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Computer-Aided Simulation, Analysis, and Design in Orthopedic Surgery

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Computer-aided analysis of three-dimensional reconstructions of radiographs and computed tomographic images has clinical application in the analysis, simulation, and design of a wide variety of orthopedic reconstructive procedures. The three-dimensional anatomy of bone and soft tissue[23,32,33] can be reconstructed by the computer for presentation and analysis. These computer reconstructions may be applied clinically to osteotomy, total joint replacement, and allograft reconstructive surgery.

The goal of pelvic and femoral osteotomies is to prevent the development and progression of osteoarthritis by changing the mechanics of the joint. Alteration of the mechanics are primarily achieved through changes in the shape, surface area, location, or orientation of the hip joint.[1,2,22,28,29] None of these important parameters can be measured accurately using standard radiography or fluoroscopy. As a result, the alterations that are achieved by surgery have never been quantified, the long-term result of individual patients undergoing osteotomies cannot be predicted, and the theoretical mechanisms of osteotomies cannot be proven.

On the other hand, with the availability of three-dimensional reconstructions from computed tomographic images, changes in the shape, surface area of contact, location, and orientation of the hip joint can be analyzed. Moment arms and lengths of the major muscles acting about the hip can also be measured. These computerized reconstructions may then be used to simulate osteotomies in individuals, to test the theoretical mechanisms of osteotomies, and to quantify the corrections to be achieved by each type of osteotomy. Improvement of long-term results in individual patients may potentially result.

Total joint replacement is another specialty of orthopedic surgery that is particularly well suited for computer-aided analysis. Selection of standard artificial joints for individual patients and the design and manufacture of custom artificial prostheses are the two principal areas of application.

Noncemented implants are being used with increasing frequency and have been demonstrated to have proximal femoral surface strain distributions that are more normal than the strain distribution of cemented implants.[25,26] The accurate preoperative selection of an appropri-

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ate implant is more critical for noncemented than for cemented prostheses. If a noncemented prosthesis is too small, it will have poor implant-bone apposition, resulting in increased micromotion between the implant and bone and accelerated loosening.[5,8,10,14,25,27,31] Conversely, a noncemented implant that is too large by a small amount may result in cortical fracture, a potentially disastrous complication of elective surgery.

The simulation of reamers and rasps and the simulated implantation of prostheses allow for the selection of implants for individual patients. The amount of bone to be removed and the surface area of contact between the prosthesis and the bone can be quantified. The use of these techniques to select standard prostheses preoperatively has the potential both to improve results by improving geometric fit and to reduce complications by reducing the incidence of fractures.

The design and manufacture of custom orthopedic implants has been largely restricted to patients with primary bone neoplasms or unusual deformities. Until recently, these implants have been manufactured from handcrafted wax images, which were designed using hand-drawn blueprints. As a result of the difficulty in designing and manufacturing highly customized implants, surgeons frequently use standard implants and fill bony defects with methyl methacrylate when a custom implant would have been a biomechanically superior choice.[3] Three-dimensional reconstructions of patient anatomy, combined with the computer-aided design and manufacturing techniques, improve both the accuracy and efficiency of custom implant design and manufacture. The availability of such reconstructions provides the surgeon with additional options in the treatment of complex reconstructive problems.

Allograft reconstructive surgery is a third area of orthopedic surgery that potentially benefits from preoperative analysis and simulation. Bone allografts are frequently used in the reconstruction of failed total joint replacements[6,7,12,13] and after tumor resection.[18,19,30] Allograft bone is used more frequently than in the past since this technique offers several advantages over custom implants in selected cases. These advantages include mechanical properties that are more similar to bone than prosthetic materials[4] and the potential for augmentation rather than depletion of existing bone stock. Also, allograft bone is readily available, an important factor in the management of tumors.

Careful sizing and shaping of large allografts may be very time-consuming. This results in prolonged operating and anesthesia time as well as increased blood loss. However, computer-aided preoperative analysis of the anatomy may be used to accurately define the degree of bone deficiency. This information can then be used to generate a plastic model of the region to be reconstructed. This highly accurate template can, in turn, be sterilized and used by the surgeon to prepare the bulk allograft independently of the principal procedure. This approach can save 2 to 3 hours of operating time, potentially reducing morbidity and complications.

This review describes methods for generating and displaying three-dimensional reconstructions to support applications in orthopedic reconstructive surgery. Computer techniques specific to the analysis, simulation, and design of osteotomy, total joint replacement, and allograft reconstructive surgery are described. Clinical examples of each application are demonstrated and discussed.

METHODS

Three-Dimensional Reconstruction and Display

CT Images. The majority of three-dimensional reconstructions of human anatomy are based on CT images. Each CT image is comprised of many rows and columns of small, rectangular bricks called voxels. There are two common methods of generating three-dimensional reconstructions from CT images; one will be referred to as the voxel method, the other as the contour method. Using the contour method, a contour (or outline) of a bone, such as the femur or pelvis, is produced by following the density transition between bone and soft tissue. The contour outlining each bone is calculated on each of the sequential CT images. The three-dimensional model is obtained by stacking up the contours in space according to the longitudinal position of the CT images from which they were derived. This three-dimensional geometric model can be viewed by displaying the model in perspective on a graphics device.

A more realistic three-dimensional presentation is possible if the contours obtained from the different CT slices are connected by triangular tiles (Fig. 1*A*). Using these tiles, the object can be shown as a surface-shaded image.[9] Very lifelike views result (Fig. 1*B*).

The contour representation for objects has some definitive advantages for computer analysis. Precise borders can be defined by inter-

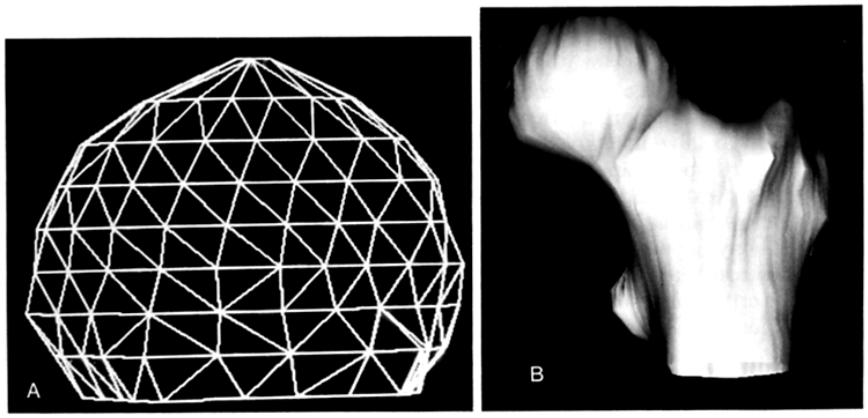

Figure 1. *A*, The contour method creates a series of stacked contours. Points on adjacent contours are linked by triangular surface patches. *B*, Typical bony reconstructions have approximately 10 times the number of surface tiles shown here. The tiled volume may be displayed as a surface-shaded image.

polating between voxels on the same slice. The coarser resolution of CT data along the axial direction can be improved by creating additional contours that are much more closely spaced by interpolating between the CT images. Also, computer-controlled manufacturing machines for making models rely on contour representations.

Each of the above advantages are critical to orthopedic applications. Nevertheless, there are some disadvantages to the contour representation. Branching volumes are difficult to handle, as is the case for the branching of the femoral shaft into the femoral neck and greater trochanter, or the branching of the innominate bone into the pubis and ischium. Furthermore, rotations, intersections, and unions of contour sets require complex software and significant computation time.

Alternate computer representations are possible which handle these problems more easily. Using the voxel method, the set of cubic voxels is used to directly build up the object[15,16,21] (Fig. 2). Voxel representations of bone, for example, are created by identifying the voxels on all CT images that have the density of bone and displaying these voxels in three dimensions. Rotations, intersections, and unions are implemented with simple algorithms. Branching problems are handled easily.

The disadvantage of voxel representations is that they are difficult to edit. For example, metal artifacts are difficult to remove from voxel reconstructions. Furthermore, the separation of different structures with similar density is difficult since the voxel representation considers all objects of the same density as a single structure. For example, since the femur and pelvis are considered as a single structure, they cannot be separated. Therefore, if a surgeon were planning a pelvic osteotomy, it would be difficult to separate the femur from the acetabulum to view the surfaces of the joint, or to display or manipulate the two bones independently. By contrast, the contour representation allows the user to create separate contour sets for each bone. As a

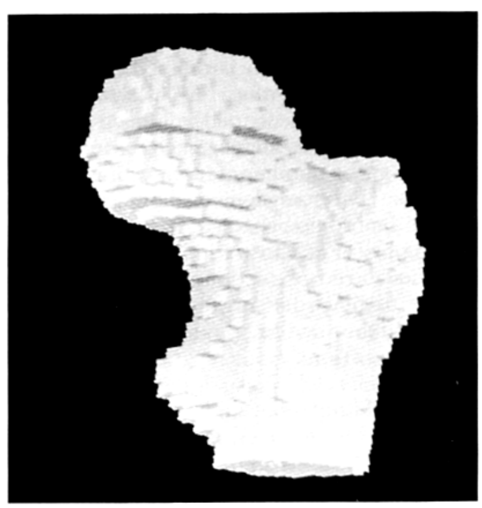

Figure 2. The voxel method of creating three-dimensional images. Note the small rectangular blocks that are used in the reconstruction.

result, all bones may be displayed separately and manipulated independently.

The present work is based primarily on the representation of structures as a set of contours. Although somewhat time-consuming, this method can be used to solve many of the problems presented by orthopedic applications.

Radiographs. The use of standard radiographs is the second principal method of generating reconstructions of bony anatomy. In everyday practice, surgeons use plane radiographs and templates to make critical measurments and decisions such as selecting appropriate implants, planning osteotomies, and measuring leg lengths. Similarly, implant manufacturing companies also use standard radiographs quantitatively for the design of standard and custom artificial joint replacements. However, standard radiographs are not accurate because they do not account for divergence of the x-ray beam, even if radiographic rulers are used. These inaccuracies have become more important with the increasing use of noncemented artificial joint replacements that require a more precise fit than traditional cemented implants.

With the use of computer-aided methods, standard radiographs may be combined to produce accurate, three-dimensional reconstructions of bony anatomy. At least two radiographs are needed[11] and the positions of the source and film for each exposure must be known.

To create the three-dimensional reconstruction of the object, the contour of the object, as it is seen on each of the films, is entered into the computer. Conically shaped volumes are formed by joining the contour points on each radiographic film to the source of the radiation (Fig. 3). The structure is defined in three dimensions by calculating the intersection between the conically shaped volumes. The precision of the three-dimensional reconstruction increases as the number of intersecting volumes increases. Therefore, four or eight radiographs produce a more precise reconstruction than two radiographs[17] (Fig. 4). As with CT images, three-dimensional reconstructions from radiographs may be displayed using either the contour method or the voxel method.

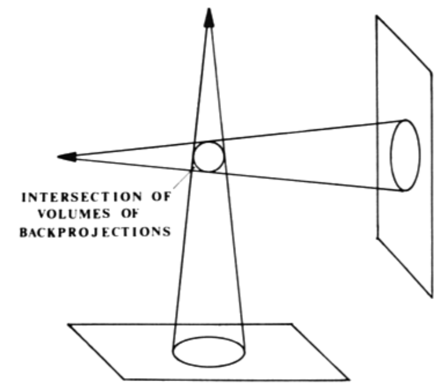

Figure 3. Two orthogonal radiographs may be used to calculate the volume of intersection of two orthogonal backprojections. The object that is visualized on each film lies within the intersection volume. This technique may only be used when specific radiographic markers are used to correlate the two films exactly.

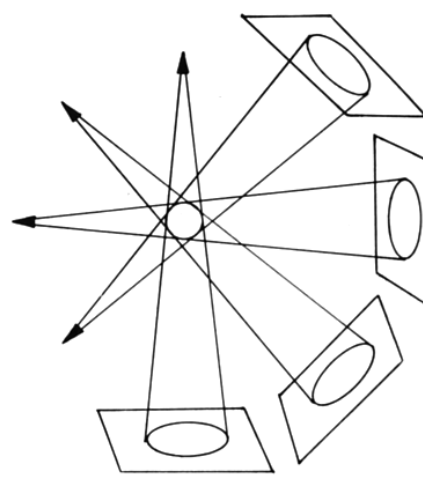

Figure 4. Four or eight radiographs further refine the volume of intersection within which the object lies. With these additional radiographs, the volume of intersection of the backprojections more closely resembles the shape of the original object.

Analysis, Simulation, and Design Based on Three-Dimensional Reconstructions

Three-dimensional reconstructions using CT images or standard radiographs provide the anatomic basis for specific applications in orthopedic surgery. Pelvic and femoral osteotomies, total joint replacement surgery, and allograft reconstructive surgery each require specialized software for analysis, simulation, and design.

Pelvic and Femoral Osteotomies. The CT study of osteotomy patients requires one CT image each through the iliac spines, pubic symphysis, femoral heads, and distal femoral condyles.[20,25] The locations of the iliac spines and pubic symphysis define the pelvic coordinate system so that variations in patient positioning do not influence the analysis. Reference points on the femur are used to define the anteversion plane, the condylar plane, and a femoral coordinate system.

Additional images are generated through the acetabuli and femoral heads. The surfaces of the bone on each of these images is automatically determined using a contour-following algorithm that identifies the interface between bone and soft tissue or cartilage. The parts of these contours that represent subchondral bone are identified and stored as surface points of the acetabulum and femoral head. These points may be used to calculate the average centers of the acetabulum and femoral head. The vector between the two centers quantifies the magnitude and direction of dislocation.

Dividing the acetabular and femoral surfaces into latitudes and longitudes allows for more detailed anatomic analysis. Analysis of the latitude angles around the acetabular rim identifies the location and extent of acetabular deficiency and instability (Fig. 5). Comparison of radii along latitudes and longitudes over the subchondral bone surfaces quantifies the congruity between the acetabulum and femoral head either statically or through a simulated flexion–extension arc. The simulation of varus, valgus, flexion, extension, or rotational osteotomies by modification of the position of the femoral head allows for prediction of the change in congruity as a result of osteotomy. The surgeon can use this information in planning the osteotomy.

Using these techniques for measuring congruity, containment angles, and dislocation vectors, the pre- and postoperative anatomy of osteotomy patients may be quantified, the anatomic correction achievable by each type of osteotomy may be measured, and the mechanisms of osteotomies may eventually be understood.

Total Joint Replacement. The two principal uses of three-dimensional reconstructions for total joint replacement surgery are the selection of the optimum type and size of artificial joint and the custom design of artificial joint replacements.

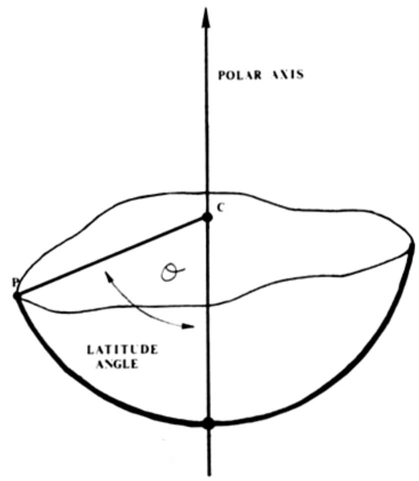

Figure 5. The rim latitude angle for a given longitude is a precise estimate of the peripheral containment of the acetabular rim. The rim latitude angle is the angle between the polar axis (vector normal to the opening plane of the acetabulum) and the vector between the points c, the best fit center of the acetabulum, and p, the point on the acetabular rim.

Implant Selection. Computer-assisted implant selection involves the comparison of the three-dimensional structure of standard artificial joints to that of an individual patient's anatomy. Comparing the patient's anatomy with standard artificial joints requires a library of all types and sizes of standard joint replacements. A library is created by studying and entering into the computer the geometry of one size of each common artificial joint design. Models of all available sizes of each prosthesis design are generated by scaling the implants appropriately. Similarly, if an implant is designed with right and left versions, the contralateral geometry is created simply by transforming the design. This technique produces a large library of standard artificial joint designs for comparison with individual patients. Libraries of reamers and rasps for each implant are created using the same methods (Fig. 6).

A patient referred for preoperative implant selection is studied using a three-dimensional representation of anatomy derived either from multiple radiographs or computer tomography. The method of selecting the appropriate implant closely parallels the method of implant selection

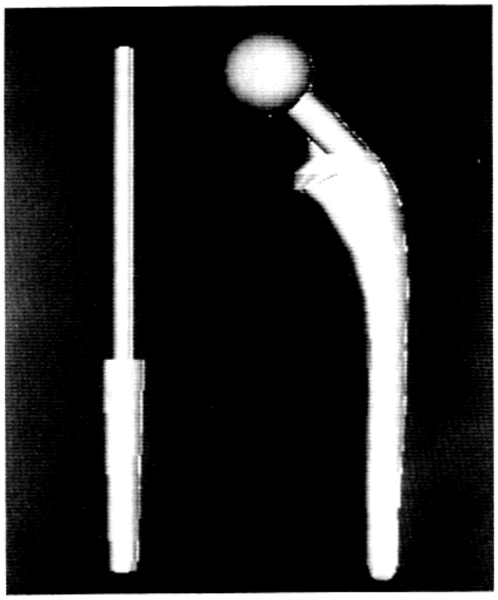

Figure 6. A library of standard implants and their associated instruments may be used to simulate surgery on an individual patient in an effort to select the optimum type and size of artificial joint preoperatively. A standard femoral component and its matching reamer are shown.

in the operating room. The femoral head of the computer model is removed to simulate osteotomy of the femoral neck. The model then is reamed, as would occur at surgery, by inserting the reamer within the canal at the desired depth and positioning the proximal and distal ends of the reamer so that the least volume of cortical bone is removed. Once this position of the reamer is calculated, the geometry of the canal is modified to reflect the areas of bone removed by the reamer.

The geometry of the reamed canal is modified by a rasp, again as would occur at surgery. The simulation of a femoral rasp differs from that of a reamer in that bone is removed only in selected areas. Only cancellous, but not cortical bone is removed. To simulate the effect of a rasp, the computer representation of the rasp is inserted into the femoral model to the desired level and positioned so that there is no intersection between the rasp and the cortical bone. Overlap of cancellous bone is allowed only in the regions where the rasp is designated to cut. If there is more than one solution to these requirements, the rasp is rotated into a position that achieves anatomic anteversion. With the rasp in the selected position, the model of the femoral canal then is modified to reflect the effect of the rasp. This is accomplished by removing the cancellous bone that intersects the geometry of the rasp.

The model of the implant is then inserted into the femoral model, which has been modified by both the reamer and the rasp. The implant is positioned to occupy the same position that the rasp had occupied. With the implant in its final position, the surface area of contact between the implant and the bone may be calculated as a per cent of the surface area of the implant.

Several implantation trials, either using different sizes of the same prosthesis or different prosthesis designs, may be evaluated in the same manner. The surgeon then compares the surface area of contact between the prosthesis and the bone the volume of bone that needs to be removed for each prosthesis when selecting a standard prosthesis for implantation.

Custom Implant Design. Patients who are referred for the design of a custom artificial joint replacement have three-dimensional reconstructions of the involved bones and if present, failed implants and cement fragments. As in the operating room, the failed implants and cement are removed and osteotomies are made. Since most custom implants are modifications of standard designs, the most appropriate standard design is positioned within the bone. The location and volume of gaps between the implant and the bone are identified. With this information, the custom modifications of the standard design are then developed to fill the bony defects. If cement is to be used, and an even cement layer between the implant and the bone is desired, the design is made smaller by moving all points on the surface of the design inward by a distance equal to the desired cement thickness. If long stems are required, the length, diameter, taper, and curvature of the stem and the angle and location of attachment to the standard component are calculated.

Custom implants are manufactured using the same methods as used for standard implants. Femoral condylar knee components, and sometimes femoral hip components, are cast from wax images. Tibial, acetabular, and most femoral hip components are machined from forged blanks using computer-controlled machines.

Since the computer instructions for machining standard components already exist, the manufacture of custom modifications of standard components is based on the computer instructions for that standard component, but altered to reflect the custom modifications of the design. Custom modifications of cast parts, such as the femoral condylar component of total knee designs, are usually manufactured using traditional methods based on the calculated location, angles, and taper of the stems and sizes and locations of the defects.

ALLOGRAFT RECONSTRUCTIVE SURGERY

Adequate preoperative planning of allograft reconstructive surgery requires detailed knowledge of the nature and extent of bone loss. In the reconstruction of the acetabulum after failed total hip replacement, for example, the surgeon should know of the presence and extent of all acetabular defects, especially the presence of defects in the medial or posterior walls of the acetabulum or in the acetabular rim. If this information is available preoperatively, the surgeon may confirm the availability of necessary allografts, hardware, and surgical instruments, and anticipate intraoperative difficulties.

Computer-aided preoperative planning of acetabular allograft reconstructive surgery begins with three-dimensional reconstructions of the acetabular and femoral bone, implants, and cement fragments. The implants and cement are removed from the reconstruction, leaving the deficient bone stock as it will appear at surgery. A standard hemispheric acetabular component is placed within the acetabular model in the anatomic position to simulate the ideal positioning at the completion of surgery. Analysis of the volume, shape, and location of the gaps between the acetabular bone and the acetabular component delineates and quantifies the bone deficiency to be replaced with allograft. The size of available allograft femoral heads, distal femoral condyles, proximal tibia, and acetabuli may be compared to the reconstruction requirements in order to identify and confirm the availability of the allografts to be used.

Plastic models of the acetabular bone that are manufactured based on the three-dimensional reconstruction allow for the preparation of allografts immediately prior to surgery. As a consequence, operating and anesthesia time and blood loss can be reduced.

The manufacture of acetabular models requires specialized machining techniques because standard computer-controlled milling machines are not capable of machining models of such a complex structure. Instead, acetabular models are manufactured by cutting two-dimensional cross-sections of the model using a computer-controlled laser, and then stacking the cross-sections to create the three-dimensional model. However, cutting two-dimensional cross-sections at the levels corresponding to the CT images would result in a coarse model. To improve the resolution of the model, additional intermediate cross-sections that lie between the CT images are calculated.

Thus, preoperative computer-aided techniques may be applied to allograft reconstructive surgery to quantify and characterize bone loss, to identify allografts to reconstruct the defects, and to manufacture bone models to be used as templates for the preoperative preparation of allografts.

CASE EXAMPLES

Case 1: Pelvic Osteotomy

A 4-year-old girl with a lumbar meningiomyeloceole and bilateral congenital hip dislocation underwent closed reduction 3 years prior to this writing and bilateral varus osteotomies 1 year prior to admission. The left hip remained unreduced with progression of a dysplastic acetabulum. A CT study was performed preoperatively and a three-dimensional surface shaded reconstruction was generated (Fig. 7*A*). A plastic model of the preoperative anatomy is shown in Figure 7*B*. Comparison of the average centers of the femoral head and acetabulum revealed a subluxation of 1.3 cm (1.0 cm superiorally, 0.7 cm laterally, 0.5 cm posteriorly). The greatest acetabular deficiency appeared to be superolaterally, where the latitude containment angle was the least at 49.6 degrees (a full hemisphere would be 90 degrees). The acetabulum was quite vertically orientated with an abduction angle of 71.2 degrees from the horizontal.

The patient underwent a Pemberton osteotomy in an effort to improve the containment of the acetabulum, the abduction of the acetabulum, and the reduction of the femoral head. The innominate bone was completely divided proximal to the acetabulum and the distal fragment was rotated about the triradiate cartilage. The fragment was maintained in this position with autogenous cortical–cancellous grafts from the ipsilateral ilium.

A three-dimensional, postoperative reconstruction of the hip is shown in Figure 7*C*. Analysis of the data demonstrated that the rotation of the distal innominate fragment about the triradiate cartilage accomplished several goals. First, the center of the acetabulum was moved inferomedially. Second, the center of the fem-

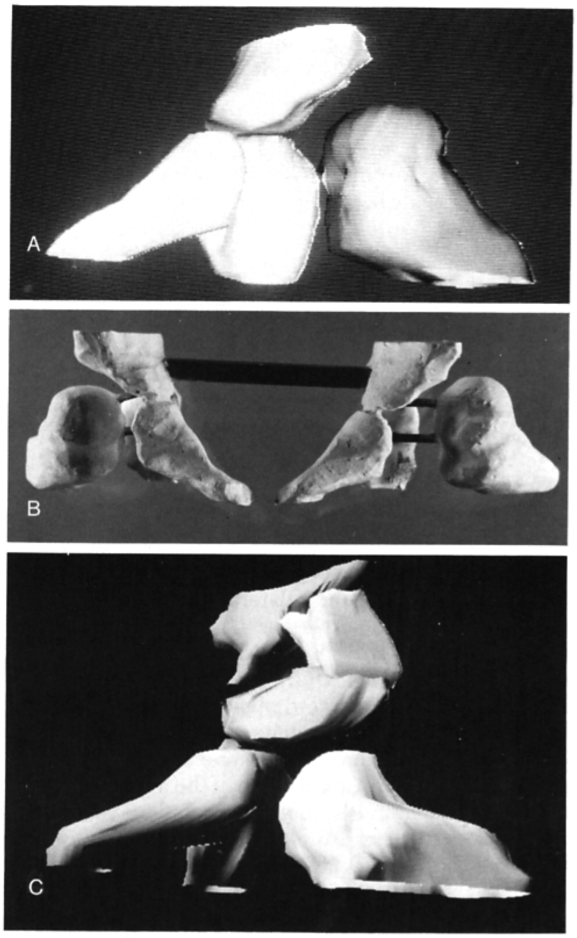

Figure 7. *A*, Three-dimensional reconstruction of the left hemipelvis and femoral head of a 4-year-old girl. Note that the femoral head (right) is subluxed laterally and superiorly and that the acetabular roof (left top) does not contain the femoral head. *B*, A plastic model of the bony anatomy depicting the same abnormalities. *C*, Three-dimensional reconstruction of the same 4-year-old girl immediately following a Pemberton osteotomy. The autogenous bone grafts (white) are shown in the osteotomy site between the proximal and distal ilium (gray). Note that the lateral extreme of the acetabular roof is better able to contain the femoral head and that the femoral head is better reduced.

oral head was also moved inferomedially. This change in location of the femoral head resulted in improved reduction, with the distance between the average centers of the femoral head and acetabulum reduced from 1.3 cm to 0.4 cm. Third, the peripheral containment of the superolateral acetabular rim was improved from 49.6 to 69.6 degrees. Finally, the acetabular abduction angle was reduced from 71.2 to 57.0 degrees.

Case 2: Implant Selection

A 28-year-old woman with left congenital hip dislocation presented with progressive pain, limb length discrepancy, and limitation of motion. The surgeon selected standard noncemented total joint replacement as the treatment of choice. He sought to achieve a press-fit between the implant and the bone to obtain initial implant stability and maximal bone contact. Since the patient was small and with comparatively thick femoral cortical bone, there was a concern that noncemented total hip replacement might be complicated by a femoral fracture. The surgeon wanted to know exactly what size and type of implant should be used and exactly how much cortical bone should have to be reamed to implant the prosthesis.

The patient was studied using CT. From these data, a three-dimensional reconstruction of the left femur and hemipelvis was generated (Fig. 8*A*). Noncemented implants were selected for comparison and three-dimensional reconstructions of each, contained in a computer library,

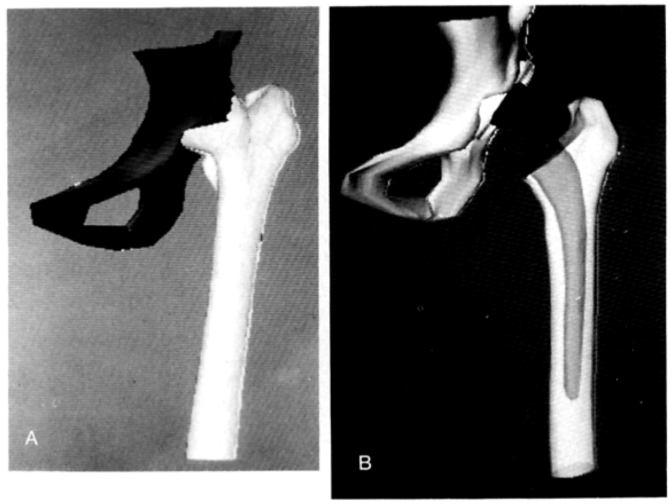

Figure 8. *A* and *B*, Preoperative three-dimensional computer reconstructions of the left hip of a 28-year-old woman with congenital dislocation of the hip. Note the superolaterally subluxed femoral head and the superolateral osteophytes on the acetabular rim overlying the femoral head. Figure 8*B* is a computer-aided simulation of the surgical result following the total hip replacement. This simulation required osteotomy of the femoral neck, abduction and distal translation of the femur, reaming and rasping of the femoral canal, and implantation of the prosthesis. Similarly, the acetabulum was reamed, the osteophytes were removed, and the acetabular cup was implanted. The femoral bone is displayed translucently so that the implant also may be seen.

were considered for implantation. The initial femoral geometry was modified with the reamer and rasp that matched the implant was inserted into the femoral canal. After analysis of four implants, the implant type and size, which required approximately 1 mm of cortical reaming of the femoral diaphysis and which afforded a maximum of bone contact (76 per cent of the implant surface area), was selected for implantation.

Using computer simulation techniques, the surgically prepared femoral model was translated inferiorally and abducted. The selected standard noncemented femoral and acetabular components were placed in their anatomic positions and acetabular osteophytes were removed. An entirely computer-simulated postoperative result was developed (Fig. 8*B*). The patient underwent the procedure and the implant that was selected preoperatively was press-fit into the medullary canal as planned.

Case 3: Custom Implant Design

A 59-year-old woman with rheumatoid arthritis of the right knee who underwent total knee arthroplasty 5 years prior to admission presented with gross loosening of the tibial component, loss of bone on the medial tibial plateau, and a varus deformity (Fig. 9*A*). The surgeon selected custom artificial knee replacement as the treatment of choice.

A three-dimensional model of the distal femur and proximal tibia was created and the volume of bone loss between a standard artificial knee replacement and the remaining bone was determined. The standard artificial knee design was augmented by adding metal to the medial tibial plateau to replace the area of bone loss. In addition, the location of attachment, diameter, and angle of a long stem was calculated. The tibial component design that was developed using the computer-aided design and manufacturing system (Fig. 9*B*) was machined using computer-controlled milling machines.

The patient was taken to the operating room and the knee was exposed to reveal the bony defects that were predicted. The custom knee prosthesis was implanted as planned preoperatively (Fig. 9*C*).

Case 4: Allograft Reconstructive Surgery

A 53-year-old woman with a history of congenital dislocation of both hips underwent open reduction bilaterally at the age of 2, had a right-cemented total hip replacement 13 years prior to this writing, and had a left cemented total hip replacement 12 years prior to admission. Over the past several years, the left acetabulum had progressively loosened at both the bone-cement and the cement-polyethylene interfaces, and the acetabular bone had undergone significant bone lysis. Recent radiographs demonstrated protrusion of the medial wall of the acetabulum, marked migration, and complete inversion of the

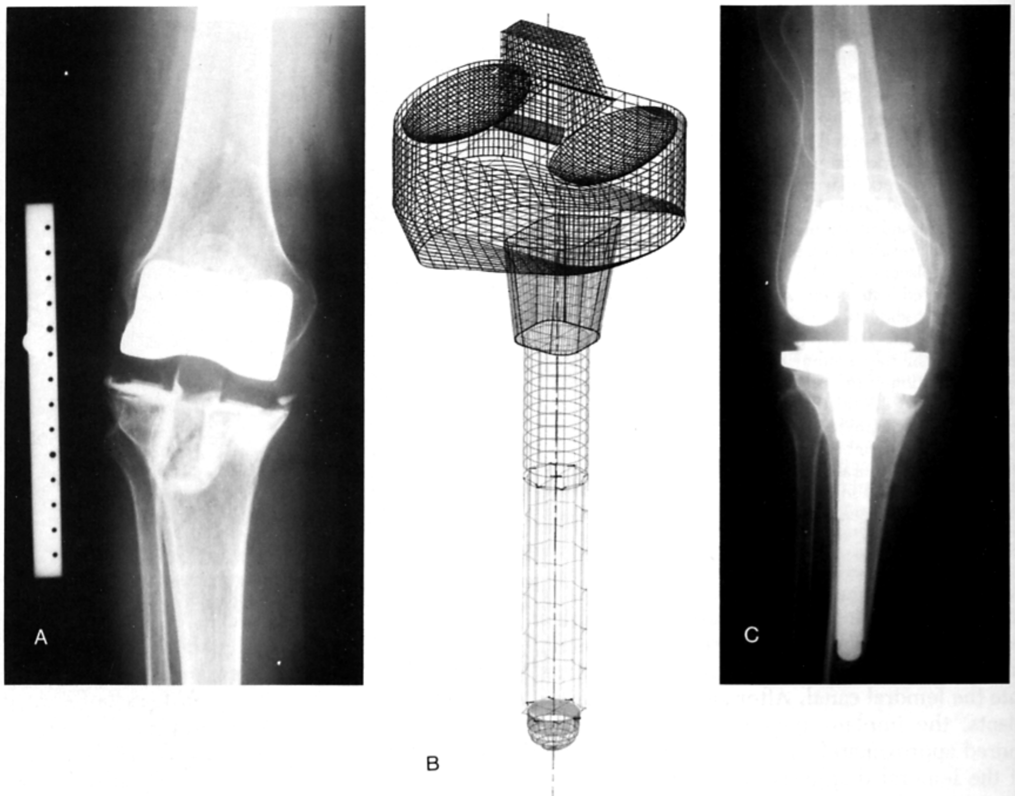

Figure 9. *A,* Preoperative radiograph of the patient in case 3 demonstrates a grossly loose polyethylene tibial component that has subsided on the medial tibial plateau, leaving the patient with a varus deformity and bone stock loss. *B,* A wire frame model of a custom tibial component designed with a long fluted stem and metal augmentation of the medial tibial plateau. *C,* A postoperative radiograph of the same patient after implantation of the prosthesis.

acetabular component. The prosthetic femoral head articulated directly with the ilium in the proximal acetabular cavity (Fig. 10*A*).

Three-dimensional reconstructions of the acetabular bone, bone cement fragments, polyethylene cup, metal femoral component, and femoral bone clearly demonstrated the inverted acetabular component and medial acetabular protrusion (Fig. 10*B*). Extensive bone stock deficiencies were quantified after the cement fragments and prosthetic components were removed from the computer reconstruction (Fig. 10*C*). The models also demonstrated the extremely thin posterior rim of the acetabulum, as well as the absent medial wall. The central acetabular defect measured 6.5 × 7.0 × 5.3 cm. An allograft of large distal femoral condyles was found that would appropriately fill this defect. Similarly, smaller defects in the pubic and ischial rami were identified that would be adequately reconstructed with a combination of femoral head allografts and autografts from the ilium.

The condylar and femoral head allografts were thawed and sculpted to fit the larger bony defects that were predicted based on the computer reconstruction and demonstrated at the time of surgery. The femoral condylar graft was secured to the ilium using screws and then the noncemented acetabular component was screwed into place to complete the reconstruction (Fig. 10*D*). Postoperatively, the patient did well and was discharged on the eighth postoperative day.

DISCUSSION

Three-dimensional reconstructions of bony anatomy provide the basis for a wide range of

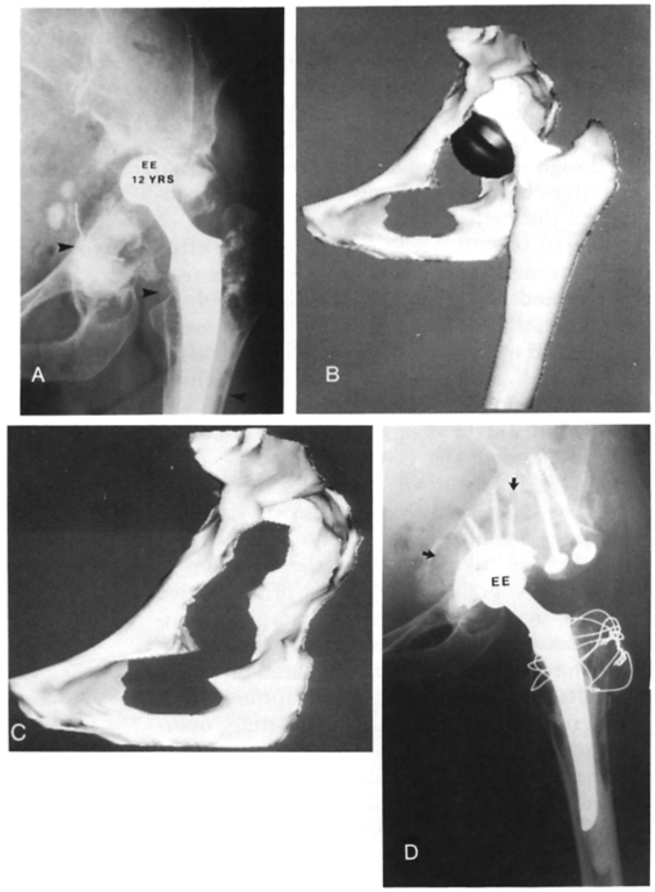

Figure 10. *A*, Preoperative radiograph of a 53-year-old woman 12 years after left total hip replacement. The acetabular cup is grossly loose and inverted (wire markers), there is a defect in the medial acetabular wall, and the prosthetic femoral head is articulating with iliac bone. Standard radiographs and fluoroscopy are unable to quantify the extent of the bone loss accurately and cannot be used for precise preoperative planning. *B*, Left anterior oblique view of a three-dimensional computer-aided reconstruction of the left hip of the same 53-year-old woman based on CT images. The large cement fragments have been removed from the reconstruction to reveal a very large defect in the medial acetabular wall. Although the polyethylene cup (black) is radiolucent and cannot be contoured based on density, the cup was generated by computer using knowledge of the center, inside diameter, outside diameter, and anteversion and abduction angles. *C*, Three-dimensional reconstruction of the distal hemipelvis after the femur, prosthetic components, and cement fragments are removed to reveal the bone stock that will present to the surgeon at the time of surgery. In addition to the large medial wall defect, note that both the anterior (left) and posterior columns are extremely thin. *D*, Postoperative radiograph of the left hemipelvis and femur after allograft reconstruction and acetabular revision. Arrows denote the extent of the allograft bone. The center of the hip joint is still medial to the original anatomic position. Further lateralization could be achieved using an allograft acetabulum.

research and clinical applications in orthopedic surgery. Applications of three-dimensional reconstructions to surgery require the reconstruction of bones as separate geometric models. Bones can be displayed, translated, or rotated individually or together. Colors or shades of grey can be used to distinguish the individual parts from one another.

In osteotomy surgery, computer models of the acetabulum and femoral head allow the parts to be displayed separately. This enables the surgeon to see the surfaces of the joint and enables the computer to quantify acetabular anteversion and abduction angles, latitude angles on the acetabular rim, and congruity. Proposed femoral and pelvic osteotomies may be simulated and analyzed preoperatively, both statically and dynamically, over a flexion–extension arc. The separate femoral model may be rotated and translated within the acetabulum. Analysis of separate reconstructions of the acetabular and femoral joint surfaces of patients, both pre- and postoperatively, may provide the information to test the relative importance of changes in congruity, surface area of contact, and total joint reaction force on the success or failure of osteotomies.

The movement of separate geometric models relative to one another has many applications in joint replacement surgery as well. The movement of reamers and rasps within the femoral canal, for example, are used to simulate the preparation of the femur at surgery. The relative movement of standard joint replacements within bony parts allows for the selection of the standard joint replacement that will maximize implant–bone apposition. If custom implants are required, the location and volume of gaps between the remaining bone and an ideally positioned standard implant quantifies the areas of a standard design that require augmentation. The design information can be used to program computer-controlled milling machines to manufacture the custom joint.

Allograft reconstructive procedures are often time-consuming operations. Allografts are usually selected and prepared intraoperatively at the midpoint of the operation, when the rate of blood loss is at a peak. Preoperative reconstructions of each geometric part produces realistic three-dimensional images of the bone and any existing prosthetic components and bone cement fragments. The geometric models of the implants and cement will appear for reconstruction at the time of the operation. Analysis of the location and volume of the bone loss provides the necessary information for the selection of allografts preoperatively. Models of the native anatomy manufactured using computer-controlled lasers may be sterilized and used as templates for the preoperative preparation of the allografts. The appropriate use of sterile models preoperatively reduces anaesthesia time, operating time, and blood loss.

The computer-aided analysis, simulation, and design to osteotomy, total joint replacement, and allograft reconstructive surgery based on three-dimensional reconstructions are similar. In all three areas, computer-reconstructed models allow the surgeon to view the bony anatomy and to simulate the proposed procedure prior to entering the operating room. In selected cases, this preoperative analysis has the potential to improve long- and short-term results and to decrease operating time, complications, and morbidity.

SUMMARY

Three-dimensional computer reconstructions of bony anatomy based on computed tomographic images and radiographs may be used to analyze, simulate, and design certain orthopedic procedures. In osteotomy surgery, the computer-reconstructed models may be used to measure critical angles, surface area, and congruity of the joint surfaces. Computer reconstructions may be used in total joint replacement surgery to simulate the effect of surgical reamers and rasps, to select the geometrically optimum standard implant, or to design a custom implant. In allograft reconstructive surgery, computer reconstructions may be used to measure bony defects and to identify the appropriate allografts for the reconstruction. Plastic models may be sterilized and used as templates to sculpt the allografts immediately preoperatively. In all three applications in orthopedic surgery, three-dimensional, computer-aided reconstructions have the potential to improve results and reduce morbidity.

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