# V Technology

# 38 Computer-assisted Surgery: Principles

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## Summary

Computer-assisted surgery has emerged as an important adjunct in total knee arthroplasty and will improve the precision of mechanical alignment and ligament balancing of most surgical techniques. Current methods utilize computed tomography, imageless methods, or fluoroscopic referencing for image acquisition. Evolving minimally invasive surgical approaches will benefit from the "virtual" imaging of computer-assisted navigation.


## Introduction

Computer-assisted orthopedic surgery (CAOS) has recently been defined as the ability to utilize sophisticated computer algorithms to allow the surgeon to determine three-dimensional placement of total joint implants in situ [1]. A rapid ongoing evolution of technical advances has made it possible to move from cumbersome systems requiring preoperative computed tomography to more elegant systems that utilize image-free registration or the simple C-arm fluoroscopy at the time of surgery. Several reports on total knee replacement have cited the accuracy with which implants can be placed using computer-aided surgical navigation.

From a historical perspective, ROBODOC was the first modern attempt to use computers to place implants in bones. In this example, a cementless metal femoral stem was actively navigated into the proximal femoral canal. The goal was to improve the precision of implant placement and eliminate errors from a variety of sources including inaccurate plain radiographic templating, morphological anatomical variation, and problems related to the insertion of the implants. The ROBODOC system was conceived in 1986 by Bargar and Paul, and was developed over the next several years with grants from IBM. That team developed proprietary software for the CT imaging to obtain an accuracy of one pixel for the raw data. This advance allowed them to create three-dimensional CT reconstructions for choosing the implant sizes and planning the robotic surgical intervention. Originally, the fiducial markers for the robotic system were placed during a separate operative procedure. The marker was used to specifically orient the robotic tool into the inner canal of the proximal femur. This changed with the ability to register the unique anatomy of the patient intraoperatively. With improvements in software, the system could be referenced by using a digitizing probe for the key areas of the proximal femur. Small incisions were used about the midshaft of the femur for distal referencing [2, 3].

## Components of Computer-assisted Navigation

In the early 1990s, other possibilities arose for computer navigation. While "active" or robotic navigation held promise, "passive" navigation developed with the possibility of remotely tracking the instruments and anatomy. The idea here was to reference the target object with "passive" markers. In this case, that would be the human hip or knee joint, which would then be tracked passively in space. For surgical navigation, computed tomography was first used to acquire a digital image representation of the anatomical structure to which the "passive" markers would be applied [4] (Fig. 38-1).

C-arm fluoroscopy referencing followed, and ultimately "imageless" methods developed for total knee arthroplasty [5] (Fig. 38-2). Optoelectronic tracking of the "passive" markers was developed, as that system was readily available from other industrial applications and was not affected by the surgical environment. Other referencing methods such as electromagnetic trackers and ultrasonography had certain disadvantages. The system required the use of multiple cameras that viewed markers in a three-dimensional fashion much as global positioning satellites are used for determining land navigation. As with the Global Postioning Satellite network, surgical navigation can be quite accurate, with most systems documented to an accuracy of 1-2 mm or degrees.

In order to determine the exact spatial orientation of the patient or any surgical instrument, at least three non-collinear points on a fixed body (dynamic reference base) must be recognized by a camera system which then

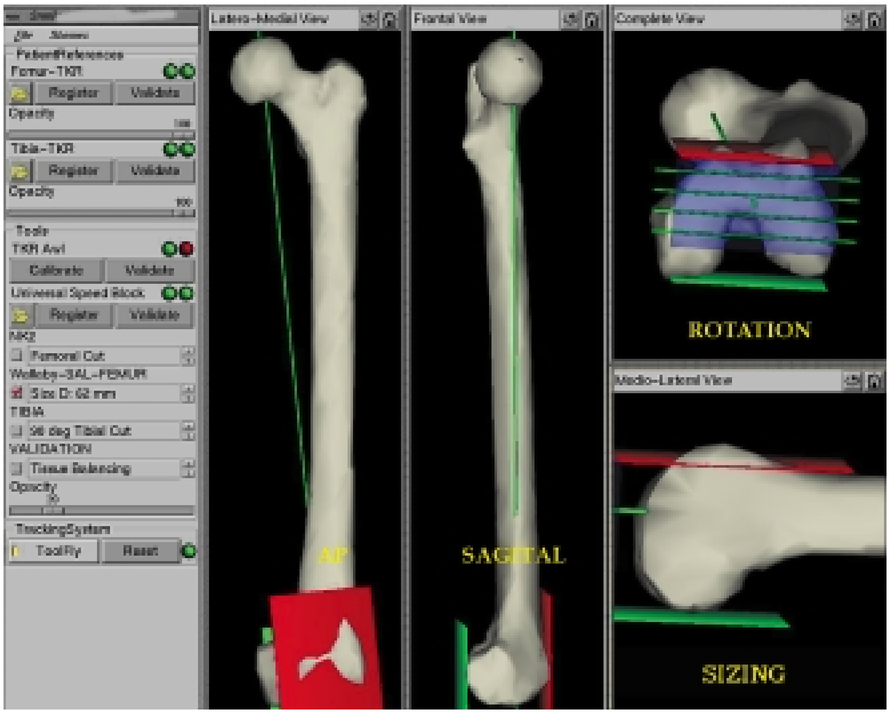


**Fig. 38-1.** The monitor view of a CT-based application demonstrates the portrayal of the femur where femoral component sizing, validation of the anterior distal femoral resection level, and the distal rotation of the femoral component can be realized. (From [16])

**Fig. 38-2.** Monitor view of the real fluoroscopic views that have been overlayed with the virtual CAD models of the implants. Note the detail of axes including the mechanical axis, coronal plane axis and the resection planes, including the resulting position of the planned prosthetic placement. (From [16])

inputs data into the computer for "virtual" referencing. The camera system generally will consist of two or three CCDs (charged couple devices) that pick up the light signal from the DRBs. The computer referencing protocol collects all components including the patient's anatomy and all registered surgical instruments. The DRBs may be active, consisting of light-emitting diodes (LEDs), or passive, where reflector balls are placed on the DRB and reflect infrared light originating from a light source on the camera. By differentiating the sphere arrangements on the DRBs, the computer can then detect the specific DRB, such as the marker on the distal femur or a paddle probe.

## Computer Referencing Methods

Registration is the process by which the computer recognizes the various three-dimensional objects that it must "virtually" characterize. For all DRBs the process is simply finding the appropriately defined DRB with the camera system and registering it with the computer (Fig. 38-3).

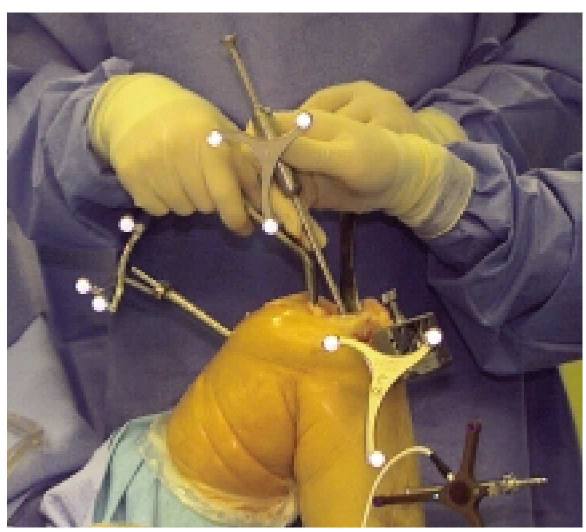

**Fig. 38-3.** Typical arrangement of DRBs with femoral, tibial, and "touch" pointer rigged with reflective balls that can be "viewed" by the camera system. (From [16])

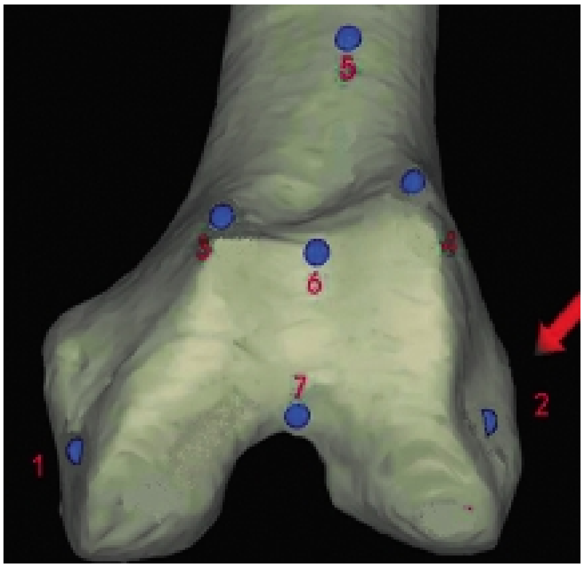


**Fig. 38-4.** Referencing of the CT 3D model requires point matching from the patient's distal femur which creates the virtual model on the computer for navigation. (From [16])

For instruments and implants, the exact dimensions and orientation of the referencing source are encrypted into the software. For the patient, the goal is to reference or "match" the anatomy of the patient into the computer model (Fig. 38-4).

There are two methods of performing this step. Paired-point matching takes prominent anatomical points that have been predetermined and then intraoperatively uses a space digitizer (pointer probe) that identifies or "matches" the same landmarks. The computer algorithm then matches these points to a "virtual" leg or pelvis built into the software system. Surface registration is a secondary referencing method whereby a small number of points may be digitized into the system to describe a surface contour such as the distal femoral condyle. An additional step is verification, which is cross-referencing additional points on the anatomy with the virtual object on the computer. From this information, the surgeon may judge the operational accuracy of the system.

The advantage of the CT scan for referencing is that it provides a three-dimensional data set for creating a patient-specific virtual model in the computer (see Fig. 38-4). However, acquisition of the CT scan adds additional logistical and financial factors to the process. The CT scan must be obtained preoperatively and must be digital in format for use on the computer [4]. Additional time will be required by the surgical team to manipulate the data, to pick the primary referencing points, for templating, etc. Also there are certain examples such as in navigated fracture reduction, where the bone topology of the CT scan will be intentionally altered during the surgical procedure. Other intraoperative referencing options include two-dimensional C-arm fluoroscopy or a direct imageless anatomical approach. With fluoroscopy, the two-dimensional images may be used as portraying the virtual patient, while with the direct imageless system, the landmarks are established on a "universal" limb model [5] (see Fig. 38-2). Fluoroscopy requires specific calibration to maintain the desired accuracy of the imaging technique. It is known that the earth's magnetic forces will significantly distort the image acquired, and this must be accounted for. In practice, a calibrated grid with markers of known size and spatial relationship are combined with the image to create an accurate virtual portrayal on the computer. The images are then acquired with the patient's DRB in position to obtain the virtual model that allows navigation of the fluoroscopic image. The imageless applications require simply touch pointing the anatomical landmarks, which are then registered onto the computer. This has been quite effective and successful for navigating total knee arthroplasty and has now become the standard technique with most "open" systems. With any of these systems, the variability comes from the precision with which the surgeon inputs the desired points. The surgeon must be knowledgeable of the specific points required and know exactly where those points should arise. For example, with the Medtronic "Universal Knee" system, which is an imageless system, the proximal tibia center point has been defined as the midpoint of the proximal tibial surface on the medial-lateral and anterior-posterior dimension.

## Total Knee Applications

Total knee arthroplasty requires attention to the entire complex of knee-joint mechanics, active muscle forces, and passive ligament structures. One has to appreciate that minimal malpositioning of intra- and extramedullary tools may lead to considerable variations of implant positioning [6, 7]. Thus, reconstruction of the mechanical lower extremity axis, as well as soft-tissue balancing, is vital for good results. TKA survivorship of 80%-95% after 10 years is reported but this is significantly reduced in cases with more than 4° of varus or valgus alignment, as Rand and Coventry reported in their series with 71% and 73%, respectively, compared with 90% in cases where the component alignment was within the range of 4° [8]. In a similar study, Jeffrey et al. demonstrated that the loosening rate after 12 years was 3% in well-aligned TKA (less than 3° varus/valgus) and 24% in less optimal aligned cases (more than 4° varus/valgus) [9]. In addition, Fehring et al. have shown that chronic ligamentous instability causes a substantial number of revisions after primary total knee arthroplasty, on the order of 27% [10]. There is a compelling roll for better surgical technique to create the desired positioning and tensioning of prosthetics in total knee arthroplasty.

Historically, the first total knee navigation was done by Saragaglia and Picard in 1997 [11]. Following the navigation experience of others, they were interested in developing a method for total knee replacement. As landmarks of the knee joint are relatively accessible, point matching logically would be easy and this led to the totally imageless method of referencing. The direct imageless approach in total knee arthroplasty requires that the surgeon create the virtual computer model by digitizing the various points of the anatomy with a navigated probe. A novel approach has evolved for determining the hip center location whereby the center of rotation of the hip joint is determined kinematically by simply rotating the lower extremity in a large circular motion (Fig. 38-5).

The computer automatically finds the smallest point of movement from the applied DRB, which in this case should be the center of the femoral head. The pelvis is held absolutely rigid for this maneuver. The mechanical axis of the lower extremity is defined by point matching the center of the distal femur, the center of the proximal tibia, and a factored point between the ankle malleoli for the most distal center. Other points such as the epicondyles, the joint surfaces, and the tibial tuberosity are referenced to provide the joint lines and appropriate rotational references [12,13]. Certain proprietary software applications have added surface matching to this direct method to supplement the anatomical features [14].

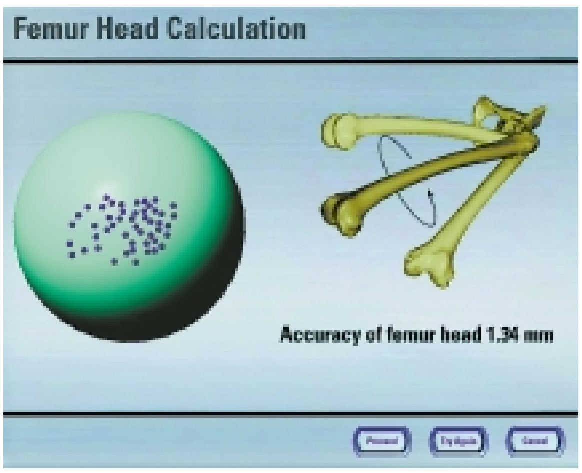


**Fig. 38-5.** Kinematic verification of the femoral center is done by holding the pelvis rigid, rotating the lower extremity with femoral DRB attached, and computer viewing of the movement of the lower extremity. (From [16])

What are the typical objectives of navigation in total knee arthroplasty? The most obvious goal is to determine the mechanical axis of the lower extremity. This is particularly helpful in cases where ligament release may be extensive and an error may include inadequate release. Each of the joint surface cuts can be made based on the relationship to the mechanical axis. The anterior-posterior cuts of the distal femur may be done using an anterior or posterior cortical reference and the relationship to the transepicondylar axis. One of the recent applications allows for assessment of the gaps before the primary cuts have been made, assessing the precise distance as well as the eventual implant sizes (Fig. 38-6).

Typical navigation will allow for assessing the mechanical alignment and femoral/tibial deviations throughout the range of motion. One may then measure the amount of laxity at each position of flexion through the range of motion. Optimal technique would place the final alignment at 0° for the mechanical axis. A posterior tibial slope should match the required implant. The distal femoral component position should be at 90° to the mechanical axis on the AP view and at 90° to the distal femoral axis on the sagittal plane view. The latter requires 4°-5° of flexion of the implant to the mechanical axis of the lower extremity. Transverse plane femoral rotation should be the prescribed 3°-4° for external rotation to the posterior condylar axis or on the transepicondylar axis.

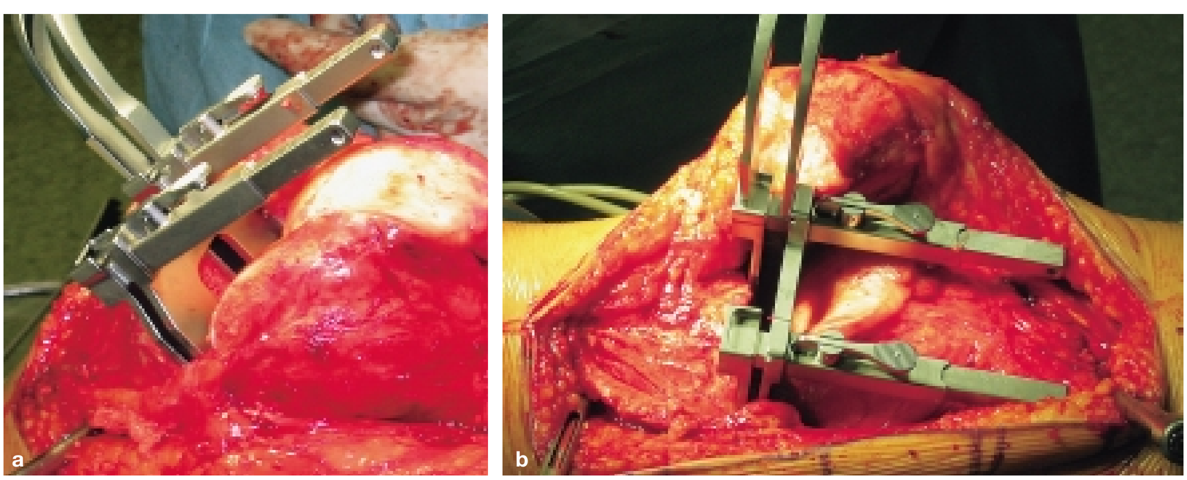


**Fig. 38-6a, b.** Typical soft-tissue balancing systems available with currently available navigation systems allow assessment of gap dimension prior to resection and positional data that will guide implant sizing. (From [16])

The anterior cortical reference should match the final anterior cut to prevent notching of the distal femur. The mobile-bearing TKA technique typically uses the "tibial cut first" method for determining femoral rotation, which involves flexion spacing. Femoral rotation is based not on a measured distal femoral resection but on the results of a flexion space tensor. The femoral rotation in this scenario tends to reflect the initial flexion space rotation prior to ligament release, or may have an opposite variant rotation based on an extensive extensor release, such as may occur with a severe varus deformity.

## CAS in Minimally Invasive Surgery

The applications to minimally invasive surgery will evolve from a unique combination of the above-noted techniques. The surgical problem with small incisions is that certain landmarks become inaccessible for direct point touch matching. While one may easily identify the lower extremity centers for the total knee quadriceps-sparing technique, accessory landmarks such as the epicondyles may not be readily obtained. Fluoroscopy provides images for which these additional landmarks may be point matched directly from the computer screen. The surgeon then has the option of either direct or indirect referencing of the various landmarks. Once referenced, the fluoroscopic images may be utilized for appropriate sizing and positioning of the implants, either with "stick models" of the surface cuts or with CAD model overlays (see Fig. 38-2). Future applications will include newer technologies such as electromagnetic sensors that can be made into miniature DRBs and the use of more sophisticated imaging systems such as three-dimensional C-arms and intraoperative CT scanners [15]. There are currently available technologies that will allow the surgeon unlimited capabilities where navigation may be combined with robotics and robotic-assisted ligament balancing (Fig. 38-7).

The interested surgeon must understand that both technologies of MIS and CAOS are recent innovations that are still evolving in terms of validation assessment and clinical efficacy. While both methods will potentially enhance total knee outcomes, only limited clinical studies are currently available. CAOS has clearly been shown to improve mechanical alignment of total knee arthroplasty in several clinical studies. However, the real advantage of CAOS may be in the ability to improve other aspects of surgical technique such as ligamentous balancing and refined component placement. The surgeon must also be cautioned to avoid attempting mastery of both technologies without adequate experience. A logical approach would be to choose one or the other and then gradually refine the technique over an extended period of time (Fig. 38-8).

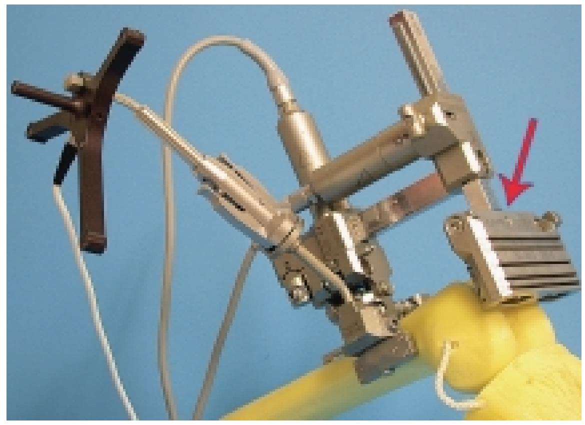

**Fig. 38-7.** Futuristic combination of robotic cutting devices (*arrow*) attached to navigation DRBs allows more precise bone resection along with an integrated ligament tensioner. (From [16])

**Fig. 38-8.** Senior author demonstrates flexion spacing of a mobile-bearing total knee arthroplasty with the focus of attention to the computer monitor, which is out of the picture. (From [16])

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