Navigated Total Hip Arthroplasty Using a 3-D Freehand Ultrasound System: Technical Note and Preliminary Results

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abstract

Ultrasound-navigated cementless total hip arthroplasty (THA) was performed in 10 consecutive patients with primary osteoarthritis of the hip between August 2008 and October 2009 (M:F, 6:4; median age, 61 years; age range, 30-86 years). The pelvic orientation was defined by preoperative digitization and registration of bony landmarks. Cup inclination and anteverision were documented for each patient intraoperatively (epidigitized vs ultrasound-assessed landmarks). The median difference between the palpated and ultrasound anterior pelvic plane was 8° (range, 4°-18°) for pelvic tilt (rotation around the transversal axis), 1° (range, −3° to 2°) for rotation around the longitudinal axis, and 0.25° (range, −2.0° to 5.0°) for rotation around the sagittal axis. The median difference in cup orientation resulting from pelvic tilt error was 6° (range, 3°−13°) for anteverision and 3° (range, −1° to 5°) for inclination. There were no intra- or postoperative complications. The measured width of soft tissue layer anterior to the pelvic symphysis correlated significantly with the measured difference in cup inclination and anteverision. One centimeter of soft tissue anterior to the symphysis resulted in a median 2° (range, 1.75°-2.3°) difference in pelvic tilt.

Ultrasound-assisted navigation in THA is a promising technology able to eliminate systematic errors in anterior pelvic plane orientation, in contrast to conventionally navigated THA using percutaneous palpation of landmarks or THA without navigational support.
Computer assistance in orthopedic surgery represents one of the most significant medical advances of the past decade. The rate of patients operated with computer-assisted surgery has increased over past years, particularly in joint replacement. Most articles describe navigated total knee arthroplasty, but some studies exist on navigated total hip arthroplasty (THA). Besides proper control of joint offset and leg-length navigation, computer-assisted THA aims for a more accurate orientation and positioning of the cup component, in particular its inclination and anteversion. Lewinnek et al and McCollum and Gray considered inclination and anteversion angles of the cup to be important factors in patient outcome after THA. They found an inclination of 40° ± 10° and anteversion of 15° ± 10° to be associated with lower wear, dislocation, and impingement rates. Generally, current computer-assisted orthopedic surgery systems in THA are either image-free or image-based systems. Image-free navigation systems rely on epidigitation of the landmarks with a pointer. However, in cadaver studies, particularly in obese patients, the image-free, pointer-based imaging modality was associated with significant errors concerning anteversion and inclination. Image-based systems typically use preoperative computer tomography (CT) or intraoperative fluoroscopy as imaging modalities. Intraoperatively, the pre-registered data are matched to the patient’s individual coordinates by identification and palpation of various landmarks. The major disadvantage of these systems is the associated exposure to ionizing radiation.

This article presents the preliminary results of 10 patients operated with a novel 3-D freehand ultrasound system for navigated THA, highlighting its clinical applicability, specific problems, and limitations.

**MATERIALS AND METHODS**

Between August 2008 and October 2009, ultrasound-navigated cementless THA using a Zweymüller rectangular straight stem and MPF cup (Smith & Nephew, Baar, Switzerland) and Ceramtec ceramic head (Stuttgart, Germany) was performed in a total of 10 consecutive patients (M:F, 6:4; median age, 61 years; age range, 30-86 years) with primary osteoarthritis of the hip (Figure 1). An ultrasound imaging system with a 5- to 10-MHz linear probe (EchoBlaster 128; Telemed, Lithuania) was used together with an infrared optical localizer system (CamBar; Axios3D Services GmbH, Oldenburg, Germany) and a graphical user interface (PiGallileo; Smith & Nephew) to realize a freehand 3-D ultrasound system (Figure 3).

During 3-D ultrasound acquisition, the system guided the user to record a sweep of 50 images bilaterally in 4 defined regions around the pelvic with an appropriate pose of the probe (anterior pelvic spine longitudinal, anterosuperior pelvic spine vertical, anteroinferior pelvic spine, and pubic tubercle). The automatic determination of the anterior pelvic plane was based on an online image segmentation algorithm, which used heuristics on bone representation in sonograms. It led to a voxel cloud showing the delineation of the bone’s surface in the landmark regions. Then, a model-based procedure was used to match a linear scalable 3-D pelvic model with corresponding local landmark geometry into the voxel cloud. The orientation of the patient’s anterior pelvic plane was defined as that of the linearly scaled 3-D model, and the result could be inspected and confirmed by the surgeon in the graphical user interface. In a cadaver study, the accuracy of the described method was determined to be within ±3° for the resulting cup orientation (inclination, anteversion) (M.T. Hirschmann, unpublished data, 2009).

Preoperatively, the pelvic orientation was determined with conventional epidigitation and ultrasound-based registration of the landmarks. The difference in angles between conventional navigation and ultrasound-based navigation was measured in degrees for pelvic tilt, anteversion, and inclination.

The pre- and intraoperative data of the navigational system, including cup inclination, anteversion, femoral anteversion, leg length, range of motion, and offset changes, were documented for each patient. The width of soft tissue layer anterior to the pelvic symphysis was measured.
using ultrasound and correlated with the measured difference in anteversion and inclination of the cup.

A conventional anteroposterior pelvic overview radiograph was used for preoperative planning of cup implantation. A PACS (Picture Archiving Communication System; Phillips Easy Vision, Eindhoven, The Netherlands) measurement program was used. The desired cup position was predetermined and, if necessary, any desired changes with regard to leg length and lateral offset were defined.

**Surgical Technique**

The patient was positioned supine with an elevated ipsilateral pelvis. Disinfection and draping were performed in a standardized manner. The draping enabled the surgeon (M.T.H., C.H.) to assess all reference landmarks (both superior anterior iliac spines, inferior anterior iliac spines, and pubic tubercles) with the ultrasound probe and pointer. Both legs remained fully accessible and movable. The groin was covered with a sterile trouser draping. The sterile draping of the ultrasound head with the transducer cover was made according to the supplier’s manual. For the navigated ultrasound probe, the NeoGuard Surgi-Tip Cover (CIVCO Medical Solutions, Kalona, Iowa) was used (Figure 2).

Sterile gel was inserted into the sterile cover, followed by the probe. The cover had to be closely fitted to the ultrasound probe. Care had to be taken that there were neither bubbles nor folds between the cover and the probe surface. A pelvic and distal femoral reference tracker screw (65-, 80-, and 110-mm speed-pin) and a transcutaneous locator plate were firmly fixed at the patient’s iliac crest and distal femur after a small stab incision (Figure 3). Secure fixation was proven by manually shaking the reference tracker.

The first step of the navigational process was the assessment of the references, first using the pointer and second using the ultrasound probe (Figure 3). The superior anterior and inferior anterior iliac spines on the left side and then the right side, and then the pubic tubercle on both sides, were registered by pointer palpation (Figure 4). To control reliability, this procedure was repeated 3 times. The system then showed the ideal positioning of the ultrasound transducer for each region scan. If the transducer was in an appropriate position, this was indicated in the graphical user interface. If the scan head orientation was plausible, the orientation indicator was blue; otherwise it was red. A progress bar showed the actual
number of images recorded in this region. By adjusting the ultrasound settings, the user was able to improve image quality for bone structures. The ultrasound images were continuously segmented for bone surfaces during image acquisition. The recording of regions could be repeated either for single regions or the whole configuration. After image acquisition, the system started a matching procedure and determined the best fit of the detected bone surfaces to a matching procedure and determined the landmarks using ultrasound. The median acquisition time under pre- and intraoperative conditions was 10 minutes, respectively (range, 7 to 15 minutes). In all 10 patients, complete and plausible data sets were recorded using ultrasound. The median difference between the palpated and automatically determined ultrasound anterior pelvic plane was 8° (range, 4° to 18°) for pelvic tilt (rotation around the transversal axis). For rotation around the longitudinal axis, the median difference was 1° (range, −3° to 2°). The median difference for rotation around the sagittal axis was 0.25° (range, −2.0° to 5.0°). The median differences in cup orientation angles resulting from pelvic tilt error were 6° for anteversion (range, 3° to 13°) and 3° for inclination (range, −1° to 5°). Figure 5 illustrates the difference in point clouds of the epidigitized and ultrasound registered data.

The calculation time for the automatic algorithm was <1 minute for each data set. No intra- or postoperative complications were related to the use of any part of the navigation equipment. No pin-site infections, pain, or stress fractures were observed.

The measured width of soft tissue layer anterior to the pelvic symphysis correlated significantly with the measured difference in cup inclination and anteversion (t test, P<.001). One centimeter of soft tissue anterior to the symphysis resulted in a median 2° (range, 1.75° to 2.3°) difference in pelvic tilt.

**DISCUSSION**

Only a few clinical studies address ultrasound-based navigation in THA. In our study, the presented ultrasound-supported navigation technique was piloted in a small series of patients. This method is safe and clinically feasible and resulted in no intra- or postoperative adverse events. However, its routine clinical use is still a problem because a number of drawbacks (lengthened operation time, sterility of draping, cost effectiveness). In an early study using a CT-based system, Amin et al19 examined the accuracy of 2-D ultrasound imaging for reference purposes at a phantom pelvis and in surgical application. The result was that the accuracy compared to point digitization directly on the bony structures is within 2 mm and thus is highly acceptable. The study also described the challenge of ultrasound imaging of bony landmarks in the pelvic region. The study did not qualify the error arising from the soft tissue layer in percutaneous palpation of bony landmarks.19

Imageless navigation is typically based on intraoperative epidigitization of anatomical bony landmarks on the hip. Its major problem is that such landmarks can hardly be identified, particularly in obese patients. In a considerable number of patients, this may lead to an incorrect calculation of the anterior pelvic plane or the pelvic tilt, and hence subsequent malposition of the THA. This finding is in agreement with Richolt and Rittmeister, who demonstrated a mean anteversion error of the cup of 8° (range, 2° to 24°). In patients with a body mass index (BMI) >27 kg/m², Parratte and Argenson found an increased error in measuring acetabular cup position using imageless navigation. Hasart et al also proved this by showing a significant correlation between acetabular cup anteversion error and BMI.

**RESULTS**

All landmarks were registered with the ultrasound probe without complications. The median acquisition time under pre- and intraoperative conditions was 10 minutes, respectively (range, 7 to 15 minutes). In all 10 patients, complete and plausible data sets were recorded using ultrasound. The median difference between the palpated and automatically determined ultrasound anterior pelvic plane was 8° (range, 4° to 18°) for pelvic tilt (rotation around the transversal axis). For rotation around the longitudinal axis, the median difference was 1° (range, −3° to 2°). The median difference for rotation around the sagittal axis was 0.25° (range, −2.0° to 5.0°). The median differences in cup orientation angles resulting from pelvic tilt error were 6° for anteversion (range, 3° to 13°) and 3° for inclination (range, −1° to 5°). Figure 5 illustrates the difference in point clouds of the epidigitized and ultrasound registered data.

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In our study, the measured depth of prepubic fat pad correlated significantly with the measured difference in pelvic tilt. One centimeter depth of prepubic fat pad resulted in a median 2° difference in pelvic tilt, which is clinically significant and may help surgeons adjust surgery accordingly, even pointer-based navigation methods. Although Anda et al25 reported that acetabular tilt, which is clinically significant and may benefit surgeons adjust surgery accordingly, even pointer-based navigation methods. Although Anda et al25 reported that acetabular pelvic rotation of 1° leads to 0.5° change in anatomical anteversion, no clear relationship between pelvic tilt and anteversion or inclination has been described. Richolt and Rittmeister21 showed that pointer-based imaged less navigation leads to a mean underestimation of the acetabular anteversion of only 2.88° ±1.88°. They further concluded that, in relation to the wide range of Lewinnek’s safe zone, this is negligible.21 In contrast to their study, we found a wider, more clinical significant range, which may be attributed to the patient’s body mass and depth of the prepubic fat pad.

We consider the small number of patients in our study a limitation. However, the study describes the method used and critically discusses the benefits and drawbacks of ultrasound-based navigation, none of which is affected by the sample size.

Knowing that a good outcome does not rely solely on acetabular cup position, further studies should be performed to investigate its effect on femoral stem positioning.13 Furthermore, postoperative CT scans should be acquired to validate the accuracy of this system.

CONCLUSION

Ultrasound-supported navigation in THA is a promising technology that has the potential to eliminate systematic errors in anterior pelvic plane orientation in relation to conventional THA using percutaneous palpation of landmarks or THA without navigational support. The discussed navigation concept with integrated ultrasound landmark detection is not yet ready for routine use, and the surgeon who wants to use this technology should be fully aware of the benefits and limitations of this system.

REFERENCES