



# Computer-Aided Orthopedic Surgery with Near-Real-Time Biomechanical Feedback

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**T**his article describes our ongoing efforts in computer-aided surgery. We are developing and testing a biomechanical guidance system that will interact with the surgeon and report the biomechanical state of the joint during hip surgery. The system uses information from the imagery of a computer-assisted navigation system and displays the contact pressure distribution in the hip joint as the joint realignment is modified intraoperatively. We describe the use of the presented technique for preoperative planning, assessment of surgical outcome, and validation of results as well as intraoperative applications. Although the focus of this work is on periacetabular hip osteotomy, applications of this research can be extended to other types of hip osteotomies, joint osteotomies, and total joint replacement techniques.

## INTRODUCTION

Computer-aided surgery (CAS) systems provide a broad range of technologies to surgeons before and during surgical procedures. Examples of these technologies include navigation systems, computer models, robotic assisted tools, and visualization devices. CAS systems can be used as both training and research tools and in routine clinical practice. CAS enables the surgeon to develop new, more accurate, and less invasive surgical techniques. In orthopedic surgery, CAS systems combining preoperative modeling and planning with navigational or robotic intraoperative assistance are becoming increasingly accepted among surgeons. The individual applications may differ, but the fundamental paradigm of these systems is as follows:

- Patient-specific preoperative planning through creation of three-dimensional (3D) virtual environments using medical imagery
- Intraoperative registration of the virtual environment (which includes the patient model and the surgical plan) to the actual patient and the interventional system
- Computer-assisted execution of the plan using a variety of technologies

This paradigm—combining preoperative planning, registration, and execution—has been discussed extensively by various authors,<sup>1-4</sup> including a co-author of this article.<sup>5-8</sup>

## Patient-Specific Planning

Computer-aided preoperative planning for orthopedic surgery aims at creating virtual environments using 3D reconstructed computed tomography (CT) images and radiographs. In orthopedic applications for the hip, preoperative planning is commonly developed for osteotomies<sup>9-12</sup> and total hip replacements.<sup>13-17</sup> Many studies have demonstrated the importance of biomechanical analyses for preoperative planning environments.<sup>18-22</sup> Few preoperative environments, however, include detailed biomechanical planning. Rather, they are commonly based on the kinematics and geometrical analysis of the patient's anatomy. One reason is that the development of high-quality patient-specific biomechanical models, such as finite element models (FEMs), obtained from 3D images is not an automated process, and simulations take a considerable amount of time. These techniques are less desirable for the structural optimization scheme usually required for surgical planning.

## Computer-Assisted Registration and Execution of the Plan

The most common systems for CAS execution use some sort of 3D tracking device to sense the relative positions of the surgical instruments in the surgical field. The coordinate system of the tracking device is registered to the patient and to the preoperative images. Interactive displays are often used to provide information that helps the surgeon perform the surgery. These types of systems have been applied extensively in orthopedics,<sup>23-28</sup> neurosurgery, and craniofacial and maxillofacial surgery. To our knowledge, the available systems do not provide intraoperative biomechanical information to the surgeon. Therefore, any modification to the surgical plan during the surgery would deal only with geometrical constraints.

## PERIACETABULAR OSTEOTOMY: AN APPLICATION OF CAS

In this article, we describe our previous and ongoing work on the development and validation of the CAS system with pre- and intraoperative biomechanical guidance for planning and execution of the surgery. In one application, we apply the system to image-guided periacetabular hip osteotomy surgery.

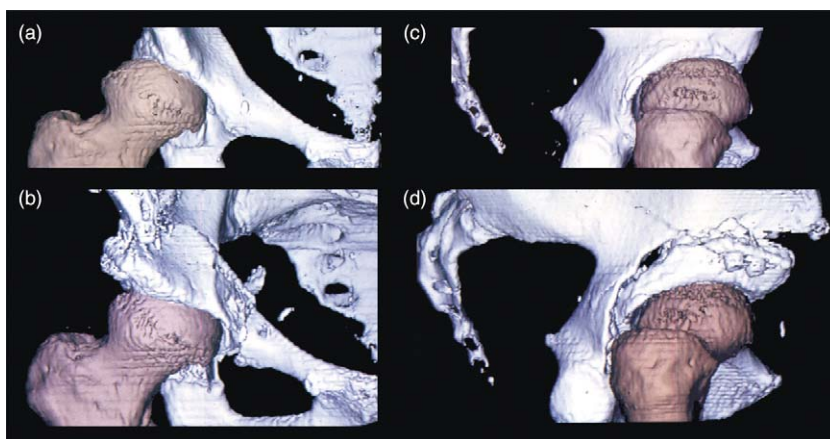
Periacetabular hip osteotomy is performed on patients with hip dysplasia to reduce abnormally high contact stresses within the acetabulum (hip socket). Hip dysplasia, also

known as shallow hip socket, is a condition in which the acetabulum of the patient is not adequately developed; rather, the acetabulum is shallow and its roof is obliquely rotated outward. Therefore, the superior and anterior part of the femoral head is not covered (Fig. 1). This results in abnormally high stresses on the lateral edge of the acetabular rim. Patients with hip dysplasia cannot walk long distances, have chronic pain, and usually limp. Hip dysplasia may result in osteoarthritis,<sup>29,30</sup> fracture of the acetabular rim, and/or breakdown of the cartilage of the acetabular rim.<sup>31</sup>

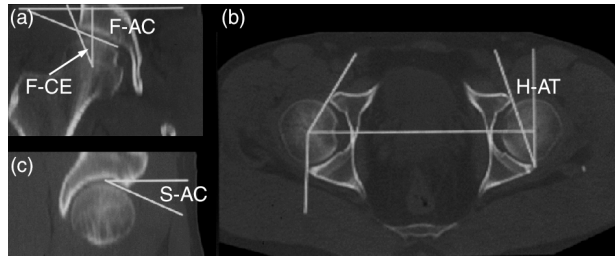
A variety of techniques can be used to treat hip dysplasia, including arthroscopic procedures, total hip replacement, and hip osteotomy surgeries.<sup>32-37</sup> Total hip replacement surgery is the preferred choice for elderly patients. However, because the effective life of current hip prostheses is less than 15 years, it is not suitable for young patients. Patients younger than 45 years may need two to four additional hip revision surgeries during their lifetime. Periacetabular hip osteotomy is the technique of choice for young adults. In this procedure, the surgeon completely detaches the acetabular cup from the rest of the pelvis. The surgeon then realigns the acetabular cup in order to restore predefined anatomical angles in three orthogonal planes, similar to the alignment of a normal joint (Fig. 2). Periacetabular osteotomy usually requires preoperative planning to determine the amount of necessary acetabular rotation. Preplanning is usually performed using radiographs or CT scans. As mentioned, while the goal of surgery is to reduce abnormally high stresses, few surgeons use biomechanical analysis for preoperative planning.

## Image-Guided Intervention in Periacetabular Osteotomy

Bernese periacetabular osteotomy, first performed by Ganz et al. in 1988,<sup>35</sup> is the most common osteotomy.



**Figure 1.** Views of a dysplastic hip (also known as shallow hip socket) using volume-rendered CT data: (a) preoperative frontal, (b) postoperative frontal, (c) preoperative lateral, and (d) postoperative lateral.



**Figure 2.** Reconstructed CT-slices in the (a) frontal plane, (b) horizontal plane, and (c) lateral (sagittal) plane. The realignment angles shown in their respective views are F-AC, the articular cartilage angle in the frontal plane; F-CE, the center edge angle in the frontal plane; H-AT, the anteversion angle in the horizontal plane; and S-AC, the articular cartilage angle in the sagittal plane. F-AC is the angle between the horizontal line and a line connecting the medial edge of the sourcil line and the most lateral point on the acetabulum (points 4 and 5 in Fig. 7) measured clockwise. F-CE is the angle between a vertical line passing through the center of the femoral head and a line between the center of the femoral head and the most lateral edge of the acetabulum measured counter-clockwise. H-AT is the angle of a line parallel to the opening of the acetabulum and a line perpendicular to the line drawn through the centers of the femoral heads. S-AC is the angle between a horizontal line and a line passing through the anterior edge of the contact surface and the uppermost point of the acetabular contact surface.

This technically challenging technique consists of a sequence of cuts through the ischium, pubis, and ilium using various surgical instruments. The procedure completely detaches the acetabular cup from the rest of the pelvis. The cup is then realigned and fixed to the pelvis to improve the femoral head coverage and contact pressure distribution in the hip joint (Fig. 1). During surgery, the surgeon must perform some of the chiseling without having a clear view of the surgical instruments. In addition, there is always a potential to damage the neural and vascular structures near the site of surgical activity.<sup>35</sup> Therefore, this surgery can benefit greatly from the use of image-guided navigation systems, which are more widely used for total joint replacement surgeries. Langlotz et al.<sup>38</sup> reported on the first 12 cases of the use of free-hand navigation for periacetabular osteotomy. They found no intraoperative or postoperative complications. Other recent examples include intraoperative navigation for the Kingston periacetabular osteotomy.<sup>39</sup> The Kingston osteotomy has been reported on eight patients, with successful results in seven of the cases. This technique offers a less challenging approach; however, it requires an extra step of detachment of the femoral head.

Few other surgeons in the world use image-guided navigation for periacetabular osteotomy surgeries. Perhaps the broad clinical application is hindered by high costs, additional time required during the intervention, problems regarding the surgeon/machine interface, and space constraints in the operating room. Nevertheless, we feel the benefits regarding the added safety and precision of the surgery, and the possibility of integrating preoperative planning with intraoperative

navigation, remain attractive. Currently a co-author of this article, Dr. Lepistö, is one of the few surgeons who perform image-guided periacetabular osteotomies.

### Intraoperative Revision of the Preoperative Plan

The current state of research has shown the advantages and importance of using biomechanics and joint contact pressure calculations in planning the periacetabular osteotomy.<sup>9,19,21</sup> For the following reasons a significant improvement can be obtained if the surgeon can intraoperatively access and visualize the biomechanical state of the surgery:

- There is a degree of unpredictability in the final fixation of the bone fragment because of variations in quality, the thickness of cortical structures, and the final shape of the cut of the bone fragment. Because of concerns regarding secure fixation and bone healing, trade-offs in alignment are often necessary. The interactive biomechanical guidance system (BGS), therefore, can help the surgeon to revise the plan in real time and find the new optimal fixation.
- Bone or soft tissue impingement may become evident during surgery, requiring the surgeon to revise the plan and consider an alternative alignment.
- If the realignment strategy is modified as a result of either of the above conditions, the joint congruency needs to be re-checked. Simultaneous femoral osteotomy may have to be considered in order to improve congruency.
- Conducting an intraoperative range-of-motion test of the hip provides a better assessment of joint stability.

### Desired Characteristics of a Biomechanical Guidance System

To perform near-real-time contact pressure calculations and biomechanical analysis, a fast and accurate algorithm is required. In addition, since the technique will be used in a surgical environment, the biomechanical model should work with minimal free parameters to promote ease of use. FEMs are the most detailed and accurate modeling technique used to calculate the stress distribution in bones and around joints; however, they have a significantly long run time. When contact surfaces and dynamic loadings (time-dependent loads) are presented in the FEM, the simulation may take several hours. Thus, it is prohibitive to apply detailed FEMs for individually based functional data.

The discrete element analysis (DEA) technique,<sup>20,40,41</sup> in contrast, is extremely fast. A typical simulation that may take days to perform using FEMs can be completed in a few seconds with the DEA technique. It is especially suitable when there is a drastic difference among the stiffness properties of the materials used in simulation (e.g., bone and cartilage). In addition, the technique is fault tolerant and forgiving of inaccuracies when

defining the contact area. Also, in contrast to FEMs, running DEA algorithms requires defining very few parameters. Later, we discuss our preliminary results for experimental validation of the DEA technique for approximating the pressure distribution and location of maximum stress in the hip joint.

In the following sections we present an overview of the architecture of image-guided hip osteotomy with the intraoperative BGS and its components. We discuss the algorithms for 3D reconstruction of the acetabular cartilage and femur for preoperative planning and intraoperative biomechanical guidance of the surgery. Next, we describe our computer-aided preoperative planning and postoperative results for 12 patients who have undergone periacetabular hip osteotomy. Finally, we present our experimental validation studies for contact pressure distribution of the hip.

## SYSTEM OVERVIEW

The overview of the image-guided system with biomechanical feedback to the surgeon is shown in Fig. 3. The BGS will be integrated with Medivision's Surgi-Gate Navigation system. The Surgi-Gate system uses an optical tracking camera (Optotrak, NDI Inc., Waterloo, Canada) to register the pelvis and femur of the patient to a 3D model developed preoperatively from CT data. It then tracks the location of the surgical instrument with respect to the pelvis. Since the BGS will run on an independent computer, it can also be integrated with other navigation systems. The following is a brief functional description of the components of the system.

### Preoperative Planning

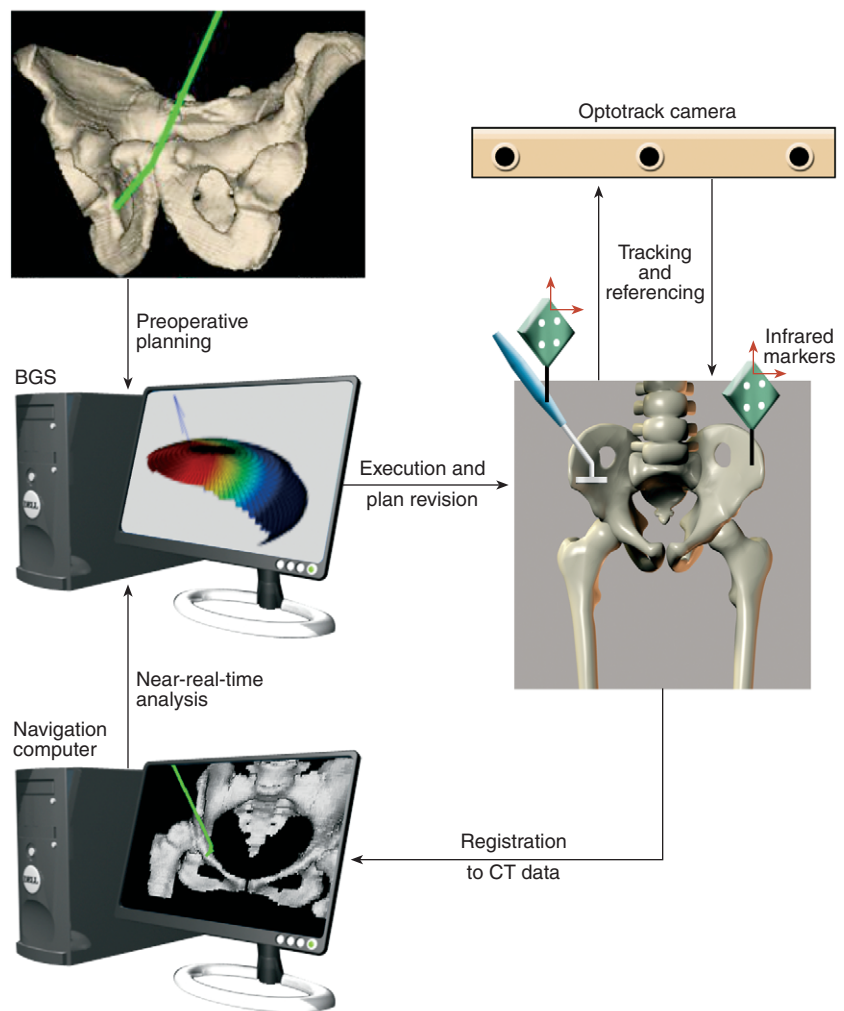
The CT images of the pelvis of the patient in a supine position are collected, and volume rendering is performed to develop its 3D image. The cartilaginous area of the acetabulum and the volumetric geometry of the proximal femur are also reconstructed from CT slices using our semi-automatic algorithm,<sup>42</sup> and relevant anatomical angles (Fig. 2) are determined.<sup>43</sup> The biomechanical planning is performed, simulating the cuts and minimizing the critical hip joint contact pressure.

### Intraoperative Registration

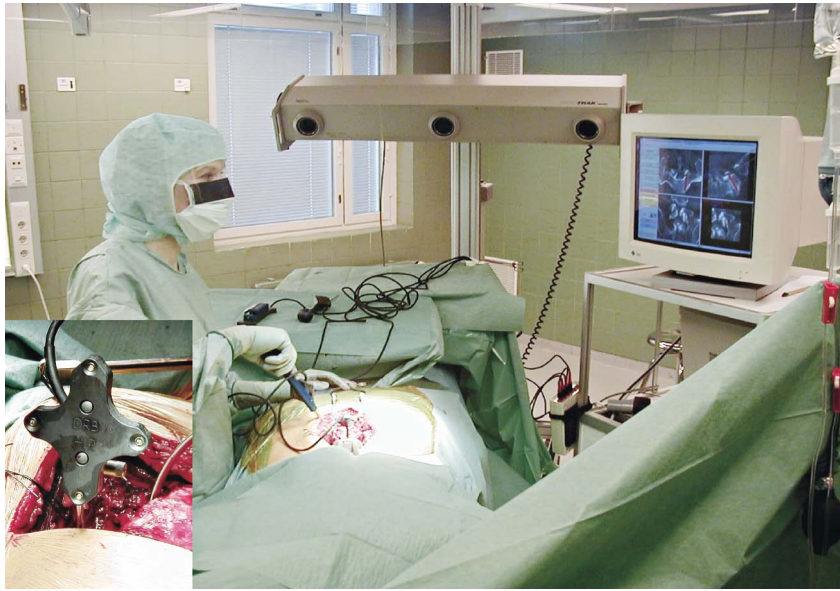
In the operating room, an optical tracking camera is used to detect the coordinates of the anatomical landmarks on the pelvis using infrared markers (attached to the reference screws) and a digitizing probe. The 3D image and the 3D biomechanical model of the pelvis are registered to the pelvis of the patient using anatomical landmarks and surface-matching algorithms. Details of the registration technique are described in the Intraoperative Navigation section.

### Intraoperative Tracking

Infrared diodes are attached to the pelvis to reference its position. They are also attached to surgical instruments (Fig. 4). During the surgery their location and trajectory are overlaid on the referenced 3D image of the pelvis to help the surgeon chisel the bone without a clear view. The camera system also tracks the acetabulum after it is detached from the pelvis.



**Figure 3.** Architecture of the computer-aided navigation system with biomechanical guidance.



**Figure 4.** The computer-aided navigation system at ORTON Hospital, Finland. The computer image shows the position of a surgical instrument overlaid on the volume-rendered CT data of the patient. The insert (lower left) shows infrared diodes attached to the surgical instrument. An Optotrak camera (NDI Inc., Waterloo, Canada) (as shown in the figure) detects the spatial location of these diodes to calculate the position of the tip of the surgical instrument.

### Biomechanical Guidance

During the surgery, the BGS tracks the location of the acetabulum. At any time, the surgeon can test the range of motion of the hip and look at the contact pressure distributions for the given range. If the surgeon aims at realigning the acetabular cup to a certain position, the BGS can then suggest optimal rotations to reach the desired alignment.

### Intraoperative Execution

The realignments determined by the BGS satisfy constraints set by the surgeon before surgery. These constraints ensure that the optimized result is always within a desired range of anatomical angles from that of normal joints. The BGS is designed to assist the surgeon in decision making and revising the surgical plan. The surgeon may accept or reject the suggested plan during surgery.

### BGS ARCHITECTURE

Briefly, the BGS algorithms find the outer surface of the femur and the cartilaginous surface of the acetabulum, mesh these surfaces, and develop mesh coordinate systems with respect to the coordinate system attached to the pelvis. The algorithms can then calculate the contact pressure distribution for various scenarios, including the stance phase of the gait cycle, extremes of the hip range of motion, and any other desired configuration.

The registration and real-time tracking of the cartilage surface during surgery are performed by a commercially available navigation system. However, the data

are transferred to an independent computer to perform the BGS calculations. This allows the program to run independently of the commercial image-guided system used during surgery. The procedure for applying the DEA technique for hip osteotomy is as follows.

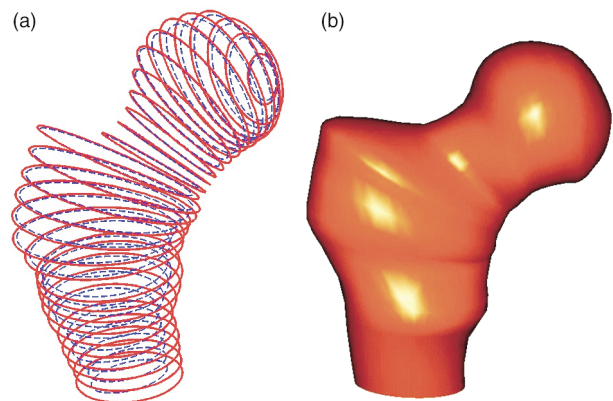
### Generating the Surface Geometry of the Femur

The CT scans of the hip, the proximal femur (the section of femur that is closer to the trunk), and the distal femoral condyles (the portion of the femur in the knee joint) are obtained with the patient in the supine position. The surface geometry of the femur is needed to approximate the direction of the femoral and abductor muscle loads and to locate the insertion point of the abductor muscles. A semi-automatic algorithm is developed to extract the surface geometry of

the proximal femur and its distal condyles from the CT data (Fig. 5). These surface geometries are used to locate the center of the femoral head and the orientation of the femur. To reduce the amount of CT radiation exposure to the patients, the mid-shaft between the proximal femur and the distal condyles is usually not scanned. The surface geometry of the mid-shaft is interpolated, and a full-length model of the femur is reconstructed.

### Locating the Center of the Femoral Head

The location of the center of the femoral head must be known to determine loading conditions when the DEA technique is applied. The coordinates of several



**Figure 5.** Typical proximal femur (a) outline and (b) surface model developed by our semi-automatic algorithm. The dashed blue line in the outline represents the boundary between the two different types of bone: outer cortical shell and inner cancellous (also known as spongy) bone.

points on the surface of the femoral head are selected. The center of the femoral head is approximated by performing an ellipsoidal fit of the selected points on the surface of the femoral head.

### Extracting the Surface Geometry of the Acetabular Cartilage

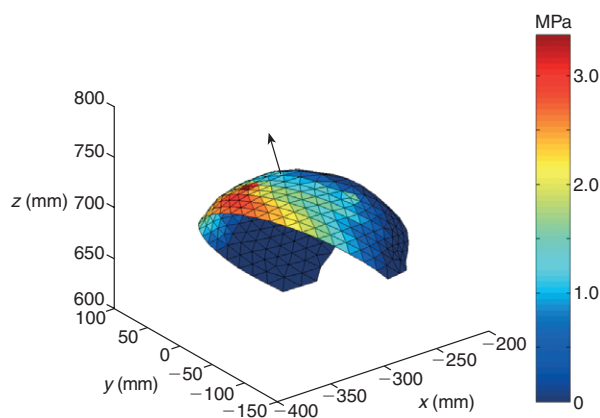
We have developed a technique for extracting the surface geometry of the acetabular cartilage from CT data. On each CT slice, the edges of the cartilaginous area are digitized. A spherical fit is performed over digitized points of the CT slices, and a congruent 3D cartilaginous surface is created. Figure 6 shows a typical surface generated using this technique. We are currently extending this technique to develop a more accurate surface geometry. Since the DEA technique is fault tolerant, a moderate accuracy for determining this surface is expected to be adequate.

### Loading on the Acetabular Cartilage

The orientation of the femur with respect to the pelvis is used to determine the line of action of the abductor muscle forces. The insertion of the equivalent abductor force is determined on the greater trochanter. Given the direction of the abductor force and the body weight acting on the L4-L5 vertebrae, static analysis is used to find the direction and magnitude of the reaction force on the acetabular cartilage.<sup>44</sup> This commonly used technique simplifies the determination of the loading conditions. Because no type of contact is required for this technique, the speed of the calculations drastically improves as compared to multibody and finite element analysis.

### Hip Joint Contact Pressure Distribution

The DEA method is applied to determine contact pressure distribution on the surface of the acetabular



**Figure 6.** A typical 3D acetabular cartilage surface generated from CT data using our in-house algorithm. The DEA algorithm was used to calculate contact pressure distribution as shown. An arrow indicates the direction of the femoral load.

cartilage. Experimentation at APL has validated this model for the pressure distribution in the hip joint.<sup>45</sup> Other researchers have validated the technique for pressure distribution in the patella-femoral joint<sup>46,47</sup> and have compared it with analytical models and FEMs.<sup>48</sup> Recall that DEA approximates the pressure distribution with very few parameter settings and is therefore very suitable for near-real-time application to the surgery.

In our application, the pelvis is assumed to be a rigid body and its movement is assumed to be constrained in three dimensions. The loading magnitude and direction are varied with the loading of the femur. More complicated boundary and loading conditions can also be applied; however, our preliminary analyses have shown that these settings are sufficient for a first approximation.<sup>45</sup> DEA assumes that the acetabular cartilage surface is an elastic surface modeled by a series of parallel shear and compressive springs distributed over the surface mesh. This assumption is valid because there is a drastic difference in stiffness between the pelvis bone and the acetabular cartilage. The method calculates the pressure distribution recursively using the principle of minimum potential energy. Any spring in tension will be deleted from the contact area, and the analysis will be repeated on the new contact surface until a contact area with only compressive springs is determined. As noted previously, because the actual contact area for different situations does not include the entire cartilage area, the technique is fault tolerant and not sensitive to the inaccuracies in determining the acetabular cartilage area.

## BGS APPLICATIONS

### Preoperative Planning

Two independent modules are designed for the preoperative planning phase. The first module automatically calculates the angles of rotation for the osteotomized acetabulum in the three orthogonal planes, based on minimizing the maximum contact pressure in standing position, and for extremes of the range of motion as defined by the surgeon. A nonlinear optimization algorithm (BFGS algorithm<sup>49</sup>) is used to minimize the maximum contact pressure for the three orthogonal rotations. The angles of rotation are reported in terms of the acetabular index angle in the sagittal plane (S-AC), the acetabular index angle in the frontal plane (F-AC), the center edge angle in the frontal plane (F-CE), and the anteversion angle in the horizontal plane (H-AT) since surgeons usually work with these angles (Fig. 2).

$$\begin{aligned} &\text{Minimize } \sigma_{\max} = F(X) \\ &\text{Such that } X - \bar{X} < C_{\max}, \end{aligned}$$

where

- $\sigma_{\max}$  = the maximum contact pressure in the standing position,
- $X$  = the desired vector of three anatomical angles, S-AC, F-AC, and H-AT,
- $\bar{X}$  = the vector of the above three anatomical angles measured in the normal joint of the patient, and
- $C_{\max}$  = the vector of maximum permissible deviation from  $\bar{X}$  as obtained from the literature.

Several initial conditions in the neighborhood of  $\bar{X}$  are used during the optimization to ensure the existence of a unique solution (global minimum). The second module enables the surgeon to select the change of angle in the three orthogonal planes or based on selecting S-AC, F-AC, and H-AT angles.

### Intraoperative Navigation

During surgery the registration of the pelvis follows the protocol designed for Medivision's SurgiGate system as follows. Three or four pairs of points on the bony fragment of the pelvis are registered by a digitizing pointer. Next, 12 or 13 points on the surface of the bone near the line of the osteotomy are digitized (bone surface registration). An additional registration step is performed for the BGS: three small screws or pins are attached to the bony fragment of the pelvis that is relocated during the osteotomy. Before the bone is osteotomized, the coordinates of these screws are digitized using the digitizing pointer. After the osteotomy is performed, at any time during the surgery, the surgeon can digitize the new coordinates of these screws. The new coordinates are the input to the BGS used to calculate the new orientation of the osteotomized fragment using both Euler angles and the surgical reference angles (S-AC, F-CE, F-AC, and H-AT). The BGS then finds the contact pressure distribution, the location and magnitude of the maximum contact pressure, and the centroid of contact pressure.

Finally, the BGS performs optimization to determine whether there is any orientation in the neighborhood of the existing orientation that would minimize the maximum contact pressure for the stance phase and the extremes of the range of motion. For the new set point, the surgeon checks the new range of motion, and the calculations are updated.

### PRELIMINARY RESULTS

The following describes our preliminary results, which include (1) the validation of the biomechanical technique as the core of the BGS architecture, and (2) the application of the DEA to preoperative planning. These studies demonstrate the importance of biomechanical analysis in the successful performance of the periacetabular osteotomy and present original surgical outcome data that can be compared to the results of the application of the BGS architecture.

### Significance of Biomechanical Analysis

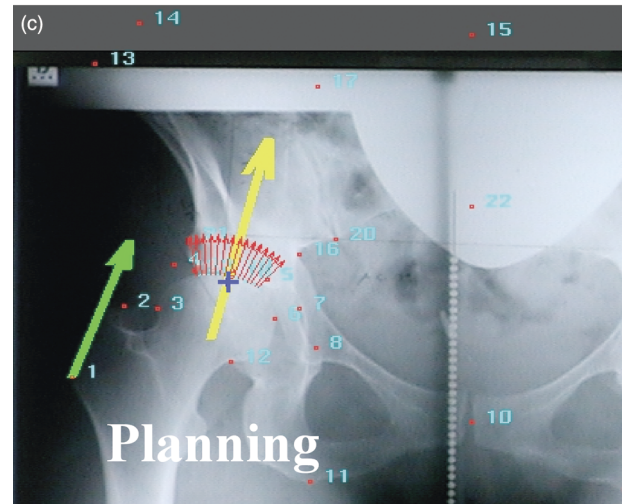
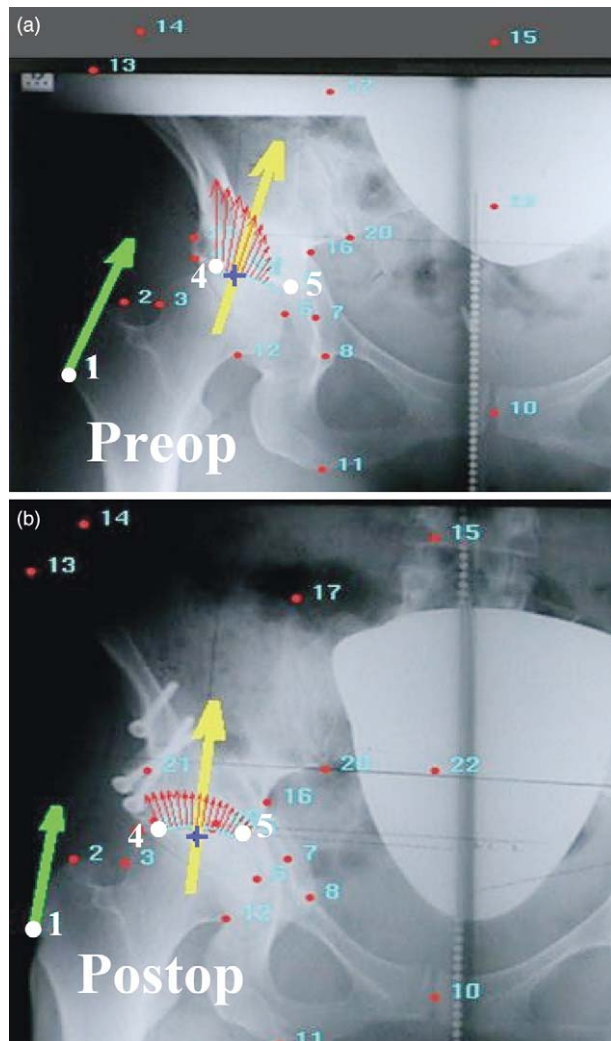
We analyzed the effect of periacetabular osteotomy on hip dysplasia using CAS of joint contact pressure on regular standing anterior-posterior radiographs.<sup>50</sup> These results were compared with the results of surgery based on realignment of the acetabular angles to the normal hip. Twelve consecutive periacetabular osteotomies with no femoral head deformity were studied. The median age of the patients, all females, was 35 years (range, 20–50 years). The median follow-up was 2 years (range, 1.3–2.2 years). Patient outcome was measured with the total score of a self-administered questionnaire (q-score)<sup>51</sup> and with the Harris hip score.<sup>52</sup> Radiographic alignments of the acetabulum and patient outcomes were assessed independently. The pre- and post-operative orientation of the acetabulum was defined using reconstructed 3D CT slices. The lateral femoral coverage was measured with the acetabular index angle (F-AC) and the CE angle of Wiberg (F-CE) in frontal CT slices (Fig. 2). Peak contact pressure, weight-bearing area, and centroid of the contact-pressure distribution (CP ratio) were calculated from standing anterior-posterior radiographs (Fig. 7).

While 9 out of 12 patients showed decreased peak pressure after surgery, the mean changes in weight-bearing area and peak contact pressure were not statistically significant. However, the CP ratio changed significantly ( $p < 0.001$ ) with surgery. Postoperatively, patients with CP ratios between 0.40 and 0.59 had a low pressure gradient (mean/peak pressure  $0.79 \pm 0.12$ ), their q-scores and Harris hip scores improved, and their peak pressure was significantly lower than the preoperative results. Patients with CP ratios outside the range of 0.40–0.59 had a high pressure gradient (mean/peak pressure  $0.55 \pm 0.03$ ), and after the surgery their peak pressure did not improve significantly. Also, the radiographically measured angles did not always associate with the objective biomechanical goals of realignment osteotomy. Biomechanical analysis, therefore, can be a valuable tool in guiding periacetabular osteotomy surgery.

### Experimental Validation of the DEA Technique

As mentioned, the core of the BGS architecture is based on the application of techniques for determination of the contact pressure distribution in the joint. We performed the following study to validate this technique.<sup>45</sup>

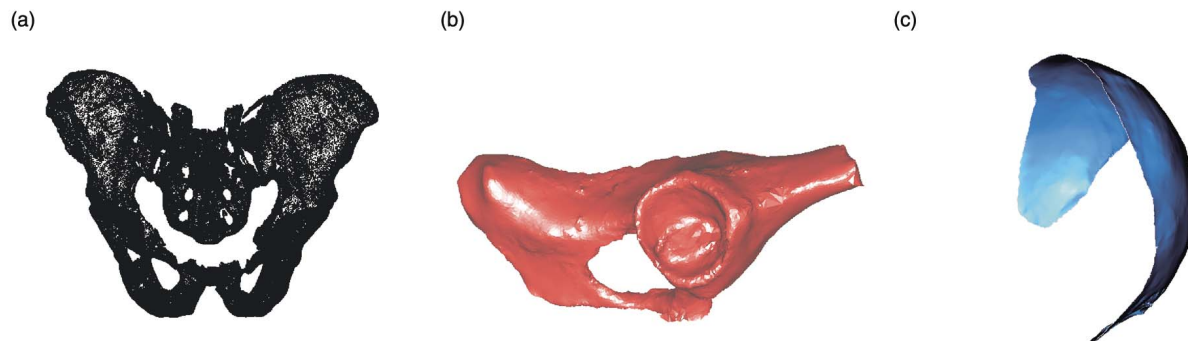
The objective was to determine whether the contact pressures on hip joints calculated using the DEA technique could be experimentally validated. The 3D surface geometry of porcine pelvis and femur specimens was digitally scanned using an H40 laser head with an Nvision Faro arm laser scanner. A computer model of the acetabular cartilage of the hip was generated from the digitized scanned data (Fig. 8).



**Figure 7.** An example of pre- and postoperative analysis and preoperative planning. (a) The preoperative radiograph shows that the contact pressure distribution (red arrows) does not span the entire potential contact area (defined by the area between the lateral edge [point 4] and the medial edge [point 5] of the sourcil). The peak contact pressure is on the lateral edge (point 4). Also shown are the lines of pull of the abductor force with its origin at the most lateral edge of the greater trochanter (point 1), and the joint reaction force passing through the centroid of contact pressure (shown by the + sign). (b) The postoperative radiograph shows an even distribution of the contact pressure after surgery. The size of the weight-bearing area has approached that of the potential contact area (between points 4 and 5). The peak pressure is not on the lateral edge, and the centroid of the contact pressure distribution has moved to the center of the contact area (CP ratio approached 0.5). (c) Preoperative planning on the preoperative radiograph results in an even distribution of contact pressure produced by rotating the detached acetabulum by  $8^\circ$  laterally.

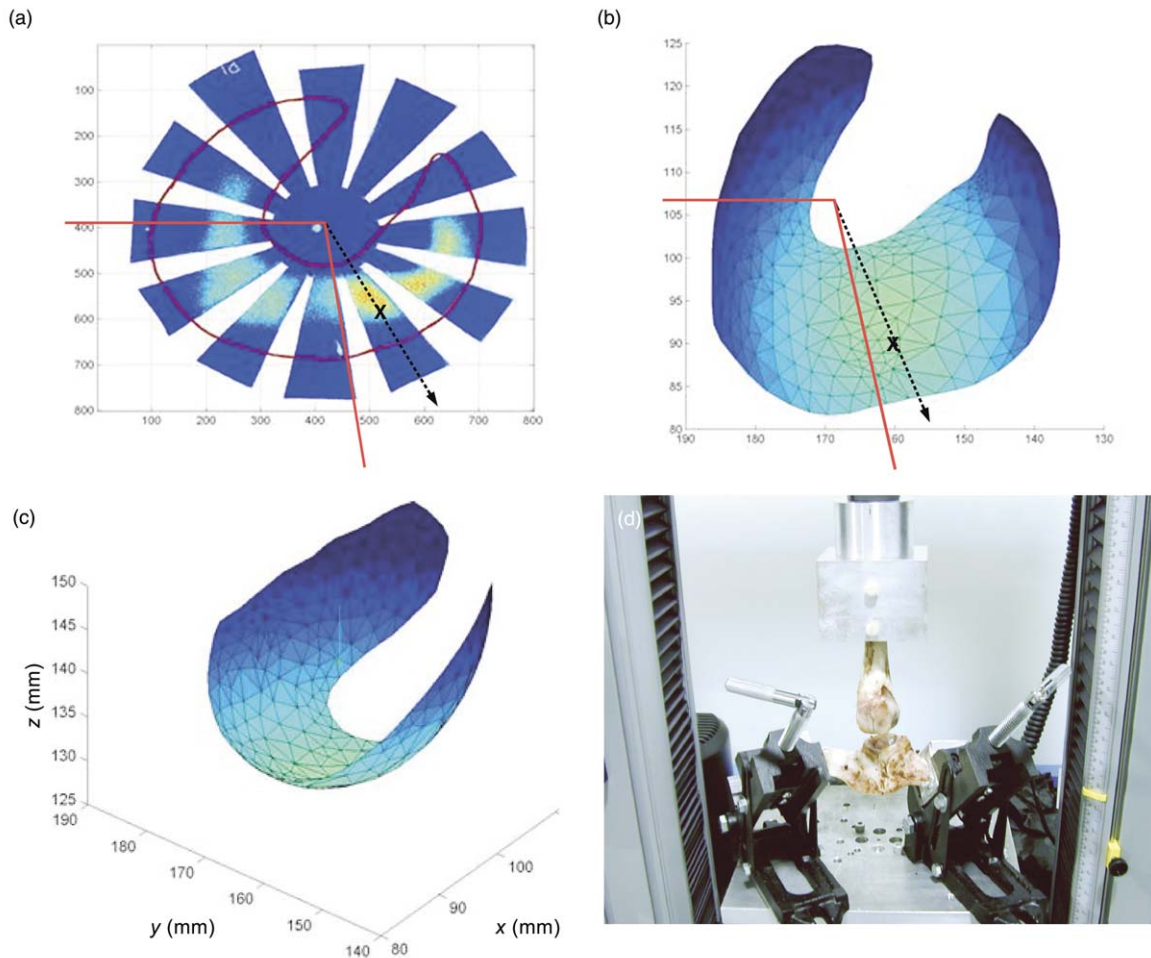
The DEA technique was used for four different pelvic orientations and three sets of loads (890, 1335, and 1780 N). To validate the modeling results, Fuji prescale film was used to measure joint contact pressure (Fig. 9a) when a preset axial force was applied from the femur to the pelvis using an Instron testing machine (Fig. 9d). The DEA model (Figs. 9b and 9c) consistently predicted the location of the maximum contact pressure with an error

of less than  $\pm 8^\circ$  as compared to experiments (three experiments for each configuration). Such a range seems to be an acceptable approximation of the pressure distribution. This technique is at least 2 orders of magnitude faster than finite element analysis for contact analysis. Therefore, it can be used for surgical applications (e.g., osteotomies and joint replacements) that require dynamic and subject-specific models of pressure distribution.



**Figure 8.** (a) A typical point cloud created from the surface geometry of the pelvis using the Faro arm system. (b) A surface geometry created from point clouds of the half pelvis. (c) The contact surface of the acetabular cartilage extracted from the surface geometry of the pelvis.





**Figure 9.** (a) Contact pressure distribution on the surface of the acetabular cartilage. The load of the femur is 1335 N along the z axis. (b) Projection of the cartilage surface into a plane. The solid lines separate anterior, superior, and posterior portions of the cartilage. The arrow and the x represent the polar coordinates of the maximum pressure. (c) Experimental contact pressure distribution on a rosette cut from Fuji prescale films. (d) Experimental setup for loading the pelvis.

## FUTURE WORK

After completing the development of the BGS and integrating it with image-guided navigation systems, we plan to test the protocol for computer-assisted periacetabular osteotomy with online biomechanical guidance and to study the reliability of the results when using the BGS. The BGS will be tested on four cadavers to verify its reliability and functionality during surgery. The functionality of the BGS will be tested by addressing the following questions. (1) Is the thigh marker always in the sight of the camera for various thigh angles? (2) Are the tracking screws (attached to the osteotomized pelvic bone) always accessible and their coordinates readable by the computer-aided navigation system? (3) Are the angle calculations based on the coordinates of the tracking screws accurate? The test of reliability will be performed by showing that BGS solutions always satisfy minimum criteria established from previous literature. For instance, while it is desirable to reduce the F-AC, it should remain positive.<sup>53</sup> Also, the F-CE must

usually remain greater than  $20^\circ$ .<sup>10,20</sup> Therefore, the solution proposed by the BGS will be considered reliable if it satisfies the above conditions and does not reduce the range of motion drastically.

Once the ability of the BGS for maintaining the minimum criteria for successful surgery is demonstrated, we will test the system during actual periacetabular surgery on patients with dysplastic hips. We hypothesize that computer-aided navigation of the periacetabular osteotomy based on biomechanical feedback of the contact pressure distribution will improve the outcome of the surgery when compared to the conventional technique of realigning the angles of the dysplastic hip with alignment of the normal side. We will explore this hypothesis by using the system during actual surgery of 10 patients undergoing periacetabular osteotomy and performing 6-month follow-up exams on them. The results (both radiological and clinical) will be compared with our existing pool of data on patients with dysplastic joint that have undergone surgery with the conventional technique.

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