Introduction

As one who has been involved with robotics in orthopedic surgery since its inception, in my opinion the answer is: yes! We have been taught that the three most important things required for accurate surgery are “exposure, exposure, exposure”. Henry’s book on “Extensive Exposure” [1] is a classic example. But, with minimally invasive surgery (MIS), there is (by definition) less exposure. This means that many of the usual soft-tissue and bony landmarks are not visible. Thus, to maintain the accuracy required in TJA using minimally or less invasive surgical (LIS) techniques, we need help. That help will come from computer-aided tools such as computer navigation, robotics or other so-called “smart tools”. Robotics offers some specific advantages that make it attractive.

Accuracy is the key point. Using conventional techniques, we currently enjoy a very high success rate in TJA with excellent longevity and a very low complication rate. This is due, in large part, to the accuracy and reproducibility of our technique. There is little question that MIS/LIS techniques offer less peri-operative morbidity and more rapid recovery than conventional open procedures. However, these advantages may be potentially outweighed by a lower success rate due to inaccuracies and human error.

This chapter will compare and contrast navigation and robotic systems. It will emphasize the importance of accurately positioning the components and avoiding human error. Additionally, it will provide a basis for you to evaluate these devices as they become available.

Definitions and Classification

A “robot” is a mechanical manipulator capable of autonomous movement based on a pre-programmed set of instructions. A “navigation system” is a tracking device used to locate and follow an object’s position in three-dimensional space.

Surgical robots can be classified as “active”, “passive” and “semi-active”. An “active” robot manipulates surgical tools that operate on the patient. A “passive” robot manipulates instruments to provide guidance or retraction, but the surgeon is free to use the surgical tool without restriction. A “semi-active robot” restricts the motion of surgical tools along a path or in a specific envelope, but the surgeon provides the motivating force.

Origins of Robotic and Navigation Systems

The first use of a robot in surgery is credited to Kwoh [2] who used it in brain surgery as a passive pointing device in lieu of a stereotactic frame. The first active surgical robot was RobodocTM (Integrated Surgical Systems, Davis, California, USA) (Fig. 19.1). The chronology of its development is covered in more detail elsewhere [3]. It began in the late 1980s, and the initial application was in primary cementless total hip replacement. Robodoc was approved for sale in the European Union in 1994. It has evolved mainly in Germany to include applications for revision THR, primary TKR and unicompartmental knee replacement. It is not yet approved for sale in the U.S., and is completing its second FDA multicenter study. CasparTM (URS-Ortho GmbH, Germany, now closed), no longer available, was another active robot developed later in Europe with application in primary THR and TKR. AcrobotTM (The Acrobot Company, Ltd., London, England) is a semi-active robot developed in England by Brian Davies and Justin Cobb [4] with potential applications in orthopedics (TKR), spinal and maxillofacial surgery. Many other robotic devices have been developed for...
spine surgery and fracture fixation and are in the pre-clinical application phase.

Navigation systems began as tool-tracking devices used in spine and neurosurgery in the early 1990s [5]. Application in TKR and THR was begun in the late 1990s mainly in Europe. Navigation systems may be attractive because of the rather high cost of robotic systems. Many surgeons will more readily accept freehand use of conventional tools in preference to autonomous mechanical systems. Many navigation systems (Fig. 19.2) are commercially available in Europe, and they are slowly being introduced to the U.S. market.

The advent of minimally invasive TJR has generated renewed interest in both navigation and robotic systems. There is an important distinction between these two systems. With navigation systems the surgeon still performs the actual surgery. In active robotic systems, the pre-programmed robot prepares the bone for prosthesis placement.

Pre-Operative Planning

While pre-operative planning is important to the success of a TJR, it is rarely performed in more than a cursory fashion by most clinicians probably because they find it of little value. One reason may be that the pre-operative plan is frequently not very accurate. The plan can serve as a general guide, but most surgeons rely more on what they see and feel during the operation, to make the critical decisions on implant size and position. With less invasive techniques, however, accurate pre-operative planning becomes more important.

Conventional pre-operative planning is usually done using radiographs and acetate templates (Fig. 19.3). These two-dimensional radiographs are subject to magnification and rotational variations that can introduce large errors. CT scans, on the other hand, can eliminate rotation and magnification errors, and provide the surgeon with three-dimensional information. Robodoc, as well as some navigation systems, use pre-operative imaging with CT scans (Fig. 19.4). This can allow more accurate pre-operative planning. The accuracy of the software used to create the image as well as to plan the size and position of the implant is of utmost importance. Unfortunately, information on the accuracy of this part of many systems is not available. If the image in either a robotic or navigation system is not accurate, errors can occur.

In active robotic systems, the robot executes precisely the pre-operative plan. Many surgeons are reluctant to
They feel this is a major disadvantage of robotic surgery. It is the ability to accurately execute a pre-operative plan, however, which can be considered a major advantage of robotics. Both robotics and navigation systems have as a goal the reduction of human error on the part of the surgeon. Only robotics, however, has the potential to eliminate intra-operative human error.

Some navigation systems offer what they consider the potential advantage of eliminating the need for any pre-operative planning. A phantom bone is used and is scaled using surface point collection. No planning is required as long as the surgeon accepts the goals of the desired implant position and fit that are built into the software. These are the so-called "CT-free" systems [6] most used for total knee replacement.

Registration

Both robotics and navigation require registration of the orientation of the bone(s) to the device's coordinate system. There are two methods by which registration is accomplished: surface point collection/surface mapping and fluoroscopic image matching. Surface point collection requires the surgeon to physically touch a probe to specific bony landmarks or multiple points on a surface of the bone (Fig. 19.5). These points are then mapped onto the CT image and the bone is then registered into the CT coordinate system. Using fluoroscopic image...
matching, points are identified on the image in two views and the position of the bone is then transformed into the fluoroscope's coordinate system (Fig. 19.6). Both of these methods can be a potential source of significant error. Studies showing the accuracy of registration techniques are vital for both robotics and navigation systems. Unfortunately these are usually internal studies done by the manufacturer. They are not usually published and therefore have not been subject to peer review.

**Bone Tracking**

Most surgeons associate this task with navigation. In fact, however, both robotics and navigation systems track the bone position in space. In robotics, the bone is usually held rigidly to avoid unwanted motion during milling. Robodoc uses a mechanical "bone motion monitor" (Fig. 19.7) to detect motion. In navigation systems, the bone is allowed to move freely, and metal markers are optically tracked (Fig. 19.8). If a bone marker loosens or moves relative to the bone, inaccuracies can occur.

In robotic systems the bone is held tightly in a fixator, so loosening is unlikely. If false movement is detected, the robot stops, re-registration is required, but no surgical error occurs. With navigation systems it is not possible to detect loosening or movement of a marker relative to the bone. If loosening occurs, the surgeon would not be aware of it, the data on bone position would be inaccurate, and error could result.

**Extra Time Required**

Both robotics and navigation require extra time in surgery to setup and register the systems. Once the setup and registration are complete, however, the two systems can differ dramatically in the time for surgical execution. For example, Robodoc requires a predictable 12–20 min for milling the femur, depending on the size and
shape of the implant. With navigation, the amount of time needed to complete the surgery depends on how the computer-aided information is presented to the surgeon, and how many choices and actions are required. This can be unpredictable and could take considerably longer. Longer operative times potentially add to the risk of infection and blood loss, factors which may influence a surgeon's willingness to accept this technology.

Clinical Track Record

Robodoc is now a proven technology. Over 10,000 cases have been performed worldwide. A number of Robodoc units are being used in Europe, Japan and Korea. In controlled studies [7], radiographs have shown better accuracy of implant fit, position and alignment. Intra-operative fractures have been virtually eliminated. Laboratory studies [8] have shown that the dimensional accuracy of the implant cavity is nearly 40 times better than free-hand broaching techniques. One negative report has been published [9], but the problems encountered in that report can be attributed in part to the type of implant used. In addition, the surgeon apparently did not adequately protect and retract the soft tissues at the time of surgery. These details are the responsibility of the surgeon and are not robot-related errors. The United States multi-center study [7] did not encounter these problems.

Navigation, in contrast, is just beginning to be used clinically. There are few clinical publications showing the efficacy of these systems. With time, their utility and accuracy will be determined. As of now, navigation systems are not in widespread clinical use.

Choice for the Future

While navigation systems are cheaper and more readily acceptable by surgeons than robotic systems, their accuracy is still in question. Robotic systems offer precision. They execute the pre-operative plan, and offer the potential to eliminate human error (although the surgeon must protect soft tissues). In the future, a blend of robotic and navigational technologies may be best. Part of an operation that requires less precision may be more adaptable to navigation (e.g. acetabular cup placement), whereas other parts that require more precision and pre-operative planning may be more suited to robotics (e.g. femoral stem placement).

Conclusions

Minimally invasive surgical techniques are changing the practice of joint-replacement surgery. The challenge is to maintain the required standard of precision with limited exposure. The ultimate acceptance of computer-aided surgery techniques in orthopedics depends on the concept of what might be called "clinical utility." This is a term used by the United States Food and Drug Administration, but is not defined. I propose that a new device has "clinical utility" if it can answer at least one of the following questions in the affirmative:

- Does it solve a real problem in orthopedic surgery?
- Does it improve the outcome of patients?
- Does it result in savings without lowering quality?
- Is it worth the investment?

To paraphrase a recent movie: "Clinical utility ... if you prove it, they will come."

References

8. (Internal Data), Integrated Surgical Systems, Davis, CA