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REVIEW

Enhanced acetabular component positioning through computer-assisted navigation

Thomas Ybinger · Wolfgang Kumpan

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Abstract Optimal positioning of the acetabular component improves the long-term success of total hip arthroplasty by reducing the rate of adverse outcomes, such as component wear and dislocation. Mechanical guides designed to facilitate proper component orientation are inadequate, as they do not account for variations in patient position and pelvic motion during surgery. Pioneering image-guided surgical navigation systems were developed to provide surgeons with improved methods for intraoperatively measuring orientation and alignment. Although enhanced orientation has been reported with such systems, they require preoperative CT scans and are therefore limited by the need for preplanning, the necessitiy of matching CT data with the actual patient position, and the additional costs associated with CT. The recent development of CT-free navigational tools addresses these disadvantages and offers real-time surgical feedback regarding the actual position of the acetabular component and instruments relative to the pelvis. Proper training and enhanced identification of bony landmarks will improve upon the success of these systems.

Introduction

Proper positioning of the acetabular cup is essential for improving the long-term success of total hip arthroplasty (THA) [1, 8, 11, 13]. Higher rates of pelvic osteolysis, asymmetric polyethylene wear, and component migration have all been observed when malpositioning of the acetabular component occurs [8], and surgical experience indicates that improper orientation of the acetabular component is the major cause of dislocation [13]. A multicenter analysis of 6,774 THAs reported that excessive anteversion or inclination was the most common surgical error resulting in dislocation [1]. Lewinnek et al. studied the cases of 9 dislocations in a series of 300 THAs and found a statistically significant association between increased acetabular component anteversion and anterior dislocations [11]. Posterior dislocation did not appear to be influenced by cup-orientation angle. As the risk of dislocation is significantly higher in those who have already experienced dislocation or after revision surgery [12], obtaining proper cup positioning during initial surgery is crucial.

Optimal cup positioning requires that the surgeon attains adequate anteversion and inclination of the acetabular component, the optimal ranges of which have been extensively debated in the literature. In analysing standardised postoperative radiographs from a series of 300 THAs, Lewinneck et al. determined that acetabular cups outside of the “safe range” of 5° to 25° of anteversion and 30° to 50° of inclination were approximately four times as likely to dislocate [11]. McCollum and Gray determined that 30° to 50° of abduction and 20° to 40° of forward flexion provided the safest range to prevent dislocation and impingement [13]. More recently, Kummer and colleagues reported that achieving maximal range of motion while maintaining component stability required an anteversion between 0° and 10° and an inclination between 35° and 45° [9]. However, their study utilised a Sawbones hemipelvis model and was unable to account for the influence of soft tissues on the range of motion of the hip.

It is difficult to achieve these target orientations of the acetabular component on a reproducible basis. The majority

T. Ybinger (✉) · W. Kumpan
Department of Radiology, Kaiser Franz Josef Hospital Vienna,
Kundratstraße 3,
1100 Vienna, Austria
e-mail: thomas.ybinger@wienkav.at

of intraoperative mechanical guides for component orientation is designed to obtain inclination of 45° to 50° and flexion of 15° to 25° [7]. These instruments are highly flawed, however, as they utilise the plane of the operating room table as a reference when orienting the cup without accounting for the significant variance in the positioning of the bony pelvis. McCollum and Gray noted decreased accuracy of cup abduction when patients were in the lateral decubitus position due to an adduction of the superior acetabulum toward the foot of the table. In this position also the lumbar lordotic curve is flattened, which results in a flexion of the pelvis and consequently an error in prosthetic cup flexion [13]. Intraoperative measurements also attest to significant variations in positioning of the pelvis on the operating table during placement of the acetabular component [3].

Using Lewinneck and colleagues' [11] theoretical safe range as a surgical goal, Hassan et al. analysed acetabular component anteversion and vertical tilt obtained through an intraoperative mechanical guide in 50 consecutive THAs [5]. After comparing final component positions recorded intraoperatively with postoperative radiographic measurements, they noted that 42% of cups were outside of the safe zone, despite the belief among participating surgeons that they had placed all components within this range. DiGioia et al. conducted a similar study, in which acetabular implant orientation using a mechanical guide was compared with alignment measurements recorded via a computer-assisted navigation system, and noted 78% of hips would have been implanted outside Lewinnek and colleagues' safe zone using only the mechanical guidance [2].

Recently, a number of new surgical navigation systems has provided surgeons with enhanced tools to measure acetabular cup positioning during surgery, most notably the pioneering computer-assisted navigational systems that utilise preoperative planning with computer tomography (CT) scans. Although highly successful in improving the rate of components positioned within acceptable ranges, these systems are limited by the necessity for extensive preoperative planning and other disadvantages associated with the use of CT, such as high cost and matching CT data with actual patient position. The development of CT-free navigation has given surgeons a more intuitive means for orientation and measurement of the acetabular component. In this review, the authors will discuss different means for measuring acetabular cup positioning, with an emphasis on their own recent data with a CT-free navigation system.

Conventional radiography

Debate exists as to whether plain radiographs can provide reliable estimates of acetabular cup inclination and anteversion during follow-up examination. Given their low cost and accessibility, radiographic images potentially represent a relatively simple means for measuring cup positioning and determining acetabular loosening. Although acknowledging the limitations inherent in the use of two-dimensional plain radiographs, Widmer reported success in determining acetabular cup anteversion by measuring the short axis of the projected ellipse in relation to the total cross-section of the projected cup along the short axis [15]. Hassan et al. reviewed anteroposterior radiographs of an acetabular component placed in mould in five separate positions of anteversion [6]. They reported excellent intraobserver reliability, with mean measurements of anteversion in a clinically acceptable range.

However, the use of radiographic images is significantly complicated by pelvic flexion and extension, which diminish the probability that the anterior pelvic plane (both anterior superior iliac spines and the pubic tubercles) will remain parallel with the plane of the film and ensure proper alignment of the beam. Jaramaz et al. hypothesised that this cause of error may explain the failure of certain large clinical trials to detect the influence of component malpositioning on long-term dislocation rates [7]. Comparing intraoperative measurements by a surgical navigation system with radiographic measurements, they observed up to 20° variation in the version of the acetabular cup due to pelvic flexion and extension. Significant variations between cup orientation measurements taken intraoperatively and postoperatively also led DiGioia et al. to declare radiographic images unreliable [2].

Origins of computer-assisted navigation systems

To address the limitations inherent in conventional methods of component positioning, DiGioia and colleagues developed a pioneering image-guided navigational tool to enhance acetabular implantation during THA [3]. The Hip Navigational System (HipNav) employs a preoperative plan generated from CT scans of the pelvis to determine optimal position and orientation of the cup. Intraoperative guidance is provided via an optical localiser, which tracks infrared light-emitting diode markers attached to the pelvis and to the cup positioning guide, allowing continuous tracking of the pelvis. Data from the first eight patients enrolled in the HipNav clinical trial indicated that the navigational system achieved cup abduction and flexion closer to that recommended by the implant manufacture than would have been achieved with mechanical guides [7].

Similarly, Leenders et al. reported a significant reduction in variability of acetabular cup abduction when using a CT-based computer navigation system, with 48 of 50 cups placed inside the preoperatively planned range and no cups placed in the more extreme positions, although their analysis was limited by the use of standard radiographs to measure postoperative abduction [10].

Although CT-based navigation has proven to be a significant advance for acetabular cup positioning, all CT-based systems are presently limited by the necessity for preoperative scanning. Other disadvantages include the possibility of impaired image quality of CT scans when metallic implants are present, the additional costs associated with CT scans, and the often time-consuming procedure required to match the image-generated pelvic model to the actual patient [14].

CT-free navigation

Concerns regarding the aforementioned limitations led to the development of a new CT-free navigational system (PiGalileo THR, Plus Orthopedics, Aarau, Switzerland), which locates the anterior pelvic plane during surgery through the use of an optical unit consisting of infrared locators that enter the orientation of the bony landmarks into a computer system. Additionally, a firmly fixed pelvic locator allows the surgeon to obtain the exact location of the implants and instruments relative to the pelvis throughout the surgical procedure despite pelvic movement.

The authors have recently provided data from a prospective study of 37 patients (20 females, 17 males, mean age 65 years, and 18 right and 19 left hip joints) undergoing THAs with the PiGalileo THR system at four contributing centers [16]. All patients received a cementless threaded biconical cup of pure titanium with a polyethylene inlay and a cementless tapered straight titanium alloy stem with a ceramic ball head (Plus Orthopedics, Rotkreuz, Switzerland). The navigation system recorded acetabular component positioning at the end of surgery, which was compared with CT data obtained after patients completed their rehabilitation programme. The radiologist centrally evaluating CT data was blinded to the intraoperative measurements.

Cup inclination and anteversion, as recorded by the navigation system and measured by CT, differed by a mean of 3.5° (S.D. 4.4°) and 6.5° (S.D. 7.3°), respectively. By comparison, Hassan et al. reported a mean error of 5° (0°–20°) regarding vertical tilt and 9° (0°–24°) regarding version when conventional methods for acetabular component positioning were employed [5].

The authors also found the anterior superior iliac spines were an effective reference point for measuring inclination. There was a 1.5° mean difference in inclination when measuring with a tangent on the ischial tuberosities compared with a line connecting the centers of both anterior superior iliac spines.

Although intraoperative location of the bony landmarks provided by this navigation system enables improved component orientation, proper identification of the anterior pelvic plane is complicated by the presence of a thick soft tissue layer. The author and colleagues found soft tissue thickness to be a significant factor affecting precision of cup implantation. Soft tissue thickness overlying the anterior superior iliac spines (ASIS) and the pubic symphysis (PS) was measured in axial CT images and averaged 33 mm (range: 5–110 mm) and 47 mm (range: 20–112 mm), respectively. By obscuring the center of the iliac spine, thick soft tissue overlying the anterior superior iliac spine impacts the accuracy of the system in defining the horizontal plane. Consequently, there was a statistically significant correlation between tissue thickness over the ASIS and the error in cup inclination ($r=0.44$; $p=0.007$). A statistically significant correlation was also established between the error in cup anteversion and the thickness of the soft tissues overlying the pubic tubercles ($r=0.52$; $p=0.001$).

As is to be expected with any new surgical technology, this navigation system does have a learning curve, although one that can easily be surmounted with experience. Data from the most experienced center participating in the study demonstrated mean differences in inclination and anteversion of not more than 2.9° and 5.1°, respectively. In an analysis of a similar CT-free navigation system for THA, Dorr et al. suggested that with proper training with an experienced operating room staff the learning curve would most likely be overcome after only five to ten operations [4].

While CT-free computer navigation is a recently developed technology, and reports of its use in the literature are limited, there are several studies supporting the utility of this approach. Dorr et al. reported on 195 THAs with CT-free computer navigation [4]. After further refining their system (e.g., obtaining optimal registration of the bone through puncturing the skin over the pubis), there was a 2.5% rate of outliers from radiographic measurement recorded for inclination and anteversion for the final 40 procedures. In one laboratory study, Zheng et al. demonstrated high precision of placement of the acetabular cup and the femoral component when using a hybrid CT-free system based on percutaneous point-based digitization and fluoroscopy-assisted biplanar landmark reconstruction [17]. In a series of 118 consecutive patients undergoing THA with a hybrid CT-free system, Wentzensen et al. observed comparable system accuracy to CT-based navigation methods, with a maximal error of 5° for inclination and 6° for anteversion [14].

As the application of these CT-free systems is improved through enhanced landmark registration in the coming years, it should be possible to offer even greater specificity in the orientation of prosthetic components. Obtaining a more exact measurement of postoperative component orientation through navigation will also give us the means to better understand the relationship between malpositioning and adverse clinical outcomes.

Conclusions

Malpositioning of the acetabular component is a significant factor contributing to postoperative complications such as pelvic osteolysis, component wear, and dislocation. CT-based navigation has greatly improved the success of component orientation, but is limited by its necessity for complex preoperative imaging and planning. The authors' analysis and those of other researchers support the concept that CT-free navigation can facilitate proper orientation of the acetabular component. Strategies to enhance the registration of bony landmarks will add to the success of these systems, with an associated improvement in the short- and long-term success of THA.

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