The initial stability and contact mechanics of a press-fit resurfacing arthroplasty of the hip

I. Udofia,
F. Liu,
Z. Jin,
P. Roberts,
P. Grigoris

From University of
Leeds, Leeds,
England

Finite element analysis was used to examine the initial stability after hip resurfacing and the effect of the procedure on the contact mechanics at the articulating surfaces. Models were created with the components positioned anatomically and loaded physiologically through major muscle forces. Total micromovement of less than 10 μm was predicted for the press-fit acetabular components models, much below the 50 μm limit required to encourage osseointegration. Relatively high compressive acetabular and contact stresses were observed in these models. The press-fit procedure showed a moderate influence on the contact mechanics at the bearing surfaces, but produced marked deformation of the acetabular components. No edge contact was predicted for the acetabular components studied.

It is concluded that the frictional compressive stresses generated by the 1 mm to 2 mm interference-fit acetabular components, together with the minimal micromovement, would provide adequate stability for the implant, at least in the immediate post-operative situation.

Resurfacing arthroplasty of the hip is becoming increasingly popular for young patients, who may require a second procedure in their lifetime.¹⁻⁴ It is a conservative operation that allows preservation of bone, particularly in the proximal femur, thereby facilitating revision should it be required. Resurfacing arthroplasties have a large bearing size, similar to the natural geometry of the hip, which helps maintain stability and a normal range of movement with a reduced risk of dislocation and impingement.^{5,6} Various metal-on-metal hip resurfacing designs are commercially available and recent short- and medium-term clinical results have been promising.^{2,3,7-11}

All contemporary metal-on-metal hip resurfacing designs use a cementless acetabular component. Primary stability is essential for secondary fixation through bone ingrowth. Initial stability can be influenced by the method of fixation (press-fit or adjunctive), the surgical technique, the quantity and quality of the bone, component geometry and loading conditions.¹² Press-fit fixation involves inserting an acetabular component into an under-reamed acetabulum, where the primary stability is achieved through the frictional compressive forces generated about the acetabular periphery.¹³⁻²⁰ Increasing the degree of interference should result in increased stability through a

reduction in the relative movement between the component and the bone.^{16,20,21} Most acetabular components are implanted with a diametral interference ranging between 1 mm and 2 mm,^{2,22-24} whereas interference values up to or beyond 4 mm require excessive reaming and could cause fracture.²⁵ In contrast, a line-to-line fit (zero interference) could result in excessive movement between the component and bone, and may require some form of adjunctive fixation.

The aim of this study was to examine the stability of press-fit hip resurfacing acetabular components using the finite element method. Also, given that the interactions at the interface between the acetabular component and the bone could potentially affect the tribology of the bearing,²⁶⁻²⁸ the effects of the press-fit procedure on the contact mechanics at the articulating surfaces were also investigated.

Materials and Methods

A conceptual design of a typical commercially-available metal-on-metal hip resurfacing arthroplasty (Durom, Zimmer GmbH, Winterthur, Switzerland) was examined (Fig. 1). The acetabular component had a nominal inner bearing diameter of 50.145 mm and a uniform thickness of 4 mm. Fixation was by press-fit insertion. A 50 mm femoral head component

■ I. Udofia, PhD, Research Fellow
■ F. Liu, PhD, Research Fellow
■ Z. Jin, PhD, Professor of Computational Bioengineering Institute of Medical and Biological Engineering, School of Mechanical Engineering University of Leeds, Woodhouse Lane, Leeds LS2 9JT, UK.

■ P. Roberts, MA(Oxon), MB, FRCS, Consultant Orthopaedic Surgeon Royal Gwent Hospital, Cardiff Road, Newport NP20 2UB, UK.

■ P. Grigoris, MD, PhD, FRCS, Visiting Professor, Consultant Orthopaedic Surgeon School of Engineering, Design and Technology University of Bradford, Richmond Road, Bradford BD7 1DP, UK.

Correspondence should be sent to Dr I. Udofia; e-mail: i.j.udofia@leeds.ac.uk

©2007 British Editorial Society of Bone and Joint Surgery
doi:10.1302/0301-620X.89B4.18055 \$2.00

J Bone Joint Surg [Br]
2007;89-B:549-56.

Received 27 April 2006;
Accepted after revision 1 November 2006

Fig. 1a

Fig. 1b

Photograph of a) the Durom hip resurfacing prosthesis (Zimmer GmbH, Winterthur, Switzerland) and b) a diagram of the three-dimensional finite-element bone model of the hip joint.

Fig. 2a

Fig. 2b

The finite-element bone model showing a) the loading conditions and boundary constraints and b) the implantation angles (45° inclination and 10° anteversion).

was used, with a resulting diametrical clearance between the acetabular component and the femoral head of 145 μm . The femoral component was fixed into the femur with acrylic cement with the thickness ranging approximately between 1 mm and 1.5 mm. The short tapered stem provided the only alignment for the femoral component.

Three-dimensional solid models of the arthroplasty were created and implanted into solid models of the hemipelvis

and femoral bone obtained from the visible human project.^{29,30} The solid models were meshed in I-DEAS (Version 11, UGS PLM Solutions Inc., Plano, Texas). The resulting finite-element models (Fig. 2) were then solved using ABAQUS (version 6.5-1, ABAQUS Inc., Providence, Rhode Island).

The components were made of cobalt chromium alloy with an elastic modulus of 220 GPa and Poisson's ratio of

0.3. All the materials in the finite-element model were assumed to be homogeneous and linear elastic.³¹⁻³⁵ The elastic modulus and Poisson's ratio for the cortical bone were 17 GPa and 0.3, respectively.³⁶ The elastic modulus in the cancellous bone of the pelvis and femur was assumed to be 0.5 GPa and 1.5 GPa, respectively, with a Poisson's ratio of 0.3.³⁶ The cement mantle had an elastic modulus of 2.5 GPa and a Poisson's ratio of 0.25.³⁶

The pelvic model consisted of cancellous bone by a uniform cortical shell 1.5 mm thick. The subchondral acetabular bone was assumed to have been reamed completely prior to implantation. The acetabular component was positioned anatomically in 45° of abduction and 10° anteversion (Fig. 2). The contact interface between the outer surface of the component and the acetabulum was modelled using surface-based contact elements with an applied friction coefficient of 0.5.^{34,37,38}

During surgery, seating the cementless acetabular component involves impacting it into an under-reamed acetabulum. This impaction procedure was not simulated into the finite-element model instead, the “*CLEARANCE” and “*CONTACT INTERFERENCE” formulation options available in ABAQUS were used, which simulated press-fitting by pushing apart the contact surfaces of the acetabulum and the cup by the required amount of interference. Also, pre-compression of the acetabulum was permitted, the acetabular component was assumed to be perfectly seated, and the procedure facilitated the convergence of the numerical solutions without causing large numerical errors. The finite-element models considered for this study included 1 mm press-fit, 2 mm press-fit, line-to-line, and, for purposes of comparison, a fully bonded acetabular component (all Durom), which assumed a long-term condition, with 100% osseointegration between the component and the acetabulum, a situation not normally present clinically.

On the femoral side, only the proximal third of the femur was considered for the finite-element model (Fig. 2), as it was assumed that the distal regions of the femur would have a negligible influence on the contact mechanics at the articulating surfaces or the fixation interactions at the acetabular component-bone interface.³⁹⁻⁴¹ The femoral component was implanted at 45° of abduction and 10° anteversion (Fig. 2). The contact interfaces in the femoral model between cement and bone and cement and implant were all assumed to be perfectly bonded. Surface-based contact elements were used to model the contact between the surfaces of the femoral component and the femur.

The contact at the bearing surfaces between the femoral head and the acetabular component was modelled by frictionless surface-based contact elements to simulate a well-lubricated condition. A mesh convergence study was performed to examine contact mechanics at the articulating surfaces and the stresses in bone. The finite-element models were composed of a total of approximately 80 000 elements, consisting of predominantly four-node tetrahedral

elements, three-noded shell elements (to mesh the cortical shell in pelvis), eight-node brick elements (to mesh the contact surfaces), and six-node wedge elements.

A fixed resultant contact force of 3200 N was applied to the joint through medial and anterior muscle forces and subtrochanteric forces in order to represent the mid to terminal stance loading of the gait cycle (Fig. 2).^{42,43} Coordinates of the muscle forces were obtained from the literature and applied to the nodes on these locations.⁴⁴ The boundary conditions applied to the model were as follows (Fig. 2):

1. To simulate sacral support, the nodes situated in the sacroiliac joint were fully constrained, thus preventing their movement in any direction. The nodes within and around the pubic symphysis were also fully constrained.⁴⁵

2. Nodes around a transverse section of the femur were partially constrained, allowing only one or two degrees of freedom.

In order to determine the immediate post-operative stability of the acetabular component prior to any bone ingrowth, the total relative micromovement between the component and the acetabulum was determined. Paired nodes across the acetabular component-bone interface were identified and the total relative micromovement was calculated for the duration of the analysis.⁴⁵ A comparison of the total relative micromovement between the finite-element models was made for the total percentage surface contact area experiencing micromovement above and below the 50 µm threshold required for osseointegration. The maximum total relative micromovement for each of the finite-element models was also considered.

The contact mechanics at the acetabular component-bone interface and the bearing surfaces, as well as the stresses generated in the acetabulum for the finite-element models, were also examined. Contour plots of the predicted contact pressure distribution for the models at the acetabular component-bone interface and the bearing surface were obtained. The predicted maximum von Mises stresses and contact pressures experienced at the articulating surfaces for all the models were also given.

In order to determine the approximate deformation of the acetabular component, the positions of four arbitrary nodes on its rim, located along its axis, were noted in their unloaded state. The positions of these nodes were also recorded after press-fitting and loading. The approximate deformation was determined from the displacement calculation, which was taken to be the difference in the nodal position before and after loading.

Results

The total area of the acetabular component surface experiencing micromovement less than 50 µm was shown to be significant, with approximately 80% of the contact surface of the press-fit and the line-to-line models experiencing micromovement below this threshold value (Fig. 3a). Whereas the maximum relative micromovement for the press-fit models was less than 10 µm, the maximum micro-

Fig. 3a

Fig. 3b

A comparison of the approximate percentage area of the acetabular component experiencing a) relative micromovement at the cup-bone interface, and b) less than the 50 μm threshold required for osseointegration.

Table I. Comparison of the predicted maximum relative micromovement between the acetabular component and the bone, contact parameters at the acetabular component-bone interface, and the maximum von Mises stress in the acetabulum for the finite-element (FE) cup models

FE model	Maximum micromovement (μm)	Maximum contact pressure (MPa)	Total contact area (mm^2)	Maximum von Mises stress (MPa)
1mm press-fit	6.8	24.3	3772	67
2 mm press-fit	5.9	53.6	3647	125
Line-to-line	60.1	7.3	3219	22.2
Fully bonded	NA*	NA	NA	22.4

* NA, not applicable

movement for the line-to-line model was approximately 60 μm (Table I). The distribution of the total percentage contact area experiencing micromovement less than 50 μm is shown in Figure 3b. Over 70% of the contact area experienced micromovement under 10 μm for the press-fit models whereas 15%, 28% and 13% experienced micromovement under 10 μm , between 10 μm and 25 μm , and between 25 μm and 50 μm respectively, for the line-to-line acetabular components (Fig. 3b).

The contact between the acetabular component and the bone for the press-fit models occurred predominantly about the periphery of the acetabulum, as shown in the contour plots of the contact pressure distribution (Fig. 4). However, for the line-to-line model, contact appeared to be distributed across the acetabulum. A significant sevenfold increase in the predicted maximum contact pressure at the acetabular component-bone interface was noted between the line-to-line and the 2 mm press-fit models (Table I), with an approximate twofold increase in the predicted maximum contact pressure between the 1 mm and 2 mm inter-

ference press-fit models. The corresponding reduction in the total contact area between these two models was 3%.

Increasing the diametral interference also resulted in significant increases in the acetabular stresses. An approximate six-fold increase in the maximum von Mises stress was observed between the line-to-line and the 2 mm press-fit models (Table I). There was negligible difference in the acetabular stress between the line-to-line model and the fully-bonded model.

A moderate reduction in the predicted maximum contact pressure by approximately 30% was observed as the interference was increased from a line-to-line fit to the 2 mm press-fit model (Fig. 5). This reduction in contact pressure was accompanied by a corresponding increase in the predicted total contact area by up to 40%. Comparison between the 2 mm press-fit model and the fully-bonded model showed an approximately 35% increase in the maximum contact pressure (Table II) and a corresponding 53% reduction in contact area.

Max. contact pressure: 24.3 MPa
Total contact area: 3772 mm²

Fig. 4a

Max. contact pressure: 53.6 MPa
Total contact area: 3647 mm²

Fig. 4b

Max. contact pressure: 6.7 MPa
Total contact area: 3267 mm²

Fig. 4c

Fig. 4d

Contour plot showing a comparison of the predicted contact pressure distribution at the cup-bone interface for a) the 1 mm press-fit model and b) the 2 mm press-fit model and c) the line-to-line model. d) Diagram showing the direction from which the contour plot of the acetabulum is viewed.

The compressive forces generated as a result of the press-fit procedure created significant deformation of the component. A comparison of the approximate radial deformation in the anteroposterior and superoinferior directions is shown in Table II for the different finite-element models. Increasing the interference resulted in a corresponding rise in radial deformation, particularly in the superoinferior direction.

Discussion

The stability of cementless acetabular components used in total hip replacement has been well documented.^{12,15,17,23,24,46-48} However, little has been reported on the stability, tribology and contact interaction across the fixation at the bearing surfaces in the large-diameter metal-

lic monoblock components used in hip resurfacing. The stability of a metal-on-metal hip resurfacing arthroplasty was examined in the present study by determining the total relative micromovement between the acetabular components and the acetabular surfaces. The predicted contact area at this interface occurred over approximately 87%, 84% and 75% of the total surface area of the acetabulum for the 1 mm press-fit, 2 mm press-fit and line-to-line cups, respectively (Table I). Of this, the total percentage area experiencing micromovement below the 50 μ m threshold required for bone ingrowth, was found to be just over 71% for the press-fit cup models and approximately 56% for the line-to-line reamed model. Studies have shown that relative displacements between implant and bone of less than 50 μ m tend to encourage osseointegration, whereas displacements

Max. contact pressure: 15.2 MPa
Total contact area: 365 mm²

Fig. 5a

Max. contact pressure: 14.2 MPa
Total contact area: 425 mm²

Fig. 5b

Max. contact pressure: 17.8 MPa
Total contact area: 302 mm²

Fig. 5c

Max. contact pressure: 19.2 MPa
Total contact area: 277 mm²

Fig. 5d

Fig. 5e

Contour plot showing a comparison of the predicted contact pressure distribution at the bearing surfaces for a) the 1 mm press-fit model, b) the 2 mm press-fit model, c) the line-to-line model and d) the fully bonded model. e) The direction from which the contour plot in the acetabular cup is viewed.

greater than 50 μm impede bone ingrowth.⁴⁹⁻⁵³ This therefore suggests that all the models considered would provide adequate conditions for ingrowth. However, the press-fit acetabular components would provide the more ideal conditions required for initial stability than the line-to-line model. For the latter, only approximately 5% of the contact area experienced micromovement above 50 μm . Bone ingrowth would be possible in this case in some areas; but, it might be impeded by fibrous tissue growth in other areas, increasing the risk of late implant loosening.^{50,51} It must be noted that the line-to-line model considered in this study did not include adjunctive fixation, as may not be the case clinically. Adjunctive fixation, such as screws or peripheral

cup fins, would further limit the relative micromovement between the implant and the bone for both the line-to-line and the press-fit cup models.

The reduction of relative micromovement in the press-fit models was largely due to increased compressive and frictional stresses generated in the acetabulum, which provided the load transfer across the interface between the acetabular component and the bone needed to hold and secure the cup and to resist micromovement. The acetabular stresses were found to increase significantly as the interference was increased. Such stresses could potentially be damaging to the supporting bone or any potentially out-growing bone tissue.^{25,54} However, it must be noted that the finite-element

Table II. Comparison of the predicted maximum contact parameters at the bearing surfaces and the approximate deflection at the rim of the acetabular component in the anteroposterior and superoinferior directions for the finite-element (FE) models

FE model	Maximum contact pressure (MPa)	Total contact area (mm ²)	Deflection at cup rim (μm)	
			Anteroposterior direction	Superoinferior direction
1 mm press-fit	15.2	365	24.4	48.7
2 mm press-fit	14.2	425	45.3	94.6
Line-to-line	17.8	302	69.4	7.5
Fully bonded	19.2	277	21.9	9.9

model used in the study did not consider the heterogeneous nature and the viscoelastic, time-dependent behaviour of the cancellous bone. In the clinical situation, consideration of these properties would result in stress reduction and the relaxation of the bone surrounding the implant.⁵⁵⁻⁵⁷ Instead, for this study, the bone was assumed to be homogeneous and linear elastic. This would add to the overall rigidity in the finite-element models and the over-estimation of the stresses predicted.^{20,55} This model therefore gives a qualitative, rather than a quantitative evaluation of the predicted stresses. Viscoelastic finite-element models of bone are not readily available in the literature; however, a recent study demonstrated similar behaviour in the predicted results between homogeneous linear elastic and heterogeneous finite-element models.³³ This further justifies the homogeneous, linear elastic models used in the present study.^{32,34,35} Furthermore, this study only simulated the immediate post-operative situation, and the predicted results represent a possible worst-case mechanical scenario due to the material property assumptions, although not clinically relevant in terms of *in vivo* simulation.

Design and manufacturing parameters, such as diametral clearance, femoral head diameter and surface roughness, have been shown to significantly influence the contact mechanics and tribology at the bearing surfaces of hip resurfacing prostheses.^{26,36,58} The effect of the press-fit procedure on the contact mechanics at the bearing surfaces for a metal-on-metal hip resurfacing arthroplasty was examined. Increasing the interference resulted in a moderate reduction in the predicted contact pressure, which can be largely attributed to the increased contact area and acetabular component/femoral head conformity. However, there was a significant increase in deformation of the acetabular component as the interference was increased (Table II). No edge contact was identified, although it was shown that increasing the interference resulted in a twofold increase in the approximate deformation of the acetabular component in the anteroposterior and superoinferior directions for the press-fit models. Deformation in the superoinferior direction was found to be greater than in the anteroposterior direction. The anteroposterior direction experienced greater compression and coincided with the acetabular regions, reinforced anterosuperiorly by the bodies of the ilium and pubis, and posteroinferiorly by the body of the ischium. The superoinferior direction corresponded to bony regions about the acetabulum that were less

stressed, which resulted in these regions experiencing expansion into the acetabular notch.

The predicted deformation about the rim of the acetabular component was up to 65% with increasing interference, and could possibly result in edge contact should the interference be further increased. Edge contact could potentially result in lubricant starvation and increased wear generation; however, no edge contact was found for the press-fit models in this study. The anteroposterior deformation for the line-to-line fully-bonded models showed greater values than in the superoinferior direction, a different trend from that observed for the press-fit models. This was largely due to anteroposterior translation, with the line-to-line model undergoing more translation. The predictions of deformation in the present study were found to compare qualitatively with recent experimental and finite-element studies.^{59,60}

Factors such as poor bone quality due to age or disease could influence both the initial and the long-term stability of resurfacing arthroplasties. In such cases, the deterioration and reduction in bone-tissue properties could significantly increase the risk of fracture or loosening.⁶¹⁻⁶³ However, for the conditions considered in the present study, the results suggest that provided the acetabulum is mechanically sound, press-fit acetabular components between 1 mm and 2 mm should have adequate fixation for initial post-operative stability. This study further reinforces previous clinical and experimental findings on the importance of press-fit fixation on establishing initial implant stability.

The authors wish to thank the Arthritis Research Campaign (ARC), UK, for financial support.

One or more of the authors have received or will receive benefits for personal or professional use from a commercial party related directly or indirectly to the subject of this article.

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