4.1 Evolution of Total Hip Arthroplasty: Computer-Assisted, Minimally Invasive Techniques Combined with Alumina Ceramic-Ceramic Bearings

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Introduction

Total Hip Arthroplasty was initially introduced as a cemented construct with a metal femoral stem and a polyethylene acetabular component, performed through a transtrochanteric exposure. Over the ensuing thirty years, improvements to total hip arthroplasty have included the advent of uncemented acetabular and femoral components components and the popularization of alternative exposures including the posterior and anterolateral exposures. The potential improvements and potential perils of total hip arthroplasty have accelerated greatly in the very recent past with improvements in bearings, surgical exposures, and computer-assisted techniques all occurring simultaneously. These current surgical procedures barely resemble the conventional procedures that are so well established. The current manuscript reviews personal perspectives on and results of less invasive surgical techniques, computer-assisted techniques, and alumina ceramic-ceramic bearings for total hip arthroplasty.

Computer-Assisted Total Hip Arthroplasty

Computer-assisted techniques are very simple in principle. Systems can be categorized by their method of tracking and their method of imaging. Thereafter, all navigation systems will allow for tracking of the pelvis and/or femur and allow for the tracking of any desired rigid surgical instruments. In addition, the change in leg length and impingement-free range of motion of the hip can be calculated, if both the femur and pelvis are tracked during surgery [1].

Tracking Methods

Bones and surgical instruments can be tracked optically or using electromagnetic fields (EM). Infrared stereoscopic optical tracking is currently the standard method used by most navigation systems. Optical tracking has the advantage that it is simple and reliable in most circumstances. The primary limitation is that the optical camera must have a clear view of the surgical field. In contrast, electromagnetic systems have distinct advantage that a clear optical view of the surgical field is not necessary. Unfortunately, many of the instruments that we typically use during hip surgery are incompatible with EM tracking since many of our conventional metal and power instruments distort EM fields, preventing accurate navigation.

Imaging Methods

Image-free navigation

Each surgeon must make a choice about what, if any, images are used as part of computer-assisted total hip arthroplasty techniques. Image-free navigation refers to techniques where all navigation is based on landmarks that are digitized at the time of surgery without confirmation by imaging. For the pelvis for example, a reference frame is attached to the pelvis and the superior spines and pubic symphysis landmarks are digitized while the optical camera tracks the pelvic reference frame and digitizer simultaneously. A coordinate system for the pelvis is then established and the position of the pelvis can be tracked throughout the procedure as long as the pelvic reference frame is visible to the optical camera. Image-free techniques are the simplest and are therefore popular. They are especially useful for surgeons who operate with the patient in the supine position because the necessary landmarks are easily accessible (Fig. 1).

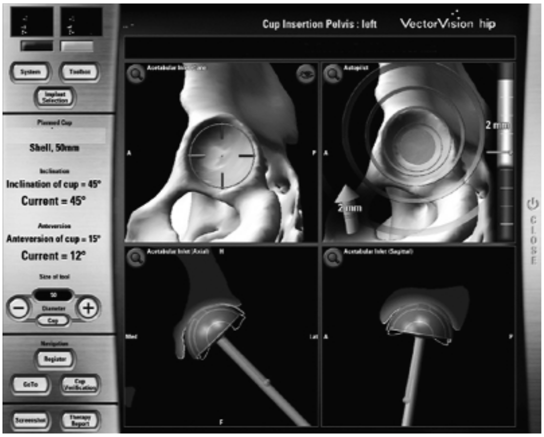

Figure 1:
Image-free hip navigation is based simply on digitized landmarks. The bone models are idealized images and are not based on the patient's actual anatomy.

Image-free navigation is somewhat less useful if the patient is operated upon while in the lateral position since the reference must be applied first with the patient in the supine position. The patient is then re-prepped and draped in the lateral position after the landmarks are digitized. Image-free navigation has another profound limitation: there is not way to assess the accuracy of the navigation in any individual patient. This means that if a critical landmark is incorrectly digitized, the navigation will be inaccurate. This is a particular risk in larger patients where landmarks are more difficult to palpate.

Fluoroscopic Navigation

Fluoroscopic navigation involves applying references frames to the bones to be tracked and to the fluoroscopic intensifier. The system then records the positions of these frames at the time that the given image is taken. Each fluoroscopic image allows for very accurate two-dimensional navigation. Combining information from more than one image taken at different angles then allows for three-dimensional navigation. For example, if two images of each superior spine and the pubic symphysis are taken during surgery, the three-dimensional positions of these critical landmarks can be calculated.

Fluoroscopic navigation has several advantages. First, no preoperative imaging or planning is necessary. Second, if anything changes during the surgery, new images can be acquired. Fluoroscopic navigation is especially useful then in cases of revision THR where metal artifact may degrade preoperative CT images, but where some form of imaging is necessary, particularly in cases where cement is lodged far into the distal femur or where hardware is broken and buried in the bone. In these cases, image-free navigation is useless, and CT-based navigation is unpredictable. Since fluoroscopic navigation is very versatile, it is especially useful in very complex cases, such as conversion of a hip fusion to a total hip arthroplasty (Fig. 2).

Figure 2a:
A surgically fused hip in a 42 year old woman preoperatively.

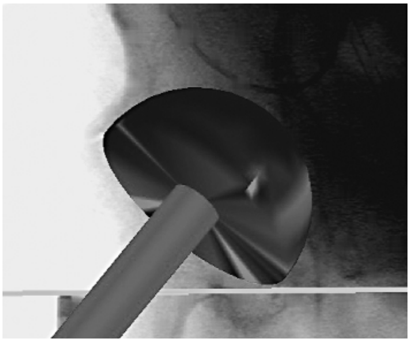

Figure 2b:
Navigation of an acetabular reamer on a fluoroscopic image.

Figure 2c:
Postoperative reconstruction following ceramic-ceramic THA with fluoroscopic navigation.

Fluoroscopic navigation though has the distinct disadvantage that fluoroscopic equipment must be available and that the surgery is disrupted, however briefly, by the acquisition of the fluoroscopic images. Fluoroscopic techniques are also less sophisticated than CT-based techniques in so far as the bony anatomy, implant placement, predicted range of motion, and alteration in leg-length cannot be analyzed and planned pre-operatively.

CT-based Navigation

CT-based navigation is the gold-standard for hip navigation and greatly enhanced cababilities as compared to image-free and fluoroscopic-based navigation. CT-based navigation allows for detailed preoperative planning of components sizes and positioning, leg-length alteration, and calculation of impingement-free range of motion. CT-based methods also allow for the calculation of the effect of any variable such as neck length, neck diameter, head diameter, cup position, and stem position on motion and leg length. The pre-operative computer models are linked to the actual bone models at the time of surgery using a process called registration. Registration involves digitizing points on the bone surface at the time of surgery and then performing a calculation that maps those points onto the computer model of the bone. The accuracy of the matching can be calculated and quantified at the time of surgery by placing a digitizer on the bone surface and calculating the distance between the actual and predicted bone surface at any desired location. CT-based registration has the advantage that it is very rapid. Compared to fluoroscopic navigation, it has the advantage that no intra-operative imaging equipment is required and that no intraoperatively acquired images are necessary (Fig. 3).

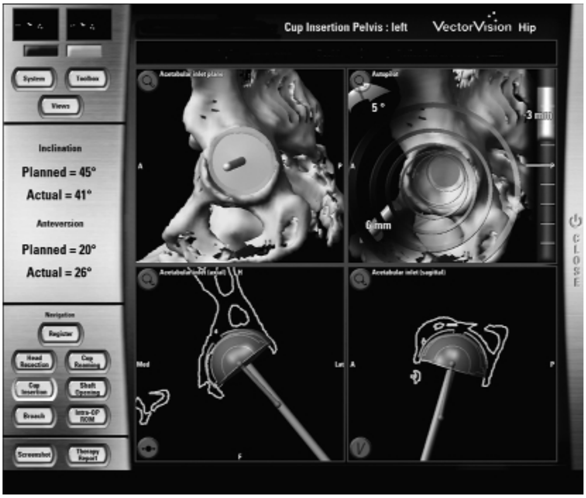

Figure 3:
CT-based navigation showing the patient-specific CT model during placement of the acetabular component.

Compared to image-free methods, CT-based navigation has the advantage that the surgery and registration can both be performed in the lateral position without the need for repositioning during surgery. CT-based navigation also has the advantage that the accuracy of the navigation can be checked. Conversely, CT-based navigation has the disadvantage that preoperative imaging and analysis are necessary.

CT-Fluoro Matching

CT-Fluoro matching involves pre-operative CT analysis followed by the use of fluoroscopic images, rather than surface points digitized on the bone, to achieve registration (Fig. 4).

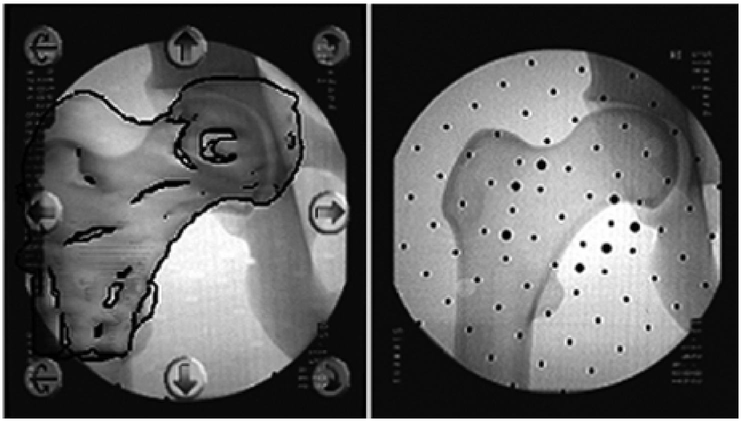

Figure 4:
CT-fluoro registration utilizes intraoperatively acquired fluoroscopic images to register a preoperatively acquired CT dataset to the patient's anatomy.

CT-Fluoro matching has the additional advantage that anatomic information further away from the hip (that is accessible to fluoroscopic imaging, but not to a digitizer) can be acquired. Data that is further from the hip reduces any potential errors in the registration process, potentially improving the accuracy.

Minimally-Invasive Total Hip Arthroplasty

Minimally-invasive total hip arthroplasty is a term that can mean almost anything and is therefore almost meaningless. Less-invasive surgical techniques are better classified by the soft-tissue interval used for the surgery and by the structures that are divided and those that are intended to be preserved during the surgery. While some less-invasive techniques can greatly accelerate recovery, less-invasive techniques have also been associated with increases in perioperative complications. In general, the maximal preservation of normal tissue around the hip joint during total hip arthroplasty requires significant effort whereas injury to normal tissue is virtually effortless. Consequently, the effective performance of less-invasive, tissue-preserving methods is very technically demanding and requires significantly more attention to detail than do more conventional surgical methods. There are a wide variety of techniques available to perform total hip arthroplasty through smaller incisions; some are tissue-preserving, some are traditional operations performed through smaller incisions, and some may produce more tissue damage than conventional procedures. Each technique should be considered for its advantages and disadvantages.

Anterior Exposures

Anterior exposures for arthroplasty have been employed since the time of mold arthroplasties and so these techniques actually pre-date total hip arthroplasty. Refinements in the use of the Smith-Petersen exposure have evolved with better instrumentation and with the use of the fracture table as popularized by Joel Matta, M.D. [3]. The Smith-Petersen exposure is especially effective for acetabular instrumentation, but has significant limitations when attempting to instrument the femur.

Posterior Exposures

Mini-posterior exposures for total hip arthroplasty are basically the same as traditional posterior exposures through a smaller incision. The surgery is facilitated by minor modifications of traditional instruments and the more judicious use and placement of retractors. While the posterior capsule and short rotators are incised during the surgery, they are typically repaired at the conclusion of the procedure. This technique has been proven to be safe and effective in the hands of many surgeons although a recent clinical study demonstrated that there was no difference in recovery between patients having the posterior exposure through a traditional or a shorter incision [13]. The primary limitation of the posterior exposure is that the risk of dislocation his higher than with other exposures so unlimited motion cannot be safely allowed after surgery. Further, a clinical studies have clearly shown that repaired external rotators typically fail early following surgery [11,12].

Direct Lateral Exposure

The direct lateral exposure has many forms, but generally involves developing an anterior flap that includes the anterior third of the gluteus medius, the gluteus minimus, and the anterior of the hip joint capsule. The mini-direct lateral exposure is simply the same technique performed through a smaller incision [7]. Using this technique, excellent exposure of both the acetabulum and femur can be achieved and the posterior hip joint capsule and short rotators are preserved which allows for safe unrestricted motion after surgery. While the primary advantage of this procedure is the maintenance of hip joint stability, the primary disadvantage of this procedure is that the abductions must be protected after surgery to allow them to heal so immediate progression to full weight bearing cannot be safely recommended. Further, even when the abductors are protected during the healing phase after surgery, the abductors fail to heal in a small percentage of patients leading to residual pain, a limp, or both.

Two Incision Minimally Invasive Techniques

There are a number of two incision techniques that have been developed. All basically using one exposure for the femur and another for the acetabulum. Typically, one of the incisions in the primary incision and the other is a subordinate incision. The technique that has gained the greatest notoriety is a method developed by Dana Mears, MD. It involves using the Smith-Petersen exposure as the primary exposure and for acetabular implantation. The femur is then prepared and inserted semi-blindly through an interval that is either behind or through the abductor muscles. This technique is the most anatomically offensive of the available surgical techniques because respect for the abductor muscles is a paramount principle of hip surgery and the abductor muscles are not adequately protected using the technique. Anatomical studies have documented that injury to the abductor tendons and muscle is significantly greater using this technique as compared to a mini-posterior exposure [2]. Several clinical reports have noted higher than acceptable incidences of femur fracture, stem loosening, and lateral femoral cutaneous nerve injury in addition to the high incidence of abductor injury.

Evolution of Tissue-Preserving Total Hip Arthroplasty through a Superior Capsulotomy

The technique of performing a total hip arthroplasty through an incision in the superior capsule began as a two exposure technique. The initial goal was to combine the abductor rehabilitation advantages of the posterior exposure with the hip joint stability advantages of the direct lateral exposure while eliminating the disadvantages of both techniques [4,6,8]. It was clear immediately that the femoral component could easily be inserted through an incision in the superior capsule that was placed posterior to the abductors and anterior to the piriformis tendon. The acetabulum could then be inserted anteriorly through a Watson-Jones exposure. The femur was prepared with the head and neck left intact to minimize motion of the femur, to allow the use of leverage retractors around the femoral neck, and to maintain the strength of the proximal femur during broaching to minimize the risk of femur fracture. The femoral neck.was always transected insitu and the femoral head was excised without hip dislocation, since the act of posterior/superior hip dislocation can cause avulsion of the short rotators and posterior capsule. Using these two intervals, the components could be placed while preserving the abductors, posterior capsule, and short rotators.

As experience with the superior capsulotomy exposure increased, more and more of the procedure was performed through that interval. For example, the acetabular reamers and acetabular components were placed into the acetabulum through the superior capsulotomy and connected to straight reamer and impactor handles that were inserted through the Watson-Jones interval using a small incision. Over time, this anterior incision became shorter and shorter, down to about 15mm eventually. At that point, it became apparent that the anterior incision could be eliminated entirely if angled instruments were for cup reaming and cup impaction were manufactured (Fig. 5).

Figure 5:
Evolution of 45 degree angled reamers for tissue-preserving THA through a superior capsulotomy.
Left: July, 2003
Middle: March, 2004
Right: March, 2005

With these new instruments, the technique evolved back into a single incision by July of 2003 and has remained so since.

Detailed Description of Technique

The patient is prepped and draped in the lateral position and the leg is flexed and internally rotated with the foot on a Mayo stand. An incision 7 to 8cm in length is made beginning at the tip of the greater trochanter and extending proximally, in line with the femoral shaft axis. The gluteus maximus fascia is incised and the fibers are spread at the level of the greater trochanter. The posterior border of the gluteus medius is identified and retracted anteriorly to reveal the piriformis tendon. The piriformis tendon is incised at its insertion. This tendon may be repaired at the conclusion of the procedure if desired.

The posterior border of the gluteus minimus muscles is then elevated from posterior to anterior, developing the interval between the minimus and capsule as far anterior and inferior as the minimus tendon insertion. A blunt homan retractor is placed deep to the minimus, outside the capsule, on the anterior femoral neck reflecting the minimus anteriorly. A spiked homan retractor is placed into the anterior ilium, deep to the minimus as well. A second blunt homan retractor is placed posteriorly in the interval between the posterior capsule and short rotators to fully expose the superior capsule.

A vertical capsulotomy is then made in the superior capsule from 6 o'clock in the trochanteric fossa to about 1 hour posterior of 12 o'clock at the acetabular rim. The anterior capsular flap is tagged with a suture at the acetabular rim (Fig. 6).

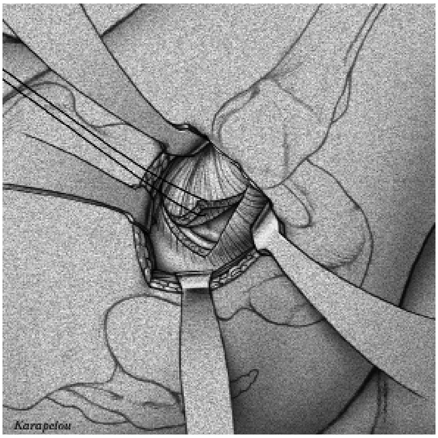

Figure 6:
The superior capsule is exposed by developing the interval posterior to the minimus and anterior to the piriformis tendon. Reprinted with permission from Operative Techniques in Orthopedics.

The anterior capsule is then opened along the acetabular rim for about 15mm and along the femoral neck, deep to the minimus tendon. This creates a U-shaped flap of anterior capsule with its base along the anterior acetabular rim. The posterior capsule is left undisturbed. A second spiked homan is placed into the posterior/superior portion of the femoral head to facilitate the exposure. A spike homan retractor is not placed in the region of the posterior acetabular rim so as not to injure this area. The blunt homans are placed inside of the capsule around the anterior and posterior femoral neck and the femoral diaphysis is entered by passing reamers through the trochanteric fossa. Conical metaphyseal milling instruments are used to open up the proximal femur to ensure that the diaphyseal reamers are properly aligned.

Once the diaphysis is prepared, the superior portion of the femoral neck and head are opened to allow broaches to be fully seated up to the final size (Fig. 7).

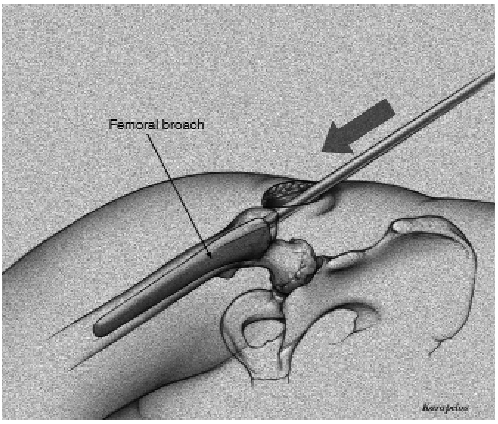

Figure 7:
The femur is fully prepared prior to transection of the femoral neck and removal of the femoral head. Reprinted with permission from Operative Techniques in Orthopedics.

A pelvic reference frame for surgical navigation is percutaneously affixed to the iliac wing and a pre-reconstruction leg-length measurement is made. The femoral neck is then transected using an oscillating saw, using the blunt homan retractors to protect the surrounding soft tissues. A long shanz screw is placed into the femoral head and a T-handle chuck is attached. A slap-hammer attached to the T-handle chuck is used to extract the femoral head.

The blunt homan retractors are then placed inferiorly through the anterior and posterior capsule to complete the acetabular exposure. Data for CT-based navigation or images for fluoroscopic navigation are acquired to establish the pelvic coordinate system.

The acetabulum is reamed using a 45 degree angled reamer and a Z-shaped cup impactor is used to insert the acetabular component (Fig. 8).

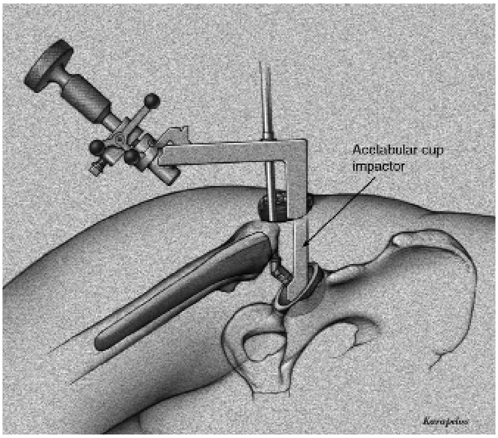

Figure 8:
Insertion of acetabular component using a double-angled impactor that exits the incision vertically. Reprinted with permission from Operative Techniques in Orthopedic Surgery.

Typically, the femoral head is inserted into the acetabulum and the femoral neck is reduced into the head. This maneuver appears to require less displacement of the surrounding soft-tissues than does a traditional reduction maneuver. After the real implants are inserted, the superior capsule is closed as is the fascia over the gluteus maximus. Patients are allowed to progress to unrestricted motion as tolerated and to progress weight bearing so long as there is no limp without support.

Clinical results of alumina ceramic-ceramic, computer-assisted, and tissue-preserving total hip arthroplasty techniques

To date, the we have performed 369 alumina ceramic-ceramic total hip arthroplasties beginning in 1997, 251 total hip arthroplasties using computer-assisted techniques beginning in 2001, and 179 total hip arthroplasties using tissue-preserving techniques. 165 of the 179 tissue-preserving total hip arthroplasties were performed using computer-assistance and 170 of the 179 tissue-preserving total hip arthroplasties received alumina ceramic bearings. Our alumina ceramic bearing experience demonstrates an implant survivorship (from all causes of failure) of 99% at 7 years (Wright Medical Technology, Arlington, TN and Biolox Forte XLW acetablular liners and femoral heads by Ceramtec AG, Plochingen, Germany). There have been no cases of osteolysis or bearing fracture [9]. Experience with computer-assistance has clearly demonstrated that the standard deviation of acetabular cup position is greatly reduced as compared to conventional THA using both fluoroscopic and CT-based navigation [10]. Finally, a prospective study comparing THA using the modified direct lateral exposure versus the tissue-preserving technique demonstrated a statistically significant faster recovery at 6 weeks in the tissue-preserving group [5]. There was no selection bias in the groups based on surgical complexity or body mass index. In fact, contrary to studies that have demonstrated a higher incidence of complications with less invasive surgical techniques, the complications in the tissue-preserving group were actually lower than in the conventional THA group.

Discussion

The advent of alumina ceramic-ceramic bearings, the use of computer-assisted surgical navigation, and the development of new, less-invasive techniques have all contributed dramatically to the practice of total hip replacement surgery. Alumina ceramic bearings clearly result in a very low wear state and a dramatic reduction in the incidence of periprosthetic osteolysis as compared to traditional total hip arthroplasty bearings. Computer-assisted techniques reduce the likelihood of component malposition, even as less-invasive techniques and smaller incisions are used. Tissue-preserving techniques, while technically demanding, offer the potential to produce a stable hip joint with minimal abductor morbidity and rapid rehabilitation.

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