Numerous authors have investigated outcomes following total knee arthroplasty (TKA), finding that malalignment greater than 3 degrees resulted in a significantly higher potential for mechanical loosening and implant failure. Petersen and Engh investigated the radiographic results of 50 patients who underwent primary TKA with conventional methods, noting a 26% failure to achieve alignment within the optimum of 3 degrees of varus or valgus from the mechanical axis.\(^1\) Jeffery and associates noted satisfactory postoperative coronal alignment (mechanical axis deviation less than 3 degrees) in 68% of their TKAs. In operated knees with mechanical axis deviation greater than 3 degrees in the coronal plane, a mechanical loosening rate of 24% occurred at 8 years, as opposed to 3% mechanical loosening for normally aligned knees.\(^2\) Berend and colleagues investigated tibial component failure mechanisms, noting that malalignment of the tibial component at more than 3 degrees of varus increased the odds of failure.\(^3\)

Computer-assisted navigation of TKA has been shown to produce improved mechanical axis alignment in the clinical setting and offers significant advantages, particularly in cases with severe deformity resulting from long-standing arthritis or traumatic causes.\(^4\) Access to bony landmarks with open procedures has made TKA navigation a very feasible system when imageless referencing protocols are used. After the original navigation system was developed in 1991 by Dr. Stephane Lavallee at the University of Grenoble for anterior cruciate ligament reconstruction, Saragaglia and coworkers introduced the first kinematic navigation protocol for determining the centers of the hip and ankle; this paved the way for a reproducible and simple imageless approach.\(^5\) Optical tracking has been the primary data accrual method for most current systems.\(^6\) This review discusses the basis of that technology, clinical methods, and outcomes offered by current methods of computer navigation in TKA. Additionally, problem areas that have shown limited acceptance of this technology are addressed by the introduction of a system that makes navigation a simple and limited surgical tool customized to the individual needs of each surgeon.

**Components of a Computer Navigation System**

Three elements are required for computer navigation: (1) the computer platform; (2) the tracking system; and (3) the group of dynamic reference bases (DRBs) that constitute the target objects of the navigation procedure. These target objects include the patient’s bones, the surgical instruments, and the implants used in the surgical procedure. Important choices regarding each of these components face the practicing surgeon, who must decide from a variety of options. The surgeon should be knowledgeable about possible sources of measurement error that may be demonstrated by a computer navigation system.

**Computer Platform**

The most basic component of a computer navigation system is the computer on which the system relies for coordination of inputs from the surgical field, mathematical interpretation of the datasets, and display of the resultant information on a monitor. Currently utilized systems require hardware capable of a robust, real-time calculation. Commonly, this results in pairing of powerful microprocessors and software platforms based on Windows or Linux systems. These base operating systems are considered more responsive and stable for the use of mission critical applications. The measurement system is designed in such a fashion that the three-dimensional position of objects or targets in the operative field can be determined with low rates of error—much as a global positioning satellite system would function. Computer platforms may be considered closed, or proprietary, if the navigation provides support limited to a specific implant system or surgical technique. The other possibility is an open system that is more general and allows, for example, a software protocol to support the implantation of total knee implants from different manufacturers. The advantage of a proprietary system is that more elaborate representations are usually supported such that virtual implant sizing to a virtual reconstruction of the patient’s anatomy can be performed.

A typical capital system will have a rolling cart with computer, keyboard, mouse, LCD monitor, foot pedal activator, and optical tracking camera. The optical camera may be placed on a boom or a separate tower to allow placement in its appropriate position during the operative procedure. The optical camera system typically will have two charged-coupled device (CCD) receivers that will pick up laser impulses from an active tracker or reflected beam from passive balls attached to a passive tracker. Portable options have been developed that allow similar hardware and applications but with smaller desktop computers and microcameras or tracking devices that may be quickly assembled from a suitcase. This allows manufacturers’ representatives to conveniently bring in a full navigation system for limited one-time use as a service that may be purchased by the hospital. This option is a great opportunity for the surgeon who is new to computer navigation and who may not be committed to asking his hospital to make the several hundred thousand dollar (U.S.) purchase of a capital system. It is an excellent option for low-volume surgeons and hospitals that may not have resources to afford the large investment for more permanent systems, in that

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\(^\text{1\)References 2, 3, 5-7, 9, 14, 15, 18, 20, 24, 32, 33, 35, 38, 39, 42, 48, 49, and 51.}

\(^\text{2\)References 1, 8, 11, 13, and 26.}
Tracking Technologies

An important element of any computer navigation system is the mechanism or technology chosen to track the target or object. The basic elements are trackers that may be attached to the patient’s bones or surgical instruments. These trackers are then used in an environment that consists of a camera, electromagnetic coil, or ultrasonic probe that will pick up laser or electromagnetic pulses that originate from the trackers. Recently, video monitoring has been added as a “real-time” tracking option, but this method has not reached significant clinical application.

Optical tracking systems require two or three CCD cameras to pick up laser impulses from the trackers that are recognized by a minimum of three and possibly four or five active emitters or passive reflective balls. The computer calculates the three-dimensional position of the trackers based on recognition of the spatial footprint of the tracker emitters. The footprint of each tracker is unique and allows differentiation of bones, instruments, and implants. Conventional optical cameras function by being placed 6 to 8 feet from the object trackers, and must have an unobstructed “line of sight” to the trackers. This requires that operating personnel must be aware of this relationship, but if positioning is optimal, staff readily adapt to the requirement. Clinical validation studies of optical tracking systems have demonstrated very high reliability and accuracy with a typical translational error of 0.25 mm.\(^{23,35,52}\) This absolute measurement error increases trigonometrically with increasing distance from the camera.\(^{43}\)

Electromagnetic (EM) tracking relies on small trackers that create an electromagnetic impulse that is recognized by an electromagnetic coil placed 20 to 30 inches away.\(^{29}\) These trackers may be placed inside the wound but require small wires that go directly to the computer system for activation. The magnetic coil then measures interference created by the tracker as it moves within the electromagnetic field. The disadvantage of current electromagnetic tracking systems is distortion of the field created by ferrous metals that are inherently magnetic, but any metal such as brass and copper and even nonmetals such as Kevlar may interfere. Current computer algorithms have been calibrated to shut down the system if distortion is recognized. However, the EM approach still remains vulnerable to many other potentially distorting fields that are found in the typical operating room. Clinical validation studies have identified this problem, and although the electromagnetic system seems to perform with the precision of current optical systems at the 0.5 mm level, the occasional outlier may be off by several degrees, which makes this method less reliable.\(^{1,11,13,24}\)

Referencing Methods

For the surgeon, referencing of target objects is the most significant problem and requires a thorough knowledge of both the technology and the desired anatomic points to be matched on the virtual computer model. The process basically is to define points in space with a tracker that can be triangulated by the tracking system. For surgical instruments, a referencing tool allows the surgeon to capture the “marked” instrument such as a pointer probe. The precision of the instrument will be within 250 to 500 \(\mu\) of error.\(^{21}\) Imageless referencing is possible if the targeted objects are directly visible, and is most applicable in TKA. Numerous studies have demonstrated the efficacy of imageless referencing as compared with conventional instrumentation for TKA, but these results depend on the expertise of the surgeon to choose the correct reference points.\(^{59}\) Computer algorithms are written with the assumption that the ideal point will be selected. For example, referencing of one universal total knee protocol prescribes that the femoral center is chosen as a point that is under the roof of the intercondylar notch and lies on both the transepicondylar line and the anteroposterior axis of Whiteside. Deviation from this “ideal” point adds error.

Kinematic referencing in TKA as pioneered by Lavallee has been a novel innovation for determining the center of the hip and ankle joints, markedly simplifying this procedure.\(^{29}\) Because the hip joint is not directly visible, a method was needed by which to accurately reference the hip center. This was accomplished by tracking the femur with the optical camera as the femur was rotated in a circular motion. The movement of the tracker described the base of a cone, which when projected to its zenith closely approximates the center of the hip joint. The computer algorithm calculates the root mean square error or the standard deviation, which must fall within a limited range for the computer to accept the hip center reference point.

A secondary method of referencing is bone morphing, which involves selecting hundreds of surface match points by “painting” the bone with the pointer probe.\(^{46,47}\) This method does not require the segmented three-dimensional model typical of computed tomography (CT) but uses a virtual model that is then constructed by the computer algorithm. The virtual image created allows enhanced capabilities such as prosthetic sizing, “live” bone resection, and kinematic assessment. However, this additional technology usually adds time and complexity to the operative procedure and may limit the surgeon’s choice of prosthetic implants. One current morph technology is to limit the referenced areas to small patches. For example, surgeons find difficulty referencing the femoral posterior condyle in finding the most posterior or dorsal position. This process can be simplified and made much more precise by morphing a small patch, allowing the computer to find the optimum position.

Ultrasound image capture is a newer method of referencing that is evolving as a potential technique whereby multimodal referencing is performed.\(^{8,25}\) Depending on frequency and the acoustical properties of the object, point localization is accurate to submillimeter levels on the order of 0.25 to 0.75 mm with ultrasound, whether it is 2-dimensional, 2.5-dimensional, or 3-dimensional in the modality of image capture. Segmentation is possible when this image may be matched with a preoperative CT image or even an intraoperative “bone morphed” image. However, the clinical applications remain limited for a variety of reasons. Definition of baseline anatomic points is difficult with ultrasound, which creates an error on the order of 2 to 5 mm, which is unacceptable for clinical practice. However, the promise of ultrasound is that it can be done through the tissues intraproactively without the need for skin incision or radiation exposure.
**Clinical Methods**

The specifics of navigation referencing constitute an important element of the technique and bear detailed description. Tracker placement requires rigid fixation of the dynamic reference base to the femur and tibia, because any movement creates error. Current systems have validation checkpoints that may be established and then remeasured throughout the procedure to monitor tracker error. Recent studies have favored two pins of 3 mm diameter. It is important to note that single pins of 5 mm and bicortical placement should be avoided, as incidental fractures have been described. Placement of the femoral pins in the medial femoral condyle or in a percutaneous transepicondylar position avoids the potential for neurovascular injury (Fig. 115-1). Hip center determination is done using the kinematic method originally described by Saragaglia.

Anatomic referencing of the patient’s landmark, the most critical step for the surgeon, requires a thorough understanding of what the system’s software engineers had in mind when they designed the system. This becomes the most likely source of error. For typical referencing, the computer definition of the femoral center is a point under the roof of the intercondylar notch that is in the middle of the intercondylar notch and lies in the anteroposterior axis of Whiteside (Fig. 115-2). From dissections, this point also lies directly on the transepicondylar axis of the distal femur. The surgical epicondyle depression is the reference for the medial epicondyle, and the lateral epicondyle is the most prominent point of that landmark.

For the tibial reference, the tibial center is defined as the bisection of the transverse tibial axis. The transverse tibial axis is a line that connects the anteroposterior midpoints of the medial and lateral condylar surfaces. The tibial center approximates the lateral insertion of the anterior cruciate ligament (Fig. 115-3). The anteroposterior tibial axis is a perpendicular extension of the tibial center of the transverse tibial axis. This point typically matches the extension of the femoral anteroposterior axis that may be extended onto the anterior surface of the tibia. Great care must be taken to determine the tibial center, as this will affect both coronal and sagittal plane measurements. The posterior condylar axis of the tibia is 3 to 4 degrees external to the transverse tibial axis. The center of the tibial tubercle is typically about 18 degrees external to the anteroposterior axis of the tibia. Finally, the transverse tibial axis should nearly approximate the transepicondylar axis with regard to coupled rotation. The center of the distal tibia is determined by picking points that center over the medial and lateral malleoli—the transmalleolar axis. The computer algorithm then kinematically picks a point on the transmalleolar axis that is 40% from the most medial point.

Once referenced, the computer system may be used to assess each step in the surgical technique. For the beginning surgeon, the logical method is to perform the standard surgical technique using the computer as an adjunct to conventional instrumentation. This allows the surgeon to become comfortable with the navigated measurements and eliminates the early risk of error from inexperience. With practice, the surgeon will learn to depend on the increased precision of the navigated steps, and may be able make cuts even without conventional instruments. The computer, which becomes an excellent source of information regarding the surgical procedure, will teach the surgeon about the potential measurement errors that may occur with his conventional techniques.
Table 115-1 Clinical Studies That Compare Conventional Manual Surgical Techniques With Computer Navigation in Placing Limb Alignment Within ±3 Degrees of the Mechanical Axis of the Lower Extremity

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<td>74 (P &lt; .001)</td>
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Clinical Outcomes

Literature Review

Computer-assisted alignment devices were developed to improve the positioning of implants during TKA. Early data on the use of these image-free optical tracking systems appeared positive with improved mechanical alignment, frontal and sagittal femoral axis alignment, and frontal tibial axis alignment. Furthermore, no studies have demonstrated increased complications compared with hand-guided techniques. Yau and associates compared the combined intraobserver error for image-free acquisition of reference landmarks during TKA, finding that the maximum combined error for the coronal plane mechanical axis alignment was 1.32 degrees.53 Perlick and colleagues compared an image-free navigation system versus a conventional method using an intramedullary femoral guide and an extramedullary tibial guide. They reported postoperative mechanical alignment to be within 3 degrees varus or valgus in 96% of navigation cases versus 78% in the conventional group.32 Sparmann and coworkers determined that an image-free navigation system produces significant improvement in mechanical alignment, frontal and sagittal femoral alignment, and frontal tibial alignment (P < .0001) compared with a hand-guided technique. Postoperative mechanical alignment was within 3 degrees varus or valgus in 87% of the conventional group versus 100% of the navigation group.42 A significant number of studies have compared the use of imageless computer-assisted navigation versus conventional methods for TKA. All studies demonstrated a statistically significant improvement in terms of placing the final mechanical alignment of the knee within 3 degrees of the ideal mechanical axis. Furthermore, we noted that 93% of overall cases from these studies reached this level of precision with computer navigation compared with 73% when conventional methods were used (Table 115-1).

Results of assessment of the transepicondylar axis or the anteroposterior axis of Whiteside are inconsistent as compared with mechanical axis alignment. This most likely reflects the difficulty involved in reproducibly picking the epicondylar or anteroposterior axis landmarks. Prior studies have confirmed this problem, finding a large amount of variability in the basic anatomic landmark and in the ability of the surgeon to clinically define the structure.8 The problem with using the anteroposterior axis for computer navigation referencing can easily be understood by the fact that distances for landmarking are very short. Slight errors in judgment can

*References 12, 17, 30, 37, 41, and 50.
be off by several degrees. This contrasts with mechanical axis landmarking, in which an error of just one degree will require a point matching mistake of at least 5 mm. Yau and associates found that errors in the transepicondylar axis could be as high as 9 degrees. Restrepo and colleagues reported that the fixed posterior condylar axis reference could result in malalignment of more than 5 degrees in 17% of cases as compared with other rotational axes. Siston and coworkers suggested that improvement is needed in determining femoral alignment accuracy.

Other image acquisition and tracking methods are available, beyond the current standard imageless total knee systems; these include CT, fluoroscopy, and electromagnetic tracking. Perlick and associates compared CT with imageless referencing methods in TKA and found that 92% with CT versus 97% with imageless systems produced TKA mechanical axis alignment less than 3 degrees. Victor and colleagues used fluoroscopic image acquisition in a randomized study with TKA to find that 100% of navigated knees had mechanical alignment within ±3 degrees, while 73% of conventional TKAs were within ±3 degrees.

Blood loss has been significantly reduced with the use of computer navigation and avoidance of intramedullary rods. Kalairajah and coworkers were able to reduce blood loss from 1747 mL to 1351 mL by using pin-placed trackers instead of intramedullary guided femur and tibia jigs; this represented a significant difference in 60 patients. Kalairajah and associates performed a transcranial Doppler study on 14 patients, finding that all patients who had undergone intramedullary instrumentation of the femur and tibia with conventional TKA had documented intracranial microemboli compared with only 50% of those who had undergone procedures in which only intracortical tracking pins had been placed. However, Kim and colleagues could not find a significant difference with fat or bone marrow embolization when comparing navigation with conventional instrumentation.

Navigation with minimally invasive total knee approaches has been shown to offer some advantages. Dutton and associates demonstrated that with a minimally invasive technique, 92% of patients were within the ±3 degrees target with navigation as opposed to 68% with conventional instruments. Although navigation increased operating room time by 24 minutes, both length of hospital stay and functional recovery at 1 month were improved by the method. Stiehl was able to show that increased navigation time could be diminished by using a custom computer protocol for the specific surgeon, and noted that navigation actually had a 10-minute average shorter duration compared with conventional instrument techniques. Novak and colleagues studied cost-effectiveness with computer navigation and suggested that the typical added cost of $1500 for navigation would need to be reduced to less than $629 for the method to become effective in decreasing the morbidity shown with poorer total knee alignment.

**Evolv**

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Evolutionary Technologies

We have alluded to our recent efforts to develop a futuristic system that provides the surgeon with a highly accurate tool that may be abbreviated or customized to his particular needs. Most contemporary systems are “one size fits all,” and the surgeon not only must learn the navigation system but often will need to change his own approach, which he may have painstakingly developed over several years. He may not have great skills with the computer, nor the inclination to struggle through the learning curve needed for this technology. We are developing a very limited system with a laptop computer and a compact camera that may be placed directly into the surgical field (Figs. 115-4 and 115-5). More important, we want the system to be customized for each surgeon, such that he may develop his own custom protocol. The number of navigated steps, their order in the software protocol, and actual surgical field screen views are developed by each individual surgeon with help from a manufacturer’s representative. By navigating only the critical steps in the procedure, we believe the surgeon improves the accuracy of the surgical procedure with the strength of the technology; this technique may be more efficient than the use of conventional manual instruments.

Our new PICO station has limited, legible numbers with appropriate screen prompts or diagrams to enhance the flow. This focus came from our middle-aged surgeons, who were having trouble reading screens that were 6 to 8 feet away. We were told that each surgeon was looking for a certain number of pixels to be displayed on the screen. We have alluded to our recent efforts to develop a futuristic system that provides the surgeon with a highly accurate tool that may be abbreviated or customized to his particular needs. Most contemporary systems are “one size fits all,” and the surgeon not only must learn the navigation system but often will need to change his own approach, which he may have painstakingly developed over several years. He may not have great skills with the computer, nor the inclination to struggle through the learning curve needed for this technology. We are developing a very limited system with a laptop computer and a compact camera that may be placed directly into the surgical field (Figs. 115-4 and 115-5). More important, we want the system to be customized for each surgeon, such that he may develop his own custom protocol. The number of navigated steps, their order in the software protocol, and actual surgical field screen views are developed by each individual surgeon with help from a manufacturer’s representative. By navigating only the critical steps in the procedure, we believe the surgeon improves the accuracy of the surgical procedure with the strength of the technology; this technique may be more efficient than the use of conventional manual instruments.

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This system favors minimally invasive cutting blocks, has all of the technology improvements noted earlier, and avoids intramedullary device placement, but it significantly shortens surgical time by removing the guesswork of the procedure.

**DISCUSSION**

In conclusion, computer-assisted navigation offers significant advantages for improving the precision of surgical technique with TKA. This review has attempted to clarify the general nature of the technology and to point out the strengths and weaknesses of various approaches. Improved mechanical axis alignment is the signal refinement offered to TKA; this may also be applied to unicordyly and revision arthroplasty. Navigation provides the ability to assess ligamentous balance and overall kinematics after prosthetic reconstruction. However, certain elements such as determining the femoral and tibial rotational axes are less precise with current applications. One must consider that constant technology evolution is occurring, but the overall advantages of computer navigation in TKA have been recognized and will not change substantially in the near future.

**KEY REFERENCES**


Full references for this chapter can be found on www.expertconsult.com.
REFERENCES

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