Computer-assisted Navigation in Orthopedic Surgery

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ABSTRACT

Computer-assisted navigation has a role in some orthopedic procedures. It allows the surgeons to obtain real-time feedback and offers the potential to decrease intraoperative errors and optimize the surgical result. Computer-assisted navigation systems can be active or passive. Active navigation systems can either perform surgical tasks or prohibit the surgeon from moving past a predefined zone. Passive navigation systems provide intraoperative information, which is displayed on a monitor, but the surgeon is free to make any decisions he or she deems necessary. This article reviews the available types of computer-assisted navigation, summarizes the clinical applications and reviews the results of related series using navigation, and informs surgeons of the

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disadvantages and pitfalls of computer-assisted navigation in orthopedic surgery.

Computer-assisted navigation was initially used in orthopedic spinal surgery more than 15 years ago, with the goal of improving the accuracy of pedicle screw insertion. Since then, it has gained wide acceptance among orthopedic surgeons and has become an invaluable tool for some orthopedic procedures, such as reconstructive hip and knee, sports injury, trauma, spine, and tumor surgery.

Computer-assisted navigation offers surgeons real-time feedback of the surgical field, enabling them to adjust the surgical technique to improve postoperative outcomes and decrease intraoperative errors.

Types of Computer-Assisted Navigation

Computer-assisted navigation systems can be active or passive. Active navigation systems can either perform surgical tasks or prohibit the surgeon from moving past a predefined zone. Passive navigation systems provide intraoperative information displayed on a monitor, but the surgeon is free to make any decisions he or she deems necessary. Based on the method of referencing information, computer-assisted navigation systems are further classified into computed tomography (CT) based, fluoroscopy based, and imageless.

Computed tomography–based navigation systems use CT scans of the area of interest. The CT scans are performed either pre- or intraoperatively with an O-arm (Medtronic Navigation, Inc, Minneapolis, Minnesota) and used to reconstruct 3-dimensional (3-D) images. Two working modes can be used: guidance and real-time. In guidance mode, the operative steps and actions are planned preoperatively and are displayed on the monitor; intraoperatively, the surgeon has to match the operative actions with the virtual ones. In real-time mode, the instruments and implants can be visualized and navigated as they are moved in the surgical field. Computed tomography–based navigation offers a precise representation of the surgical anatomy and allows for precise placement of the implants without the need for preoperative planning. However, the use of a CT scan is associated with additional cost and increased radiation for the patient.

Fluoroscopy-based navigation systems use several markers placed on specific anatomical landmarks, which are captured by a small series of fluoroscopic images. A computer software program synthesizes these images to relate the surgical area of interest in space and identify the position of the instruments and implants. An advantage of this system is the virtual fluoroscopy, which allows surgeons to take arbitrary images intraoperatively and then choose the most appropriate position from the gallery of these images. In addition, fluoroscopy-based navigation is independent of intraoperative changes in the patient’s position because navigation is only performed using the chosen image. An evolution of standard fluoroscopy-based navigation is 3-D fluoroscopy-based navigation, which not only offers all of the benefits of virtual fluoroscopy but also permits visualization in the axial plane, basically functioning as an intraoperative CT scanner. Using a computer software program, the 2-D images are converted into coronal, sagittal, and axial reconstructions, similar in appearance to CT images.

Imageless navigation systems consist of a computer platform, a tracking system (usually an optical camera), and a set of infrared markers. Depending on the planned operation, a predefined number of markers are positioned to specific anatomical bony landmarks using pointer probes with the method of triangulation. When needed, kinematics can also be used to determine the center of joint rotation. The referencing information is then processed by the computer software, which uses a large number of stored CT scans to construct a model that fits the registered surface points. The main advantage of imageless navigation is the complete avoidance of radiation for the patient and surgeons. The disadvantage is that it relies mainly on the surgeon’s precision, experience, ability, and learning curve to mark the optimal anatomical bony landmarks for the application of the pointer probes.

Total Knee Arthroplasty

Restoration of the normal mechanical axis of the knee joint is important for long-term survival of total knee arthroplasty (TKA) prostheses to prevent eccentric load sharing, abnormal polyethylene wear, premature loosening, instability, and early implant failure. Optimal knee axis alignment correlates with less pain, better knee range of motion, faster rehabilitation, and improved quality of life for patients. Fixation of the prosthesis needs to be accurate in all 3 axes to ensure smooth tracking of the patella and soft tissue balance and to avoid notching the anterior femoral cortex. However, knee axis alignment errors greater than 3° may occur in up to 20% of all TKA procedures, even those performed by experienced surgeons. Computer-assisted navigation has been associated with significantly less deviation from the 3° threshold of mechanical axis malalignment and better alignment of both the femoral and tibial prostheses in the coronal and sagittal planes (Figure 1).

Knees with complex deformities are prone to measurement errors in radiographs performed while the patient is in a standing position; the average difference in the mechanical axis between the supine and standing position can be up to 1.6°. Therefore, surgeons using computer-assisted navigation for TKA should be aware that navigation may underestimate a major perceived deformity in preoperative planning; in this setting, soft tissue release and bone cuts should be performed.
with caution to not overcorrect what seems like a major deformity on preoperative radiographs.\textsuperscript{21}

Adequate flexion and extension gap balancing is important in TKA for optimal knee kinematics and the prevention of polyethylene wear and loosening.\textsuperscript{14,22} Extension gap depends on soft tissue release and flexion gap on appropriate femoral sizing and implant rotation.\textsuperscript{23} Tight gaps are associated with reduced range of motion and flexion contractures of greater than 4°, whereas loose gaps are associated with knee recurvatum, pain, instability, and accelerated wear due to eccentric loading and increased muscle force required to control the unstable knee.\textsuperscript{24,25} Computer-assisted navigation has been shown to achieve more precise soft tissue balancing and prevent joint line elevation compared with the standard TKA technique.\textsuperscript{23} In addition, computer-assisted navigation allows surgeons to quantify the soft tissue balancing before the femoral cut is made, to select the size of the femoral component that optimally tenses the ligaments throughout the full range of knee motion, and to make adjustments independently to each collateral ligament.\textsuperscript{22,26}

A major complication of TKA is fat embolism,\textsuperscript{27} which has been associated with an increase in the intramedullary pressure as occurs during the placement of the intramedullary guide needed for the alignment of the femoral cutting block in conventional TKA. A major advantage of computer-assisted navigation is the use of extramedullary guides, which potentially reduce the risk of fat embolisms\textsuperscript{27-29} and blood loss and transfusion requirements.\textsuperscript{8,30,31} The advantage of computer-assisted navigation has also been supported for revision TKA; in this setting, it allows the surgeon to check the

AUGUST 2013 | Volume 36 • Number 8
Navigation in Orthopedics | Mavrogenis et al
633
mechanical axis at every step of the procedure, to visualize the joint line in cases with significant bone loss, and to facilitate the fixation of the revision prostheses at the coronal and sagittal planes. However, caution is necessary during the referencing process of the referencing information in cases of revision TKA; CT-based navigation registration may be flawed due to artifacts, whereas imageless navigation registration may be inaccurate due to bone loss that complicates the definition of surgical landmarks.

### Total Hip Arthroplasty

The orientation of the acetabular component in total hip arthroplasty (THA) is considered an important variable for a successful THA. Cup malorientation is associated with increased rates of dislocation, impingement, polyethylene wear, and loosening. Using mechanical guides, positioning of the acetabular component may be inaccurate. Computed tomography–based and imageless navigation significantly improve the surgeon’s ability to insert the acetabular component in the optimal orientation. However, caution is necessary during referencing the pubic tubercles because they are covered by a thick layer of soft tissues; it is necessary to position the referencing probe as close to the bone as possible because cup anteversion will otherwise be underestimated by a mean of 3°.

Restoration of leg length is also important for the outcome of patients undergoing THA. Leg-length discrepancy can cause pain, stiffness, heterotopic ossification, and early implant failure. Different techniques using Kirschner wires and Steinmann pins have been described, with different success rates for intraoperative measurement and leg-length restoration. In current clinical practice, computer-assisted navigation seems to be the most accurate method to obtain leg-length equality.

Hip resurfacing arthroplasty has gained popularity as an alternative to THA in younger patients due to preservation of the femoral bone stock, improved hip stability and proprioception, and a lower risk for leg-length discrepancy. However, caution is necessary during the referencing process of the referencing information in cases of revision TKA; CT-based navigation registration may be flawed due to artifacts, whereas imageless navigation registration may be inaccurate due to bone loss that complicates the definition of surgical landmarks.

### Corrective Osteotomy

High tibial osteotomy has been used for more than 50 years to treat unicompartmental varus gonarthritis in select young patients. It enables the redistribution of body weight to the normal lateral compartment, unloading the affected medial knee compartment. When the mechanical axis passes through the center of the knee, the medial compartment bears 67% of the load during single-leg stance. If the mechanical axis is moved to 6° valgus, 60% of the load is placed on the lateral compartment and 40% on the medial compartment. However, using the standard technique, approximately 20% of patients will have a suboptimal limb correction due to inadequate preoperative planning, inappropriate wedge osteotomies, or poor intraoperative control of the knee axis alignment. Computer-assisted navigation provides real-time intraoperative information about the sagittal, coronal, and transverse axes of the knee joint and can compensate for the shortcomings of preoperative radiographic planning. In addition, it may reduce the risk of valgus undercorrection in the coronal plane and posterior tibial slope overcorrection in the sagittal plane.

Closed reduction and casting is the treatment of choice for most patients with distal radius fractures. However, approximately 5% of these fractures will result in malunion; patients will malunion may experience chronic wrist pain and compromised hand function. When symptoms or deformities are severe, corrective osteotomy of the distal radius is necessary. Conventionally, the shape and size of the osteotomy is estimated preoperatively on radiographs or CT scans; however, preoperative imaging is often inadequate to calculate the accurate displacement and rotation inside the joint.

Several computer-assisted navigation techniques have been described that have promising results for the surgical and functional outcomes of patients with distal radius malunion. These techniques use the contralateral radius, if normal, for referencing information to restore the affected side. They offer surgeons the ability to perform multiple simulations of the surgical procedures preoperatively, which can be used to optimize the plan and identify potential problems during realignment, thus producing consistently better correction of the dorsal angulation and rotation of the radius compared with the conventional techniques.

### Anterior Cruciate Ligament Reconstruction

Anterior cruciate ligament rupture is one of the most common sports injuries in young athletes, requiring surgical reconstruction to allow patients to return to an active lifestyle and prevent secondary cartilage and meniscus damage. However, inaccurate placement of either the femoral or the tibial tunnel may occur in up to 15% of procedures using standard surgical techniques; this may result in laxity, instability, suboptimal clinical results, and increased revision rates. Computer-assisted navigation is currently used to improve the accuracy and reproducibility of the tibial and femoral tunnels and restore the normal knee kinematics by measuring anatomical references and graft isometry. Most studies have shown better positioning of the femoral tunnel with computer-assisted navigation. With respect to the tibial tunnel, although the mean positioning is similar to the standard techniques, the deviation
is decreased with the use of computer-assisted navigation techniques. However, despite these advantages, conflicting results exist regarding knee function and stability in patients treated with computer-assisted navigation for anterior cruciate ligament reconstruction.

Double-bundle anterior cruciate ligament reconstruction is considered the reconstruction of choice for improved anterior and rotational knee stability. However, precise drilling of the femoral and tibial tunnels is technically demanding because the bundle insertion sites change depending on the flexion angle of the knee; the insertion sites are vertically oriented in extension but become horizontal at 90° of knee flexion. In this setting, computer-assisted navigation may provide intraoperative imaging assistance, leading to consistently more accurate results.

**Cartilage Defects of the Knee**

If left untreated, chondral defects in the weight-bearing areas of the knee joint can lead to early arthritis due to increased focal contact pressures. Transplantation of autologous osteochondral grafts is commonly used to treat small (less than 2 cm²) full-thickness cartilage defects. The technique of mosaicplasty involves removal of cylindrical grafts from a nonweight-bearing area of the unilateral knee and transferring them to the debrided defect. It is important to achieve as congruent and smooth surfaces as possible to restore normal-level contact pressures. This depends mainly on the angle and depth of the graft insertion, as well as the size and shape of the grafts and the overall surface covering. This procedure is extremely demanding because the cartilaginous plugs need to be press-fitted relatively parallel to each other while at the same time remaining perpendicular to the joint surface. Inaccurate placement can predispose to loosening of the cartilaginous plugs and incongruency of the articular surface. Navigation can provide accurate information and visualization of the graft, as well as the graft and recipient socket, producing results that are difficult to achieve with the conventional technique. This applies even more when the procedure is performed arthroscopically because of the limited visualization and the 30° optical angle of the arthroscope. Currently, all available information derives from experimental cadaveric studies; therefore, further research is necessary to draw important conclusions for computer-assisted navigation for cartilage defects of the knee.

**Fracture Treatment**

Currently, minimally invasive fracture reduction and osteosynthesis techniques are used for the treatment of fractures. These techniques rely on intraoperative fluoroscopy images obtained by the use of an image intensifier. However, extensive operative fluoroscopy is often necessary for optimal reduction and osteosynthesis. Computer-assisted navigation has been used to optimize fracture reduction and osteosynthesis and decrease intraoperative fluoroscopy time in various percutaneous management procedures for fractures of the femoral neck and shaft, the iliac wing, the sacroiliac joint and acetabulum, and the tibial plateau and shaft, as well as 3- and 4-part fractures of the humeral head.

Using fluoroscopy-based computer-assisted navigation for the use of percutaneous osteosynthesis with cannulated screws to treat femoral neck fractures may allow surgeons to accurately determine the entry point and angle of insertion of the screws in 2 planes prior to the placement of the guide wires. Thus, it reduces the number of the drilling attempts and optimizes the orientation of the screws.

Standard intramedullary nailing for femoral shaft fractures has been associated with more than 15% of rotational deformity in up to 30% of fractures. Standard intramedullary nailing for femoral shaft fractures, much time can be saved intraoperatively due to the decreased need for imaging for fracture reduction and nail insertion and locking. Imageless computer-assisted navigation can also be used for the insertion of distal locking screws in patients treated with intramedullary nailing for femur and tibia fractures.

**Shoulder Surgery**

The function and survival of shoulder replacement arthroplasty depends on the proper positioning of the glenoid component. Improper orientation may lead to eccentric loading, increased stress on the bone-implant interface, loosening, and failure. However, the amount of reaming and fixation of the prosthesis in the proper orientation relies on the surgeon’s experience and skill. Computer-assisted navigation provides real-time feedback for proper glenoid reaming orientation and fixation of the prostheses in accurate orientation.

Reverse total shoulder arthroplasty is usually reserved for patients with rotator cuff arthropathy and revision shoulder arthroplasty. Apart from proper alignment of the prostheses, stable fixation to the native glenoid is required. However, fixation may be difficult because of poor bone quality, reduced glenoid bone stock, and inadequate visualization of the anatomical landmarks. A previous biomechanical study showed that the inferior screw of the glenoid prosthesis is important for early stability of the prosthesis; this screw needs to be firmly placed within the scapular pillar. A recent study showed that screw...
fixation is more accurate with the use of computer-assisted navigation and can potentially decrease intra- and postoperative complications.\(^8\)

The functional outcome and survival of shoulder hemiarthroplasty require restoration of normal anatomy and kinematics, which may be challenging in patients with comminuted humeral head fractures.\(^8\) Often, the humeral head is displaced inferoposteriorly, which results in abnormal joint kinematics, posterior glenoid wear, instability, and secondary arthritis.\(^8\) Computer-assisted navigation using the contralateral shoulder, if normal, for referencing information can provide an approximation of the normal anatomy of the fractured humerus, increasing the accuracy and consistency of the anatomical restoration of the prosthetic joint compared with the conventional technique.\(^8\)\(^5\),\(^8\)
Computer-assisted navigation has also been used to improve the accuracy of the insertion of bone anchors on the glenoid rim for the repair of anterior labral tears. Computer-assisted navigation offers a multiplanar visualization throughout the procedure, resulting in a more accurate placement of the bone anchors.

Spine Surgery

Computer-assisted navigation was first introduced in spinal surgery for accurate insertion of pedicle screws into the lumbar spine. Currently, it is used in a variety of spine procedures, such as spinal decompression, implant insertion, and minimally invasive surgical techniques aiming to improve the surgical outcome and decrease intraoperative complications. However, despite the current use of intraoperative fluoroscopy and electrophysiologic monitoring in spine surgery, the incidence of malpositioned spinal implants remains high, even among experienced surgeons, ranging from 5% to 41% for the lumbar spine and from 3% to 55% for the thoracic spine. Although many of these misplaced screws are not clinically significant, up to 25% of them may put visceral organs at risk.

Computer-assisted navigation provides additional anatomical details that may improve the accuracy of spinal instrumentation and reduce the risk of neurological and vascular injuries.

In the cervical spine, CT-guided navigation has been used to facilitate insertion of C1-C2 transarticular screws in patients with atlantoaxial subluxation; by using navigation techniques, the rate of malpositioned screws and neurovascular complications has been significantly reduced. Computer-assisted navigation has also been used with excellent results for the insertion of transpedicular C2 screws in patients with traumatic spondylolisthesis of the axis vertebra (hangman’s fractures). In the lower cervical spine, computer-assisted transpedicular screw insertion has consistently better results, although the number of critical cortical breaches has not been statistically decreased.

Instrumentation of the thoracic spine is particularly demanding due to the small size and variable anatomy of the thoracic pedicles and the narrow spinal canal. Although studies have shown that misplacement of the screws is approximately 20% without the use of intraoperative image guidance, this percentage remains unacceptably high when compared with CT-guided techniques, which is significantly lower at a range of 2% to 4.5%. Furthermore, the use of 3-D fluoroscopy-based navigation allows for direct intraoperative evaluation of the position of the screws, enabling immediate revision of the misplaced screws and, therefore, significantly reducing the rate of complications and the need for reoperation.

The efficacy of computer-assisted instrumentation in the lumbar spine has been documented for approximately 15 years and has achieved a 5-fold decrease in the number of misplaced screws. Subsequent clinical studies further confirmed that computer image guidance greatly facilitates transpedicular instrumentation in the lumbar spine (Figures 2, 3). Intraoperative navigation is also useful for the placement of motion-sparing intervertebral devices, such as artificial disks, because their long-term survival and function depend on their optimal positioning.

Decompression of the spine is often used to alleviate symptomatic compression of neural elements. However, to achieve adequate decompression and avoid damage to the surrounding neurovascular structures, thorough visualization of the relevant anatomy is required. In the cervical spine, computer-assisted navigation enables surgeons to achieve a more extensive anterior vertebrectomy,

Figure 4: Computed tomography–based navigation in tumor surgery in a patient with pathological fracture of the sacrum from metastatic renal cancer. Virtual guidance of sacroiliac screws (A). Axial computed tomography scans before (B) and after (C) computer-assisted sacroiliac screw fixation.
producing a more reliable and accurate decompression without violating the foramina. Similar favorable results have also been observed with CT-based navigation systems in the thoracic spine for complete spinal cord decompression without neurological or vascular complications. The main advantage of minimally invasive spinal procedures is that they require less extensive tissue dissection, thereby limiting iatrogenic injury of the paraspinal muscles; reducing postoperative pain, length of hospital stay, and absence from work; and improving functional outcomes. Computer-assisted navigation is ideally suited for minimally invasive spinal procedures because it offers the necessary spatial and anatomical data without requiring direct visualization of the spine. Three-dimensional fluoroscopy-assisted navigation has been used for a variety of spinal procedures, such as posterior cervical arthrodesis, kyphoplasty, and transforaminal lumbar interbody fusion. Computer-assisted navigation has also been used with favorable results as an adjunct for thoracoscopic diskectomy and percutaneous insertion of translaminar facet screws.

Musculoskeletal Tumor Surgery

Over the past 3 decades, advances in imaging, metallurgy, and implant design have enabled limb salvage surgery for musculoskeletal tumors, with excellent functional results without compromising survival and local recurrence. In these cases, computer-assisted navigation offers 3-D visualization of the tumor that enables preoperative planning of the level and margins of tumor resection on a computer platform; these data can then be used intraoperatively to facilitate the resection.

Resection of epiphyseal or juxta-articular sarcomas requires precision to achieve tumor-free margins and preservation of the articular surface. Computer-assisted navigation allows surgeons to plan the optimal level of resection without compromising the surgical margins of resection. In the pelvis, the rate of contaminated margins after sarcoma resection ranges from 12% to 75%, and the rate of local recurrence ranges from 70% to 80%. In these locations, CT- and MRI-based navigation can be used for preoperative planning of the level of the osteotomies and improved intraoperative view, stabilization of the posterior pelvic ring (Figure 4) and spinopelvic fixation (Figure 5). Computer-assisted navigation is also particularly useful for the resection of periacetabular sarcomas and fixation of periacetabular prostheses.

Disadvantages of Computer-Assisted Navigation

Potential disadvantages of computer-assisted navigation include an increase of operative time that may be up to 20 minutes (for TKAs), risk of fractures and...
superficial infection at the sites of probes insertion,\textsuperscript{118} need for a learning curve,\textsuperscript{119} delayed recovery of the quadriceps muscle,\textsuperscript{7} and increased cost compared with standard techniques. The risk of fractures at the sites of probe insertion has been almost alleviated with the use of novel navigation probes that use 3.2-mm instead of 4- or 5-mm pins.\textsuperscript{117} The increase in the rate of soft tissue infections has not been statistically significant.\textsuperscript{118}

Computer-assisted navigation may seem cumbersome to inexperienced surgeons, but, after the appropriate learning curve (which is considered to be the first 30 operations for TKAs), the results and the mean navigation time are greatly improved.\textsuperscript{119} Delayed recovery of the quadriceps muscle has been observed after computer-assisted navigation with positioning of the probes within the surgical incision;\textsuperscript{2} this can be avoided by percutaneous positioning of the probes outside of the operating field.

**Pitfalls of Computer-Assisted Navigation**

Although computer-assisted navigation is more precise than the conventional techniques, it is still subject to errors. The tracking system of the navigation markers has an inherent error of 0.1- to 1-mm for each of the 3 coordinates in space.\textsuperscript{7} Also, the referencing probe may miss the intended bony structure due to overlying soft tissue or cartilage or the surgeon’s inexperience.\textsuperscript{38} In osteoporotic bones, the probes holding the markers may move, rendering the acquired data unreliable.\textsuperscript{9} In sclerotic bone, even if the cutting guides are placed in the optimal position using navigation, bending of the saw blade during the osteotomy may compromise the result.\textsuperscript{7} If cement fixation is used, malalignment may occur due to differences of the cement mantle around the prosthesis, even though the resection level may be excellent.\textsuperscript{7}

**Conclusion**

“If you cannot measure it, you cannot improve it.”\textsuperscript{120} Although this phrase, attributed to Lord Kelvin, is more than 100 years old, it expresses the current concept of navigation. Although navigation systems are still in their infancy, they can provide invaluable intraoperative information and assist surgeons in achieving consistently more accurate results. However, the majority of the referenced studies show a lack of improved clinical outcomes. Many show improved accuracy and better postoperative imaging, but they have not necessarily made their patients any better than they would have with conventional procedures. Therefore, long-term studies of computer-assisted navigation are needed to prove its benefit.

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Review Article


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