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Computer-assisted orthopedic surgery

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Abstract Computer-assisted surgery (CAS) utilizing robotic or image-guided technologies has been introduced into various orthopedic fields. Navigation and robotic systems are the most advanced parts of CAS, and their range of functions and applications is increasing. Surgical navigation is a visualization system that gives positional information about surgical tools or implants relative to a target organ (bone) on a computer display. There are three types of surgical planning that involve navigation systems. One makes use of volumetric images, such as computed tomography, magnetic resonance imaging, or ultrasound echograms. Another makes use of intraoperative fluoroscopic images. The last type makes use of kinetic information about joints or morphometric information about the target bones obtained intraoperatively. Systems that involve these planning methods are called volumetric image-based navigation, fluoroscopic navigation, and imageless navigation, respectively. To overcome the inaccuracy of hand-controlled positioning of surgical tools, three robotic systems have been developed. One type directs a cutting guide block or a drilling guide sleeve, with surgeons sliding a bone saw or a drill bit through the guide instrument to execute a surgical action. Another type constrains the range of movement of a surgical tool held by a robot arm such as ACROBOT. The last type is an active system, such as ROBODOC or CASPAR, which directs a milling device automatically according to preoperative planning. These CAS systems, their potential, and their limitations are reviewed here. Future technologies and future directions of CAS that will help provide improved patient outcomes in a cost-effective manner are also discussed.

Key words Computer-assisted orthopedic surgery · Navigation · Robot · Fluoroscope · Registration · Augmented reality

Introduction

Computer-assisted surgery (CAS) utilizing robotic or image-guided technologies has been introduced into various orthopedic fields. CAS was initially developed to locate brain tumors based on stereotactic principles.[7] Since then, the field of CAS has expanded to include many other surgical subspecialties, including computer-assisted orthopedic surgery (CAOS). Orthopedics is particularly well suited for CAS. Bones and periarticular soft tissues can be evaluated easily and accurately using diagnostic technologies such as radiography, fluoroscopy, computed tomography (CT), and magnetic resonance imaging (MRI). Subsequently, bony and soft tissue structures can be reconstructed to create three-dimensional (3D) images that can be used in simulations of surgical procedures preoperatively, showing the effect of various surgical actions. Also, bone is a rigid structure that does not deform significantly when drilled or cut. Thus, it is easier to apply preoperative imaging and planning information to surgery for hard tissues than to surgery for elastic tissues such as the brain or abdominal organs.

Computer-assisted surgery is subclassified into passive systems, semiactive systems, and active systems.[29] Passive systems do not perform any actions on patients; they assist surgeons during preoperative planning, surgical simulation, or intraoperative guidance (surgical navigation). Semiactive systems perform some actions, such as moving a drill guide sleeve or a cutting jig, but they do not perform surgical actions. Active systems such as ROBODOC (Integrated Surgical Systems, Davis, CA, USA) and CASPAR (URS Ortho GmbH, Rastatt, Germany) perform some surgical actions that are programmed preoperatively.

In the present paper, we discuss specific clinical and surgical applications of CAOS, including navigation and robotic systems. Some of these systems are under development, whereas others are already commercially

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available. It is important to understand the potential and the limitations of these technologies and tools and to choose the clinical application that allow improved patient outcomes in a cost-effective manner.

Surgical navigation

Surgical navigation is a visualization system that provides positional information about surgical tools or implants relative to a target organ (bone) on a computer display. Like a global positioning system for car navigation, it uses 3D position sensors to track the target organ and surgical tools or implants. A surgical plan is formulated that includes positional information about surgical tools or implants (corresponding to a road map in car navigation). There are three types of surgical planning. One makes use of volumetric images such as CT, MRI, or ultrasound echography. Another makes use of intraoperative fluoroscopic images. The last type makes use of kinetic information about joints or morphometric information about the target bones obtained intraoperatively. Systems that involve these planning methods are called volumetric image-based navigation, fluoroscopic navigation, and imageless navigation, respectively. For CAOS, an optical sensor or a magnetic sensor is used. Optical systems use charged coupled device (CCD) cameras to obtain positional information, which is usually based on infrared light from a dynamic reference frame (DRF) with infrared light-emitting diodes (LED) or infrared light-reflecting markers. The DRF is attached to the target bones and surgical tools to be tracked. Measurements by optical sensors are highly accurate and fast; and many LEDs can be tracked simultaneously, although an uninterrupted line of sight must be maintained between the CCD camera and DRFs. The accuracy of OPTOTRAK3020 (Northern Digital, Waterloo, ONT, Canada) with active LED markers is reportedly 0.1 mm (length and breadth) and 0.15 mm (depth) of 3D root mean square (RMS) at 450 Hz and a distance of 2.25 m. The accuracy of POLARIS (Northern Digital) with passive reflective markers is reportedly 0.35 mm 3D RMS at 60 Hz. Active markers usually require power cords, which may obstruct the surgical field, but a cordless active LED marker with a battery is available (Smart Instruments; Stryker Leibinger, Portage, MI, USA). On the other hand, there is no line of sight problem with magnetic sensors, although there are concerns about their accuracy, which may be disturbed by the motor of the operating room (OR) table or metallic tools. It may be practical to use a magnetic sensor as a miniature marker for catheter tip tracking, but most navigation systems for orthopedics use an optical sensor.

Volumetric image-based navigation

Surgical planning of volumetric image-based navigation can be performed using CT, MRI, or ultrasound echography. However, CT is the most frequently used imaging modality because of its high resolution, high contrast between the bone and its surrounding soft tissues, long scanning range, and short scanning time. Segmentation of bones is easy on CT. Images of long skeletal segments such as the entire spine and lower extremities can be obtained in a single scan. Distortion of 3D skeletal models due to motion artifacts of patients can be avoided by using high-speed CT machines. This type of navigation system has been used successfully for spine pedicle screw insertion,[2,3,6,23,32,47] total hip arthroplasty (THA),[10] pelvic osteotomy,[27] total knee arthroplasty (TKA),[9,26] and reconstruction of knee cruciate ligaments.[25]

Imaging modalities and imaging methods are chosen based on the goals of navigation. Spine pedicle screw insertion requires CT images with a slice pitch of 1 mm and a resolution of at least 0.3 mm. Enhanced CT may be useful for imaging vascular structures and tumor lesions. For joint reconstruction surgery, CT images with a slice pitch of 1 to 10 mm and a resolution of at least 0.8 mm should be selected based on the size and morphological characteristics of the target joint.[41,42] To avoid motion artifacts, bracing of the lower extremities is recommended. There are two methods for detecting distortion of 3D skeletal models due to patient motion. An object such as a rod can be scanned along with the body part to compare for distortion. The other method is to view bone models from several directions to assess distortion.

For preoperative planning based on volumetric images, 3D image data are presented in two ways. One of these is a multislice method, in which the patient's anatomy is usually shown in three orthogonal planes (coronal, sagittal, axial). Computer-aided design (CAD) files of implants are superimposed on the view planes to show the position and orientation of the implants. The magnification, position, and orientation of the view planes can be changed at the surgeon's discretion. Using this method it is easy to formulate a plan for placing implants that have a straight shape, such as screws and femoral components of THA. In another method, volume rendering or surface models are used to image bones and implants in 3D. This method facilitates comprehension of complete constructs (e.g., socket placement in cases of congenital subluxation). For total joint arthroplasty, 3D CAD files and surface bone models allow simulation of range of motion. However, it is difficult to adjust the fit and fill of implants to the bone if it is examined from a limited number of viewpoints.

When the aim of navigation is to insert a pedicle screw that passes through the center of the pedicle or to guide an approach to a lesion such as a tumor, it is not necessary to measure quantitatively the position and orientation of implants or tools relative to the target bones. However, for navigation during total joint arthroplasty, osteotomy, or fusion of multiple spine segments, it is important to measure the alignment between bones or between the bone and the implant. To do this, standard coordinates of the target bones should be designated based on anatomical landmarks. Functional neutral (zero) positions of joints of extremities may not vary among patients, but functional zero positions of the hip and spine may be affected by the individual shape, aging, or spinal deformity due to osteoporosis.[34] This variation can affect the measurement of socket anteversion during THA.

Because target bones, implants, and tools can be tracked using DRFs attached to them, the implants and tools can be shown on volumetric images of the bones after registration of the bones and calibration of the implants and tools. Registration is a computational procedure that matches preoperative images or planning information to the position of the patient on the OR table. Calibration is a procedure that matches CAD files of implants or tools to their positions relative to the DRFs. There are two registration methods. For paired matching registration, the surgeon must identify three or more 3D landmarks on the preoperative images and the corresponding 3D landmarks on the patient during surgery.[40] This method is not reproducible. To resolve this irreproducibility, fiducials are placed in the target bones before volumetric images are obtained (fiducial-based registration). These fiducials are used to create a 3D reference for the patient's bone. The intraoperative locations of the fiducials are used to relate the position of the patient's bone to the preoperative plan. This method is accurate but requires an additional operation to place the markers. Shape-based (surface) registration is an alternative method that has been developed recently and used in many applications.[40] With this method, the point on the computer model nearest the measured surface point is designated the corresponding point, and the calculation is repeated to reduce the average distance between each measured point and the corresponding surface point. Mathematical calculations are performed using the iterative closest-point algorithm and the least-squares method. To avoid local minima, baseline registration is performed using the paired point method to obtain the starting position for registration. Then a certain number of surface points are used for the final matching, for which the calculation is repeated until it saturates. Using this surface-matching technique, the shapes of the bone surface model generated from preoperative images are matched to surface data points collected during surgery. Intraoperative surface data points can be collected using a touch probe with a DRF or an ultrasonic probe with a DRF.

The accuracy of the surface registration depends on the accuracy of the computer models and the quality and quantity of intraoperative data sampling. Generally, 3D models of bones are made by cutting off the surrounding soft tissues at a CT threshold value beyond which the size and shape of the models are affected. Accurate surface registration of the pelvis can be obtained using computer models made with thresholds ranging from 140 to 260 Hounsfield units by assessing the balance between soft tissue noise and bone surface defects. At least 20 surface points are needed for accurate surface registration of the spine, hip, or knee.[23,33,44,45] These points should be collected dispersively because they constitute the XY, YZ, and ZX planes of the target bone.

The residue of registration indicates the state of data fitting between the intraoperative data and the preoperative models. However, the residue of registration is not the same thing as accuracy of navigation, although it correlates with it. For any given value of residue of registration, the accuracy of navigation deteriorates as the target area moves away from the area where the surface points data for registration are obtained. Clinically, a residue of registration of more than 1 mm should not be accepted, even if the target area for navigation is close to the data sampling area. Surgeons should also verify registration by determining whether the bone surface points measured for navigation are touched. After registration, surgeons must be careful not to lose rigidity between DRFs and the target bones. This type of navigation is more useful for guiding socket orientation during THA than a conventional mechanical guide.[11,31] It can also be used to guide femoral components, control limb length, and select optimal modular parts for THA.[43] For periacetabular osteotomy, guiding osteotomes using this method increases the safety and accuracy of the procedure.[27] The advantages of volumetric image-based navigation are its accuracy (due to its 3D nature) and the fact that intraoperative radiographic control is not needed. The disadvantage of this system is that it is more costly and time-consuming than other systems for preoperative preparation.

Fluoroscopic navigation

For fluoroscopic navigation, which is less costly than volumetric image-based navigation, fluoroscopic images are used to construct the guiding map used during the operation. A C-arm fluoroscope is a standard piece of equipment in the OR. If fluoroscopic images are obtained while attaching DRFs to the C-arm and the target bones, the positions of the images relative to the patient can de determined. Thus, CAD files of implants and tools with DRFs can be superimposed on the images without the need for registration. This system does not require registration, and it reduces imaging time and radiation dosage because the first several images are used repeatedly to guide operative procedures.[18,19,22] This system has been used for spinal pedicle screw insertion and fracture reduction and fixation. Fluoroscopic navigation using 3D images reconstructed from isocentered multiple C-arm images is an option for imaging the precise structure of the spine or pelvis. However, its 3D C-arm images are of poorer image quality and smaller image size than CT images. C-Arm fluoroscopes usually use an image intensifier, which distorts the peripheral portion of the image. To correct this image distortion in this type of navigation system, calibration markers are imaged simultaneously. In the future, when flat panel detectors replace intensifiers, no calibration markers will be needed, and the quality and size of 3D C-arm images may be increased.

Imageless navigation

Imageless navigation does not use preoperative or intraoperative images for planning or guiding surgery. Instead, intraoperative kinetic information about joints, morphological information about bones, or both are used for planning and guiding maps. This system was initially developed for TKA,[9,26] and several THA applications are being developed. To find mechanical axes of the femur and tibia during TKA, DRFs are fixed to the pelvis, femur, tibia, and foot. The centers of the hip, knee, and ankle are then calculated as centers of relative motion of DRFs during passive movement of each joint. Recently, a method has been developed in which the centers of the knee and ankle are obtained from intraoperative morphological information. This type of navigation does not require registration. Varus/valgus and sagittal alignment are measured with the mechanical axes. Femoral rotational alignment is adjusted by referring to the epicondylar line, posterior condylar line, or sulcus line, which are determined by touching landmarks. Tibial rotational alignment is adjusted by referring to the posterior tibial line or the tibial tubercle. To improve visual information about the knee, a method has been developed in which bone is "morphed" from the surface points digitized intraoperatively.[13] This may help surgeons determine the most beneficial trade-off, taking into account ligament balancing and axial alignment. For preoperative imaging and planning for TKA or THA, imageless navigation is less costly and time-consuming than CT-based navigation.

Robotic surgery

Surgical navigation involves visualizing the surgical plan and the positions of the surgical tools. Surgeons may not place the tools according to the plan as precisely as machines. To overcome the inaccuracy of hand-controlled positioning of the surgical tools, three robotic systems have been developed. One system moves a cutting guide block or a drilling guide sleeve, with surgeons sliding a bone saw or a drill bit through the guide instrument to execute a surgical action. Another system constrains the range of movement of a surgical tool held by a robot arm such as ACROBOT.[20] The tool can be moved freely in space by the surgeon's hand within the preprogrammed range; it is never moved by the robot. The last system is an active one, such as ROBODOC[4] or CASPAR,[39] which moves a milling device automatically according to preoperative planning.

When introducing these robots into ORs, it is important to consider safety measures and hygiene. Cutters are single-use devices. Cutter sleeves and motors are sterilized in an autoclave. The body of a robot is covered by sterilized drapes. Robots must have several fail-safe mechanisms. Its weight should not be too great, and it should be designed so it stands by itself if the electricity fails. The speed of its active movement should not be too quick, so surgeons have enough time to check the robot motion and press the stop button if necessary. The system should have its own independent electricity supply to avoid spike currents, which may cause inappropriate movement of the robots.

ROBODOC was the first active robot in any surgical field to perform part of a surgical procedure by itself.[4] It was used in a Food and Drug Administration (FDA)-authorized multicenter study in the United States during 1994–1995 and has been used for clinical practice in Germany since 1994. The system was developed to improve implant selection, implant sizing, positioning of the implant within the bone, and accurate preparation of the bone cavity that is to accept the implant. ROBODOC consists of a preoperative planning computer workstation (called ORTHODOC) and a five-axis robotic arm with a high-speed milling device (end effector). For ORTHODOC, 3D preoperative planning is performed based on CT data. ORTHODOC can be used to select the optimal design for each patient by comparing the fit and fill of several designs.[17] Data, including the optimized plan, are transferred to ROBODOC, which mills the bone cavity in the same dimension as the corresponding rasp after registration of the femur. Initially, three titanium screw fiducials were used for registration.

The US study involved 136 hip replacements and was controlled and randomized. There were no significant differences in the Harris hip scores or Short Form Health Survey data between the ROBODOC group and the control group. However, radiographs showed that the fit and positioning of the femoral component were significantly better in the ROBODOC group. The only complication for which there was a significant difference between the groups was intraoperative femoral fracture: three in the control group and none in the ROBODOC group.

In a German study of 900 hip replacements performed using ROBODOC (858 unilateral hip replacements and 42 bilateral hip replacements, including 30 revision cases), there were no intraoperative femoral fractures. In cemented cases with a large cement mantle, the revision software allowed gentle removal of even large, deep cement mantles. Cement removal was safer and faster when performed by the robot than when performed by hand.

These findings indicate that the ROBODOC system is safe and effective, and that it produces radiographically superior implant fit and positioning while eliminating femoral fractures. Thus, the system aids in preventing well known mistakes in cementless total hip replacement that are generally considered to contribute to failure (undersizing of the implant, malpositioning the varus or valgus, reaming defects, fractures). Medial knee pain at the pin site has been shown to be associated with use of fiducial markers with ROBODOC, but this can be avoided using another marker site[36] or pinless registration with surface shape matching. Osteonecrosis due to heat generation from milling of bones has been mentioned as a possible disadvantage of ROBODOC (even if irrigation is used),[35] but no adverse clinical effects due to heat generation have been reported. Less heat is generated by robotic milling during TKA than by bone saws.[28] CASPAR is an active system similar to ROBODOC. It has been used to prepare bone tunnels for cruciate ligament reconstruction in the knee[8] and to prepare bony floor to accept implants of TKA and THA. One TKA study showed that CASPAR executed the preoperative plan based on CT data without any complications and that tibiofemoral alignment was better with the CASPAR procedure than with the manual procedure.[39] The tibiofemoral alignment achieved with CASPAR in that study was better than that achieved in a TKA study with a navigation system.[21] Bone surfaces prepared by robotic milling are flat and are suitable for cementless fixation.

Future technologies

The goals of CAS are to (1) eliminate outliers from radiological results by improving the accuracy of surgical procedures; (2) make minimum invasive surgery easier; (3) explore new concepts in surgery; and (4) use CAS for training and education. Early results from studies of robotic and manual navigation systems indicate that CAS improves surgical accuracy, and that it is safe to introduce these technologies into the OR environment. Preoperative computer planning allows simulation of surgery and optimization of the surgical plan; and it can be used for training and educating surgeons. However, although the dosage of intraoperative radiation can be reduced by volumetric image-based navigation and the volume of intraoperative pulmonary embolisms can be reduced by robotic milling,[15] some of the methods discussed above can increase surgical invasiveness (by requiring additional operations for marker implantation), prolong the duration of an operation, and increase blood loss. In this context, fluoroscopic navigation is useful because it can reduce both radiation dosage and operating time.

The CAS technologies have the potential to reduce invasiveness via integration of new instruments, new methods of image hybridization or visualization, and new methods of registration. Intraoperative image data acquisition using ultrasound devices or fluoroscopes may allow surface registration or 2D/3D registration[16,46] without skin incision. If video images of the surgical object can be properly supplemented by computationally reconstructed images,[1,14,26] it may be possible to perform some procedures less invasively using a small manipulator or a robot-controlled bone cutter. It is expected that augmented reality technologies, such as image overlay displays,[5] overlay binoculars,[12] and laser beam guidance,[30,38] will enhance navigational efficacy. These technologies can also be used for surgical training and rehabilitation.[37] Instrumented trial components can reduce the duration of time-consuming portions of surgery such as selection of modular parts for THA or soft tissue balancing during TKA.

Minimally invasive and more rapid surgical procedures using current orthopedic techniques are the obvious next steps for CAS technology. Eventually, these enabling technologies will permit the development of a new generation of surgical procedures that surgeons are currently not capable of performing because of technical limitations. Evolutionary changes may include the development of new hip and knee implants that are smaller than regular implants, as well as the combining of partial replacement of cartilage and ligament reconstruction into a single procedure that requires only a small incision. Even during an era in which revolutionary tissue engineering technologies replace artificial joint replacement, CAS will have an important role to play in controlling the shape of tissues and replacing damaged tissue with new tissue precisely and less invasively.

Cost-benefit analysis

From a purely financial point of view, the cost-benefit analysis of CAS technologies is not difficult. Savings from reduced surgery costs to the hospital and reduced patient morbidity due to less blood loss and shorter operating times may be the most important immediate cost savings resulting from deployment of CAS technologies. Near-term cost savings may include decreased rehabilitation time, which results in shorter hospital stays and less loss of time from work.

Longer-term cost savings may include delay or elimination of costly reoperations and an associated increase in worker productivity over time. For example, malalignment of components (particularly tibial components in TKA and acetabular components in THA) is one of the leading causes of component instability (as well as dislocation or loosening) and subsequent reoperation. Eliminating this cause of component failure would save the health care system a significant amount of money by eliminating or delaying reoperations. Depending on how these technologies are integrated into countries' health care systems, hospitals or insurers will have to determine whether these savings outweigh the investment required for hospitals or clinics to purchase (or develop), train on, utilize, and maintain the systems. Financial analysis performed in a vacuum assumes that the technology will be "pushed" into the marketplace by hospitals or insurers as a means of saving money. In a competitive business environment, such technologies could be used to market a clinic's services to patients, who may begin to demand the higher quality of service that such technologies can provide. In such an environment, the technology could be "pulled" into the market by customers (patients) demanding a higher level of service. In this scenario, as CAS becomes more of an industry standard, the increased purchasing of CAS technologies will lead to more rapid and focused industry-wide research into advancements in such technologies.

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