Total hip reconstruction in acetabular dysplasia

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TOTAL HIP RECONSTRUCTION IN ACETABULAR DYSPLASIA

A FINITE ELEMENT STUDY

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In acetabular dysplasia, fixation of the acetabular component of a cemented total hip prosthesis may be insecure and superolateral bone grafts are often used to augment the acetabular roof. We used finite element analysis to study the mechanical importance of the lateral acetabular roof and found that the lateral acetabular rim plays an important role in the load transfer of the pelvic bone. When the superolateral rim was lacking, the load shifted to the posterosuperior rim and to the area of pubic support, and the stresses in all materials, especially in the cement and in the trabecular bone, increased greatly. At the cement-bone interface the tilting component of the shear stress increased threefold. In a model in which the dysplastic acetabulum was augmented by a rigidly fixed, load-transmitting bone graft, the stresses were considerably diminished.

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In congenitally dysplastic or dislocated hips, fixation of the acetabular component of a total hip prosthesis may be difficult (Charnley and Feagin 1973). Several studies have shown that lack of lateral coverage of the socket correlates with an increased risk of aseptic loosening (Sutherland et al 1982; August, Aldam and Pynsent 1986; Röttger and Elson 1986; Linde and Jensen 1988; Ohlin and Önsten 1990; Sarmiento et al 1990); thus, bony containment should always be aimed at. Several solutions have been proposed: the use of small prosthetic components (Tronzo and Okin 1975; Crowe, Mani and Ranawat 1979; Woolson and Harris 1983), medialisation of the socket (Hess and Umber 1978; Linde and Jensen 1988;

McQueary and Johnston 1988), and bone grafting. A disadvantage of medialisation is that it destroys the subchondral bone which is necessary for adequate fixation (Jacob et al 1976; Kobayashi and Terayama 1990).

Bone grafting of a deficient acetabulum was first reported by Harris, Crothers and Oh (1977). Resorption of the bulk autografts which they originally used has proved to be a major problem at longer follow-up (Mulroy and Harris 1990). With smaller grafts, resorption has not been a significant feature (Chambat et al 1978; Marti and Besselaar 1981, 1983; Wolfgang 1990; Schuller and Marti 1992). Radiologically, these superolateral grafts incorporate and become a structurally integrated part of the iliac bone (Fig. 1).

The clinical importance of bony containment of the cup and the widespread use of reconstructions of the acetabular roof directed our interest to the following questions. What is the mechanical importance of the lateral part of the acetabular roof in a patient with a total hip prosthesis? What happens when this lateral rim is lacking? Could a superolateral reconstruction improve the mechanical situation?

We have used a finite element (FE) model to calculate the stresses which occur in the pelvis around a cemented acetabular cup in normal and in dysplastic hips. A three-dimensional model was used because the geometry, the mechanical behaviour and the loading conditions of the pelvic bone are so complex that, unlike femoral FE models, a two-dimensional or axisymmetrical model is inadequate (Dalstra and Huiskes 1990, 1991).

MATERIALS AND METHODS

The standard FE mesh was based on digitised sections of a normal left male hemipelvis. Adjustments were made to the standard mesh to simulate dysplastic acetabula, which lack mainly superolateral support. Three degrees of dysplasia were modelled by moving the nodes on the superior acetabular rim 6, 12 or 18 mm into the material. The acetabular prosthesis was a cemented hemispherical ultra-high-molecular-weight polyethylene cup with an external diameter of 52 mm. It articulated with a 32 mm ceramic prosthetic head. After insertion, a 2 mm thick

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Fig. 1a

Fig. 1b

Fig. 1c

An example of acetabular roof reconstruction in total hip arthroplasty of a dysplastic hip. Radiograph before operation (a), immediately after operation (b) and 11 years later (c).

Fig. 2

Frontal views of the standard (non-dysplastic) mesh (a) and the meshes with 6 mm (b), 12 mm (c) and 18 mm of dysplasia (d). The visible (uncovered) part of the cement mantle is dotted.

layer of subchondral bone was assumed to remain and the cement mantle had a uniform thickness of 4 mm. The interfaces between the cup and the cement and between the cement and the bone were both considered to be fully bonded. Grooves on the outer surface of the cup and modern cementing techniques are used in clinical practice to ensure the bonding of these surfaces, but these details were not taken into account in the model. Contact between the cup and the femoral head was modelled by radial tying of the corresponding nodes on both surfaces, allowing the femoral head to transfer only normal loads on to the cup, thus simulating a frictionless contact with no shear. The standard mesh consisted of 1260 elements, of both isoparametric 8-node solid brick elements and 4-node membrane elements. The latter were used to represent the thin cortical shell of the pelvic bone which was assumed to have a uniform thickness of 1 mm. In Figure 2, a frontal view of the standard mesh is shown,

Table I. Young's moduli and Poisson's ratios as used in the finite element models

Material	Young's modulus (MPa)	Poisson's ratio
Pelvic trabecular bone	70	0.2
Subchondral bone	2000	0.3
Cortical bone	17 000	0.3
UHMW polyethylene*	700	0.3
Bone cement	2300	0.3
Ceramic	420 000	0.3

* ultra-high-molecular-weight polyethylene

together with the meshes with 6, 12 and 18 mm of dysplasia. The materials used in the analyses were assumed to be isotropic and homogeneous. Except for the pelvic trabecular bone, all material properties were based on current values reported in the literature (Table I). For the trabecular bone, the values were based on our own measurements (Dalstra, Odgaard and Huiskes 1992).

The models were assumed to have fixed support at the sacroiliac joint and the pubic symphysis. The direction and magnitude of the hip force during the one-legged stance phase of a normal walking cycle were based on the data of Bergmann, Graichen and Rohlmann (1990). This force reaches three times body-weight, which in the models amounted to 2158 N; it was modelled as a distributed load acting on the prosthetic head to guarantee its smooth introduction into the acetabular cup. The resultant intersected the acetabular surface close to the centre of the superoanterior quadrant.

The models also included muscle forces. EMG data

have shown that, during one-legged stance, 15 muscles contribute to the overall loading of the hip (Crowninshield and Brand 1981). The directions of these muscle forces were deduced from the locations of their proximal and distal attachments (Dostal and Andrews 1981; Table II).

Finally, an attempt was made to study the effect of

superolateral acetabular augmentation. A further model was introduced, consisting of the 18 mm dysplastic mesh with some elements added to simulate a load-transmitting superolateral corticocancellous graft (Fig. 3).

The analyses were performed, using the MARC/MENTAT FE model and pre- and postprocessing codes (MARC Analysis Corporation, Palo Alto, California), running on the EX-60 mainframe computer (Hitachi Data Systems, Bells Hill, UK) of the University of Nijmegen.

RESULTS

The normal model. Figure 4 shows the calculated von Mises stress contours in the non-dysplastic model. The von Mises stress consists of all the individual stress components and is a measure of the stress intensity (Huiskes 1991). In all the materials, apart from the cup itself, the highest stresses occur in the region of the superior acetabular rim. In the cortical shells, the stresses reach values of almost 50 MPa, whereas in the cancellous bone they do not exceed 2 MPa. In the *cup* (Fig. 4a) the stresses are greatest around the point to which the hip force is directed. The underlying *cement mantle* (Fig. 4b), however, does not display such a stress pattern. The load has already split into a major component directed towards the superior acetabular rim and a minor component directed towards the area supported by the pubis. The area around the point at which the resultant of the hip is directed actually shows diminished stress intensity

Fig. 3

Frontal (a) and lateral (b) views of the 18 mm dysplastic model with a simulated reconstruction of the acetabular roof.

Fig. 4

The normal (non-dysplastic) hip. Von Mises stress contour plots of the cup (a), cement mantle (b), subchondral bone (c), cancellous bone (d) seen from an anteroinferior position, and the cortical shell (e) seen from a posterosuperior position.

compared to the surrounding areas. In the *subchondral bone* (Fig. 4c) and the underlying *cancellous bone* (Fig. 4d), the stresses have a more uniform distribution with a slight increase towards the superior acetabular wall. Finally, the stress pattern in the *cortical shell* (Fig. 4e) shows how the load is transferred from the supra-acetabular region to the sacroiliac joint and the pubic symphysis.

Von Mises stresses are non-directional and therefore the *individual stress components* should be used to study the stresses in a particular direction (e.g. interface stresses). In the case of hemispherical interfaces (Fig. 5), the stress components are defined as normal (σ_{norm}); circumferential (σ_{hoop}), tangential (σ_{tang}), torsional (τ_{tors}), tilting (τ_{tilt}), and parallel shear stress (τ_{par}). The normal

stress and the torsional and tilting shear stresses are the actual interface stresses. Both at the cup-cement interface and at the cement-bone interface the normal (compressive) stresses are greatest in the anterosuperior quadrant. In the same region, the shear stresses show sharp gradients and their maximum and minimum values lie closely together. The highest stresses occur at the cement-bone interface with values of 4.5, 1.5 and 0.8 MPa for the normal, torsional, and tilting shear stresses respectively.

The dysplastic model. When acetabular dysplasia is introduced into the model, the site of load transfer shifts from the anterosuperior part of the acetabular rim to the area supported by the pubis and to the posterosuperior rim (Fig. 6). The magnitudes of stress in the various materials, except in the cup itself, significantly increase, as shown in Figure 7. The individual stress components behave similarly. The stresses in the cup and at the cup-cement interface are little affected by acetabular dysplasia, but the hoop, tangential and parallel shear stresses in the cement show substantial increases, especially for the major degree of dysplasia. The most significant increase

Table II. The muscles, and the magnitude of their forces during one-legged stance, as used in the finite element models

Muscle	Force (N)
Gluteus maximus	930
Gluteus medius	1053
Gluteus minimus	140
Tensor fascia lata	132
Sartorius	88
Semimembranosus	368
Semitendinosus	140
Biceps femoris (long head)	202
Adductor longus	88
Adductor brevis	114
Obturator internus	123
Piriformis	175
Quadratus femoris	96
Superior gemellus	88
Rectus femoris	123

Fig. 5

Representation of the six individual stress components, defined at each interface. σ_{norm} = normal stress, σ_{hoop} = circumferential stress, σ_{tang} = tangential stress, τ_{tors} = torsional shear stress, τ_{tilt} = tilting shear stress and τ_{par} = parallel shear stress.

Fig. 6

Von Mises stress contour plots in the cement mantle (above) and in the subchondral bone (below) in the normal model (a) and in the 6 mm (b), 12 mm (c) and 18 mm (d) dysplastic models.

Fig. 7

Fig. 8

Interface shear stress peaks at the cement-bone interface for each of the three degrees of dysplasia. The bold line in each graph denotes the value in the non-dysplastic case.

Fig. 9

Von Mises stress contour plots in the cement mantle (above) and in the subchondral bone (below) in the normal model (a) and in the 18 mm dysplastic model before (b), and after (c) reconstruction.

is found at the cement-bone interface. Although the torsional shear stress remains more or less the same, the tilting component increases, up to threefold in the case of major dysplasia (Fig. 8).

The reconstructed dysplastic model. After superolateral reconstruction, the stress distributions in the various materials and interfaces are 'normalised' (Fig. 9) and the peak stresses are reduced to levels similar to those of the non-dysplastic model. In the models with 12 mm and 18 mm of dysplasia, however, even after a reconstruction, the tilting shear stress at the cement-bone interface remains twice as high as in the non-dysplastic case.

DISCUSSION

From an engineering point of view the pelvic bone consists of two thin cortical shells kept apart by trabecular bone, resembling a sandwich construction. Such structures are used to combine high strength and low weight; the thin cortical shells carry the bulk of the load while the trabecular bone acts merely as a spacer (Jacob et al 1976; Dalstra and Huiskes 1991). The acetabular roof plays an important role in the load transfer of the normal pelvic bone after hip replacement. It allows the smooth transfer of the hip force from the acetabular cup to the cortical shell of the iliac bone. In all materials, apart from the cup, the highest stresses occur in the area of the superior acetabular rim. When the superior wall is reduced by dysplasia, the area of load transfer shifts from the anterosuperior to the posterosuperior rim and to the area of pubic support. The extent of this shift depends on the degree of dysplasia; and the stresses in the materials and interfaces increase accordingly. In the cup itself the increases are small and are not so dependent on the degree of dysplasia. In the cement and the subchondral bone, increases of almost 100% were found and in trabecular bone the stress increased as much as 110% in the most dysplastic model.

It is the cement-bone interface which is the most affected by dysplasia. Here, the tilting component of the shear stress was greatly increased, whereas the increase in the torsional component was only slight. In the most dysplastic model the tilting component of shear stress was more than three times as high as in the non-dysplastic case.

The FE model of a dysplastic acetabulum reconstructed by a superolateral bone graft is a simplification of the reality. It does not consider the biological changes which occur within the graft and at its interfaces. It serves, however, to demonstrate the theoretical possibility of diminishing the stresses if the surgeon succeeds in augmenting the acetabular roof by a load-transmitting bone graft.

The present study takes no account of any migration of the cup or of the effect that this would have on the distribution of stresses in the materials and at the interfaces. We have modelled only the immediate

postoperative situation in which all interfaces are considered to be fully bonded.

Several authors have estimated, from clinical experience, the extent to which an acetabular cup should be contained, i.e., covered by bone. Charnley and Feagin (1973) stated that no more than 5 mm may be left uncovered; they used cement as a buttress. Crowe et al (1979) suggested that at least 75% of the cup should be contained; Gerber and Harris (1986) proposed 80%, Harris (1987) 70%, and Wolfgang (1990) 80%. The study of Sarmiento et al (1990) convinced us that there should always be 100% bony coverage, and the present theoretical analysis supports this view.

We conclude that after total hip replacement the lateral part of the acetabular roof plays an important role in load transfer. If part of the acetabular prosthesis is not covered by load-transmitting bone, there is a significant increase in the stresses in the materials especially in the cement, the subchondral and the trabecular bone, and at the cement-bone interface. A load-transmitting superolateral bone graft may serve to normalise these stress patterns.

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REFERENCES

- August AC, Aldam CH, Pynsent PB. The McKee-Farrar hip arthroplasty: a long-term study. *J Bone Joint Surg [Br]* 1986; 68-B: 520-7.
- Bergmann G, Graichen F, Rohlmann A. Instrumentation of a hip joint prosthesis. In: Bergmann G, Graichen F, Rohlmann A, eds. *Implantable telemetry in orthopaedics*. Berlin: Freie Universität Berlin, 1990:35-63.
- Chambat P, Nourissat C, Poppon P, Dejour H. Les prothèses totales de hanche avec abaissement et butée osseuse. *Rev Chir Orthop* 1978; 64Suppl.2:26-32.
- Charnley J, Feagin JA. Low-friction arthroplasty in congenital subluxation of the hip. *Clin Orthop* 1973; 91:98-113.
- Crowe JF, Mani VJ, Ranawat CS. Total hip replacement in congenital dislocation and dysplasia of the hip. *J Bone Joint Surg [Am]* 1979; 61-A:15-23.
- Crowninshield RD, Brand RA. A physiologically based criterion of muscle force prediction in locomotion. *J Biomech* 1981; 14: 793-801.
- Dalstra M, Huiskes R. The pelvic bone as a sandwich construction; a three dimensional finite element study. Seventh meeting of the European Society of Biomechanics. University of Aarhus, 1990:B32.
- Dalstra M, Huiskes R. The influence of metal backing in cemented cups. Proc 37th annual meeting of the Orthopaedic Research Society, Anaheim, 1991:272.
- Dalstra M, Odgaard A, Huiskes R. Mechanical and textural properties of pelvic trabecular bone. *Trans Orthop Res Soc* 1992; 17:556.
- Dostal WF, Andrews JG. A three-dimensional biomechanical model of hip musculature. *J Biomech* 1981; 14:803-12.
- Gerber SD, Harris WH. Femoral head autografting to augment acetabular deficiency in patients requiring total hip replacement: a minimum five-year and an average seven-year follow-up study. *J Bone Joint Surg [Am]* 1986; 68-A:1241-8.
- Harris WH. Bone grafting for acetabular deficiency in association with total hip replacement. In: *The Hip*. Proc 14th meeting of the Hip Society. St Louis: CV Mosby, 1987; 39-46.

- Harris WH, Crothers O, Oh I.** Total hip replacement and femoral-head bone-grafting for severe acetabular deficiency in adults. *J Bone Joint Surg [Am]* 1977; 59-A:752-9.
- Hess WE, Umber JS.** Total hip arthroplasty in chronically dislocated hips: follow-up study on the protrusio socket technique. *J Bone Joint Surg [Am]* 1978; 60-A:948-54.
- Huiskes R.** Biomechanics of artificial-joint fixation. In: Mow VC, Hayes WC, eds. *Basic orthopaedic biomechanics*. New York: Raven Press, 1991:375-442.
- Jacob HA, Huggler AH, Dietschi C, et al.** Mechanical function of subchondral bone as experimentally determined on the acetabulum of the human pelvis. *J Biomech* 1976; 9:625-7.
- Kobayashi S, Terayama K.** Radiology of low-friction arthroplasty of the hip: a comparison of socket fixation techniques. *J Bone Joint Surg [Br]* 1990; 72-B:439-43.
- Linde F, Jensen J.** Socket loosening in arthroplasty for congenital dislocation of the hip. *Acta Orthop Scand* 1988; 59:254-7.
- Marti RK, Besselaar PP.** Spanplastiken bei primärer totalprothese und totalprothesenwechsel. *Z Orthop* 1981; 119:711-4.
- Marti RK, Besselaar PP.** Bone grafts in primary and secondary total hip replacement. In: Marti RK, ed. *Progress in cemented total hip surgery and revision*. Amsterdam: Excerpta Medica, 1983:107-29.
- McQueary FG, Johnston RC.** Coxarthrosis after congenital dysplasia: treatment by total hip arthroplasty without acetabular bone-grafting. *J Bone Joint Surg [Am]* 1988; 70-A:1140-4.
- Mulroy RD, Harris WH.** Failure of acetabular autogenous grafts in total hip arthroplasty: increasing incidence. *J Bone Joint Surg [Am]* 1990; 72-A:1536-40.
- Ohlin A, Önsten I.** Loosening of the Lubinus hip: 202 cases followed for 3-6 years. *Acta Orthop Scand* 1990; 61:244-7.
- Röttger J, Elson R.** A modification of Charnley low-friction arthroplasty: representative ten-year follow-up results of the St. Georg prosthesis. *Clin Orthop* 1986; 211:154-63.
- Sarmiento A, Ebramzadeh E, Gogan WJ, McKellop HA.** Cup containment and orientation in cemented total hip arthroplasties. *J Bone Joint Surg [Br]* 1990; 72-B:996-1002.
- Schuller HM, Marti RK.** Supero-lateral bone grafting of acetabular deficiency in total hip replacement. *Acta Orthop Scand* 1992; 63Suppl.248:39.
- Sutherland CJ, Wilde AH, Borden LS, Marks KE.** A ten-year follow-up of one hundred consecutive Müller curved-stem total hip-replacement arthroplasties. *J Bone Joint Surg [Am]* 1982; 64-A:970-82.
- Tronzo RG, Okin EM.** Anatomic restoration of congenital hip dysplasia in adulthood by total hip displacement. *Clin Orth* 1975; 106:94-8.
- Wolfgang GL.** Femoral head autografting with total hip arthroplasty for lateral acetabular dysplasia: a 12-year experience. *Clin Orthop* 1990; 255:173-85.
- Woolson ST, Harris WH.** Complex total hip replacement for dysplastic or hypoplastic hips using miniature or microminiature components. *J Bone Joint Surg [Am]* 1983; 65-A:1099-108.