Proceedings of the 1994 Winter Simulation Conference
ed. J. D. Tew, S. Manivannan, D. A. Sadowski, and A. F. Seila

FINITE ELEMENT PRE-OPERATIVE SIMULATION OF CEMENTLESS HIP REPLACEMENT

Christopher D.Visnic
Robert H. Reid
Omar Ghattas

Computational Mechanics Lab
Carnegie Mellon University
Pittsburgh, PA 15213

Anthony M. DiGioia III
Branislav Jaramaz

Center for Orthopaedic Research
Shadyside Medical Center
Pittsburgh, PA 15232

ABSTRACT

Cementless hip replacement surgery requires increased precision of the bone preparation and appropriate biomechanical feedback to avoid problems of implant instability and bone damage. This paper presents finite element simulations of both femoral and acetabular cementless components. The models focus on the simulation of replacement surgery and its biomechanical consequences. Geometries of the femur and the acetabulum are idealized axisymmetric, but the model includes nonlinearities associated with material law and contact coupling. Results of our studies show that the assembly strains resulting from the press fit procedure must not be ignored.

KEYWORDS: modeling, medicine, implant, orthopaedic biomechanics, finite element

1 INTRODUCTION

Total hip replacement is now one of the most common and successful orthopaedic procedures. Osteoarthritis is the most common cause of hip replacement and the frequency is expected to increase as the population ages. The typical patient is older than the general population, but there are numerous young recipients as well.

Two components are used for a total hip replacement. The acetabular component is a hemispherical cup placed into the pelvis. The femoral component replaces the neck and head of the femur and is inserted into the medullary canal. Either may be cemented or press fit in place.

The long term clinical success of cementless hip implants depends upon bone growing into the porous surface of the implant. Achieving adequate ingrowth requires both implant stability and intimate bone contact with the implant surface. These important prerequisites may be achieved by press fitting an oversized porous implant into the prepared bony cavity.

The press fit procedure generates assembly stresses in the surrounding region of the bone. Assembly stresses occur during implantation, before the application of external loads. The magnitudes of the assembly stresses are sometimes large enough to compromise the integrity of bone. This is apparent when bone fractures occur during the insertion of excessively oversized implants. At the same time, the assembly stresses help to stabilize the implant, and to stimulate bone growth. Without stimulation, bone can recede and loose its structural strength, becoming prone to failure. It is therefore important to identify the interface between the implant and bone, to locate areas of contact and gaps between the two surfaces, and to understand resulting load transfer mechanisms that can affect bone ingrowth.

Previous finite element models neglected the press fit procedure in total hip arthroplasty, ignoring the consequences of assembly stresses. We developed nonlinear, contact coupled axisymmetric finite element models of both the acetabulum and femur and their respective implants to examine mechanical consequences of press fitting. To reduce the level of complexity, both models are idealized as axisymmetric. The models, however, preserve other aspects of natural complexity, including large deformations, large strain, nonlinear material behavior, and general contact coupling between the implant and bone. The models were parametrically defined to study the effects of different sizes of implants and bone diameters. The results of the two-dimensional axisymmetric models may also provide important information that can be applied to clinical techniques for ensuring implant stability and intimate bone contact with the porous implant surface.

2 METHODOLOGY

Acetabulum

The parametric design of our finite element model allowed the study of several different acetabular diameters with varied implant oversizing. The acetabular diameters examined were 40mm, 50mm and 60mm. Three different implant oversizing of 1mm, 2mm and 4mm were considered for each bone diameter. The mesh was comprised of approximately 1000 quadrilateral finite elements and 400 contact elements, varying depending on the model geometry. The nonlinear material behavior of bone was modeled using bilinear-kinematic hardening. In addition, all models permitted large displacements and large strains.

The material constants of the implant were the same for all models. The acetabular cup was modeled after HGP II implant with a titanium shell (E=110.0 GPa, ν=0.3) covered by a titanium mesh (E=55.0 GPa, ν=0.3). The acetabulum was modeled using elastic-perfectly plastic properties for cortical, cancellous, and subchondral bone, with elastic moduli of 16.0GPa, 1.0GPa, and 0.05GPa for cortical (Hayes and Mow 1991), subchondral and cancellous (Dalstra, Huiskes and Odgaard 1993), respectively. Poisson's ratio was 0.3 for all bone materials.

The press fit procedure is simulated in three phases. In the first phase, the implant was gradually displaced into the acetabular cavity by a series of displacements applied on its inner surface. This procedure mimics a clinical one, in which the implant is forced into the acetabular bed. Further displacement of the implant is stopped when the reaction forces begin to grow rapidly with very little additional displacement of the implant (around 1% of initial displacement step). In the second phase the applied displacements are gradually released. In order to have a controlled and gradual process, the displacements applied at the implant's surface are replaced with the equivalent forces. These forces are then gradually released within several load steps. At the end of this phase, which corresponds to the end of replacement surgery, the model is free of any outside loads, and the implant is held in its position only by the friction forces. In the final phase, the loads equivalent to external joint loads are applied. Three joint loads of increasing magnitude were successively applied to the implant approximately one-third the arc length distance from the polar axis of the implant. The press fitting analysis is performed by using contact elements along the periphery of the implant and the inner lining of the acetabulum. The coefficient of friction used in all three cases is 0.48 (Rancourt, Shirazi-Adl and Drouin 1990).

Femur

A parametric model of the femur was generated in order to study the effects of press fitting femoral implants. The bone geometry was obtained using scan data from an actual patient. The femur was modeled from just above the condyles to the distal portion of the lesser trochanter, that is, all of the femur which could reasonably be considered axisymmetric. Cortical bone was modeled as an anisotropic material with longitudinal stiffness of E = 16 GPa. Both radial and circumferential stiffness were E=10 GPa. The cortical bone was modeled as elastic-perfectly plastic with a yield stress of 60 MPa. This strength, although considerably lower than the longitudinal compressive strength, was based on the radial and circumferential tensile strengths, since femoral assembly strains are primarily circumferential tension. The geometry considered includes only a minimal amount of cancellous bone, particularly in the region of interest. The material properties used for the cancellous bone were E=500 MPa and yield stress σy=15 MPa. Cobalt-chrome AML (DePuy, Warsaw IN) implants were used. The implant was modeled using E=220 GPa for the base metal and E=101 GPa for the porous coating. For the patient considered, a 15mm implant was used with a 0.50mm press fit. To analyze the effects of press fitting, analyses were performed using 0.25, 0.50, and 0.60mm press fits and 13.5, 15.0, and 16.5mm implants. Full frictional contact was used between the bone and the implant with μ=0.5. The press fit was simulated simply by modeling the bone to have an inside diameter smaller than the implant.

The press fitting was simulated by imposing displacements on the proximal end of the implant. Figure 2a shows the implant in its initial position, just before the porous coating contacts the bone. The final position of the implant is shown in Figure 2c and an intermediate position in Figure 2b. Once the implant was in its final place, the displacement constraints used for insertion were replaced with

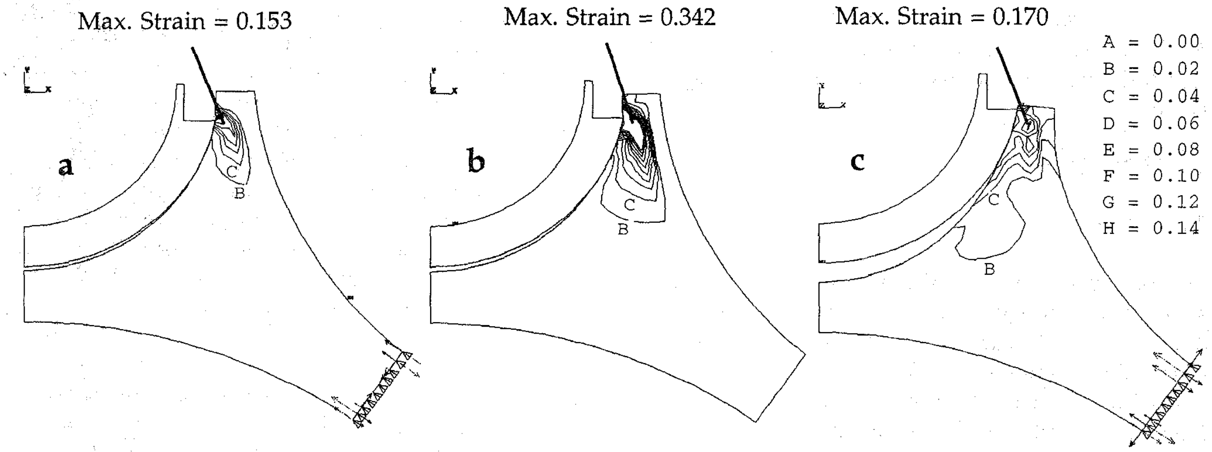

Figure 1: Total Equivalent Strain for the Acetabulum 50mm in Diameter and Implant Sizes of a) 51mm, b) 52mm and c) 54mm

equivalent forces. These forces were then removed, leaving the implant to be stabilized only by frictional contact with the bone. Joint loads were not considered for the femur, since none could be realistically modeled as axisymmetric.

3 RESULTS

Acetabulum

The press fit models show the existence of gaps in the polar region of the acetabulum, ranging from 0.4 to 2.6mm. Possible clinical consequence of such gaps is a lack of bone ingrowth at the implant/bone interface. The bone is stress free at the areas where the gaps exist, therefore, the bone is not stimulated to grow and may resorb. Another consequence is possible collection of wear debris in the void area, which reduces the interfacial stability. The debris reduces the lifespan of the implant by inducing bone disease osteolysis (Jasty 1993).

The assembly strains found in the press fit models were large enough to cause large yielding of cancellous bone and some fracture in the cortical bone located at the periphery of the acetabulum. The contact and consequently the load transfer zone in all the press fit models occurred at the distal periphery of the acetabulum. Resulting strains depend on the bone diameter and implant oversizing, but the relation is highly nonlinear. Figure 1. illustrates the effects of assembly strains for the acetabulum of 50mm in diameter and the implants oversized 1, 2 and 4 mm across the diameter.

Our results were contrasted with experiments on cadavers performed by Brown et al. (1994). The polar gap distances compared well with Brown's experimental acetabular press fit results, however, the reaction forces were higher in the computational analyses. They reported the implantation force in order of 2 to 3KN. Repeated simulations were performed to take into account the effect of a canal in the notch of the acetabulum, known as acetabular fossa. The material properties of the peripheral region of the acetabulum are lowered to compensate for the effect of discontinuity in circumferential direction. The implantation forces were reduced to 0.9kN to 1.9KN, closer to experimental results.

Femur

The femoral analyses clearly indicate that assembly strains are a critical concern for press fit implants. The strains in the cortical bone were well above yielding and approached failure in several cases, particularly in the region adjacent to the distal end of the porous coating of the implant. The cancellous bone in the proximal region of the bone was completely yielded, probably indicating local failure during insertion of the implant (Figure 2d). Another important consideration is that the assembly strains are primarily hoop tension, different in orientation than typical loads on the femur. These analyses show that cracking could occur during implantation, a consideration confirmed by clinical studies as well (Jasty et al. 1993).

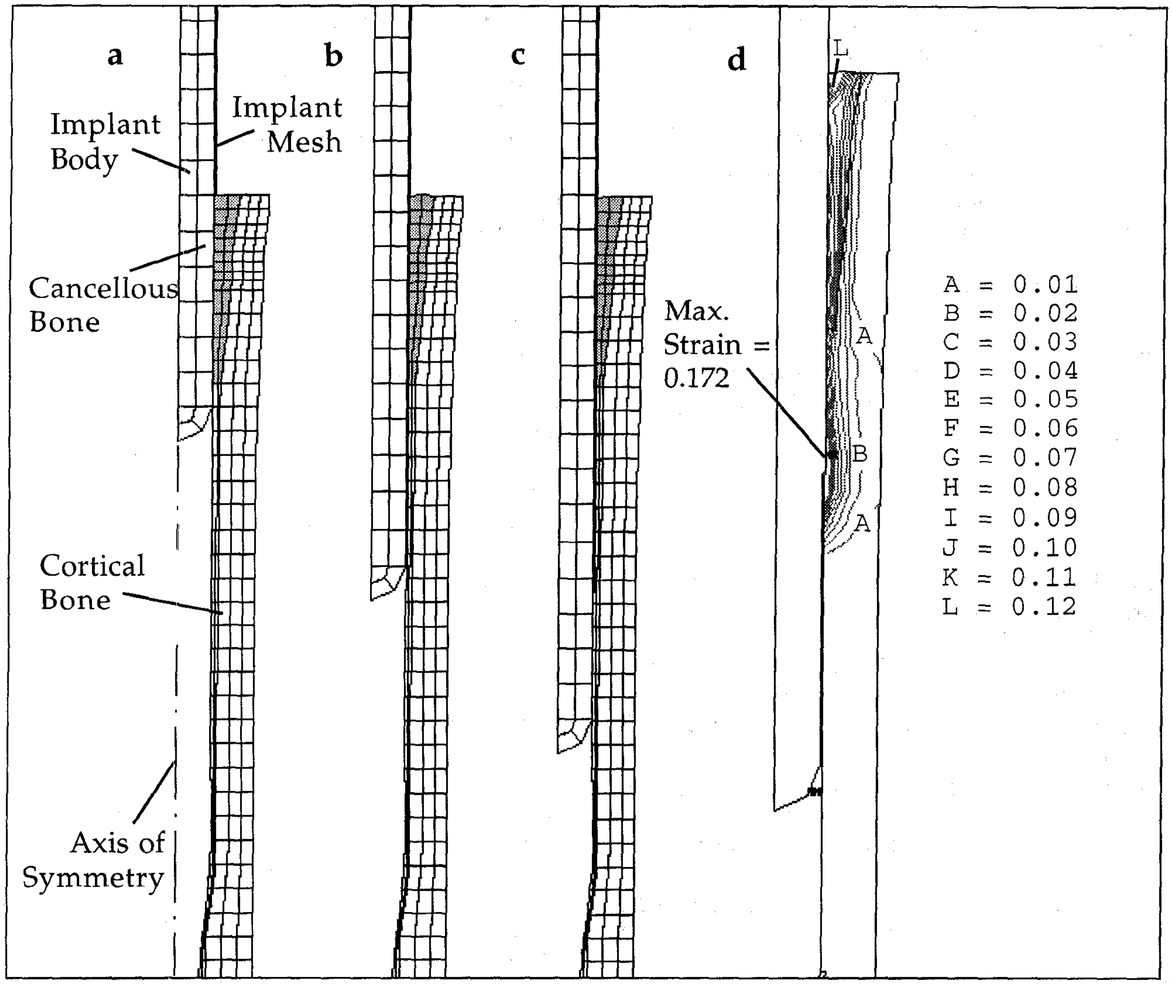

Figure 2: Simulation of Femoral Implant: Characteristic Implantation Steps (a, b, c) and Resulting Equivalent Strains in Bone (d)

Previous finite element models of press fit femoral implants have neglected the geometric interference inherent to the press fitting process. These studies show that including all phenomena associated with press fitting is essential to accurately predicting the true state of strain in the bone. Also, the large assembly strains associated with press fitting must be considered in order to accurately predict subsequent bone remodeling which would determine the long term stability of the implant.

4 CONCLUSION

These axisymmetric models of cementless hip implants are the first step toward full three dimensional contact coupled models. Important biomechanical information was obtained through the parametric study of assembly strains as a function of the implant size and amount of press fit. To simulate the implantation procedure, a large displacement models for both acetabulum and femur with respective implants, with frictional contact coupling and nonlinear material properties were developed. The problems were simulated through incremental procedure, in which the implant is gradually driven toward its planned position in the bone. The results of both analyses show the presence of large assembly strains. Such findings have important clinical consequences. A better understanding of these biomechanical processes will allow physicians and engineers to modify and improve clinical procedures. The importance of analyzing the press fit procedure is amplified in light of future robotic surgery with greater precision of implemented bone cuts. The future integration of advanced finite element models and robotic surgery could provide superior accuracy in total hip arthroplasty and ultimately increase the effective lifespan of acetabular components.

ACKNOWLEDGMENTS

This work was partially supported by the Competitive Research Fund at Shadyside Hospital and the Albert B. Ferguson Jr. Orthopaedic Research Foundation.

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AUTHOR BIOGRAPHIES

CHRISTOPHER D. VISNIC obtained his B.S. in 1992 in Civil Engineering and his M.S. in 1994 in computational mechanics, both from Carnegie Mellon University. He is continuing his research at the Center for Orthopaedic Research, Shadyside Medical Center while preparing for medical school.

ROBERT H. REID received his B.S. in Civil Engineering from University of Pittsburgh, and his M.S. from Illinois Institute of Technology. He is a Ph.D. candidate in computational mechanics from Carnegie Mellon University.

OMAR GHATTAS received his B.S.E. (1984), M.S. (1986) and Ph.D. (1988) in mechanics from Duke University. He is an Associate Professor of Civil Engineering and Associate Director of the Computational Mechanics Laboratory at Carnegie Mellon University. His research interests include Computational Solid and Fluid Mechanics, Design Optimization, Computational Mathematics and Scientific Computing.

ANTHONY M. DIGIOIA III earned his M.D. degree from Harvard Medical School in 1986. He completed his medical training in Orthopaedic Surgery at the University of Pittsburgh Medical Center from 1986 to 1991, and a fellowship in Adult Reconstructive Surgery at Massachusetts General Hospital in 1992. Dr. DiGioia is currently the Director of the Center for Orthopaedic Research at the Shadyside Medical Center and a practicing orthopaedic surgeon. He also serves as co-director for the Center for Medical Robotics and Computer Assisted Surgery within the Robotics Institute at Carnegie Mellon University.

BRANISLAV JARAMAZ received his Dipl. Ing. in Civil Engineering (1979) from the University of Split and a M.S. in Computational Mechanics (1987) from the University of Zagreb, Croatia. He obtained his Ph.D. degree in civil engineering/computational mechanics from Carnegie Mellon University in 1992. Dr. Jaramaz currently works at the Center for Orthopaedic Research, Shadyside Medical Center and is a Visiting Scientist at Carnegie Mellon University's Robotics Institute.