Computer-assisted navigation in orthopaedics

A F Mavrogenis, G Mimidis, D Koulalis, PJ Papagelopoulos

Abstract

Introduction
Computer-assisted navigation has gain wide acceptance for a variety of orthopaedic procedures. It allows the surgeons to obtain real-time feedback and offers the potential to adjust the operating technique, decrease intraoperative errors and optimize the surgical result. This article aims to present the available types of computer-assisted navigation, summarize the clinical applications, and review the disadvantages and pitfalls of computer-assisted navigation in orthopaedic surgery. It gives an extensive overview of the possibilities of computer-assisted navigation in orthopaedic surgery. As such it is of interest for all surgeons with no experience with this development to make orthopaedic procedures safer and more reliable and predictable.

Discussion
Clinical applications: Current applications of computer-assisted navigation include a variety of orthopaedic surgical procedures such as total joint arthroplasties, arthroscopic surgery, spinal surgery, tumour surgery, and fracture surgery. Disadvantages: the disadvantages of computer-assisted navigation include errors of the navigation tracking system, problematic positioning of marker pins in osteoporotic bone, fractures at the pin insertion site, a mismatch between the planned and the actual level of osteotomy, cement thickness may alter the final result, increased operating time and cost.

Introduction
Orthopaedic surgical procedures are evolving rapidly, with novel materials and techniques promising more biological and long-lasting results. The human element though remains still an unpredictable factor, as even small errors may compromise the final result. Computer-assisted navigation is here to assist to this variable. Although initially designed 20 years before aiming to facilitate the placement of pedicle screws in spinal surgery, computer-assisted navigation has evolved rapidly, to be currently used in a variety of orthopaedic procedures. Computer-assisted navigation systems use certain kinds of referencing methods to virtually reconstruct the area of interest and display it on a screen. This enables the surgeon to receive real-time feedback resulting in fewer intraoperative errors and superior results.

Introduction
Based on the method used for information referencing, computer-assisted navigation systems fall into 3 categories: computer tomography (CT)-based, fluoroscopy-based and imageless. CT-based systems require a CT scan of the area, performed either pre- or intraoperatively with a specific protocol, in order to reconstruct a three-dimensional image of the surgical field. The surgeon can either virtually plan his operation beforehand and match his actions during the procedure, or use the navigation system in real-time mode, allowing him to check the position of his instruments and implants at any given time during the procedure. Fluoroscopy-based systems require the positioning of a certain amount of markers on specific anatomical landmarks, which are then captured by a series of fluoroscopic images. The surgeon can then relate the position of his instruments in space, and proceed with his operation more safely and accurately. Intraoperative changes in position do not influence this kind of navigation as new images can be taken during the operation.

Newer systems allow for three-dimensional reconstruction of the fluoroscopy-based images, acting essentially as an intraoperative CT scanner. Imageless systems require an optical camera and infrared markers. They rely on the surgeon to pinpoint certain stable predefined landmarks with the use of the markers and determine the centre of joint rotation with the use of kinematics. The data are then processed by a computer and with the use of a pool of stored CT scans a virtual model is morphed. While on the one hand this system avoids radiation, making it safer for both the patient and the operating staff, it greatly relies on the surgeon’s skill and experience.

Discussion
This article aims to present the available types of computer-assisted navigation, summarize the clinical applications, and review the disadvantages and pitfalls of computer-assisted navigation in orthopaedic surgery. It gives an extensive overview of the possibilities of computer-assisted navigation in orthopaedic surgery. As such it is of interest for all surgeons with no experience with this development to make orthopaedic procedures safer and more reliable and predictable.

Discussion
The authors have referenced some of their own studies in this review. These referenced studies have been conducted in accordance with the Declaration of Helsinki (1964) and the protocols of these studies have been approved by the relevant ethics committees related to the institution in...
which they were performed. All human subjects, in these referenced studies, gave informed consent to participate in these studies.

**Clinical applications of computer-assisted navigation**

Computer-assisted navigation can be used nowadays in practically any kind of orthopaedic procedures. An effort will be made to summarize the most common, highlighting the clinical and theoretical benefits for these.

**Joint arthroplasties**

Joint arthroplasties are widely used nowadays to restore the function of arthritic joints and improve the patients' well-being and quality of life. The function and longevity of an arthroplasty depends on the proper placement of the implants in all three axes. In the knee joint the mechanical axis should not deviate more than 3 degrees from neutral so as to prevent eccentric loading of the polyethylene insert.4

Proper orientation of the femoral implant ensures smooth tracking of the patella and prevents notching of the anterior femoral cortex.5 With the use of computer-assisted navigation systems the number of outliers from the 3 degrees threshold is significantly lower compared to the conventional technique, and the implants are better aligned in both the transverse and sagittal plane.6 Therefore, the knee joint can be more accurately balanced and the level of the joint line can be more accurately restored (Figure 1).

Instead of relying on the surgeon's "feel" to perform the release of the soft-tissues, computer-assisted navigation enables him to quantify the medial and lateral gaps, both in flexion and extension. This allows the surgeon to make fine adjustments to each collateral ligament and also choose the appropriate size of the femoral component that properly tenses the ligaments during knee motion.7 This is important as tight joint arthroplasties can lead to flexion contractures and loose arthroplasties can lead to hyperextension; both, when more than 5 degrees and 10 degrees, respectively, are associated with poor function, pain and low Knee Society Scores.8 Additionally, although it remains controversial, many surgeons observed reduced blood loss and decreased risk for intraoperative fat embolism with computer-assisted navigation.9,10

In total hip arthroplasty the orientation of the acetabular component represents the most important prognostic factor for a successful operation. The optimal orientation of the cup (40±10 degrees abduction, and 15±10 degrees anteversion), decreases the rate of dislocation, impingement and polyethylene wear.12

Many times it is difficult to discern the correct orientation when using conventional techniques.13 Both CT-based and imageless navigation systems have shown superior results in placing the acetabular implant in the desired alignment.14 Care though has to be taken when referencing the pubic tubercle, as its thick layer of soft tissue coverage may underestimate the cup anteversion by an average of 3 degrees.15

Computer-assisted navigation can be used before inserting the femoral stem in order to access and correct leg length discrepancies with consistent accuracy.16 Equally great results have also been shown in hip resurfacing procedures during insertion of the femoral component.17

In total shoulder arthroplasty, orientation of the glenoid component is of paramount importance for the function and longevity of the arthroplasty.18 In cases of pathological retroversion of the glenoid with posterior wear this may be challenging even for experienced shoulder surgeons, and it may lead to centering of the humeral head.19

In this setting, computer-assisted navigation can provide real-time feedback during reaming of the glenoid, assisting the surgeon in achieving a neutral position.20 In reverse total shoulder arthroplasty it is important to achieve a stable bony fixation. This may be difficult due to poor bone quality and quantity, as it is usually reserved for elderly patients. It has been shown that the inferior screw of the glenoid component of reverse total shoulder arthroplasty must be placed firmly within the scapular pillar to achieve adequate fixation.21 This can be demanding to achieve intraoperatively due to limited visualization of the area. This problem can be easily surpassed with the use of navigation, resulting in reduced intra- and postoperative complications such as cut-off of the glenoid component or axillary nerve injuries.22

**Arthroscopic surgery**

Computer-assisted navigation is currently being used in arthroscopic anterior cruciate ligament reconstruction in order to improve the accuracy of tunnel positioning and graft isometry. Malpositioned tunnels are seen in up to 15% of the patients, causing laxity and instability.23 Many

**Figure 1:** Probe (left) and cutting block (right) positioning in imageless computer-assisted navigation for total knee arthroplasty.
studies have shown that although computer-assisted navigation does not improve the mean placement of the tibial tunnel, the deviation is decreased.24 As far as the femoral tunnel is concerned, studies concur that computer-assisted navigation provides superior results.25,26

In double-bundle anterior cruciate ligament reconstruction, the anatomical placement of the tunnels is of paramount importance. This procedure is technically demanding as the bundle insertion sites change depending on the flexion of the knee.27 Computer-assisted navigation leads to consistently more accurate results through the help of intraoperative image assistance.28 In arthroscopic shoulder surgery, computer-assisted navigation provides multiplanar visualization of the joint and allows for the ideal placement of the anchors, achieving thus maximal bone support and increased pullout force.29

Spinal surgery

Computer-assisted navigation has been used in practically any spinal surgical procedure including spinal decompression, implant insertion and minimally invasive techniques. Both in the cervical and thoracic spine computer-assisted navigation enables the surgeons to achieve an extensive anterior corpectomy, producing a thorough decompression without jeopardizing neural or vascular structures.30

Despite the use of conventional intraoperative fluoroscopy and other adjunctive measures, malposition of transpedicular screws is common and can reach 41% in the lumbar and 55% in the thoracic spine.31 This may lead to damage of the spinal cord, the pleural cavity or major vessels. The use of CT-guided or three-dimensional fluoroscopy-based navigation systems can improve the accuracy of pedicle screws positioning in the spine (Figure 2), with a success rate of up to 98%, and alleviate the need for reoperations.32 Yet, a recent systematic review of prospective in vivo studies showed equivalent neurological complication rates with and without the use of computer-assisted navigation in spinal surgery.31 Navigation can also be used in cases of atlantoaxial subluxation for the positioning of C1/C2 transarticular screws (Magerl technique) as well as for the positioning of C2 transpedicular screws in hangman’s fractures (Judit technique).33,34 It has also been shown to improve the alignment of intervertebral disk implants in cadaveric studies; an important finding since the function and longevity of these devices is strongly correlated to their optimal positioning.35

Computer-assisted navigation is also optimal for minimally invasive techniques in spinal surgery, offering the necessary spatial anatomy compensating for the limited surgical field available. It has been used in cervical fusion, transforaminal spinal interbody fusion, thoracic discectomy and percutaneous positioning of translaminar facet screws.36,37,38

Tumour surgery

Limb-salvage techniques have evolved in the last 4 decades. Currently, limb salvage is performed for most musculoskeletal tumour cases, without compromising the survival of the patients. However, certain cases, such as pelvic and spinal tumours, remain challenging. Tumours of the pelvis often are extensive at presentation and may involve the surrounding structures such as vessels, nerves or visceral organs. Wide excision of these tumours may be unfeasible in up to 75% of the patients; the local recurrence rates in these patients range up 70% to 80%.39 CT and MRI-based navigation systems can be used to plan the osteotomies required beforehand and with the aid of intraoperative visualization can lighten the surgeon’s burden.40 Also, in cases of juxtaarticular tumours, computer-assisted navigation enables the surgeon to perform fine osteotomies aiming for tumour-free margins with preservation of the joint for superior postoperative function.41 Last, in cases of megaprosthetic reconstructions, computer-assisted navigation can ensure accurate fitting of the implants (Figure 3).42

Fracture surgery

Computer-assisted navigation can be helpful in fracture treatment especially with minimal invasive techniques, such as percutaneous fixation of femoral head fractures with cannulated screws, fractures of the acetabulum, the
sacroiliac joint, the tibial plateau and four-part fractures of the humeral head.\textsuperscript{32,44,45,46,47,48,49} In general computer-assisted navigation can be utilized in virtually any kind of percutaneous procedure. It allows the surgeon to determine the entry point and angle of insertion of the guide wires in two-dimensional planes simultaneously, thus reducing the need for continuous intraoperative fluoroscopy, the number of necessary drilling attempts, and the surgical time significantly.\textsuperscript{43}

In patients with femoral shaft fractures, especially comminuted, computer-assisted navigation may help to restore normal limb rotation, to avoid a rotational deformity.\textsuperscript{44} It uses information from the contralateral limb to access length and rotation.\textsuperscript{45} Although extra time is needed for this step, in reality more time is saved as the need for intraoperative imaging during fracture reduction and fixation is greatly reduced.\textsuperscript{46} Imageless computer-assisted navigation can be used for the insertion of the distal screws during intramedullary nailing of tibial and femoral diaphysis fractures.\textsuperscript{47}

**Disadvantages of computer-assisted navigation**

Despite the benefits it grants, computer-assisted navigation has also been associated with potential disadvantages and pitfalls. (1) The navigation tracking system has an inherent error that varies between 0.1 mm and 1 mm for each of the three coordinates in placing the markers in space.\textsuperscript{3} (2) Care has to be taken when placing the marker pins, especially in osteoporotic bone; it is important to get a good grip of the pins as even a slight movement will throw off the measurements.\textsuperscript{3} (3) Although fractures at the pin insertion site have been reported with older systems, newer computer-assisted navigation systems have overcome this problem by using thinner, 3.2 mm pins.\textsuperscript{50} (4) Often, a mismatch is observed between the planned and the actual level of a performed osteotomy; this is usually caused because of bending of the cutting blade in areas of sclerotic bone and is not an actual fault of the navigation system. (5) In cases of cemented prostheses differences in cement thickness may alter the final result, even with excellent resection levels.\textsuperscript{3} (6) Computer-assisted navigation has been associated with an increase in operating time, which in total knee arthroplasty for example can be up to 20 minutes;\textsuperscript{51} however, after the learning curve is surpassed, which is considered to be around 30 operations, the operating time and the final results are greatly improved.\textsuperscript{52} (7) An important drawback of computer-assisted navigation is its increased cost; long-term studies are necessary to prove its superiority and clinical benefit with respect to cost-effectiveness of the technique.

**Conclusion**

Computer-assisted navigation has gain wide acceptance for a variety of orthopaedic procedures. It allows the surgeons to obtain real-time feedback and offers the potential to adjust the operating technique, decrease intraoperative errors and optimize the surgical result. Yet, computer-assisted navigation systems are still in their infancy; disadvantages and pitfalls do exist. Whether will computer-assisted navigation fulfill its promises, only time will tell.

**References**


Critical review