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Surgical navigation for total knee arthroplasty: A perspective

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Abstract

A new generation of surgical tools, known as surgical navigation systems, has been developed to help surgeons install implants more accurately and reproducibly. Navigation systems also record quantitative information such as joint range of motion, laxity, and kinematics intra-operatively. This article reviews the history of surgical navigation for total knee arthroplasty, the biomechanical principles associated with this technology, and the related clinical research studies. We describe how navigation has the potential to address three main challenges for total knee arthroplasty: ensuring excellent and consistent outcomes, treating younger and more physically active patients, and enabling less invasive surgery.

Keywords: Computer-assisted surgery; Orthopaedics; Kinematics; Soft tissue

1. Introduction

The success of total knee arthroplasty depends on many factors, including patient selection, prosthesis design, the pre-operative condition of the joint, surgical technique including proper soft tissue balancing and limb alignment, and post-operative rehabilitation. It has been suggested that the most common cause of revision total knee arthroplasty is error in surgical technique (Stulberg et al., 2002), as small changes in component positioning can lead to significant changes in post-operative performance. Alignment errors of greater than 3° in the frontal plane are associated with component loosening (Jeffery et al., 1991). Small amounts of combined femoral and tibial component internal rotation (1°–4°) have been associated with lateral tracking and tilting of the patella, while larger amounts of internal rotation (7°–17°) have been associated with patellar dislocation and prosthesis failure (Berger et al., 1998). Rotation of the femoral component of 5° from the transepicondylar axis has been reported to alter tibiofemoral kinematics (Miller et al., 2001) and increase shear forces on the patellar component (Anouchi et al., 1993; Singerman et al., 1997; Miller et al., 2001). A 5° posterior slope of the tibial component has been shown to reduce femoral rollback in posterior cruciate substituting implants (Piazza et al., 1998).

Surgical navigation systems have been developed to help reduce errors in component alignment during total knee arthroplasty (Delp et al., 1998). Several recent studies have confirmed that it is possible to reduce the variation in frontal plane alignment with these systems (Jenny and Boeri, 2001; Saragaglia et al., 2001; Hart et al., 2003; Stöckl et al., 2004). Navigation systems allow for intra-operative recording of joint range of motion and kinematics, providing the capability to study the mechanics of knees with advanced joint disease. Intra-operative measurements and improved surgical accuracy have the potential to advance biomechanics research and introduce new surgical interventions for degenerative joint disease. This article discusses the history of computer-assisted knee arthroplasty, describes the related

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biomechanical principles, and reviews the early clinical and basic research studies. The article concludes by detailing how computer-assisted surgical systems may help address some of the major challenges for total knee arthroplasty.

2. History of computer-assisted total knee arthroplasty

Computer-assisted surgical systems have been developed for procedures such as total hip arthroplasty (Spencer, 1996; Bargar et al., 1998; DiGioia et al., 1998b), anterior cruciate ligament reconstruction (Dessenne et al., 1995; Fleute et al., 1999), high tibial osteotomy (Ellis et al., 1999; Wang et al., 2005), revision total knee arthroplasty (Perlick et al., 2005), and a variety of other procedures (Taylor et al., 1995; Nolte and Ganz, 1999; DiGioia et al., 2004). This review focuses on primary total knee arthroplasty.

Several classification schemes have been proposed for computer-assisted surgical systems (Cinquin, 1993; Delp et al., 1998; DiGioia et al., 1998a; Taylor, 1998; Picard et al., 2000; Stulberg et al., 2002; Picard et al., 2004). The most recent classification scheme (Picard et al., 2004) divides computer-assisted surgical systems into three categories: active robotic systems, semi-active robotic systems, and passive systems.

The earliest and most complex systems were active robotic systems, in which a robot performed some surgical task, such as drilling, without the direct intervention of the surgeon (Picard et al., 2004). One of the first active robotic systems for total knee arthroplasty used a pre-operative CT scan of the patient to plan the surgery (Fadda et al., 1997). The first commercial European robotic system for total knee arthroplasty (Van Ham et al., 1998) afforded improved accuracy during clinical trials (Siebert et al., 2002); however, active systems have not been widely used for total knee arthroplasty because of the cost and complexity associated with using active robots in the operating room.

Semi-active systems do not perform surgical tasks but may limit placement of surgical tools (Picard et al., 2004). Matsen et al. (1993) first reported the use of a Unimation Puma 260 robot for total knee arthroplasty. With this system, the surgeon first indicates the desired position and orientation of the femoral prosthetic component on a three-dimensional digitizing template. The robot then positions the saw and drill guides so that the surgeon can make the necessary cuts and holes. Kienzle et al. (1995) described a semi-active system based on pre-operative CT images. The pre-operative images were intra-operatively registered to the patient's anatomy using small pins placed in the femur and tibia. Other semi-active systems allow the surgeon to freely operate within a pre-determined "safe zone" and provide resistance when the surgeon's actions approach the boundaries of this zone (Davies et al., 1997; Jakopec et al., 2003).

The most common example of a passive system is a surgical navigation system, in which information such as cut plane orientation and limb alignment are displayed on a computer monitor in the operating room. Navigation systems may use images to create a surgical plan or may use intra-operative measurements to guide prosthesis implantation. Pre-operative-image systems rely on models derived from CT images (Kienzle et al., 1995), or by morphing a generic model to match the bony geometry of a particular patient (Stindel et al., 2002). Intra-operative image systems most commonly use fluoroscopy (Van Damme et al., 2005). Image-free systems collect information needed for navigation through direct measurement of bony landmarks or through kinematic algorithms to determine joint centers (Leitner et al., 1997).

Image-free navigation systems are the simplest and most widely used computer-assisted tools for total knee replacement. The first image-free navigation system that was used in the operating room was described by Leitner et al. (1997). Image-free navigation systems have become the most common navigation technique, and we will focus on this topic in subsequent sections.

2.1. Principles of image-free navigation

Navigation systems are comprised of a few basic components (Fig. 1). An optical tracking system measures the position and orientation of optical reference frames that are attached to the femur and tibia, typically with bicortical bone screws. The camera also tracks a stylus that the surgeon uses to digitize bony landmarks and an instrumented plate (Picard et al., 2003) used to record the position and orientation of the cutting blocks and bone surfaces. The navigation system is controlled by a computer and software. The accuracy of tracking systems used in navigation is related to the combination of the tracking camera and associated reference frames and can range from approximately 0.5–3 mm (Khadem et al., 2000).

With image-free navigation, like with gait analysis (Cappozzo, 1984), it is necessary to create anatomical reference frames that relate the position and orientation of the optical reference frames to the underlying bony anatomy. These anatomical frames are based on the weight-bearing axis of the femur (Yoshioka et al., 1987) and tibia (Yoshioka et al., 1989). One of the goals of total knee arthroplasty is to restore neutral alignment of the mechanical axis of the lower limb; thus, the surgeon must intra-operatively estimate the location of the most proximal point of the mechanical axis, the center of the femoral head, the most distal point of the mechanical axis, the center of the ankle joint, and points around the knee.

In gait analysis, the hip center has been determined with radiographic methods (Bell et al., 1990; Kirkwood et al., 1999) and by estimating its position relative to anatomic landmarks that are accessible without imaging (Andriacchi et al., 1980; Tylkowski et al., 1982; Bell et al., 1989; Seidel et al., 1995). However, because surgical drapes typically cover the pelvis during surgery, these methods are not

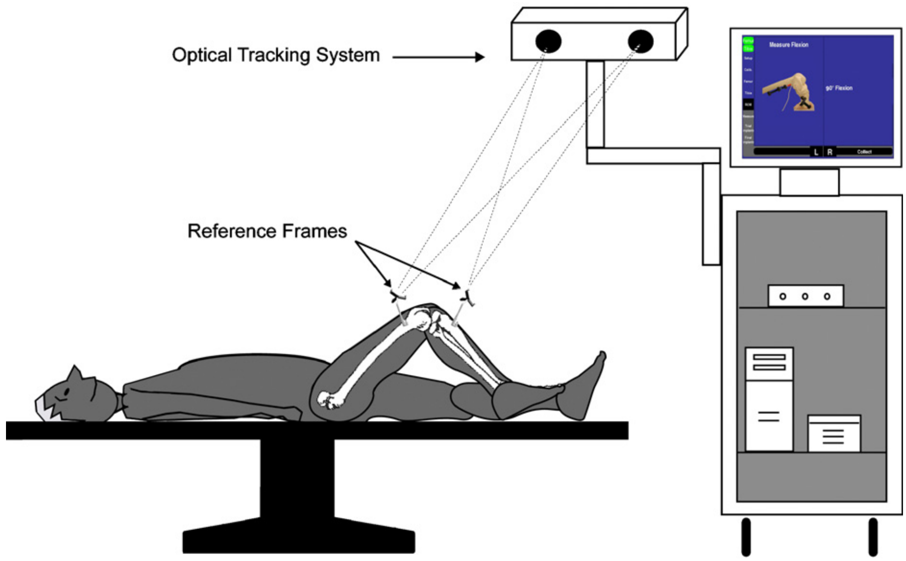

Fig. 1. Components of an image-free navigation system. The optical tracking system measures the position and orientation of reference frames that are attached to the patient's femur and tibia. Information such as cut plane orientation and limb alignment is displayed on the computer monitor.

appropriate for image-free navigation. Navigation systems estimate the center of rotation of the femur relative to the pelvis from kinematic data using algorithms similar to the so-called functional methods used in gait analysis (Cappozzo, 1984; Shea et al., 1997; Leardini et al., 1999; Piazza et al., 2001). Mechanical models have been used to determine how limited ranges of motion (Marin et al., 2003; Schwarz et al., 2005; Siston and Delp, 2006) and measurement errors noise (Siston and Delp, 2006) affect the algorithms used by navigation systems. It is desirable for navigation systems to locate the center of the femoral head with less than 7 mm of error, as this corresponds to less than approximately 1° of error in the frontal and sagittal planes.

Anatomic methods and kinematic methods have been developed to locate the center of the ankle. Anatomic methods require the surgeon to digitize anatomic landmarks around the ankle during the operation (Inkpen and Hodgson, 1999; Krackow et al., 1999; Nofrini et al., 2004). Kinematic methods require the surgeon to displace the foot and ankle through a prescribed motion, and then an algorithm estimates the center of the ankle from these data. One kinematic method treats the ankle as a ball-and-socket joint (Leitner et al., 1997); another method uses the instantaneous center of rotation from passive ankle doriflexion and plantar-flexion (Jenny and Boeri, 2001; Stulberg et al., 2002); others have proposed a biaxial model of the ankle (van den Bogert et al., 1994; Siston et al., 2005a). It is desirable for navigation systems to locate the center of the ankle joint with less than 6 mm of error, as this corresponds to less than a 1° of error in the frontal and sagittal planes. It has been recommended that establishing the midpoint of the most medial and most lateral aspects of the malleoli is an accurate, precise, objective, and fast method for estimating the center of the ankle joint (Siston et al., 2005a).

To identify the other points needed to establish the anatomical reference frames, the surgeon uses a digitizer to locate the "center of the knee" (i.e., the ends of the femoral and tibial functional axes) and landmarks on the proximal tibia and distal femur (typically the femoral epicondyles and the most medial and lateral points on the tibial plateau). Small errors in locating these landmarks can lead to significant errors in the orientation of the anatomical reference frames. For instance, a 7 mm anteroposterior error in identifying one of the epicondyles would correspond to approximately 5° of error in the transverse plane. It has been shown that identifying landmarks on the distal femur and proximal tibia is highly variable (Jenny and Boeri, 2004; Siston et al., 2005b, 2006b). In light of that difficulty, some systems use the passive motion of the knee to establish the average axis of knee rotation, which is then used as the medial–lateral axis in establishing the femoral anatomical reference frame (Jenny and Boeri, 2001; Stulberg et al., 2002).

2.2. Clinical studies

Clinical evaluations have demonstrated that the postoperative mechanical axis alignment of the limb achieved using navigation systems is significantly better than the alignment afforded by traditional mechanical instrumentation (Bathis et al., 2004; Chauhan et al., 2004; Haaker et al., 2005). Other studies have reported that using navigation reduced alignment outliers (i.e., limbs with alignment errors $>3°$) and decreased the standard deviation of mechanical axis alignment, even though no significant improvement in mean mechanical axis alignment was found (Jenny and Boeri, 2001; Saragaglia et al., 2001; Hart et al., 2003; Stöckl et al., 2004).

The alignment of the individual components can also be improved with navigation. The varus/valgus alignment of the femoral component has been shown to be improved with the use of navigation (Saragaglia et al., 2001; Sparmann et al., 2003; Bathis et al., 2004; Chauhan et al., 2004; Bolognesi and Hofmann, 2005; Haaker et al., 2005). Alignment in the sagittal plane is also improved (Jenny and Boeri, 2001; Sparmann et al., 2003; Stöckl et al., 2004; Haaker et al., 2005). Debate still exists as to whether a navigation system does (Chauhan et al., 2004; Stöckl et al., 2004) or does not (Siston et al., 2005b) improve the rotational alignment of the femoral component in the transverse plane.

The influence of navigation on the alignment of the tibial component is unclear. Several authors have reported that the varus/valgus alignment of the tibial component is improved with the use of navigation (Sparmann et al., 2003; Chauhan et al., 2004; Bolognesi and Hofmann, 2005; Haaker et al., 2005), but others (Jenny and Boeri, 2001; Saragaglia et al., 2001; Hart et al., 2003) did not find an improvement in coronal alignment of the tibial component. Most studies have concluded that the alignment in the sagittal plane (i.e., the anterior–posterior slope of the tibial component) is not improved with navigation (Jenny and Boeri, 2001; Saragaglia et al., 2001; Stöckl et al., 2004; Haaker et al., 2005), although two studies have shown an improvement in tibial slope (Hart et al., 2003; Chauhan et al., 2004). Controversy exists as to whether navigation systems do (Chauhan et al., 2004) or do not (Siston et al., 2006b) improve the rotational alignment of the tibial component in the transverse plane, although it has been reported that the rotational mismatch between the femoral and tibial components is decreased with navigation (Chauhan et al., 2004).

The surgical complications associated with the use of a navigation system have been minimal. Compared with total knee arthroplasty using traditional mechanical instrumentation, operative time using navigation systems increases by approximately 10–20 min (Jenny and Boeri, 2001; Stulberg et al., 2002; Hart et al., 2003; Stulberg, 2003; Chauhan et al., 2004; Bolognesi and Hofmann, 2005; Haaker et al., 2005). The increased operative time and the potential additional trauma as a result of bone screws used to attach the optical reference frames have not led to significant increases in blood loss (Saragaglia et al., 2001). One study reported that navigation leads to less blood loss than traditional instrumentation (Chauhan et al., 2004). The majority of studies have reported no complications (e.g., fracture, infection) from bone screws that attach the optical reference frames to the bone (Stulberg et al., 2002; Hart et al., 2003; Stulberg, 2003; Chauhan et al., 2004; Bolognesi and Hofmann, 2005), although isolated incidences of delayed wound healing and infection (Krackow et al., 2003; Sparmann et al., 2003) and stress fractures (Ossendorf et al., 2006; Seon et al., 2006) occur.

No long-term studies have proven that navigation improves post-operative functional kinematics, allows for a more rapid recovery, or decreases complication rates (Kinzl et al., 2004). As a result, debate exists on the utility of navigation as a clinical tool (Hofmann, 2005; Hungerford, 2005). Navigation systems are expensive, and it may take up to 10 cases before the surgeon feels comfortable with the system and can reliably establish the anatomical coordinate systems that are the basis of the procedure (Stulberg et al., 2002; Bolognesi and Hofmann, 2005).

2.3. Knee kinematics and laxity

Navigation systems can provide valuable feedback during surgery. Klein et al. (2004) recorded the range of motion associated with two different tibial inserts in a series of 37 total knee arthroplasties. The kinematics and the maximum range of motion associated with each insert were used to select the final implant for each patient.

A navigation system can serve as a valuable research tool. The direct and rigid attachment of reference frames to the bones eliminates errors related to the substantial motion of the skin relative to the bone associated with skin-mounted markers typically employed in gait analysis (Reinschmidt et al., 1997). We have used a navigation system to characterize the passive kinematics of osteoarthritic knees before and after the installation of implants (Siston et al., 2006a). We found significant differences in the varus–valgus rotations and the "screw-home" mechanism of osteoarthritic knees compared to normal knees but found that osteoarthritic knees displayed a normal pattern of anterior–posterior femoral translation with increasing knee flexion. After prosthetic implantation, we observed an abnormal anterior translation of the femur during the first 60° of knee flexion (Fig. 2).

Most navigation systems today offer the ability to record knee laxity. To record these data, the surgeon manipulates the leg into varus and valgus, and the navigation system

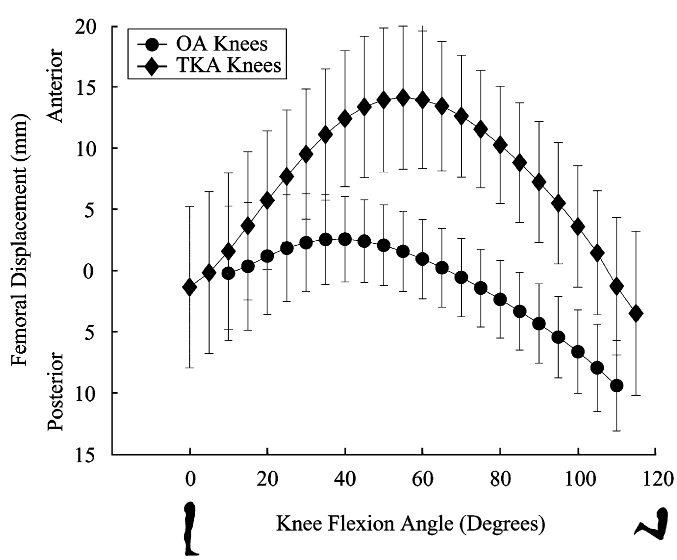

Fig. 2. Anterior (+) or posterior (−) translation of the femur with respect to the tibia in knees following total knee arthroplasty compared to osteoarthritic knees. The error bars represent one standard deviation. TKA induces an abnormal anterior translation of the femur in early flexion.

records the varus/valgus angle between the tibial and femoral mechanical axes and calculates the magnitude of the bicompartmental gaps between femur and the tibia with the knee in full extension and in flexion (Kunz et al., 2001; Klein et al., 2004). While a few studies (Kunz et al., 2001; Stulberg et al., 2002; Stulberg, 2003) have presented data on knee laxity recorded with navigation, detailed characterizations of joint laxity require an accurate means of recording both the forces applied to the limb and the resultant displacements. As navigation systems do not have instrumentation to record forces, this remains an open challenge for system developers.

Navigation has been used in cadaver studies to investigate joint laxity. Van Damme et al. (2005) used a fluoroscopic navigation system to quantify medial–lateral, anterior–posterior, and rotational laxity before and after implant installation. They did not find a significant difference between the varus–valgus laxity in a native knee and in a cruciate-retaining knee except during varus stress at 30° and 90° of knee flexion, where laxity was less pronounced following prosthesis implantation. No difference was found in rotational laxity in extension, but the specimens following total knee arthroplasty had significantly less rotational laxity at 30° and 90° of flexion.

2.4. Future directions

Future research and development of navigation systems should address three major challenges in total knee arthroplasty: ensuring consistent post-operative outcomes, treating younger and more physically active patients, and enabling less invasive surgery.

Navigation systems have demonstrated the ability to improve component alignment in the frontal plane, but their ability to improve rotational alignment in the transverse plane is unclear. Error in component rotational alignment is one factor that contributes to patellofemoral complications, a major cause for revision surgery following total knee arthroplasty (Berger et al., 1993, 1998; Bindelglass and Dorr, 1998). Despite in vivo (Stiehl et al., 1995, 2001; Komistek et al., 2000) and in vitro (Hsu et al., 1996; Miller et al., 2001; Jenny et al., 2002) research into patellofemoral kinematics associated with total knee arthroplasty, patellofemoral problems frequently occur. Navigation systems generally do not provide intra-operative feedback about either patellofemoral kinematics or placement of the prosthetic patellar component. If a reliable method of recording the position and orientation of the patellar component could be created, navigation systems may prove to become a valuable tool to assess patellofemoral kinematics in osteoarthritic knees and reduce patellofemoral complications.

The outcome of total knee arthroplasty depends on the soft tissue balancing around the knee, which is generally considered more subjective than component alignment. Little research exists on the differences in soft tissue laxity between osteoarthritic and normal knees and how joint laxity changes as a result of total knee arthroplasty. Knowing how prolonged varus/valgus deformity influences the properties of the knee soft tissues would be a valuable step toward creating an objective procedure for balancing soft tissues during a total knee arthroplasty. This is an important area for future research.

Total knee arthroplasties have documented excellent results at alleviating pain and improving function in elderly and less physically active patients, where the demands on prosthesis functionality and longevity are not great. However, total knee arthroplasties are now being performed in younger and more active patients. These younger patients demand a prosthesis that closely replicates the function of the normal knee and has the potential to withstand use for several decades. It has been suggested that the ability to carry out intra-operative kinematic measurements is important in the development of new implants and the assessment of fixed and mobile polyethylene bearings (Sparmann et al., 2003). The intra-operative kinematics recorded with a navigation system may challenge previous design assumptions and lead to a new generation of implants.

The main disadvantage of using a navigation system to characterize knee kinematics is that data are acquired under passive manipulation. Knee kinematics during activities of daily living could be different from those measured passively due to high forces generated by muscles and by interactions with the external environment. Future research should define the relationship between the passive kinematics measured in the operating room and the post-operative active kinematics recorded with gait analysis (Andriacchi et al., 2003) or cine-fluoroscopy (Dennis et al., 1996, 1998; Banks et al., 1997; Incavo et al., 2004).

Less invasive total knee arthroplasty could potentially enhance patient recovery and function following surgery. Navigation systems may aid in performing these procedures by guiding the surgeons' actions when visual queues are lost through a smaller incision. Most navigation systems are used in conjunction with traditional mechanical instrumentation for total knee arthroplasty. It is expected that a new class of surgical tools will emerge, that are designed to be used specifically with navigation systems. Complications such as fat embolism associated with the use of the intramedullary alignment rod (Cailllouette and Anzel, 1990; Monto et al., 1990) might be reduced with such instrumentation. Instead of optical tracking systems, the next generation of navigation systems is exploring the use of electromagnetic tracking, which are typically physically smaller than, and do not have the line-of-sight concerns of, their optical counterparts. Picard et al. (2004) proposed that navigation might be used to deliver tissue-engineered biological implants through minimally invasive portals.

Navigation allows some elements of total knee arthroplasty to be performed with greater accuracy. It remains to be seen whether surgical navigation becomes the standard of care for total knee arthroplasty. Currently, navigation systems are useful measurement tools that can be used to examine surgical technique, intra-operative passive kinematics, and joint laxity. In the future, surgeons may be able to consistently repair a diseased knee and help ensure improved function with novel computer-assisted tools.

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