31 Advances in Navigation and Robot-Assisted Surgery

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Introduction

Navigation is defined as the process of accurately ascertaining one's position and planning and following a route. Just as a GPS system gives a car driver visual feedback of their journey along a route, navigation in orthopedics gives a surgeon real-time feedback while performing a surgical step. Visual feedback on a screen orientates the surgeon in the surgical field to more accurately make a bony cut or position an implant.

Navigation has been in use in orthopedics for over 20 years. First reported uses were in navigation for pedicle screw placement during spinal surgery [1]. Current aims of navigation are to more accurately make bony cuts, more accurately position implants, and reduce damage to surrounding structures. The potential benefits are clear, with improved accuracy and reduced variability of implant placement, and the goal is to improve implant survivorship while at the same time minimizing soft tissue damage. Concerns remain about the potential for increasing operating time and cost without objective improvement in outcomes.

In this chapter, we will discuss different types of navigation systems available, discuss a technique for robot-assisted surgical navigation for hip arthroplasty, and review the current evidence available.

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Classification of Navigation Systems

There are numerous systems available to provide intraoperative assistance to the orthopedic surgeon: accelerometer-assisted surgery, computer-assisted orthopedic surgery (CAOS), and robot-assisted surgery. The main focus of this chapter is developments in computer-assisted orthopedic surgery, but accelerometer-based designs provide a cheaper alternative that does not require a separate console in the operating theater. They function by attachment of a device which measures dynamic movements to conventional jig systems. In accelerometer-assisted knee arthroplasty, the device is attached to the jig and, after a series of calibration movements, identifies the center of rotation of the hip and knee and subsequently is used to align the cuts relative to the mechanical axis.

Computer-assisted orthopedic surgery can be divided into active, semi-active, or passive systems [2]. The earliest and most complicated were active robotic systems. Semi-active systems do not perform the surgical tasks but limit the placement of surgical tools; they allow a surgeon to move freely within set limits but provide resistance if the operator's actions approach the boundaries of a defined "safe zone." Passive systems display information such as limb alignment on a monitor [3].

Composition of a Navigation System

There are three main components to a computer navigation system: the computer platform, a tracking system, and rigid markers. In optic-based systems, multiple cameras placed on a console in the operating theater visualize the markers, and their movements are tracked and processed by the computer system in 3D space. Markers must therefore be attached to the bones and the surgical instruments to allow them to be tracked.

Computer System

This receives input from the tracking system and interprets the data forming a 3D coordinate grid with *x, y,* and *z* components. The output from the computer system is on a monitor in the theater, displaying to the surgeon the shape and size of the instrument and its relation to the target object.

Tracking System

Tracking can be performed using optical cameras, electromagnetic coils, or ultrasonic probes.

Optical systems use two or three cameras to pick up infrared light from three to five marker arrays attached to the target object. This introduces line of sight issues—the camera must be able to "see" the markers or its accuracy decreases.

Electromagnetic systems do not use reference arrays or cameras—avoiding line of sight issues—but the field is distorted by metallic objects and trackers must be linked to the computer by wires which can prove difficult in practice [4].

Markers

These can be active or passive. Active markers emit light like a bulb. The majority, however, are passive and reflect infrared light. The tracking system must triangulate the position of each marker. A marker attached to a bone forms the "dynamic reference base" [3].

Referencing

Now we have an understanding of the components of a navigation system, the next step is how these components relate and produce real-time feedback in the operating theater.

We can consider the three components: the therapeutic object (the target of the treatment), the virtual object (3D-mapped virtual representation of the therapeutic object), and the navigator (which relates the objects) [5]. The navigator uses the 3D coordinate system to map the object and end effector, and the relation between the two can be computed. The end effector can be a different tool depending on the purpose of the system, for example, a cutting jig or the reamer of an acetabular component. In robotic devices, the robot is the navigator. For computer-assisted optic-based surgical navigation, it is the tracking device [5].

To establish a coordinate system, the effector must be calibrated; the size and shape of the effector have to be defined to the coordinate system. For image-based systems, the next step is registration of the therapeutic object with respect to the virtual object to display the end effector's location in respect to the virtual object. This is correlating the 3D model created from preoperative imaging to the patient's anatomy on the operating table by taking points in specific locations on the patient. The last step is referencing, which aims to account for movement of the navigator or the therapeutic object during the surgical procedure by either attaching a "dynamic reference base," holding optical markers to established landmarks on the therapeutic object, or immobilizing the object with respect to the navigator.

Types of Referencing in Computer Navigation

You can further categorize navigation systems by the type of referencing they use: CT based, fluoroscopy based, or imageless [3]. In CT-based systems, a 3D model is created from preoperative CT scan with the advantage of being specific to the patient's own anatomy but increasing cost and with increased radiation exposure.

Fluoroscopy-based systems use an image intensifier, and while taking the images, a marker is used and a computer relates the position of the marker to the image captured.

Imageless systems require no preoperative scans and do not use fluoroscopy. They use pooled data from CT scans of a large number of patients to create a database. During the operation, multiple predetermined landmarks are identified and used to determine center of rotation of joints. A “best fit” model is then created by the computer system using the database. The advantage of imageless is that it does not require a CT scan, reducing delay and radiation exposure. There is, however, potential for inaccuracy based on the surgeon’s ability to identify accurately the landmarks with the bony marker and the reliance on the database of “normal patients” which could prove inaccurate for patients with severe deformity or unusual anatomy.

Once referencing has been performed, we have defined a coordinate system, the target object, and effector’s position within it and can see how they relate on the screen. The next section will consider the addition of a robot into this system.

Robot-Assisted Surgery

One of the first documented uses of robotics in surgery was in 1985 using the PUMA 560 to place a needle for CT-guided stereotactic brain surgery [6]. The first robot used in orthopedics was ROBODOC (Integrated Surgical Systems, California, USA) in 1992 to prepare the femur in total hip arthroplasty [7]. Since then, numerous other systems have been designed and used in hip and knee arthroplasty, spinal surgery, foot and ankle surgery, arthroscopy, and trauma, and the two most common in current use are the MAKO (Stryker®) system and the NAVIO (Smith and Nephew®). Most evidence is available for hip and knee procedures.

The setup for robot-assisted orthopedic surgery is similar to computer-assisted surgery and will be described in more detail later. The main difference is the presence of the robot in the operating theater in addition to the camera and display console. Further, unlike conventional navigation where a tracking device is the navigator and guides an effector with its reflective markers to the target, the robot acts as the navigator. Its arm is connected to the tool and functions in a semi-active way; it can be maneuvered in the “safe zone” in the surgical field but will only allow you to perform the task according to the preoperative plan. Actions outside of the plan are restricted.

Robot-Assisted Hip Surgery

The method described here is the MAKO (Stryker®) CT-based robotic navigation system [8]. The patient requires preoperative CT imaging following specific protocols defined by the manufacturer. Reconstruction of this CT imaging then forms the basis for the “virtual object.”

Fig. 31.1 MAKO hip: example of a pre-op plan for THA

A surgical plan is then formulated based on this imaging (Fig. 31.1). In accordance with personal preferences, CT landmarks are also established.

Operative Steps

Distal landmark placement: A distal landmark is identified, for example, over the patella.

Pelvic array placement: An array of markers is placed into the pelvis either through the wound in the supra-acetabular bone or in the iliac crest.

Femoral cortical screw placement: A uni-cortical screw is placed in the proximal femur and a femoral array attached to this. The array should be visible by the camera.

Femoral registration: Femoral landmarks are identified using probe. These are the landmarks identified preoperatively on the CT scan. They orient the femur with respect to the virtual image. Registration is verified by identifying further landmarks and if inaccurate, repeated.

The femur is now registered with the system, and the planned femoral cut can be marked out with cautery and the neck resected. This allows access to the acetabulum. The femur can be broached using the robot as a guide at this stage or later in the procedure.

Pelvic registration can then be performed mapping out the orientation of the native acetabulum and registering it with the virtual acetabulum formed from the pre-op CT images.

The robotic arm then controls movement of the acetabular reamer (Fig. 31.2) and executes reaming based on the final position of the cup determined during the

Fig. 31.2 Assembled MAKO acetabular reamer

preoperative plan, and the display will turn red if a surgeon reams 1 mm past the operative plan, and if greater than 2.3 mm, the power drill will turn off. The cup can then be seated using the robotic arm as the guide.

Outcomes in Navigated Hip Surgery

Computer-Assisted Total Hip Arthroplasty (THA)

A recent review and meta-analysis comparing navigation and conventional hip arthroplasty found navigated hips had improved accuracy for anteversion and inclination than freehand placement, but there is a lack of evidence to support improved functional outcomes or reduction in complications or revision [9]. Intraoperative navigation has been demonstrated to accurately assess acetabular component position intraoperatively in the direct anterior approach [10] where fluoroscopy has previously been used.

Robot-Assisted Hip Surgery

Early work in robot-assisted hip surgery focused on correct orientation of uncemented femoral prostheses but no sustained improvement in clinical outcomes and a higher dislocation rate limited its use [11]. Others found no difference between conventional THA and robot-assisted THA, but costs and technical complications relating to the robot were greater [12]. More recent work by Domb et al. in 100 patients in a matched study assessed acetabular cup positioning and accuracy of placement in the safe zone as described by Lewinnek et al. [13]. One hundred percent of robot-assisted surgeries were within Lewinnek's safe zone compared with 80% in the conventional THA group. The impact on dislocation, wear, and revision remains unclear [14].

Advances in Navigated Knee Surgery

Limb alignment and soft tissue balancing are important for the success of knee surgery. Component malalignment is a major cause of aseptic loosening of knee arthroplasty, and navigation aims to improve accuracy of implant placement, reduce malalignment, and reduce rates of loosening. In the following section, we will consider current evidence of different techniques for navigation in knee surgery.

Accelerometer-Assisted Total Knee Arthroplasty (TKA)

Numerous studies have demonstrated improved mechanical alignment and component positioning with accelerometer-based systems compared to conventional jig methods [15–17]. As yet, this does not seem to translate to improvement in clinical outcomes.

Computer-Assisted TKA

A randomized trial from Hong Kong compared conventional instrumentation with computer-assisted TKA and demonstrated improvement in mechanical alignment and component positioning in terms of femoral component rotation but did not demonstrate any improvement in clinical outcomes at average follow-up of 5 years [18]. Similar findings have been reported in previous reviews [19]. Data from the Australian registry found non-navigated knees had a stronger association with revision compared to computer-navigated knees, with the tibial component revised more frequently than the femoral component [20].

Robot-Assisted Total Knee Arthroplasty

A retrospective study of 84 knees recently published in arthroplasty today demonstrated no statistically significant differences between the group of robot-assisted and conventional arthroplasty patients in terms of clinical or radiographic outcomes. There was a trend toward fewer radiographic outliers in the robot-assisted group, but this did not achieve statistical significance [21]. Other studies support this finding with improved accuracy at the expense of increased operative time and cost [22].

Robot-Assisted Unicompartmental Knee Arthroplasty (UKA)

A recent review in the BJJ published in 2019 [23] found that implant positioning with robotic UKA was more accurate, but there was insufficient evidence at this stage to determine whether this had any effect on mid- to long-term survivorship. This supports a similar finding by Fu et al. previously [24].

Improved gait kinematics in robot-assisted UKA compared with conventional Oxford UKA was reported by Motesharei et al.; however, they did not evaluate patient-reported clinical outcomes [25].

Navigation and Osteotomies

Osteotomies around the knee are well-established treatments that rely on accuracy and reliability of correction angles in coronal and sagittal planes [26]. To increase precision of these corrections, navigation can be a useful tool. A recent meta-analysis showed that the risk of outliers in navigated high tibial osteotomies (HTOs) was lower in navigated surgery compared with all conventional HTOs but was not significant when compared with the gap-measurement method subgroup of conventional HTOs. Tibial slope maintenance was better in navigated HTOs but no difference in patient-reported clinical outcome measures. Navigated HTO also increased operative time by approximately 10 min [27].

Navigation and Shoulder Arthroplasty

Accurate glenoid component placement is vital to prevent failure in total shoulder arthroplasty. A prospective case-control study of 60 patients demonstrated increased rates of augmentation of navigated glenoid prosthesis with final alignment more likely to be “neutral” with reduced variability. No data were presented on survivorship [28].

Navigation and Fracture Fixation

While navigation and robotics in arthroplasty are rapidly evolving areas, navigation in trauma surgery is in its infancy. Navigation offers the promise of real-time guidance of fracture reduction which could be particularly beneficial in fixation of complex intra-articular fractures. Further work is being done on potential use of robotics in application of external fixators [29]. One study reports promising results on the use of robotic surgery for wire placement during scaphoid fracture surgery [30].

Numerous systems exist to navigate the surgeon to accurately perform distal locking of intramedullary nails without the use of fluoroscopy. Higher accuracy with shorter operating time and no radiation has been reported with magnet-based navigation systems [31]. Increased costs associated with this instrumentation should be taken into account.

Other Uses

Young adult hip surgery: The potentials for planning and more accurate treatment of femora-acetabular impingement using computer-assisted hip arthroscopy are highlighted in a review by Nakano et al. [32]. Studies on clinical outcomes are lacking, but navigation can certainly be useful in what are technically depending surgeries, particularly in assessing sphericity of the femoral head arthroscopically.

Navigated tumor resection surgery: Clear resection margins are fundamental to successful tumor resection surgery, and surgical navigation clearly offers potential benefits in helping to achieve this particularly in patients where freehand resection is challenging [33]. A recent paper demonstrates effective resection and reports reduced setup time using skin markers for registration [34].

Simulation training for orthopedic surgeons: Wire placement in hip fracture surgery simulation models has typically struggled to gain widespread acceptance due to the requirement for fluoroscopy. Simulation-based training with a navigation model has eliminated the need for fluoroscopy while providing real-time feedback on wire placement. This tool has been expanded to placement of ilio-sacral screws, allowing training to occur in a simulated environment [35].

Conclusion and Future

Computer-assisted orthopedic surgery demonstrates improvements in surgical accuracy, but this does not always translate to improved functional outcomes for patients. One explanation for this is that we have still not identified what the "optimal" positions are for our implants. CAOS and robot-assisted surgery show great promise, and there are many examples where they have been demonstrated to improve surgical accuracy. Whether improvements in functional outcomes are borne out in longer-term studies remains to be seen.

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