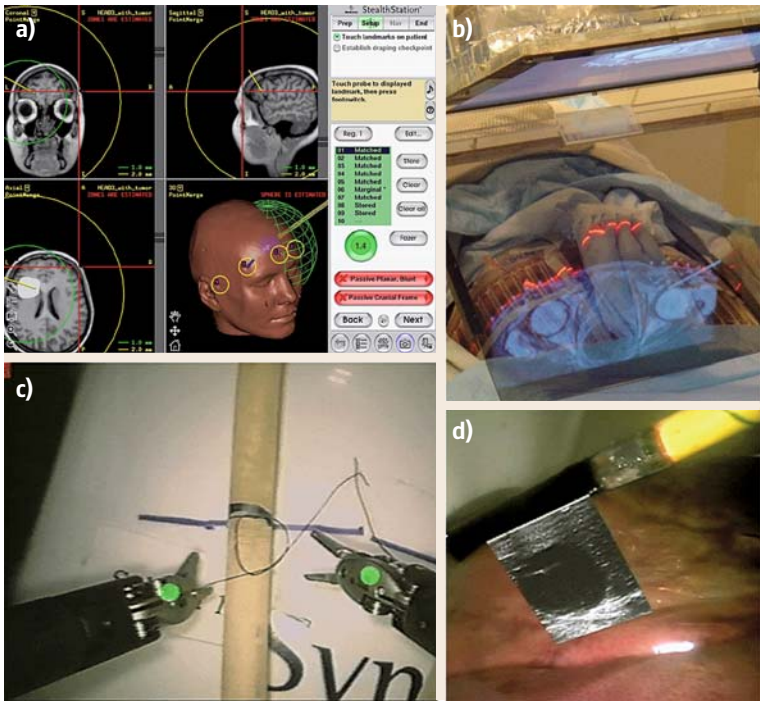

Fig. 52.8a–d Information enhancement for surgical assistance. **(a)** Display from a typical surgical navigation system, here the Medtronic StealthStation; **(b)** the JHU image overlay system [52.45] uses a mirror to align the virtual image of a cross-sectional image with the corresponding physical position in the patient's body; **(c)** Sensory substitution display of surgical force information onto daVinci surgical robot video monitor [52.46]; **(d)** Overlay of laparoscopic ultrasound onto the daVinci surgical robot video monitor [52.47]

joint replacement surgery. Similarly, osteotomies require both accurate cutting and placement of bone fragments. Spine surgery often requires screws and other hardware to be placed into vertebrae without damage to the spinal cord, nerves, and nearby blood vessels.

The Robodoc system shown in Figs. 52.5a,b represents the first clinically applied robot for joint reconstruction surgery [52.8, 9]. Since 1992, it has been applied successfully to both primary and revision hip replacement surgery, as well as knee surgery. Since this system exhibits many of the characteristics of surgical CAD/CAM, we will discuss it is some detail. In the *surgical CAD* phase, the surgeon selects the desired based on preoperative CT images and interactively specifies the desired position of the implant components. In the *surgical CAM* phase, surgery proceeds normally up to the point where the patient's bones are to be prepared to receive the implant. The robot is moved up to the operating table, the patient's bones are attached rigidly to the robot's base, and the robot is registered to the CT images either by use of implanted fiducial pins or by use of a 3-D digitizer to match bone surfaces to the CT images. After registration, the surgeon's hand guides the robot to an approximate initial starting position. Then, the robot autonomously machines the desired shape with a high-speed rotary cutter while the surgeon monitors progress. During cutting, the robot monitors cutting forces, bone motion, and other safety sensor, and either the robot controller or the surgeon can pause execution at any time. If the procedure is paused for any reason, there are a number of error recovery procedures available to permit the procedure to be resumed or restarted at one of several defined checkpoints. Once the desired shape has been machined, surgery proceeds manually in the normal manner.

Subsequently, several other robotic systems for joint replacement surgery have been introduced or proposed. The references in Sect. 52.4 provide numerous examples. One notable system is the hands-on guided Acrobot system [52.31] for knee surgery shown in Figs. 52.5c,d. Similarly, several groups have recently proposed small orthopaedic robots attaching directly to the patient's bones [52.28].

52.3.3 Percutaneous Needle Placement Systems

Percutaneous (through the skin) needle placement has become ubiquitous in interventional radiology and surgery, as the least invasive actual surgical action practised today. These procedures fit naturally within the broader paradigm of surgical CAD/CAM systems. The

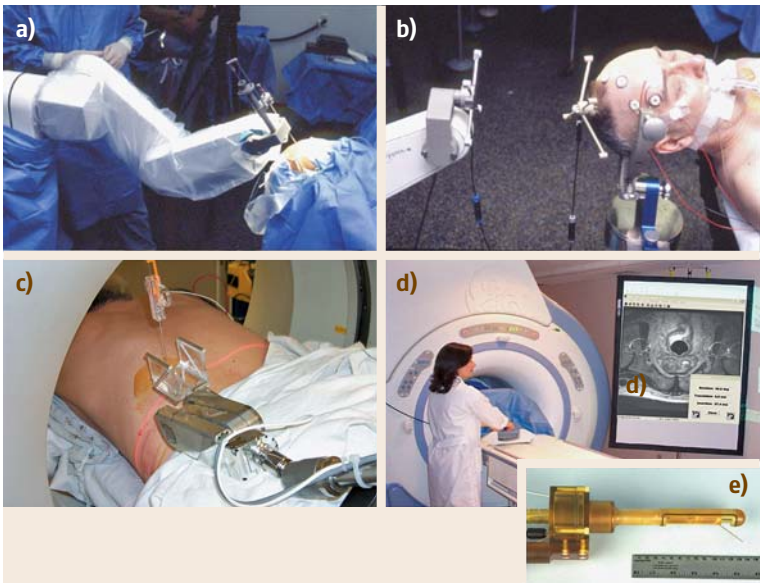

Fig. 52.9a–e Clinically deployed systems for in-scanner needle placement. (a,b) The Neuromate system [52.10] for stereotactic procedures in the brain uses a novel noncontact sensing system for robot-to-image registration; (c) Johns Hopkins system for in-CT needle placement [52.48, 49]; (d,e) Manually activated device for in-MRI transrectal needle placement into the prostate [52.50]

basic process involves use of patient images to identify targets within the patient and planning needle trajectories; inserting the needles and verifying their placement; performing some action such as an injection or taking a biopsy sample; and assessing the results. In most needle placements, an accuracy of 1–2 mm is acceptable, which is not easy to achieve freehand, because the target is not directly visible, soft tissues tend to deform and deflect, and needles often bend. Hence these procedures typically rely on some form of intraoperative imaging (X-ray fluoroscopy, CT, MRI, and ultrasound) for both guidance and verification. The surgical motion sequence involved in needle puncture typically has three phases:

1. touch down with the needle tip at the entry point
2. orientation of the needle by pivoting around this point
3. final insertion of the needle into the body along a straight trajectory

These motions are most often performed freehand, with varying degrees of information feedback for the physician. However, passive, semiautonomous, and active robotic systems are becoming more prevalent. Figure 52.9 shows several clinically deployed systems for needle placement.

Freehand Needle Placement Systems

Conventional freehand needle placement with CT and MRI guidance typically uses skin markers to locate the exact entry point [52.45], reference to the scanner's alignment laser to control needle direction, and markers on the needle to control depth. With fluoroscopy, the typical procedure is to align the X-ray system so that it looks directly along the desired needle path, place the needle and stand it up so that its X-ray image is a dot, turn the X-ray system to look from the side, and insert the needle until it reaches the target. With ultrasound, the primary reliance is on surgeon experience or the use of some sort of needle guide to drive the needle to target while it passes in the ultrasound plane. In fact, a variety of simple mechanical guides have been tried out for use with all common image modalities. Several computer-assisted approaches have been proposed to enhance a human's ability to aim the needle during freehand needle placement. These include computer-aimed laser guidance devices [52.51], augmented reality systems [52.52], and surgical navigation [52.42]. In addition, very simple variations of augmented reality have been developed for use with 2-D images such as CT or MRI *slices* [52.45]. B-mode ultrasound images (Fig. 52.8b) [52.53], where a semitransparent mirror is used together with a flat-panel display to ensure that the virtual image of the display is aligned to the corresponding physical section through the patient's anatomy, have also been used.

Passive and Semiautonomous Devices for Needle Placement

A few researchers [52.54] have proposed use of passive, encoded manipulator arms for image-guided needle

placement. After a registration step, these systems track the position and orientation of a passive needle guide and display the corresponding needle path in real time on CT or MRI images. Semiautonomous systems allow remote, interactive image-guided placement of the biopsy tool. For example, *Krieger* et al. performed transrectal prostate needle placement procedures in a conventional MRI environment [52.50] with a three-degree-of-freedom (DOF) manipulator. The device is driven from outside the bore with torsion cables, while the needle driver is tracked in the MRI system with active coils and monitored using an interactive graphical interface.

Active Robots for Needle Placement

Neurosurgery was one of the first clinical applications of active robots [52.10, 11, 13]. This is a natural application for surgical CAD/CAM. The entry and target points are planned on CT/MRI images, the robot coordinate system is registered to the image coordinate system (typically with fiducials affixed to the patient's head), and then the robot positions a needle or drill guide. The fiducial structure may be a conventional stereotactic head frame or, as in the Neuromate system [52.10], registration is achieved by simultaneous tracking of the robot and fiducials attached to the patient's skull. Special constraints of percutaneous access have led to the development of structures achieving *remote center of motion* (RCM) or fulcrum motion [52.15, 16]. In these systems, the RCM is positioned at the entry point, typically with an active Cartesian stage or a passive mechanical mechanism, and the robot sets the needle direction and (sometimes) the depth.

In order to speed up the sequence of imaging, planning, registration, and execution, one can exploit the robot's ability to work concurrently with imaging devices. This trend, again, began with intracranial applications. For extracranial use, *Stoianovici* et al. developed several variants of an RCM-based system deployed with X-ray fluoroscopy [52.15] and CT guidance [52.48, 49]. In [52.49], specialized fiducial structures have been incorporated in the needle driver to register the robot with a single image slice.

Magnetic resonance imaging (MRI) has an unmatched potential for guiding, monitoring, and controlling therapy, invoking intensive research on MRI-compatible robotic systems for needle placement [52.55] and for more complex interactive procedures [52.32].

Ultrasound (US) has many advantages for guiding needle placement and other interventional procedures. It is relatively inexpensive and compact, provides real-time images, does not involve any ionizing radiation, and does not impose significant materials constraints on the robot design. Several robotic systems have been proposed for prostate interventions [52.56] using transrectal ultrasound guidance. There has also been some exploration of US-guided robotic systems for other (i. e., nonprostate) needle placement applications. Examples include experimental systems for liver [52.47, 57], gallbladder [52.58], and breast [52.59]. Figure 52.8d shows one example of the use of information overlay to assist in needle placement in a telesurgical application [52.47]. Whatever form of image feedback is available, steering flexible needles to hit desired targets while avoiding obstacles is a ubiquitous problem, having led to several novel approaches [52.60–62].

52.3.4 Telesurgical Systems

The concepts of telemedicine, telesurgery, and telepresence in surgery date from the 1970s. Since then, the potential for telesurgical systems to facilitate effective interventions in remote or hostile environments such as the battlefield, space, or thinly populated areas has continued to be recognized [52.63], and there have been some spectacular demonstrations including a transatlantic cholecystectomy [52.33] in 2001, as well as more nearly routine use in Canada [52.34].

However, the primary uses of telesurgical systems have been with the surgeon and patient in the same operating room. Teleoperated robots have been used for over 15 years in MIS, both as auxiliary surgical support systems to hold endoscopes or retractors [52.14, 16, 64, 65] and as *surgeon extender* systems to manipulate surgical instruments [52.2, 17]. There has also been recent work to develop telesurgical systems for use within imaging environments such as MRI [52.32].

A primary challenge for auxiliary support systems is to permit the surgeon to command the robot while his or her hands are otherwise occupied. Typical approaches have included conventional foot switches [52.14], instrument-mounted joysticks [52.16], voice control [52.7, 16], and computer vision [52.16, 66, 67].

A common goal in surgeon extender systems is to provide a measure of telepresence to the surgeon, specifically, to give the surgeon the sensation of performing open surgery from inside the patient. In early work, *Green* et al. [52.68] developed a successful prototype system for telesurgery combining remote manipulation, force feedback, stereoscopic imaging, ergonomic design, etc. Subsequently, several commercial telesurgical systems have been applied clinically for MIS. Of these,

Intuitive Surgical's daVinci [52.2] has been the most successful, with over 400 systems deployed as of 2007. Experience with these systems has demonstrated that a high-dexterity wrist is often critical for surgeon acceptance. Although originally targeted at cardiac surgery, as well as more general interventions, to date one of the most successful clinical applications has been in radical prostatectomies, where significant improvements in outcomes have been reported [52.69].

One emerging area for research exploits the inherent ability of telesurgical systems to act as *flight data recorders* during surgical procedures. Several authors [52.70–72] have begun analyzing such data for such purposes as measuring surgical skill, learning surgical gestures and motions, and providing data for surgical simulators.

52.3.5 Microsurgery Systems

Although *microsurgery* is not a consistently defined term, it generally indicates procedures performed on very small, delicate structures, such as those found in the eye, brain, spinal cord, small blood vessels, nerves, or the like. Microsurgical procedures are commonly performed under direct or video visualization, using some form of magnification (e.g., microscope, surgical loupes, high-magnification endoscope). The surgeon typically has little or no tactile appreciation of the forces being exerted by the surgical instruments and physiological hand tremor can be a significant factor limiting surgical performance.

There have been several efforts to compare microsurgical anastamosis procedures using laparoscopic telesurgical systems to conventional microsurgery. *Schiff* et al. [52.73] among others reported significant reductions in tremor with either robot and significantly improved technical quality and operative times compared to conventional microsurgery. A number of groups have implemented telesurgery systems specifically for microsurgery [52.27, 74–76]. These systems are in various stages of development, from laboratory prototype to preliminary clinical experimentation.

Not all microsurgical robots are teleoperated. For example, the cooperatively controlled JHU Steady Hand robots [52.3, 4] shown in Fig. 52.3 are being developed for retinal, head-and-neck, neurosurgery, and other microsurgical applications.. A modified version of this system has also been used for microinjections into single mouse embryos [52.77].

There have also been efforts to develop completely hand-held instruments that actively cancel physiological tremor, for example, *Riviere* et al. [52.78] have developed an ophthalmic instrument using inertial sensors in the handle and adaptive filtering to estimate the tremulous component of instrument motion. A micromanipulator built into the instrument deflects the tip with an equal but opposite motion, compensating the tremor. Simple mechanical devices [52.79] for reducing tremor in specific tasks have also been developed.

An additional type of hand-held microsurgical and micro-therapeutic devices is reported in [52.80], which describes an active microendoscope for neuroendoscopy and therapy of the spinal cord able to safely navigate in the subarachnoid space and to avoid dangerous contact with the internal delicate structures thanks to a system based on hydrojets. Hydrojets come from the lateral surface of the catheter and, appropriately tuned and oriented, allow the tip of the endoscope to proceed without touching the spinal cord internal walls. The shared control system of the neuroendoscope, based on processing, segmentation, and analysis of the endoscopic images, assists the safe advancement of the tool in real time [52.81].

52.3.6 Endoluminal Robots

The term *endoluminal surgery* was first coined by *Cuschieri* et al. [52.82] as a major component of endoscopic surgery. Endoluminal procedures consist of bringing a set of advanced therapeutic and surgical tools to the area of interest by navigating in the lumina (i. e., the tube-like structures) of the human body, such as the gastrointestinal (GI) tract, the urinary tract, the circulatory system, etc. Currently, most endoluminal robots are designed for gastrointestinal applications, although there has been some initial work for other areas.

Traditionally, catheters and flexible endoscopes for endoluminal procedures have been inserted and manipulated manually from outside the body with the assistance of one or more visualization systems (e.g., direct endoscopic video, X-ray fluoroscopy, ultrasound). One major challenge is limited dexterity making it difficult to reach the desired target. Typically, flexible endoscopes have a bendable tip that can be steered by means of cable drives, and catheters may have only a fixed bend on a guide wire. There is also the inherent difficulty of *pushing a rope*. Once the target site is reached, these limitations become even more significant. Very simple instruments can be inserted through working channels or slid over guide wires, but dexterity is severely limited and there is no force feedback beyond what can be felt through the long, flexible instrument shaft.

These limitations have led a number of researchers to explore integration of more degrees of freedom in the catheter/endoscope body, as well as the design of intelligent tips with higher dexterity and sensing capabilities. Early work by Ikuta et al. led to the development of a five-segment, 13 mm-diameter sigmoidscope using shape-memory alloy (SMA) actuators. Subsequently, Ikuta developed 3 mm-diameter active endovascular devices using hydraulic actuators incorporating a novel band pass valve fabricated using micro-stereolithographic techniques [52.21].

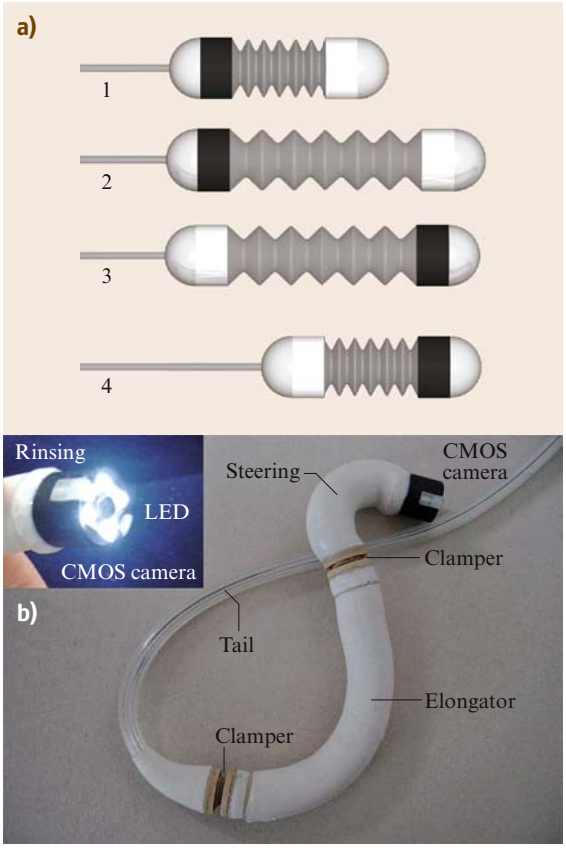

Fig. 52.10a,b Medical robot for colonoscopy [52.25]: **(a)** the *gait* cycle of the robot, consisting of: (1) proximal clamping, (2) elongation, (3) distal clamping, and (4) retraction; **(b)** a recent working prototype used for clinical trials

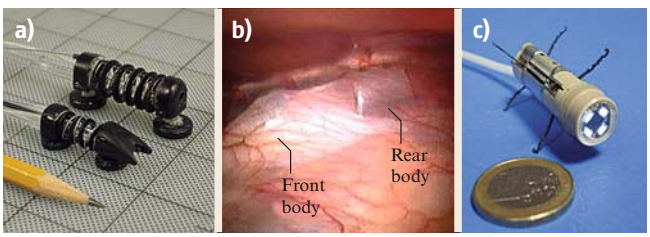

Fig. 52.11a–c Mobility inside the body. **(a,b)** *HeartLander* device for crawling across the surface of the heart [52.23]. **(c)** Legged capsule for gastrointestinal diagnosis and therapy [52.20]

Several examples exist of instrumented catheter tips with force sensors that allow the right branch of the circulatory systems to be found by estimating the force generated between the tip and the vessel walls. Basically, these sensorized endoluminal devices belong to the larger group of micro-electromechanical systems (MEMS)-instrumented surgical devices and the same sensing technologies can be also exploited for microsurgery. A recent survey article by *Rebello* [52.83] provides an excellent overview of sensorized catheters and other MEMS-based devices in endoluminal and microsurgical applications.

A third approach to endoluminal robots is represented by systems that move under their own power through the body, rather than being pushed. Early work on such systems is well summarized in [52.84]. In 1995 Burdick et al. developed an inchworm-like mechanism for use in the colon. This device combined a central extensor for propulsion and inflatable balloons for friction enhancement with the slippery colon tissue. A more advanced inchworm design for a semiautonomous robotic colonoscope was developed by *Dario* et al. [52.25] (Fig. 52.10). This device consists of a central silicone elongator, two clamping systems based on suction and gentle mechanical grasping of the colon tissue, and a silicone steerable tip integrating a complementary metal-oxide-semiconductor (CMOS) camera and a light-emitting diode (LED)-based illumination system. Thanks to its intrinsic flexibility, the robotic colonoscope applies forces on colon tissues that are ten times lower than those produced by traditional colonoscopes. More recent work on legged locomotion for GI applications Fig. 52.11c is reported in [52.20, 85]. Although the application is not endoluminal, the HeartLander system of *Riviere* et al. [52.23] shown in Figs. 52.11a,b shares many of the characteristics of these systems. It uses an inchworm-like gait to traverse the surface of the heart. Recently, Olympus has introduced a wireless gastrointestinal inspection system using external electromagnetic fields to manipulate a capsule camera [52.86]. An earlier application of electromagnetic manipulation of an object within the body was the *video tumor fighter* of *Ritter* et al. [52.87].

52.3.7 Sensorized Instruments and Haptic Feedback

Surgical procedures almost always involve some form of physical interaction between surgical instruments and patient anatomy, and surgeons are accustomed to use their haptic appreciation of tool-to-tissue interaction forces in performing surgical procedures. In situations such as where the clumsiness of instrumentation or human sensory-motor limitations limit the surgeon's ability to feel these forces, surgeons have been trained to rely on visual or other cues to compensate. Apart from the need for haptic feedback for diagnostic procedures and tissue identification, it has been demonstrated that reduced tactile and force information can result in the application of unnecessarily large forces on the patient during surgery, with possible harm to the patient [52.88]. The quality of haptic feedback available in currently deployed surgical robots is poor or nonexistent. Current research addresses the limitations firstly by integrating force and other sensors into surgical end-effectors and secondly by developing improved methods for processing and conveying the sensed information to the surgeon.

Although the most obvious way to *display* haptic information in a telesurgical system is directly through the master hand controllers, this method has several limitations, including friction and limited bandwidth in the hand controllers. Although these issues may be addressed through specialized design (which may raise costs and require other compromises) and improved control, there has been considerable interest in *sensory substitution* schemes [52.89–91] in which force or other sensor information is displayed visually, aurally, or by other means. Figure 52.8c shows one example of sensory substitution for warning when a daVinci robot is about to break a suture [52.46].

Starting in the 1990s, several groups [52.91–93] have *sensorized* surgical instruments for microsurgery and MIS by equipping them with force sensors. Generally, these efforts relied on sensory substitution to display force data, either for freehand or telesurgical application. For example, *Poulose* et al. [52.92] demonstrated that a force sensing instrument used together with an IBM/JHU LARS robot [52.16] could significantly reduce both average retraction force and variability of retraction force during Nissen fundoplication. *Rosen* et al. [52.93] developed a force-controlled teleoperated endoscopic grasper equipped with position sensors and actuated by direct-current (DC) motors whose output torque is sensed and fed back through motors integrated in a grasping handle. A similar approach was used by *Menciassi* et al. [52.94] for a microsurgery gripper equipped with semiconductor strain gauges and a PHANTOM (SensAble Technologies, Inc.) haptic interface.

Several researchers [52.95] have focused on specialized *fingers* and display devices for palpation tasks requiring delicate tactile feedback (e.g., for detecting hidden blood vessels or cancerous tissues beneath normal tissues). There has also been work to integrate nonhaptic sensors into surgical instruments, for example, *Fischer* et al. have developed instruments measuring both force and tissue oxygenation levels [52.96]. This information can be used for such purposes as assessing tissue viability, distinguishing between different tissue types, and controlling retraction so as not to cause ischemic tissue damage.

Finally, it is important to note that sensorized surgical tools have important application beyond their direct use in surgical procedures, for example, one use is in biomechanical studies to measure organ and tissue mechanical properties to improve surgical simulators.

52.3.8 Surgical Simulators and Telerobotic Systems for Training

Medical education is undergoing significant changes. The traditional paradigm for surgical technical training is often summarized as "see one, do one, teach one". This method can be effective in open surgery, where the surgical trainee directly observes the expert surgeon hands, sees the instrument motion, and follows the organ manipulation. However, in endoscopic surgery it is difficult to observe the surgeon's hand movements (outside the body) and the surgical tool actions (inside the body and only visible on a video monitor). In addition, endoscopic surgery requires different skills than open surgery, such as spatial orientation, interpretation of 2-D images in 3-D, and manipulating instruments through entry portals. These considerations led to introduction of surgical simulation systems of varying degrees of complexity and realism for endoscopic and other minimally invasive procedures. Nowadays, training simulators have achieved widespread acceptance in the field of anaesthesia, intensive care, flexible endoscopy, surgery, interventional radiology, and other fields. The use of simulators for training is so common that working groups have been set up in order to evaluate these training systems based on shared guidelines [52.97] and many teaching hospitals have extensive simulation training centers.

A recent survey [52.98] divides training simulators into three groups, depending on the type of technology used: mechanical, hybrid, and virtual reality.

Mechanical simulators are boxes where objects or organs are placed and manipulated using surgical instruments. The manipulation is observed through a laparoscope and a screen. The simulated surgical task is observed by an experienced surgeon, who gives feedback to the trainee. Generally, there are no registration processes and the simulator must be reassembled after any training session. The *LapTrainer with SimuVision* (Simulab Inc., Seattle, USA) is a training system with a simulated laparoscope that consists of a boom-mounted digital camera in an open box trainer. The Johns Hopkins Urobotics has also developed mechanical simulators and a set of experiments for training in laparoscopy, which is also able to provide a quantifiable scale of dexterity.

A hybrid simulator uses a box with objects or organs as a mechanical simulator, but in addition the performance of the trainee are monitored by a computer which gives guidance for the task execution and an objective feedback based on preplanned metrics. Thanks to this feedback, the assistance and judgement of an experienced surgeon are not strictly necessary, for example, the ProMIS (Haptica Inc., Boston, USA) is a typical hybrid simulator for training basic skills such as suturing and knot tying. Surgical instruments are passed through dedicated ports and the trainee receives the same haptic feedback as in real surgery during manipulation in the box. In addition, ProMIS analyzes the trainee's performance by tracking the instrument position in 3-D and by measuring the execution time, path length, and smoothness of task execution.

Finally, *virtual-reality* training systems combine visualization and haptic interfaces to enable surgeons to interact efficiently and naturally with real-time computational models of patient anatomy [52.99]. The development of these systems is inherently a multidisciplinary effort, including real-time computer graphics, the development of high-bandwidth haptic devices, real-time biomechanical modeling of organs, tool–tissue interactions, expertise in training assessment, and human–machine information exchange, etc. [52.100]. Research in these areas is closely related to and synergistic with comparable developments in technology and systems for performing real interventions, for example, modeling of organ motion in response to forces is necessary to improve the accuracy of needle placement procedures. Haptic feedback devices must meet similar requirements whether the forces displayed are simulated or measured directly in telesurgery, and so on. Finally, as noted earlier, *sensorized* instruments and real-time imaging are critical sources of data needed to create realistic biomechanical models.

The variety of interface devices and virtual reality laparoscopic simulators is quite wide and increasing numbers of systems are becoming commercially available. The Phantom interface is used in conjunction with virtual simulators to provide users with realistic haptic feedback (SensAble Technologies Inc., Woburn, MA, USA). The Xitact LS500 laparoscopy simulator (Xitact S.A., Lausanne, Switzerland) is a modular virtual-reality simulation platform with software for training and assessing performance in laparoscopic tasks. It is an open system including all or some of these subsystems: laparoscopic tools, mechanical abdomen, a personal computer (PC) providing the virtual-reality scenario, a haptic interface, a force feedback system and a tracking system for the tools. Several other systems for virtual reality simulation exist that exploit the hardware from Xitact or Immersion Medical, Inc. (Gaithersburg, MD, USA) and that are dedicated to specific surgical tasks: Lapmentor [52.101], the Surgical Education platform [52.102], LapSim [52.103], Procedicus MIST [52.104], EndoTower [52.105], the Reachin laparoscopic trainer [52.106], Simendo [52.107], and the Vest system [52.108]. Specifically for training eye surgeons, the surgical simulator EYESi [52.109] uses advanced computer technology and virtual reality to simulate the feel of real eye surgery, making it possible for surgeons at all levels to acquire new skills and perfect their techniques in preparation for surgery on the human eye.

Making a comparison between these different categories of simulators is not trivial. Basically, box trainers and hybrid simulators require some experienced technicians for the set up and some organizational logistics due to legal and ethical factors related to the storage of freshly explanted organs. The most evident advantage of these simulators is that the tactile response from the manipulated objects is the same as in real surgery and complicated models of organs and tissue–tool interaction are not required. On the other hand, completely virtual-reality trainers are potentially very flexible, but they are limited by currently available computer and graphics hardware capabilities, as well as by the quality of current-generation anatomical and biomechanical models. Although demonstrations exist of the ability of simulators to record, objectively score, and hone the psychomotor skills of novice surgeons [52.110], the debate about the real improvement of surgical abilities is still open and conclusions are sometimes controversial.

52.3.9 Other Applications and Research Areas

The research areas described above illustrate major themes within medical robotics, but they are by no means exhaustive. Many important application areas such as otolaryngology [52.111–114] and radiation therapy have necessarily been excluded for space reasons. For a fuller exploration, readers should consult the further reading suggestions in Sect. 52.4.

52.4 Conclusion and Future Directions

Medical robotics (and the larger field of *computer-integrated interventional medicine*) has great potential to revolutionize clinical practice by:

- exploiting technology to transcend human limitations in treating patients
- improving the safety, consistency, and overall quality of interventions
- improving the efficiency and cost-effectiveness of patient care
- improving training through the use of simulators, quantitative data capture and skill assessment methods, and the capture and playback of clinical cases
- promoting more effective use of information at all levels, both in treating individual patients and in improving treatment processes

From being the stuff of late-night comedy and science fiction 20 years ago, the field has reached a critical threshold, with clinically useful systems and commercial successes. The scope and number of research programs has grown exponentially in the past 5 years, and this chapter is by no means a comprehensive survey of the field. Interested readers are urged to refer to the further reading section for more complete treatments. In particular, the survey articles in listed at the end of this section collectively contain somewhat fuller bibliographies than space permits here.

In the future, we can expect to see continued research in all aspects of technology and system development, with increasing emphasis on clinical applications. As this work proceeds, it is important that researchers remember several basic principles. The first, and arguably most important, principle is that medical robotics is fundamentally a *team* activity, involving academic researchers, clinicians, and industry. Each of these groups has unique expertise, and success comes from effective, highly interactive partnerships drawing upon this expertise. Building these teams takes a long-term commitment, and the successes in recent years are largely the pay-off from investments in creating these teams. Second, it is important to work on problems with well-defined clinical and technical goals, in which the criteria for measuring success are ultimately related to real advantages in treating patients. In working toward these goals, it is important to have measurable and meaningful milestones and to emphasize rapid iteration with clinician involvement at all stages. Finally, it is essential that all team members recognize the level of commitment that is required to achieve success and that they enjoy what they are doing.

Books

- R. H. Taylor, S. Lavallee, G. Burdea, R. Mosges: *Computer-Integrated Surgery*, (MIT, Cambridge 1996)
- J. B. Stiehl, W. H. Konerman, R. G. Haaker: *Navigation and Robotics in Total Joint and Spine Surgery*, (Springer, Berlin Heidelberg 2003)
- A. DiGioia, B. Jaramaz, F. Picard, L. P. Nolte: *Computer and Robotic Assisted Knee and Hip Surgery*, (Oxford Univ. Press, Oxford 2004)
- R. Faust: *Surgical Robotics – History, Present and Future Applications* (Nova Sci., New York 2006)
- R. J. Maciunas: *Interactive Image-Guided Neurosurgery*, (Am. Assoc. Neurol. Surgeons, Rolling Meadows 1993)
- J. L. Prince and J. M. Links: *Medical Imaging Signals and Systems* (Prentice Hall, Upper Saddle River 2006)

Special Issues and Conference Proceedings

- *IEEE Trans. Robot. Autom.* Special Issue on Medical Robotics (2003)
- *IEEE Proceedings* Special Issue on Medical Robotics (2006)
- The *Proceedings of the IEEE Conference on Robotics and Automation* (IEEE Press) contain many medical robotics papers, especially in the years since 2003
- The *Proceedings of the International Symposia on Medical Image Computing and Computer Assisted*

Interventions, Lecture Notes in Computer Science (Springer, Berlin, Heidelberg) contain many medical robotics papers with special emphasis on image-guided systems

- The *Proceedings of the* IEEE/RAS-EMBS *International Conference Biomedical Robotics and Biomechatronics (BioRob)* report a new conference series, first held in Pisa in February 2006, with many pertinent papers.
- *Minimally Invasive Therapy* **14**, 4–5 (2005) This entire issue is devoted to surgical simulators and surgical training

Survey Articles

- R. H. Taylor, D. Stoianovici: Medical robotics in computer-integrated surgery, IEEE Trans. Robot. Autom. **19**, 765–781 (2003)
- R. H. Taylor, L. Joskowicz: Computer-integrated surgery and medical robotics. In: *Standard Handbook of Biomedical Engineering and Design*, ed. M. Kutz: (McGraw-Hill, New York 2002) 29.3–29.45.
- P. Dario, B. Hannaford, and A. Menciassi: Smart surgical tools and augmenting devices, IEEE Trans. Robot. Autom. **19**, 782–792 (2003)
- T. Peters: Image-guidance for surgical procedures, Phys. Med. Biol. **51**, R505–R540 (2006)
- J. B. Maintz, M. A. Viergever: A survey of medical image registration, Med. Image Anal. **2**(1) 1–37 (1998)
- S. Lavallee: Registration for computer-integrated surgery: methodology, state of the art. In: *Computer-Integrated Surgery*, ed. R. H. Taylor, S. Lavallee, G. Burdea, R. Mosges (MIT Press, Cambridge 1996) pp. 77–98
- P. Kazanzides: Robots for orthopaedic joint reconstruction, In: *Robotics in Surgery: History, Current and Future Applications*, ed. R. A. Faust (Nova Science, New York 2007)
- P. B. McBeth, D. F. Louw, P. R. Rizun, G. R. Sutherland: Robotics in neurosurgery, Am. J. Surg. **188** 68S–75S (2004)
- D. Burschka, J. J Corso, M Dewan, W. Lau, M. Li, H. Lin, P. Marayoung, N. Ramey, G. D. Hager, B. Hoffman, D. Larkin, C. Hasser: Navigating inner space: 3-D assistance for minimally invasive surgery, Robot. Aut. Syst. **52** 5–26 (2005)
- D. Camarillo, T. M. Krummel, J. K. Salisbury: Robotic technology in surgery: past, present and future, The Am. J. Surg. **188** (2004)
- I. Kassim, L. Phee, W.S. Ng, G. Feng, P. Dario, C.A. Mosse: Locomotion techniques for robotic colonoscopy, IEEE Eng. Med. Biol. Mag. **25**(3), 49–56 (2006)
- R. H. Taylor: *A Perspective on Medical Robotics*, IEEE Proc., **94**, 1652–1664 (2006)
- R. H. Taylor, P. Kazanzides: Medical robotics and computer-integrated interventional medicine. In: *Biomedical Information Technology* ed. D. Feng (Elsevier, 2007)
- K. J. Rebello: Applications of MEMS in surgery, Proc. IEEE **992**, 43–55 (2004)
- A. Liu, F. Tendick, K. Cleary, and C. Kaufmann: A survey of surgical simulation: applications, technology, and education, Teleop. Virt. Environ. **12**, 599–614 (2003)

References

52.1 R.H.L. Taylor Joskowicz: Computer-integrated surgery and medical robotics. In: *Standard Handbook of Biomedical Engineering and Design*, ed. by M. Kutz (McGraw Hill, New York 2003) pp. 29.23–29.45

52.2 G.S. Guthart, J.K. Salisbury: The intuitive telesurgery system: overview and application, IEEE Int. Conf. Robot. Autom. (ICRA2000) (San Francisco 2000) pp. 618–621

52.3 R. Taylor, P. Jensen, L. Whitcomb, A. Barnes, R. Kumar, D. Stoianovici, P. Gupta, Z.X. Wang, E. deJuan, L. Kavoussi: Steady-hand robotic system for microsurgical augmentation, Int. J. Robot. Res. **18**, 1201–1210 (1999)

52.4 D. Rothbaum, J. Roy, G. Hager, R. Taylor, L. Whitcomb: Task performance in stapedotomy: comparison between surgeons of different experience levels, Otolaryngol. Head Neck Surg. **128**, 71–77 (2003)

52.5 J.R. Adler, M.J. Murphy, S.D. Chang, S.L. Hankock: Image guided robotic radiosurgery, Neurosurgery **44**(6), 1299–1306 (1999)

52.6 A. Amin, J. Grossman, W. P: Early experience with a computerized robotically controlled catheter system, J. Int. Card. Electrophysiol., Vol. 12 (2005) pp. 199–202

52.7 L. Mettler, M. Ibrahim, W. Jonat: One year of experience working with the aid of a robotic assistant (the voice-controlled optic holder AESOP) in gynaecological endoscopic surgery, Hum. Reprod. **13**, 2748–2750 (1998)

52.8 R.H. Taylor, H.A. Paul, P. Kazandzides, B.D. Mittelstadt, W. Hanson, J.F. Zuhars, B. Williamson, B.L. Musits, E. Glassman, W.L. Bargar: An image-directed robotic system for precise orthopaedic surgery, IEEE Trans. Robot. Autom., Vol. 10 (1994) pp. 261–275

52.9 P. Kazanzides, B.D. Mittelstadt, B.L. Musits, W.L. Bargar, J.F. Zuhars, B. Williamson, P.W. Cain, E.J. Carbone: An integrated system for cementless hip replacement, IEEE Eng. Med. Biol. **14**, 307–313 (1995)

52.10 Q. Li, L. Zamorano, A. Pandya, R. Perez, J. Gong, F. Diaz: The application accuracy of the NeuroMate robot – A quantitative comparison with frameless and frame-based surgical localization systems, Comput. Assisted Surg. **7**(2), 90–98 (2002)

52.11 P. Cinquin, J. Troccaz, J. Demongeot, S. Lavallee, G. Champleboux, L. Brunie, F. Leitner, P. Sautot, B. Mazier, A. Perez, M. Djaid, T. Fortin, M. Chenic, A. Chapel: IGOR: image guided operating robot, Innovation Technonogie Biologie Med. **13**, 374–394 (1992)

52.12 H. Reichenspurner, R. Demaino, M. Mack, D. Boehm, H. Gulbins, C. Detter, B. Meiser, R. Ellgass, B. Reichart: Use of the voice controlled and computer-assisted surgical system Zeus for endoscopic coronary artery surgery bypass grafting, J. Thoracic Cardiovasc. Surg. **118**, 11–16 (1999)

52.13 Y.S. Kwoh, J. Hou, E.A. Jonckheere, S. Hayati: A robot with improved absolute positioning accuracy for CT guided stereotactic brain surgery, IEEE Trans. Biomed. Eng. **35**, 153–161 (1988)

52.14 J.M. Sackier, Y. Wang: Robotically assisted laparoscopic surgery. From concept to development, Surg. Endosc. **8**, 63–66 (1994)

52.15 D. Stoianovici, L. Whitcomb, J. Anderson, R. Taylor, L. Kavoussi: A modular surgical robotic system for image-guided percutaneous procedures, Med. Image Comput. Comput.-Assisted Interventions (MICCAI-98) (Cambridge 1998) pp. 404–410

52.16 R.H. Taylor, J. Funda, B. Eldridge, K. Gruben, D. LaRose, S. Gomory, M. Talamini, L.R. Kavoussi, J. Anderson: A telerobotic assistant for laparoscopic surgery, IEEE Eng. Med. Biol. Mag. **14**, 279–287 (1995)

52.17 M. Mitsuishi, T. Watanabe, H. Nakanishi, T. Hori, H. Watanabe, B. Kramer: A telemicrosurgery system with colocated view and operation points and rotational-force-feedback-free master manipulator, 2nd Int. Symp. Med. Robot. Comput. Assisted Surg. (Baltimore 1995) pp. 111–118

52.18 N. Simaan, R. Taylor, P. Flint: High dexterity snake-like robotic slaves for minimally invasive telesurgery of the throat, Int. Symp. Med. Image Comput. Comput.-Assisted Interventions (2004) pp. 17–24

52.19 K. Ikuta, M. Tsukamoto, S. Hirose: Shape memory alloy servo actuator system with electric resistance feedback and application for active endoscope. In: *Computer-Integrated Surgery*, ed. by R.H. Taylor, S. Lavallee, G. Burdea, R. Mosges (MIT Press, Cambridge 1996) pp. 277–282

52.20 A. Menciassi, C. Stefanini, S. Gorini, G. Pernorio, P. Dario, B. Kim, J.O. Park: Legged locomotion in the gastrointestinal tract problem analysis and preliminary technological activity, IEEE/RSJ Int. Conf. Intell. Robots Syst. (2004) pp. 937–942

52.21 K. Ikuta, H. Ichikawa, K. Suzuki, D. Yajima: Multi-degree of freedom hydraulic pressure driven safety active catheter, IEEE Int. Conf. Robot. Autom. (Orlando 2006) pp. 4161–4166

52.22 S. Guo, J. Sawamoto, Q. Pan: A novel type of microrobot for biomedical application, IEEE/RSJ Int. Conf. Intell. Robots Syst. (2005) pp. 1047–1052, .

52.23 N. Patronik, C. Riviere, S.E. Qarra, M.A. Zenati: The heartlander: a novel epicardial crawling robot for myocardial injections, 19th Int. Congress Comput. Assisted Radiology Surg. (2005) pp. 735–739

52.24 P. Dario, B. Hannaford, A. Menciassi: Smart surgical tools and augmenting devices, IEEE Trans. Robot. Autom, Vol. 19 (2003) pp. 782–792

52.25 L. Phee, D. Accoto, A. Menciassi, C. Stefanini, M.C. Carrozza, P. Dario: Analysis and development of locomotion devices for the gastrointestinal tract, IEEE Trans. Biomed. Eng., Vol. 49 (2002) pp. 613–616

52.26 N. Suzuki, M. Hayashibe, A. Hattori: Development of a downsized master-slave surgical robot system for intragastic surgery, ICRA Surg. Robot. Workshop (Barcelona 2005)

52.27 K. Ikuta, K. Yamamoto, K. Sasaki: Development of remote microsurgery robot and new surgical procedure for deep and narrow space, IEEE Conf. Robot. Autom. (Taiwan 2003) pp. 1103–1108

52.28 C. Plaskos, P. Cinquin, S. Lavallee, A.J. Hodgson: Praxiteles: a miniature bone-mounted robot for minimal access total knee arthroplasty, Int. J. Med. Robot. Comput. Assisted Surg., Vol. 1 (2005) pp. 67–79

52.29 P.J. Berkelman, L. Whitcomb, R. Taylor, P. Jensen: A miniature microsurgical instrument tip force sensor for enhanced force feedback during robot-assisted manipulation, IEEE Trans. Robot. Autom., Vol. 19 (2003) pp. 917–922

52.30 K. Chinzei, R. Gassert, E. Burdet: Workshop on MRI/fMRI compatible robot technology – a critical tool for neuroscience and image guided intervention, IEEE Int. Conf. on Robot. Autom. (Orlando 2006)

52.31 M. Jakopec, S.J. Harris, F.R.Y. Baena, P. Gomes, J. Cobb, B.L. Davies: The first clinical application of a hands-on robotic knee surgery system, Comput. Aided Surg. **6**, 329–339 (2001)

52.32 D.F. Louw, T. Fielding, P.B. McBeth, D. Gregoris, P. Newhook, G.R. Sutherland: Surgical robotics: A review and neurosurgical prototype development, Neurosurgery **54**, 525–537 (2004)

52.33 J. Marescaux, J. Leroy, M. Gagner, F. Rubino, D. Mutter, M. Vix, S.E. Butner, M.K. Smith: Transatlantic robot-assisted telesurgery, Nature **413**, 379–380 (2001)

52.34 M. Anvari, T. Broderick, H. Stein, T. Chapman, M. Ghodoussi, D.W. Birch, C. Mckinley, P. Trudeau, S. Dutta, C.H. Goldsmith: The impact of latency on surgical precision and task completion during robotic-assisted remote telepresence surgery, Comput. Aided Surg. **10**, 93–99 (2005)

52.35 M. Li, M. Ishii, R.H. Taylor: Spatial motion constraints in medical robot using virtual fixtures generated by anatomy, IEEE Trans. Robot. **23**, 4–19 (2007)

52.36 S. Park, R.D. Howe, D.F. Torchiana: Virtual fixtures for robotic cardiac surgery, Fourth Int. Conf. Med. Image Comput. Computer-Assisted Intervention (2001)

52.37 B. Davies: A discussion of safety issues for medical robots. In: *Computer-Integrated Surgery*, ed. by R. Taylor, S. Lavallee, G. Burdea, R. Moesges (MIT Press, Cambridge 1996) pp. 287–296

52.38 P. Varley: Techniques of development of safety-related software in surgical robots, IEEE Trans. Inform. Technol. Biomed. **3**, 261–267 (1999)

52.39 J.B. Maintz, M.A. Viergever: A survey of medical image registration, Med. Image Anal. **2**, 1–37 (1998)

52.40 S. Lavallee: Registration for computer-integrated surgery: methodology, state of the Art. In: *Computer-Integrated Surgery*, ed. by R.H. Taylor, S. Lavallee, G. Burdea, R. Mosges (MIT Press, Cambridge 1996) pp. 77–98

52.41 P.J. Besl, N.D. McKay: A method for registration of 3-D shapes, IEEE Trans. Pattern Anal. Machine Intell. **14**, 239–256 (1992)

52.42 R.J. Maciunas: *Interactive Image-Guided Neurosurgery* (Am. Association Neurological Surg., USA 1993)

52.43 R.H. Taylor, H.A. Paul, C.B. Cutting, B. Mittelstadt, W. Hanson, P. Kazanzides, B. Musits, Y.Y. Kim, A. Kalvin, B. Haddad, D. Khoramabadi, D. Larose: Augmentation of human precision in computer-integrated surgery, Innov. Technol. Biol. Med. **13**, 450–459 (1992)

52.44 J. Troccaz, M. Peshkin, B. Davies: The use of localizers, robots and synergistic devices in CAS, CVRMed-MRCAS **1205**, 727–736 (1997)

52.45 G. Fichtinger, A. Degeut, M. K, E. Balogh, G. Fischer, H. Mathieu, R.H. Taylor, S. Zinreich, L.M. Fayad: Image overlay guidance for needle insertion on CT scanner, IEEE Trans. Biomed. Eng. **52**, 1415–1424 (2005)

52.46 T. Akinbiyi, C.E. Reiley, S. Saha, D. Burschka, C.J. Hasser, D.D. Yuh, A.M. Okamura: Dynamic augmented reality for sensory substitution in robot-assisted surgical systems, 28th Annu. Int. Conf. IEEE Eng. Med. Biology Society (2006) pp. 567–570

52.47 J. Leven, D. Burschka, R. Kumar, G. Zhang, S. Blumenkranz, X. Dai, M. Awad, G. Hager, M. Marohn, M. Choti, C. Hasser, R.H. Taylor: DaVinci canvas: a telerobotic surgical system with integrated, robot-assisted, laparoscopic ultrasound capability, Med. Image Comput. Computer-Assisted Interventions (Palm Springs 2005)

52.48 S. Solomon, A. Patriciu, R.H. Taylor, L. Kavoussi, D. Stoianovici: CT guided robotic needle biopsy: a precise sampling method minimizing radiation exposure, Radiology **225**, 277–282 (2002)

52.49 K. Masamune, G. Fichtinger, A. Patriciu, R. Susil, R. Taylor, L. Kavoussi, J. Anderson, I. Sakuma, T. Dohi, D. Stoianovici: System for robotically assisted percutaneous procedures with computed tomography guidance, J. Comput. Assisted Surg. **6**, 370–383 (2001)

52.50 A. Krieger, R.C. Susil, C. Menard, J.A. Coleman, G. Fichtinger, E. Atalar, L.L. Whitcomb: Design of a novel MRI compatible manipulator for image guided prostate intervention, IEEE Trans. Biomed. Eng. **52**, 306–313 (2005)

52.51 G.A. Krombach, T. Schmitz-Rode, B.B. Wein, J. Meyer, J.E. Wildberger, K. Brabant, R.W. Gunther: Potential of a new laser target system for percutaneous CT-guided nerve blocks: technical note, Neuroradiology **42**, 838–841 (2000)

52.52 M. Rosenthal, A. State, J. Lee, G. Hirota, J. Ackerman, K. Keller, E.D. Pisano, M. Jiroutek, K. Muller, H. Fuchs: Augmented reality guidance for needle biopsies: a randomized, controlled trial in phantoms, Fourth Int. Conf. Med. Image Comput. Computer-Assisted Intervention (2001) pp. 240–248

52.53 G. Stetten, V. Chib: Overlaying ultrasound images on direct vision, J. Ultrasound Med. **20**, 235–240 (2001)

52.54 H.F. Reinhardt: Neuronagivation: a ten years review. In: *Computer-Integrated Surgery*, ed. by R. Taylor, S. Lavallée, G. Burdea, R. Moegses (MIT Press, Cambridge 1996) pp. 329–342

52.55 E. Hempel, H. Fischer, L. Gumb, T. Hohn, H. Krause, U. Voges, H. Breitwieser, B. Gutmann, J. Durke, M. Bock, A. Melzer: An MRI-compatible surgical robot for precise radiological interventions, Comput. Aided Surg. **8**, 180–191 (2003)

52.56 Z. Wei, G. Wan, L. Gardi, G. Mills, D. Downey, A. Fenster: Robot-assisted 3D-TRUS guided prostate brachytherapy: system integration and validation, Med. Phys. **31**, 539–548 (2004)

52.57 E. Boctor, G. Fischer, M. Choti, G. Fichtinger, R.H. Taylor: Dual-armed robotic system for intraoperative ultrasound guided hepatic ablative therapy: a prospective study, IEEE Int. Conf. Robot. Autom. (2004) pp. 377–382

52.58 J. Hong, T. Dohi, M. Hashizume, K. Konishi, N. Hata: An ultrasound-driven needle-insertion robot for percutaneous cholecystostomy, Phys. Med. Biol. **49**, 441–455 (2004)

52.59 G. Megali, O. Tonet, C. Stefanini, M. Boccadoro, V. Papaspyropoulis, L. Angelini, P. Dario: A computer-assisted robotic ultrasound-guided biopsy system for video-assisted surgery, Med. Image Comput. Computer-Assisted Intervention – MICCAI 2001 (Utrecht 2001) pp. 343–350

52.60 S. Okazawa, R. Ebrahimi, J. Chuang, S. Salcudean, R. Rohling: Hand-held steerable needle device, IEEE/ASME Trans. Mechatron. **10**, 285–296 (2005)

52.61 R.J. Webster III, J.S. Kim, N.J. Cowan, G.S. Chirikjian, A.M. Okamura: Nonholonomic modeling of needle steering, Int. J. Robot. Res. **25**(5-6), 509–525 (2006)

52.62 J. Engh, G. Podnar, D. Kondziolka, C. Riviere: Toward effective needle steering in brain tissue, 28th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. (2006) pp. 559–562

52.63 G.H. Ballantyne: Robotic surgery, telerobotic surgery, telepresence and telementoring, Surg. Endosc. **16**, 1389 (2002)

52.64 J.A. McEwen, C.R. Bussani, G.F. Auchinleck, M.J. Breault: Development and initial clinical evaluation of pre-robotic and robotic retraction systems for surgery, Second Workshop Med. Health Care Robot. (Newcastle 1989) pp. 91–101

52.65 P. Berkelman, P. Cinquin, J. Troccaz, J. Ayoubi, C. Letoublon, F. Bouchard: A compact, compliant laparoscopic endoscope manipulator, IEEE Int. Conf. Robot. Aut. (2002) pp. 1870–1875

52.66 A. Nishikawa, T. Hosoi, K. Koara, T. Dohi: FAce MOUSe: A novel human-machine interface for controlling the position of a laparoscope, IEEE Trans Robot. Autom. **19**, 825–841 (2003)

52.67 A. Krupa, J. Gangloff, C. Doignon, M.F. deMathelin, G. Morel, J. Leroy, L. Soler, J. Marescaux: Autonomous 3-D positioning of surgical instruments in robotized laparoscopic surgery using visual servoing, IEEE Trans. Robot. Autom. **19**, 842–853 (2003)

52.68 P. Green, R. Satava, J. Hill, I. Simon: Telepresence: advanced teleoperator technology of minimally invasive surgery (abstract), Surg. Endosc. **6**, 90 (1992)

52.69 T. Ahlering, D. Woo, L. Eichel, D. Lee, R. Edwards, D. Skarecky: Robot-assisted versus open radical prostatectomy: a comparison of one surgeon's outcomes, Urology **63**, 819–822 (2004)

52.70 J. Rosen, J.D. Brown, L. Chang, M. Barreca, M. Sinanan, B. Hannaford: The BlueDRAGON – a system for measuring the kinematics and the dynamics of minimally invasive surgical tools in-vivo, IEEE Int. Conf. Robot. Autom. (2002) pp. 1876–1881

52.71 H.C. Lin, I. Shafran, T.E. Murphy, A.M. Okamura, D.D. Yuh, G.D. Hager: Automatic detection and segmentation of robot-assisted surgical motions, MICCAI (2005) pp. 802–810

52.72 H. Mayer, F. Gomez, D. Wierstra, I. Nagy, A. Knoll, J. Schmidhuber: A system for robotic heart surgery that learns to tie knots using recurrent neural networks, Int. Conf. Intell. Robot. Syst. (IROS) (2006) pp. 543–548

52.73 J. Schiff, P. Li, M. Goldstein: Robotic microsurgical vasovasostomy and vasoepididymostomy: a prospective randomized study in a rat model, J. Urol. **171**, 1720–1725 (2004)

52.74 P.S. Jensen, K.W. Grace, R. Attariwala, J.E. Colgate, M.R. Glucksberg: Toward robot assisted vascular microsurgery in the retina, Graefes Arch. Clin. Exp. Ophthalmol. **235**, 696–701 (1997)

52.75 H. Das, H. Zak, J. Johnson, J. Crouch, D. Frambaugh: Evaluation of a telerobotic system to assist surgeons in microsurgery, Comput. Aided Surg. **4**, 15–25 (1999)

52.76 K. Hongo, S. Kobayashi, Y. Kakizawa, J.I. Koyama, T. Goto, H. Okudera, K. Kan, M.G. Fujie, H. Iseki, K. Takakura: NeuRobot: telecontrolled micromanipulator system for minimally invasive microneurosurgery-preliminary results, Neurosurgery **51**, 985–988 (2002)

52.77 A. Kapoor, R. Kumar, R. Taylor: Simple biomanipulation tasks with a steady hand cooperative manipulator, Sixth Int. Conf. Med. Image Comput. Computer Assisted Intervention – MICCAI 2003 (Montreal 2003) pp. 141–148

52.78 C. Riviere, J. Gangloff, M. de Mathelin: Robotic compensation of biological motion to enhance surgical accuracy, Proc IEEE **94**(9), 1705–1716 (2006)

52.79 W. Armstrong, A. Karamzadeh, R. Crumley, T. Kelley, R. Jackson, B. Wong: A novel laryngoscope instrument stabilizer for operative microlaryngoscopy, Otolaryngol. Head Neck Surg. **132**, 471–477 (2004)

52.80 L. Ascari, C. Stefanini, A. Menciassi, S. Sahoo, P. Rabischong, P. Dario: A new active microendoscope for exploring the sub-arachnoid space in the spinal cord, IEEE Conf. Robot. Autom. (2003) pp. 2657–2662

52.81 U. Bertocchi, L. Ascari, C. Stefanini, C. Laschi, P. Dario: Human-robot shared control for robot-assisted endoscopy of the spinal cord, IEEE/RAS-EMBS Int. Conf. Biomed. Robot. Biomechatron. (2006) pp. 543–548

52.82 A. Cuschieri, G. Buess, J. Perissat: *Operative Manual of Endoscopic Surgery* (Springer, Heidleberg 1992)

52.83 K.J. Rebello: Applications of MEMS in surgery, IE, Vol. 992 (2004) pp. 43–55

52.84 I. Kassim, W.S. Ng, G. Feng, S.J. Phee: Review of locomotion techniques for robotic colonoscopy, Int. Conf. Robot. Autom. (Taipei 2003) pp. 1086–1091

52.85 C. Stefanini, A. Menciassi, P. Dario: Modeling and experiments on a legged microrobot locomoting in a tubular, compliant and slippery environment, Int. J. Robot. Res. **25**, 551–560 (2006)

52.86 Y. Kusuda: A further step beyond wireless capsule endoscopy, Sensor Rev. **25**, 259–260 (2005)

52.87 R.C. Ritter, M.S. Grady, M.A. Howard, G.T. Gilles: Magnetic stereotaxis: computer assisted, image guided remote movement of implants in the brain. In: *Computer Integrated Surgery*, ed. by R.H. Tay-

lor, S. Lavallee, G.C. Burdea, R. Mosges (MIT Press, Cambridge 1995) pp. 363–369
52.88 C.R. Wagner, N. Stylopoulos, P.G. Jackson, R.D. Howe: The benefit of force feedback in surgery: examination of blunt dissection, Presence: Teleoperators Virtual Environments (2007)
52.89 A.M. Okamura: Methods for haptic feedback in teleoperated robot-assisted surgery, Ind. Robot **31**, 499–508 (2004)
52.90 M.J. Massimino: Improved force perception through sensory substitution, Contr. Eng. Practice **3**, 215–222 (1995)
52.91 P. Gupta, P. Jensen, E. de Juan: Quantification of tactile sensation during retinal microsurgery, MICCAI99: Second Int. Conf. Med. Image Comput. Computer-Assisted Intervention (Cambridge 1999)
52.92 P.K. Poulose, M.F. Kutka, M. Mendoza-Sagaon, A.C. Barnes, C. Yang, R.H. Taylor, M.A. Talamini: Human versus robotic organ retraction during laparoscopic nissen fundoplication, Surg. Endosc. **13**, 461–465 (1999)
52.93 J. Rosen, B. Hannaford, M. MacFarlane, M. Sinanan: Force controlled and teleoperated endoscopic grasper for minimally invasive surgery – experimental performance evaluation, IEEE Trans. Biomed. Eng. **46**, 1212–1221 (1999)
52.94 A. Menciassi, A. Eisinberg, M.C. Carrozza, P. Dario: Force sensing microinstrument for measuring tissue properties and pulse in microsurgery, IEEE/ASME Trans. Mechatron. **8**, 10–17 (2003)
52.95 R.D. Howe, W.J. Peine, D.A. Kontarinis, J.S. Son: Remote palpation technology, IEEE Eng. Med. Biol. **14**(3), 318–323 (1995)
52.96 G. Fischer, T. Akinbiyi, S. Saha, J. Zand, M. Talamini, M. Marohn, R. Taylor: Ischemia and force sensing surgical instruments for augmenting available surgeon information, IEEE Int. Conf. Biomed. Robot. Biomechatron. – BioRob 2006 (Pisa 2006)
52.97 F.J. Carter, M.P. Schijven, R. Aggarwal, T. Grantcharov, N.K. Francis, G.B. Hanna, J.J. Jakimowicz: Consensus guidelines for validation of virtual reality surgical simulators, Surg. Endo. **19**, 1523–1532 (2005)
52.98 F.H. Halvorsen, O.J. Elle, E. Fosse: Simulators in surgery, Minimally Invasive Ther. **14**, 214–223 (2005)
52.99 K. Moorthy, Y. Munz, S.K. Sarker, A. Darzi: Objective assessment of technical skills in surgery, Br. Med. J. **327**, 1032–1037 (2003)
52.100 C. Basdogan, S. De, J. Kim, M. Muniyandi, H. Kim, M.A. Srinivasan: Haptics in Minimally Invasive Surgical Simulation and Training, IEEE Comput. Graphics Appl. **24**(2), 56–64 (2004)
52.101 Lapmentor: www.simbionix.com
52.102 Surgical Education platform: www.meti.com
52.103 LapSim: www.surgical-science.com
52.104 MIST: www.mentice.com
52.105 EndoTower: www.verifi.com
52.106 Laparoscopic Trainer: www.reachin.se
52.107 Simendo: www.simendo.nl
52.108 Vest System: www.select-it.de
52.109 EYESI: http://www.vrmagic.com/
52.110 F. Cavallo, G. Megali, S. Sinigaglia, O. Tonet, P. Dario: A biomechanical analysis of surgeon's gesture in a laparoscopic virtual scenario, Studies Health Techn. Informatics **119**, 79–84 (2006)
52.111 K.T. Kavanagh: Applications of image-directed robotics in otolaryngologic surgery, Laryngoscope **194**, 283–293 (1994)
52.112 J. Wurm, H. Steinhart, K. Bumm, M. Vogele, C. Nimsky, H. Iro: A novel robot system for fully automated paranasal sinus surgery, CARS 2003. Comput. Assisted Radiol. Surg. (2003) pp. 633–638
52.113 M. Li, M. Ishii, R.H. Taylor: Spatial motion constraints in medical robot using virtual fixtures generated by anatomy, IEEE Trans. Robot. **2**, 1270–1275 (2006)
52.114 G. Strauss, K. Koulechov, R. Richter, A. Dietz, C. Trantakis, T. Lueth: Navigated control in functional endoscopic sinus surgery, Int. J. Med. Robot. Comput. Assisted Surg. **1**, 31–41 (2005)