Image-Guided Surgical Navigation: Basic Principles and Applications to Reconstructive Surgery

Stephen Murphy, MD and Reuben Gobezie, MD
Beth Israel-Deaconess Medical Center, New England Baptist Bone and Joint Institute, Harvard Medical School

INTRODUCTION

Image-guided surgical navigation has the potential to improve the accuracy of critical aspects of orthopedic reconstructive surgery and to create new, less morbid procedures that are primarily based on image-guidance. The technology allows the surgeon to predict the effect of proposed surgical steps before they are made. The position of surgical instruments can be displayed in real-time on multiple radiographic projections simultaneously – an impossibility with traditional fluoroscopic techniques. The current review explains the basic principles of surgical navigation and its applications to orthopedic reconstructive surgery.

PRINCIPLES OF SURGICAL NAVIGATION

Tracking Methods

Surgical navigation involves the tracking of bones and surgical instruments in real-time during surgery. The tracking can be performed optically, electromagnetically, or in rare cases, ultrasonographically. As electromagnetic fields are usually distorted by the drills and metal instruments used in orthopedic surgery, optical tracking is most common.

Optical tracking can be performed with the use of a stereoscopic infrared camera (Figure 1). Instruments and bones are tracked by rigidly attaching small frames on them with 3 or more spheres that reflect light or L.E.D.s that emit light (Figure 2). If the camera can see the reference frame, the position of the rest of the instrument or bone can be instantly calculated.

Imaging Methods

Tracking can be performed using image-free or image-based navigation. In image-free navigation, the positions of instruments or rigid bony segments can be tracked using optical cameras without the aid of any imaging studies. For example, leg alignment can be tracked during osteotomy or knee replacement surgery without any images. This is done by putting skeletal reference frames on the femur and tibia.

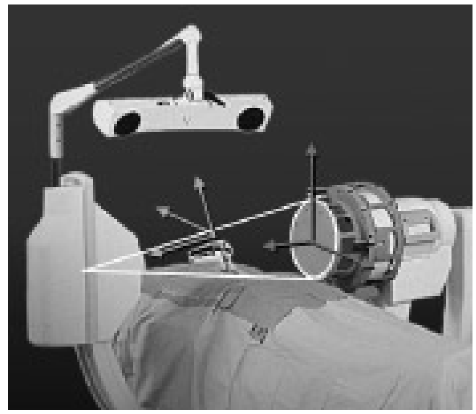

Figure 1: Infrared stereoscopic camera

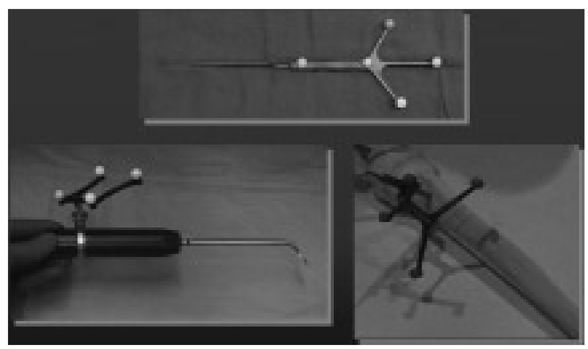

Figure 2: Infrared cameras can track the position of any rigid object in real-time to an accuracy of better than 1 mm and 1 degree.

The center of the hip can be calculated by moving the hip joint while the optical camera tracks the femoral skeletal reference frame. The center of rotation of the femoral reference frame is the center of rotation of the hip. The center of the distal femur is directly digitized with a pointer that has a reference frame attached to it. With the center of the hip and knee inputted, the mechanical axis of the femur is defined and can be tracked continuously during surgery. If a navigated saw or cutting jig is placed on the distal femur, the angle between that plane and the mechanical axis of the femur can be calculated. Using image-free techniques, all major angular and distance measurements can be tracked during total knee surgery.

Image-based navigation systems have the ability to display surgical instruments onto a background of two-dimensional (2D) or three-dimensional (3D) images of the body. While all image-based navigation systems have the capability of tracking in an image-free mode, image-free navigation systems are more limited in their applications. Imaging for image-based navigation can be done either before or during surgery.

Stephen B. Murphy, MD is a Clinical Instructor in Orthopaedic Surgery at Harvard Medical School.

Reuben Gobezie, MD is a Resident in Orthopaedic Surgery in the Harvard Combined Orthopaedic Residency Program.

Address correspondence to:

Stephen B. Murphy, MD
New England Baptist Hospital
Department of Orthopaedic Surgery
125 Parker Hill Avenue
Boston, MA 02120

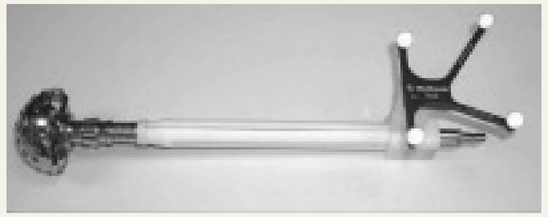

Figure 3: Navigated Acetabular Reamer

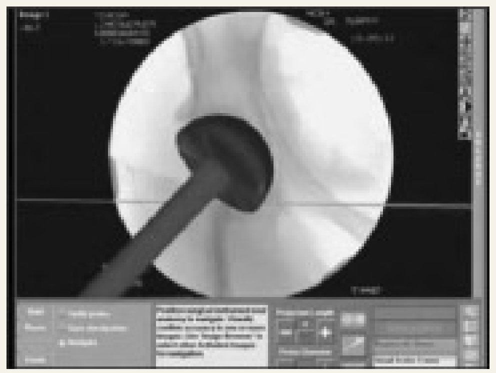

Figure 4: A CAD model of an acetabular reamer displayed in real-time as the acetabulum is being reamed during surgery

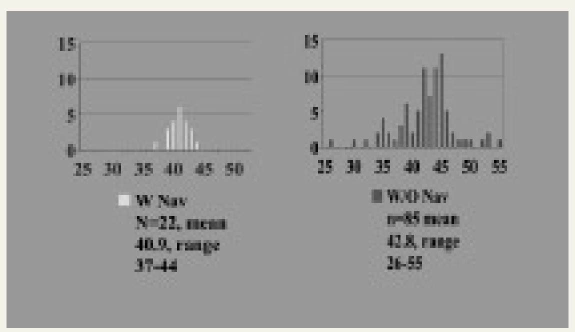

Figure 5: Navigation of acetabular component insertion eliminates the most poorly positioned cups

Pre-Operative Image Acquisition

Pre-operative CT and MRI studies have the advantage of being highly detailed 3D data sets of the bones and surrounding soft tissues. The disadvantage of pre-operative image acquisition is that the 3D data set needs to be registered with the actual 3D anatomy at the time of surgery. There are many methods of registration, including identifying matching landmarks on the images and the body (such as the superior spines of the pelvis), matching a surface on the images and the body (such as the iliac wing), or a mathematical combination of the two. Ultimately though, any preoperatively acquired images need to be registered at the time of surgery.

Intra-Operative Image Acquisition

Orthopedic applications of surgical navigation have two great advantages. First, the structures and instruments that we work with are generally rigid structures that do not bend. Second, many of the important things that we work with can be seen radiographically. This allows orthopedic applications to be based on fluoroscopic images that can be acquired at the time of surgery. Intra-operative image acquisition has the additional advantage that registration of the images is not necessary. This is because the camera can see both the reference frame on the body and the reference frame on the fluoroscopic c-arm at the exact moment that the image is taken. From then on, even if the body changes position, any surgical instrument that is brought into the field can be superimposed on the fluoroscopic image. This technique is called virtual fluoroscopy, and it forms the basis for most orthopedic applications of surgical navigation. Further, since fluoroscopic views from many different angles can be taken and then the c-arm removed, virtual fluoroscopy can show the progress of surgery instruments on many fluoroscopic views simultaneously – without the c-arm in the way. This ability to navigate using multiple views simultaneously can only be accomplished with surgical navigation.

CLINICAL APPLICATIONS TO THE HIP AND KNEE

About the hip, surgical navigation techniques can be applied to primary and revision hip arthroplasty and osteotomy. For primary hip arthroplasty, navigation of acetabular component preparation and insertion is the greatest need, since acetabular component malposition is the cause of almost 50% of all hip dislocations.[1,2] Surgical navigation can track the position of acetabular reamers during the reaming process and the exact angle of acetabular component insertion (Figures 3 and 4). Our study of 22 primary total hip arthroplasties performed with surgical navigation clearly demonstrates that all poorly positioned cups are eliminated if navigation is used (Figure 5). Elimination of poorly positioned cups with the use of surgical navigation would decrease the incidence of dislocation, revision for dislocation, polyethylene wear, and osteolysis due to polyethylene wear.[2] These data suggest that patients undergoing total hip arthroplasty with image-guided surgery may be far better off.

Application of surgical navigation to revision total hip arthroplasty has the further advantage that cement may be removed more rapidly and safely if the progress of high-speed burrs could be tracked from multiple fluoroscopic angles simultaneously. Better knowledge of the location of these instruments may both save time and decrease the risk of bone perforation.

Figure 6: The tracking of osteotomes during periacetabular osteotomy shows the progress of the surgery without taking additional fluoroscopic images

Osteotomy of the pelvis and femur can be aided by surgical navigation in a variety of ways. Intra-operative navigation of osteotomes and blade chisels (Figure 6) is clearly beneficial. Tracking these instruments with virtual fluoroscopy would greatly decrease the need for obtaining additional images throughout the procedure.

With regard to knee reconstruction, the keys to a successful total knee arthroplasty are proper alignment, ligament balance, and implant sizing. All of these can be performed with great accuracy using surgical navigation. One study of surgical navigation for total knee replacement has already shown that implant and limb alignment are more accurately achieved with navigation than without.[3] More sophisticated applications of surgical navigation for total knee replacement allow the surgeon to see bone resection depths, alignment, and the actual size and location of the proposed implants on virtual fluoroscopy before a single bone cut is made (Figures 7 and 8).[4]

Other applications of image-guided surgery for the hip and knee include accurate placement of percutaneous SI joint screws, fracture reduction and rod insertion, interlocking screw insertion, removal of buried hardware, and ligament reconstruction.

CONCLUSION

Image-guided surgical navigation has been shown to improve the accuracy of numerous orthopedic procedures and offers great potential for the development of newer, less invasive methods of solving problems about the hip and knee.

ACKNOWLEDGEMENTS

Chris Lyons, Chris Carson, and Jody Stallings, Smith and Nephew Image-Guided Surgery; Gordon Goodchild, Delphine Henry, and Dierdre Butler, Medtronics Surgical Navigation Technologies.

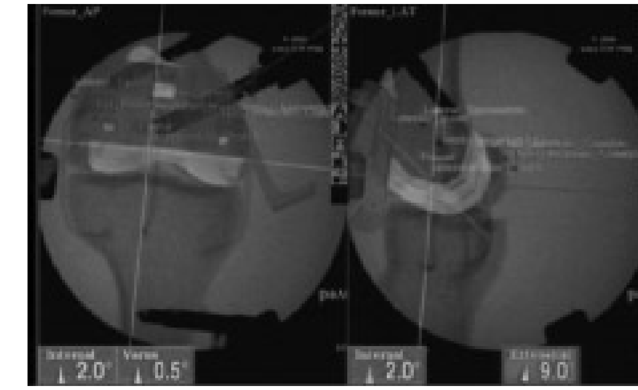

Figure 7: Use of the Distal Femoral Resection Guide shows the guide itself and the size position of the actual if the cut is made as proposed

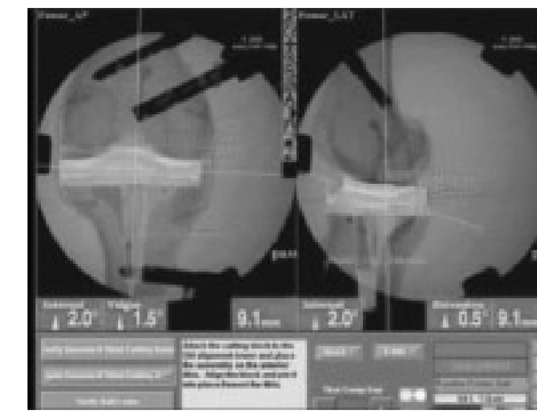

Figure 8: Use of the tibial resection guide shows the orientation and depth of the resection and future position of the implant

References

1. **Khan MAA., Brakenbury PH, Reynolds ISR.** Dislocation following total hip replacement. *J Bone Joint Surg Br.* 1981; 63B: 214-8.
2. **Kennedy JG, Rogers WB, Soffe KE, Sullivan RJ, Griffen DG, Sheehan LJ.** Effect of Acetabular Component Orientation on Recurrent Dislocation, Pelvic Osteolysis, Polyethylene Wear, and Component Migration. *J Arthroplasty.* 1998 Aug;13(5):530-4.
3. **Miehlke RK, Clemens U, and Jens JH.** Computer Integrated Non-Image Based Instrumentation in Knee Arthroplasty versus Manual Technique – A Prospective Comparative Study. Fifth Annual North American Program on Computer Assisted Orthopaedic Surgery (CAOS/USA 2001 Meeting and Surgical Academy). Pittsburgh, PA, July 6, 2001.
4. **Murphy SB.** Applications of Surgical Navigation to Primary Total Knee Arthroplasty. Fifth Annual North American Program on Computer Assisted Orthopaedic Surgery (CAOS/USA 2001 Meeting and Surgical Academy). Pittsburgh, PA, July 6, 2001.