A review of robotics in surgery

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Abstract: A brief introduction is given to the definitions and history of surgical robotics. The capabilities and merits of surgical robots are then contrasted with the related field of computer assisted surgery. A classification is then given of the various types of robot system currently being investigated internationally, together with a number of examples of different applications in both soft-tissue and orthopaedic surgery. The paper finishes with a discussion of the main difficulties facing robotic surgery and a prediction of future progress.

Keywords: robotic surgery, computer assisted surgery, active robots, passive robots, safety, imaging, pre-operative planning, registration, fiducials, haptics

1 WHAT IS A SURGICAL ROBOT?

Definitions of industrial robots vary widely. The Robot Institute of America defines a robot as 'A reprogrammable multifunctional manipulator, designed to move material, parts, tools or specialized devices through variable programmed motions for the performance of a variety of tasks'. A reasonable definition of a surgical robot would be 'a powered computer controlled manipulator with artificial sensing that can be reprogrammed to move and position tools to carry out a range of surgical tasks'. It could be argued that this definition implies that a robot has a similar functionality to that of a surgeon. This functional similarity is intentional. It is the externally powered computer controlled mechanism, with sensing and reprogrammable motions, that distinguishes the robot from both the related area of computer assisted surgery and from the surgeon. Thus, although the general functions are similar to a surgeon's, the properties that result are different. The general intention is that such robots should not replace the surgeon, but that the robot should 'assist' the surgeon while under his/her supervision.

One way for the robot to assist the surgeon is to carry out repetitive motions automatically, thus relieving the surgeon of a tiring task (e.g. making small repetitive increments of motion for diathermy of a region). Another is for the robot to position tools very accurately at a predefined location or to move them with micromotions or through a complex path. This means that the target tissue must also be accurately defined and implies the need for accurate imaging, computer modelling and for registration of the robot and tools to both the patient and to the imaging.

These benefits (and requirements) are equally applicable to the area called computer assisted surgery (CAS) (see Section 3), but robots tend to provide greater accuracy and precision than CAS. However, it is mainly in their ability to constrain the tools that robots are superior to CAS. The surgeon holds the tools in CAS and could ignore all warnings to the contrary and cut into unsafe regions. The robot, on the other hand, can be programmed to prevent motions into critical regions or only allow motions along a specified direction (e.g. in orthopaedic surgery, to drill an angled hole or cut to an inclined plane). Thus, provided the robot itself is considered to be safe, robots could be said to enhance the safety of the procedure compared with conventional surgery and to CAS. However, the difficulty is that medical robots do not have generally agreed safety recommendations. Industrial robots are required to operate inside a cage, away from people, and are only powered up when all personnel are excluded. This is clearly inappropriate for surgical robots and agreed international safety guidelines are urgently needed. The author has made proposals for safety recommendations [**1**, **2**] in an attempt to promote a consensus, since uncertainties over the needs for safety are causing robot suppliers to be reluctant to provide commercial systems.

While the above definition of surgical robots requires that they be powered and under computer control, some commentators include simple unpowered manipulator arms as 'robots' [**3**]. These manipulators are a type of localizer (i.e. a means of tracking tools), which is used to hold the tool and point it in a particular direction. With the addition of brakes, the manipulator can be used to clamp the tool at a location. However, the

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inclusion of such manipulators as 'medical robots' can cause confusion with CAS 'pointing' devices or with simple clamps and is, in the author's view, unhelpful to the concept of powered surgical robots.

Compared with CAS systems, the potential benefits available to a well-designed robotic surgery system are:

1. The ability to move in a predefined and reprogrammable complex three-dimensional path, both accurately and predictably.
2. The ability accurately and repeatedly to position and orientate at a reprogrammable point or at a series of points. While CAS systems may also have this ability, robot accuracy is generally higher.
3. The ability to make repetitive motions, for long periods, tirelessly.
4. The ability to move to a location and then hold tools there for long periods accurately, rigidly and without tremor.
5. The ability actively to constrain tools to a particular path or location, even against externally imposed forces, thus preventing damage to vital regions. This can lead to safer procedures than those achieved using CAS.
6. To be able to move, locate and hold tools within hazardous environments without damage to the surgeon (e.g. from fluoroscopic or radioactive sources).
7. To be able to make precise micromotions with prespecified microforces.
8. To be able to respond and adapt very quickly and automatically, either in response to sensor signals or to changes in commands.
9. To be able to perform 'keyhole' minimal access surgery, without the aid of vision and without 'forgetting' the path or the location.

It can be seen from the above that it is no longer appropriate to speak of the benefits of robots over conventional procedures. Rather, the use of robots should be justified over CAS procedures.

2 INTRODUCTION TO THE HISTORY OF MEDICAL ROBOTS

It may seem strange to talk of the 'history' of a subject that is as new as robotic surgery. Indeed, when the author first started research into a robot for prostate surgery in 1988, the only other work in clinical progress was that of Kwoh, who in 1985 first used a standard industrial robot to hold a fixture next to the patient's head to locate a biopsy tool for neurosurgery [**4**]. The robot was locked in position, with power removed, while the surgeon used the fixture in order to orientate drills and biopsy probes, which were inserted into the skull manually by the surgeon. Thus the robot was relegated to the role of a traditional stereotactic frame in neurosurgery. The robot used was a 'Puma 560', which was at that time marketed by Unimation Limited. Shortly after this, the company was sold to Westinghouse Limited, who refused to allow the robot to be used for surgery purposes on the basis that it was unsafe, since the industrial robot was designed to be used inside a barrier away from all contact with people. This position has continued with the present owners, Staubli Automation Limited. Thus, Kwoh's work has ceased, in spite of the encouraging preliminary results which indicated that, compared with a conventional stereotactic frame, the robot could position itself automatically and very accurately.

In parallel with this, Taylor at IBM was developing an industrial robot system for hip surgery [**5**]. This was based on an IBM 'Scara' style of robot, used to hold a rotating cutter which reamed out the proximal femur to take the femoral stem of a prosthetic implant for a total hip replacement. Following laboratory studies, the robot was used on dogs in animal studies and was subsequently transformed into a 'veterinarian robot' for replacing the hips of pet dogs under the direction of veterinary surgeon Dr Hap Paul. The IBM robot was then replaced by a Scara industrial robot from the Japanese company, whose Sanko-Seiki control system had been specifically modified by the manufacturers to incorporate additional safety structures for surgery.

It was not until late 1991 that the modified Sanko-Seiki robot system, now called 'Robodoc', was tried clinically on human patients. Prior to this, in 1988, the author's group at Imperial College carried out laboratory studies into using a Puma 560 industrial robot for soft-tissue surgery, in the transurethral resection of the prostate (TURP) for benign prostatic hyperplasia [**6**]. However, the shapes that had to be resected required two additional frameworks to be mounted on to the Puma robot, resulting in an eight degrees-of-freedom system. The robot was required to move the cutting tool during the procedure, actively to remove tissue. At this time, robot surgery was so new that no such 'active motion' robots had been attempted and there was no precedent for the approach. The author felt that the use of an industrial robot designed to have a large envelope of motions was intrinsically less safe than that of a special-purpose mechanism whose motions and forces were designed specifically for the task. The concept of such a special-purpose robot has gained credibility since that time, because, in addition to being able safely to apply limited forces and motions, a dedicated system has the possibility of using simpler software. In spite of all the advanced computational techniques used to generate safe software, 'keep the program small and simple' remains a major key to software provability [**7**].

After the Puma feasibility studies for TURP, a manually powered special-purpose framework was designed to remove the prostatic adenoma and was used clinically on 40 patients to check that the kinematics of the frame were appropriate [**8**]. Based on the kinematics of this framework, a robotic motorized system was developed which was eventually used clinically in April 1991 and prior to the clinical use of Robodoc. This was the very first time that an active robot had been used automatically to remove tissue from patients. Since that time a second-generation prostate robot (called “Probot’) has been developed at Imperial College [**9**]. This was mounted on a large floor-standing counterbalanced framework which could be locked in position using electromechanical brakes. This seems to be the first robotic surgery application of a now widely accepted concept in which a large ‘gross positioning’ system is used to support and move a smaller robot. The large positioner, often a passive manipulator, can be moved over a wide region and be locked in position at the approximate location while the smaller, purpose-built system carries out the task. Although resulting in some redundancy of motion, this technique enables the powered robot to be small and to be designed with limited motions and forces just adequate for the tasks, which helps to ensure both safety and accuracy.

Robotic surgery systems have been slow to develop, and, at this time, Probot is one of only few soft-tissue surgery active robots to have been applied clinically [**10**]. One reason for this slow rate of application has been the parallel development of CAS, which can be seen to give some of the benefits of robotics without the same degree of concern for safety. Thus, no review of robotic surgery would be complete without also mentioning the parallel developments in CAS.

3 COMPUTER ASSISTED SURGERY (CAS)

The main difference between the terms ‘robotic’ and ‘computer assisted’ surgery is that robots are moved by some sort of motorized system while computer assisted systems are generally manually powered by the surgeon. In surgery, the majority of computer-based systems are tracking systems. These may be used to track tools or parts of the anatomy, either using a sensor-based system or by clamping the tool onto a manipulator arm whose joints are monitored for position. The sensor-based systems usually use an array, either of light emitting diodes (LEDs) or of optical reflectors, attached to the tool. The position and orientation of the array in three-dimensional space can be tracked by a group of cameras. The tool and its three-dimensional coordinates can then be represented on a computer screen in relation to the coordinates of the target anatomy which is also represented. To represent the target location in the computer, it is necessary for the appropriate anatomy to undergo preliminary pre-operative imaging (usually computer tomography (CT) or magnetic resonance (MR) imaging). These three-dimensional scans are used to form a three-dimensional model of the anatomy intraoperatively. Recognizable features in the anatomy can then be located by the tracking system to ‘register’ the tracker to the patient anatomy. If no obvious anatomical markers are available, artificial markers (or ‘fiducials’) such as small screws are often added to the patient at the imaging stage. These markers are also available intraoperativley and can be used for tracking. This process ‘registers’ the current patient/tracker reference system to that of the pre-operative image and model. In orthopaedic surgery, it is usually adequate to clamp the appropriate bone of the patient and assume that the target anatomy does not move, so that only a position sensor on the clamp is required to act as a warning if the patient moves. By this technique the pre-operative models of the patient are treated as fixed during the procedure, and it is only necessary to superimpose on to them the current position of the cutting tools. At the pre-operative planning stage, the surgeon can take time to check that the information in the computer display, showing the location of the target tissue and tools, is correct. However, for soft tissue (and other ‘compliant’ parts of the anatomy, such as in the spine), a process called ‘dynamic referencing’ is used for intraoperative tracking of the moving tissue in real time and updating of the computer database to provide the current target location. For example, when drilling into a vertebra in the spine to fix pedicle screws, drill forces often distort the location of the vertebra relative to its neighbours. In CAS systems, the drill location is monitored and displayed on a computer together with the relative location of the vertebra. A separate tracking monitor on the vertebra updates the display with its new location as it distorts during drilling. However, if, for example, the vertebra motion sensor slips, it will display a false reading which shows motion of the vertebra, with no time to check if the location is correct. Thus, a degree of ‘trust’ is required that the dynamic referencing is correct, and this is why dynamic referencing is potentially one of the most safety-critical areas of CAS.

As discussed in Section 1, passive manipulators can also be used to carry and track tools. Unlike camera-based ‘localizers’, manipulator arms have the problem that they can be cumbersome and restrict the surgeon in the free motion of the attached tools. The use of a manipulator, however, can help damp out unwanted surgeon tremor and, with the addition of electromagnetic brakes, can be used to lock the tools in position while, for example, X-rays are taken. Camera-based systems which are both accurate and have a wide field of view are generally expensive. They also have the problem that they can cease to function when the surgeon leans over the patient and obscures the view of the target LEDs when seen from the camera. However, other types of tracking system can also be inaccurate, such as those using electromagnetic coils (which can be rendered inaccurate if ferrous materials are present) or ultrasound-based range finders (whose values can vary with environmental temperature). Most sensor and computer systems are more susceptible to inaccuracies in the operating room, e.g. owing to the presence of electromagnetic interference from sources such as the diathermy used for cutting and cauterization. Advocates of such systems suggest arranging the operating room (OR) to exclude all sources of distorting influence. However, in practice it is difficult to ensure this, particularly in emergencies, and so safety is likely to be compromised.

The CAS systems, unlike robots, rely on the surgeon for motive power. However, they too are vulnerable to hardware and software errors in the data provided by the tracking systems for the tools and tissue, in which case it is necessary for the surgeon to detect that there is a problem and to take corrective action or stop the procedure. In addition, just as for robotic surgery, most CAS systems use a pre-operative planning system. This allows the surgeon to take images of the patient, form them into three-dimensional models and display them on a computer together with the various tool locations. The surgeon can then simulate the whole procedure and ensure that the proposed protocol is correct, removing a lot of the worry and strain from the actual operation. The safety issues for pre-operative planners in both CAS and robots are broadly similar. For CAS, just as for robot surgery, the accurate registration of the pre-operative three-dimensional models to the intraoperative position of both the patient and the tools being tracked is important to ensure safety. The surgeon computer interface, the associated software and the underlying assumptions built into the algorithms all have a major impact on safety of CAS, as they do for robotic surgery. Thus, although at this time CAS is considered safer than robotic systems, it is probable that the inherent safety issues and problem areas for CAS are actually not significantly different. It is the perception that surgeons are more likely to take responsibility for a CAS procedure, compared with using an autonomous robot, that has tended to make the passive CAS systems more favoured by equipment developers at this time.

4 ROBOTIC SYSTEMS

As we have seen, the robot is only one aspect of an integrated surgical system. Such systems have three phases:

(a) pre-operative planning,
(b) intraoperative intervention,
(c) post-operative assessment.

Table 1 shows a typical sequence for robotic total knee replacement. It is only in the intervention aspects of the intraoperative phase that the robot is of direct benefit. As outlined in the previous section, the pre-operative planning phase is also necessary for CAS procedures. However, when a robot is to be used, the planning aspect can also include a computer simulation sequence of the robot motions. When the surgeon is satisfied that the sequence is correct and the robot will not impinge on the patient or adjacent equipment, then the motion sequence can be downloaded directly to the robot controller.

Table 1 Typical stages in robotic knee surgery

Pre-operatively:
- Image patient
- Edit images and create three-dimensional model of leg
- Create three-dimensional model of prostheses
- Superimpose prostheses over three-dimensional model of leg
- Adjust and optimize location
- Plan operative procedure

Intraoperatively:
- Fix and locate patient on table
- Fix and locate robot (on floor or on table)
- Input three-dimensional model of cuts into robot controller
- Datum robot to patient
- Carry out robot motion sequence
- (Monitor for unwanted patient motion)

Post-operatively:
- Remove robot from vicinity
- Release patient
- Check quality of procedure

If further cuts are necessary:
- Reclamp patient
- Reposition and datum robot to patient
- Repeat robotic procedure

In the intraoperative phase, it is necessary to fix the robot with reference to the patient and then ‘register’ the robot to specific markers or ‘fiducials’ on the patient, usually by touching the robot tip to the markers. These same fiducials will have been observable in the pre-operative imaging and three-dimensional models, and so this process can register the current patient fudicial location to that on the pre-operative images and models, as well as to the intraoperative robot location. The fiducials are usually small screws inserted into the bone in orthopaedic surgery or are small discs stuck to the skin, e.g. over boney prominences in neurosurgery. The more recent use of anatomical features for registration can avoid the need for artificial markers, but they need to be carefully applied. This is because the robot is touched on to 20 to 30 points on the anatomy at the time of surgery, and the points are then used to generate surfaces that are matched with surfaces in the pre-operative model. Since the interpolation of points and surface matching is a statistical process, the results need to be applied carefully to maintain accuracy. Whether artificial or natural markers are used, the overall registration process is one of the greatest sources of error in both CAS and robotic procedures.

In order to ensure that the robot is being correctly applied, an intraoperative display of robot motions is required to guide the surgeon. This should show a three-dimensional schematic of the correct position of the tool (together with the planned extremes of tool motion), superimposed over simplified views of the tissue that has been removed and of that remaining. These simplified schematic views are necessary for real-time viewing of often complex motions. More complex views, e.g. of surface or volume rendered images of the tissue, should be provided on separate displays. The robotic display needs to be kept to simple schematics, with only basic robot parameters on the screen, so as not to confuse the surgeon in an emergency. Full diagnostics, however, should be available on the screen when needed, so that, say, when a procedure is interrupted, the full status is available to judge if it is safe to continue or if it is first necessary to re-register the robot to fiducial markers. In an emergency, it may be necessary to abort the robotic procedure and it must be ensured that at all times it is possible to finish the surgery using a safe manual procedure.

An assessment phase is usually required immediately post-operatively. This requires that the robot can be readily removed and the patient unclamped so that the patient can be moved around. Rapid robot removal is also essential for safety reasons, so that if the robot malfunctions, it can be quickly removed and the procedure completed manually. Should the assessment show that further action is required, it will be necessary to reclamp the patient and reposition and re-register the robot. This implies that any fiducial markers should remain in position throughout and should not have been machined away by earlier robot actions.

5 CLASSIFICATION OF SURGICAL ROBOTS

While it is possible to classify robots according to the surgical tasks for which they are intended, it is helpful first to define the technology basis for the different types. A major division is whether the powered robot is used in a passive, power-off mode or in an active mode for active movement of the tools to perform the surgery.

5.1 Powered robots used as passive tool holders

Some of the earliest applications of powered surgical robots were to use them passively, as a means of holding fixtures at an appropriate location, so that the surgeon could insert tools into the fixture. The early work of Kwoh *et al.* [**4**] (briefly mentioned in Section 2) used an industrial Puma robot in this way to position a fixture next to the head so that a surgeon could insert drills and biopsy needles at a desired location for neurosurgery. The patient wore a standard neurosurgery stereotactic frame which was also used as part of a pre-operative CT scan. On the day of the operation, the tip of the robot was able to be touched on to the stereotactic frame, thus 'registering' the robot to the patient, and at the same time registering to the pre-operative CT scans and the three-dimensional models of both the brain and the target tumours. The robot was then moved slowly to the desired position at which an entry hole in the skull could be located, and locked in position with all power removed to make it safe. The surgeon then used the locating fixture, at the robot tip, to orientate a drill to produce the entry 'burr' hole and then to insert a biopsy probe to make a straight line of access into the tumour. Thus, the surgeon's actions were simple and limited to straight-line insertions and axial rotations. However, the unmodified industrial robot could be said to be used safely, since it was unpowered and locked in position during the surgical procedure. A similar approach was subsequently taken by Lavallee *et al.* [**11**] in Grenoble, France, where an industrial robot was fitted with additional large-ratio gear boxes so that the robot could move slowly and safely. The addition of a pre-operative planning facility based on CT imaging has made this a powerful system. Recently, a special-purpose robot called 'Neuromate', to be used 'passively', has been developed commercially by IMMI Limited, Lyon, France, and is integrated with the planner for neurosurgery. These systems have the potential to give a more stable platform and be more accurate for deep-seated tumours than equivalent camera-based localizers or localizers based on unpowered manipulator arms. However, they do tend to be more costly than their CAS equivalent.

5.2 Active robots

The use of a powered robot actively to interact with the patient can potentially allow more complex motions than the above example of a powered robot used passively. However, safety concerns are greater, and for this reason most active robots have been developed specifically for the task.

5.2.1 Laparoscopic camera robots

Probably the largest sales of a commercial system for robot surgery have been in the area of the manipulation of laparoscopes, mostly for abdominal, 'minimally invasive' surgery [**12**, **13**]. Traditionally, a surgeon uses an assistant who moves the laparoscopic camera and tries to anticipate what the surgeon wishes to view. The cramped surroundings and inability to predict the surgeon's needs often makes this a fraught task. However, some would argue it is ideal training for future 'minimal access' surgeons. Nevertheless, commercial robots have been developed for this task. The requirement for a robot to hold and manipulate the laparoscope is very demanding for abdominal procedures, since a robot must move the laparoscope (typically providing pitch, yaw, roll and in/out motions) about a remote pivot point located at the abdomen wall. To avoid obscuring the operation site, this means that the robot requires a 'remote centre' motion about the entry point, with a long power transmission mechanism linking the laparoscope to the powered robot. The need for a small 'footprint' of the mechanism within the operation site further complicates the design. Input commands for the robotic camera can be achieved by the surgeon using either foot pedals or (more recently) head motion sensors or by voice control. Because the robot is not used to cut directly or to move cutting tools, the motions are not considered as potentially dangerous and safety concerns in the use of this application are much reduced.

5.2.2 'Robodoc' orthopaedic surgery

A further active robot that is available commercially is the 'Robodoc' hip surgery robot from Integrated Surgical

Supplies Limited, Sacramento, United States [**14**] (as briefly mentioned in Section 2). The robot is instrumented with force sensing on all axes, as well as using a six-axis force sensor at the wrist. The tip of the robot carries a high-speed rotary cutter which can accurately ream out the femoral cavity for the stem of a particular hip implant (see Fig. 1). A separate pre-operative planner called 'Orthodoc' can be used, which allows a computer model of the appropriate size and shape of implant to be positioned over a three-dimensional model of the hip, reconstructed from a series of CT scans. The position and orientation of the implant can be adjusted until the surgeon is satisfied. The resulting femoral cavity can then be displayed and the sequence of robot motions automatically generated so that the surgeon can ensure that the procedure will cause no difficulties.

Once the planning has been completed, the intraoperative phase begins with the patient's leg being clamped to a rigid framework mounted on the pedestal of the robot. A further clamp holds a pin located in the femoral head so that any motion greater than 2 mm of the leg relative to the robot stand can automatically halt the procedure. In this way the femur is treated as a fixed, static object, in which the predefined motions (planned pre-operatively) can be executed. This is a much simpler procedure than say, soft-tissue surgery, where tissue motions may require intraoperative adaptation of the procedures. Once the patient is clamped, the hip is opened by the surgeon and the femoral head removed, as in conventional surgery. At this point the robot tip, carrying a high-speed rotary cutter mounted on a force sensor, is moved into the appropriate position on the femur head and the sequence of motions executed to resect the appropriate shape for mounting the implant stem. The sequence of motions can be displayed simultaneously on a computer to ensure that all is well. Force levels from each joint, as well as the wrist sensor, are also monitored for safety and the procedure is halted if forces rise above a predefined level.

Fig. 1 'Robodoc' hip surgery robot

An important step, as in all CAS and robotic surgery, is the 'registration' of the pre-operative MR, CT or ultrasound scans to the intraoperative location of the patient bone, as well as the current intraoperative position of the robot. In hip surgery, this is generally achieved by embedding 'fudicial' markers into the bone in both the proximal head of the femur and the distal femoral condyles, so that their coordinates show clearly in the pre-operative CT scans and three-dimensional models. The markers have a conical recess into which a ball can be located. The ball is held on the end of the robot arm and positioned into the cone under force control to ensure repeatability. Thus, the fiducial location on the pre-operative CT scans is registered to the current patient position and also to the robot coordinate system. Because of patient complaints of pain from the knee fiducials, attempts are being made to replace them by using anatomical features as markers. This is achieved by touching the robot tip to a series of 20–30 closely related boney points. A surface map of the points is statistically generated and matched to the pre-operative model of the surface. This has two problem areas:

1. The statistical matching of surfaces is prone to error, which is exaggerated at surfaces far from the located points.
2. The exact location of the bone surface (as distinct from soft tissue) as probed by the robot can be in error when compared with the CT scanned surface. Thus, although anatomical markers are gradually being introduced, fiducial markers still remain the 'gold standard'.

The Robodoc system underwent trials at three clinical centres in the Untied States between 1991 and 1994 in an attempt to satisfy the needs of the Federal Drugs Administration (FDA), which requires that clear clinical benefits be shown before the use of expensive technology can be sanctioned. The difficulty is that the claimed benefits for robotic procedures are good alignment of the implant stem in the femur and a very good contact area between bone and stem (better than 98 per cent for the robot, compared with typically 23 per cent by conventional manual surgery). Both benefits are claimed to give improved long-term performance of the prosthesis as well as improved bone growth. Such benefits would require a 10–15 year period to be demonstrated. Short-term benefits, however, were more difficult to demonstrate as the time for the procedure was longer, resulting in increased anaesthesia times and increased blood loss. Also, post-operative patient pain was reportedly greater owing to the use of the knee fiducials.

In the summer of 1994, Robodoc was introduced to Frankfurt Hospital, Germany, where a large number of operations have been conducted (over 2000 to date). This has resulted in improvements in protocols, so that, even though the robot is substantially unchanged, times for the procedure have been considerably reduced. This indicates the dangers of long-term assessment of CAS and robotic surgery during the early years of implementation, when both hardware and protocols are rapidly changing. Increased patient demand has now led to the introduction of 28 Robodoc systems in Europe. Recently, 250 pinless registration procedures, using a separate digitizer to locate anatomical features, have been successfully performed in Frankfurt [**15**]. It is hoped that, when this experience has been further consolidated, applications for FDA approval will be made to allow this system to be used in the United States.

5.2.3 Additional orthopaedic systems

Another recent commercial system, initially aimed at hip implants, is called ‘Caspar’ by Orto-Maquet [**16**]. This utilizes a robot based on an anthropomorphic Staubli-Automation industrial clean-room robot, which has been fundamentally modified for orthopaedic surgery. The system has been used on 75 patients in the Erlangen University Hospital. It is perhaps not surprising that the two commercially available active robot surgery systems have been developed for orthopaedic use in the hip, where the bone can be treated as a fixed, clamped object to which pre-operative imaging can be applied, with none of the concerns of tissue motion and distortion that are inherent in soft-tissue surgery. Other recent research projects using robots for orthopaedic surgery include Rizzoli Orthopaedic Institute, Bologna [**17**], which has used a Puma 560 robot, and Helmholtz-Institute, Aachen, which is developing a special-purpose parallel link robot for hip surgery [**18**]. A robot is ideal for orthopaedic surgery since it can generate the high forces needed to create accurate cuts, even though the bone resistance can vary widely. The constrained robot will also not bounce off hard surfaces and cut into vulnerable soft tissue.

5.2.4 ‘Probot’ prostatectomy robot

The reduction in urinary flow owing to a benign adenoma blocking the urinary duct is a common problem in males past middle age. The usual treatment is to remove the adenoma using a ‘hot wire’ diathermic loop resectoscope. This is passed down the centre of the penis and is used to chip away the adenoma. This minimally invasive procedure is difficult to learn as, like all such procedures, only a localized endoscopic view is available and the sequence of motions has to be ‘remembered’ in order to locate the resectoscope tip within the gland. Also, a number of features must remain unharmed to avoid impotence and incontinence. Although prostatectomy is a soft-tissue surgical procedure, it is largely a ‘debulking’ process not requiring high accuracy. Also, the prostate is held relatively immobile by the pelvic anatomy. It can thus form an ideal procedure for robotic soft-tissue surgery.

As mentioned in Section 2, the Mechatronics in Medicine Group at Imperial College has been concerned with the development and clinical implementation of an active robotic system for prostatectomies, called ‘Probot’ [**9**]. This project started in 1987, with an approach by the Institute of Urology in London to ask if a robot system could be developed for resection of the prostate. Following preliminary feasibility studies, a special-purpose ‘safety frame’ was developed to give the required motions with the minimum degrees of freedom. This was manually powered and was tried clinically on forty patients with good results [**8**]. Having proved the kinematics, the system was powered under computer control and applied clinically in 1991 to five patients (see Fig. 2).

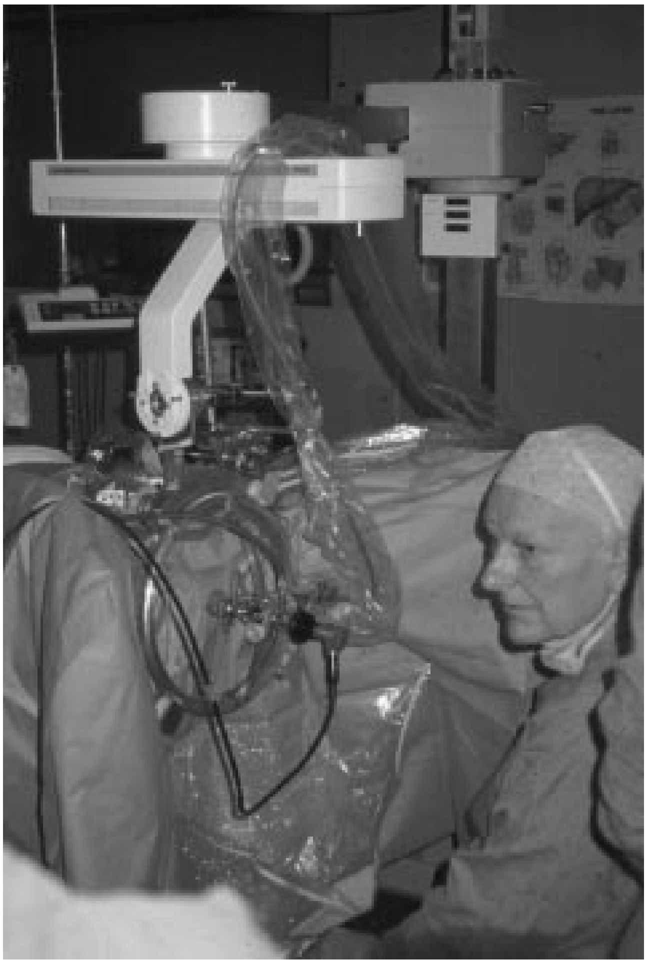

Fig. 2 Imperial College ‘Probot’ prostatectomy robot being clinically applied

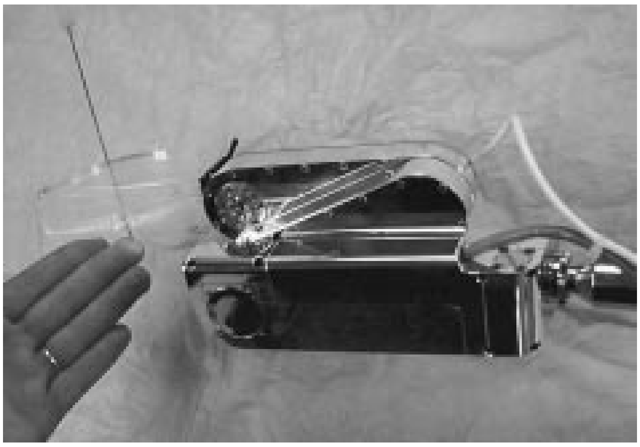

Fig. 3 Johns Hopkins University remote centre motion (RCM) robot designed for kidney puncture

This was the first time that an active robot had been used to remove tissue from a patient, preceding the Robodoc clinical human trials by some five months. A subsequent Engineering and Physical Sciences Research Council (EPSRC) UK Government grant for laboratory studies gave the opportunity to add a transurethral ultrasound probe to the robotic frame for direct measurement of the gland size at the start of the procedure [**9**]. The probe could be interchanged with a diathermic cutter to remove the prostatic adenoma. The ultrasound images are marked up by the surgeon to identify the tissue to be removed. These 'slices' are then built into a three-dimensional model of the resectable volume, which is used to generate the cutting trajectories for the robot. Clinical trials of the new prostatectomy robot have been carried out at the Minimally Invasive Therapy Unit at Guy's Hospital, London, with very good results. It has thus been shown that a fast, accurate and safe prostatectomy can be carried out robotically. The anatomy of the prostate minimizes motion of the soft tissue, as does careful selection of the cutting protocol. This, together with the fact that the prostatectomy is primarily a debulking process, for which great accuracy is not required, has meant that imaging at the start of the procedure is adequate, in spite of this being a soft-tissue procedure. Further research is being undertaken to ensure intraoperative imaging of soft tissue distortions.

A recent innovation by a group at Johns Hopkins University in the Untied States is to provide a small but versatile robot for low-force procedures such as kidney biopsy [**19**] (Fig. 3). Such systems need to have a remote centre of motion in pitch and yaw about the point where the tool enters the skin. This could be provided by software through a compound motion of several axes. However, it could be said to be safer to provide a power transmission system where kinematics are arranged to provide the pitch and yaw motions from two dedicated motor axes. A further in/out motion and tool rotation about the pitched/yawed axis complete the four axes required. This type of remote centre motion, beneficial for minimal access surgery, is also being used by the present author (in conjunction with Fokker Control Systems BV, the Netherlands) in a special-purpose four-axis robot for neurosurgery (called Neurobot) which is funded by the European Commission as part of a simulation, imaging and robotic surgery project called 'Roboscope' [**20**].

5.2.5 'Minerva' neurosurgery robot

A further example of an active robot is 'Minerva' which has been applied clinically for neurosurgery [**21**] (see Fig. 4). This is a novel special-purpose system developed by the precision mechanisms group at the University of Lausanne. A powered robot, in association with a dedicated CT imaging system, has been used in limited neurosurgery clinical trials. The robot system employs a series of special tools, located on a rotary carousel, each of which can then be locked into position on a single-axis travel. This single axis then advances the tool linearly into the region of the patient's head which is datumed to a stereotactic frame. These actions take place adjacent to the CT machine to ensure easy intraoperative imaging. The robot is extremely accurate, with an overall positional accuracy, including CT imaging, of just under 1 mm. It will be some time before the clinical benefits of Minerva's increased accuracy will be seen clinically to justify the need for a dedicated CT scanner and the increased cost and complexity compared with, for example, a computer assisted surgery 'localizer' system.

5.3 Synergistic systems—the 'Acrobot' active constraint robot

A novel control system for robotic surgery is being implemented at Imperial College, London, for prosthetic implant knee surgery [**22**]. This system will allow the surgeon to hold a force-controlled lever placed at the end of the robot which also carries a motorized cutter. The surgeon can use the lever to back-drive the robot motors within software constraints provided by the robot so that an appropriate shape is machined into the knee bones. This programmable software constraint system gives rise to the concept of an active constraint robot (known as 'Acrobot') which is shown in Fig. 5. Within a central predefined region, low-force control is provided. This control strategy allows the surgeon to feel directly the forces experienced by the cutter. Thus, if the surgeon cuts a hard piece of bone, the forces that are experienced rise and he can slow down or take a lighter cut. The force-controlled handle is supplemented with a 'deadman's handle' switch which, when released, can automatically bring the robot and cutter to a safe state. Towards the edge of the low-force region, the robot impedance gradually increases until, at the limit of the permitted region, the control system switches into high-gain position control. Thus, the robot gives an active

Fig. 4 'Minerva' neurosurgery robot in position, with the patient adjacent to a CT scanner

constraint within an accurately preprogrammed area, providing accuracy as well as avoiding damage to vulnerable areas, while the surgeon stays in control of the procedure. It is felt that this strategy will be more acceptable to the surgeon than conventional position control of an automated active robot. A series of phantom and cadaver trials has demonstrated the accuracy of the system and its ease of use. A pre-operative planning system, based on a low-cost PC, provides a simple method for planning where to place the appropriately sized prosthesis.

Acrobot represents a new type of robotic system for surgery, known as a 'synergistic' system, in which the surgeon's skills and judgement are combined with the robot's constraint capabilities to form a partnership that enhances the performance of the robot acting alone. A variation of this concept has also been applied by a French group who have produced a passive arm system that uses a series of motorized clutches to allow motion [**23**]. In this instance, the motorized clutches allow the surgeon only to move the manipulator in a preprogrammed direction. Since the arm motions rely totally on the surgeon to move them, and the power is used only in the clutching mechanism and not for powering motions, the system (called PADYC, after Passive Arm, Dynamic Control) is said to be safer than an active robot. However, the fact that motorized clutches have to be switched on and off many times a second can imply that this will not be an easy mechanism to provide smooth three-dimensional control.

Fig. 5 Imperial College 'Acrobot' knee surgery robot with force-controlled handle

The process of using technology to aid in surgery is primarily one of integration. It is only when robotic and CAS mechanisms are included in a total system within the operating theatre that their viability can be correctly judged. Thus, there is a considerable need for integrated systems to be used in the operating theatre, so that the total system with its imaging, modelling, sensing, registration and motion mechanisms (all suitably sterile) can be tried out using an appropriate 'human/computer interface' for the surgeon in a clinical setting. Even then, the complexity of the system in the operating theatre environment means that a number of development changes will inevitably be required to perfect the system. This is a relatively new requirement for medical systems, and new funding mechanisms are needed internationally for these integrated robotic systems in order to enable medical and engineering personnel to communicate and work together to develop the equipment to an appropriate level. Only then can the efficacy of the robotic or CAS systems be correctly evaluated.

5.4 Master–slave 'telemanipulator' systems

Acrobot, which uses a force-controlled lever moved by the surgeon, can be regarded as a type of master–slave system in which the master (the force lever) is, unusually, attached to the slave (the moving robot structure). However, for these telemanipulator systems (sometimes called telepresence) it is more usual to mount the slave separately from the master. The master may consist of a simple joystick input system or, more usual for surgery, may be a kinematic mimic of the slave robot. It is possible to locate the master many miles from the slave, and have a connection via high-speed telephone line or a satellite link. Such systems have been proposed for surgery, but it is more likely that they will find more immediate application in diagnostics, where the ability to transmit a sense of 'feel' remotely will be of value. In surgery, however, it is possible also to place the master controller nearby, alongside the slave in the OR. This will permit the use of scaled motions so that large movements of the master will result in micromotions, with small forces, applied by the slave. Two examples of this are the 'da Vinci' system being developed by Intuitive Surgical Incorporated [**24**] and the 'Zeus' system of Computer Motion Incorporated [**25**], both of which are being used clinically for minimally invasive 'closed' heart surgery. In both systems, a robotic arm carries an endoscope while two other manipulator arms carry interchangeable tools, such as scissors and grippers. An innovative feature is the 'wrist' inside the body, which can angle tools. This feature is of particular value in tying knots for sutures inside the body. However, at this time there is no sense of feel fed back from the master to the slave, and the surgeon relies upon the high-quality endoscopic vision for monitoring the process. This sense of feel or 'haptics' is a complex issue at the forefront of research and requires force-sensing systems at the slave to apply appropriate feedback forces to the master and hence to the surgeon [**26**]. A realistic sense of feel, however, requires more than simple force information. Rates of change in force and motion, as well as their interaction, are equally important in determining such aspects as tissue 'texture'. The best way to input this information back to the surgeon is also a research topic.

One type of autonomous robot that operates in a soft-tissue, semi-disordered environment is a colonic crawler or 'inch-worm' robot. This is used to inspect and sample the colon for possible disease. It is generally based upon a worm concept in which a concertina segment advances along the colon and attaches itself to the wall, usually by expansion or suction. A second section is advanced to the first and then in turn anchored. The first section is detached and the process repeated. This sequential process is usually pneumatic, under computer control. The flexibility and variable structure of the colon require a number of sensors and adaptive control. In order to cope with sharp bends, more than two segments are usually required. Among a number of variants of this device that are under investigation, the work of Professor Ng at Nanyang University, Singapore, is unusual in using a number of miniature 'feet' to grip the colon wall and negotiate bends without slipping. This device has been used successfully on live pigs [**27**].

6 CONCLUSIONS

In this brief overview, it has not been possible to cover all aspects of the rapidly developing area of robotic surgery. As we have seen, the various types of surgical robot can carry out all the tasks that can be performed by CAS systems. In addition, robots have the very useful property of being able to constrain and guide surgical interventions in a way that is not possible with normal CAS systems. Robots have the potential to be autonomous and to carry out repetitive actions tirelessly, as well as move through complex paths with considerable accuracy. However, since they tend to involve additional components for the system, the use of robots will inevitably make the equipment more costly and complex than CAS systems. This cost and complexity will be easier to justify in those procedures where the benefits of robotic interventions provide a clear advantage over CAS. Thus, just as it is difficult in some procedures to justify the use of CAS as compared with conventional surgery, so there will be specific procedures that can justify the use of robotics as compared with CAS. When considering the different types of robotic system, there are immediate benefits in using robotic systems passively; e.g. the ability safely to lock off a relatively unmodified industrial robot so that it can be used as a guiding fixture by a surgeon. This limited role for 'passive' robots will be less attractive once the safety requirements for 'active' medical robots have been agreed. Active robots, which perform autonomous interventional actions while being supervised by the surgeon, are likely to have a healthy future. It should be emphasized that it is not envisaged that these robots will be used to 'automate' a procedure without the surgeon being present. They will be assistive devices augmenting the capabilities of the surgeon. They may be industrial-style robots, which will need to be extensively modified for safety by the manufacturers, or special-purpose devices configured for individual tasks. It is the present author's view that the special-purpose systems are likely to be lower cost, smaller, simpler and easier to make safe. There is a worrying tendency for some research workers to purchase standard industrial robots, on the basis that these are the same as those used in surgical systems. However, while the kinematics may be similar, the surgically approved versions have extensive modifications to allow their safe use next to people. The much lower-cost industrial versions could be used in the laboratory to demonstrate the kinematics and integration concepts prior to use in the OR, but even in this environment the safety of research personnel must remain paramount.

Specific procedures that will benefit from robotic intervention in the near future are various orthopaedic cutting and drilling procedures, where the forces generated can be resisted by the robot, preventing the cutters from bouncing off hard bone and damaging other areas, such as soft tissue. In addition, the robot will provide considerable accuracy to the cuts, which will often need to be made repetitively. Orthopaedics is a good application area since, once the bone is clamped, it can be treated as a fixed object. Robotics will also be of benefit in soft-tissue surgery, particularly in minimally invasive 'keyhole' procedures. The use of a robot will overcome many problems of visualizing where the tips of the tools are located, which is such a problem with conventional endoscopic techniques. Many of these procedures also require a remote centre motion, which adds complication to the design of the robot. A particular type of keyhole surgery that will benefit from the use of robots is in neurosurgery, where the needs of a precise path and a final precise location of the tool are both critical. Here, because of the need to target features such as tumours and track them as they distort and move during the intervention, it is essential to have image guidance intraoperatively, at least intermittently but preferably continuously. This tendency for soft tissue to move when pressed or cut and to change shape makes robotic soft-tissue interventions particularly difficult. However, in some procedures, such as prostatectomy, the anatomy can be sufficiently constraining that the need for continuous imaging can be reduced. There is also considerable potential for telemanipulator master–slave systems in soft-tissue surgery, particularly where forces or motions can be scaled down for microsurgery.

A potentially beneficial type of robotic system is that of an active constraint 'hands-on' robot, such as the Acrobot used at Imperial College for knee surgery. The benefit of this concept (in which the surgeon drives a force-controlled lever attached to the robot) is that the surgeon has the potential to feel the forces exerted by the robot tool while being constrained by the robot to a safe region or to an accurate plane, a path or a location. The surgeon thus uses his innate sensing and judgement while the robot constrains, providing safety and quality. This synergy between the best robot and surgeon qualities has considerable potential for both soft-tissue and orthopaedic surgery. Recent developments in imaging will benefit CAS and robotic surgery. The lower costs and higher definition of both MR and CT imaging, as well as the availability of three-dimensional ultrasound imaging with good resolution, have improved information about the target tissue location. Developments in imaging systems and in endoscopes and cameras have meant that there has been a preponderance of vision-based sensing, associated with sensing position. Other senses, such as haptics, have been much neglected and are an area of current research. The use of the Acrobot concept is a way of supplementing currently poor artificial sensing with the surgeon's own innate sensory capability. This 'hands-on' robot forms an intermediate type of robot which bridges the gap between autonomous systems such as Robodoc and Probot and the master–slave telemanipulator such as Zeus.

The future of robotic surgery will ultimately depend not just on technology but also on the abilities of the engineers, computer scientists and medical physics groups to communicate and collaborate effectively with medical personnel. The engineering and medical disciplines are very different in training and orientation. The effective application of robotic surgery can only be achieved with understanding, dedication and enthusiasm from all personnel. The history of robotic surgery is now just over a decade old. Developments in intraoperative imaging, microsurgery and in sensory perception additional to vision (such as haptic sensing) will considerably change robotic surgery by the year 2010.

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