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Stress transfer across the hip joint in reconstructed acetabuli

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STRESS TRANSFER ACROSS THE HIP JOINT IN RECONSTRUCTED ACETABULI

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1. INTRODUCTION

The results of cemented acetabular reconstruction have been somewhat disappointing relative to femoral reconstruction, in view of loosenings reported on the longer term (e.g. Stauffer et al., 1983).

The causes for these late loosening effects are not all clear, although evidently fibrous tissue interposition at the implant/bone interface, diagnosed as radiolucency, occurs more often in the acetabulum than in the femur (DeLee and Charnley, 1976). Acetabular loosening is relatively frequent in relation with surface replacements (Strens, 1986), hence, either effects of friction or cup flexibility could play an important role. The negative effects of high cup flexibility on cement stresses have been emphasized in finite element stress analyses (Pedersen et al., 1982; Carter et al., 1982; Oonishi et al., 1986; Oonishi et al., 1983). 'Metal backing' of polyethylene sockets appeared to be a solution to that problem (Harris and White, 1982).

Others have pointed to the negative effects of reaming the subchondral bone layer, also in relation with loss of acetabular rigidity (Charnley, 1979). Conversely, the positive effects of subchondral penetration of acrylic cement for the strength of the cement/bone bond have been emphasized. High curing temperatures of acrylic cement, in particular in acetabular fixation, have been mentioned as well (Huiskes, 1980; Eriksson, 1984). Based on the sometimes disappointing clinical results of cemented cups, cementless fixation was introduced, for instance by using threaded sockets to be screwed into the acetabulum (Lord, 1979).

The purpose of the present study was to analyse the load-transfer mechanism through different types of acetabular reconstructions, including cemented and cementless polyethylene sockets, with and without subchondral reaming, metal backed sockets, surface replacement cups and threaded fixation. In addition, several fundamental questions related to finite element (FE) modelling of acetabular reconstruction in general were addressed; i.e. the applicability of 2-D FE models versus solid axisymmetric models, and the effects of elastic coupling between femoral head and socket on acetabular stress patterns and hip-joint friction.

2. METHODS

The acetabular configuration analysed was based on the FE model of Pedersen et al. (1982). This model describes a frontal section through the acetabulum and the adjacent pelvic structures, applying axisymmetric elements, allowing for non-axisymmetric loading (Fourier expansion).

The models applied in the present study are shown in Fig.1. They include the natural acetabulum, reconstruction with the cementless CLW*

* CLW is a trade mark of Protek AG, Bern, Switzerland.

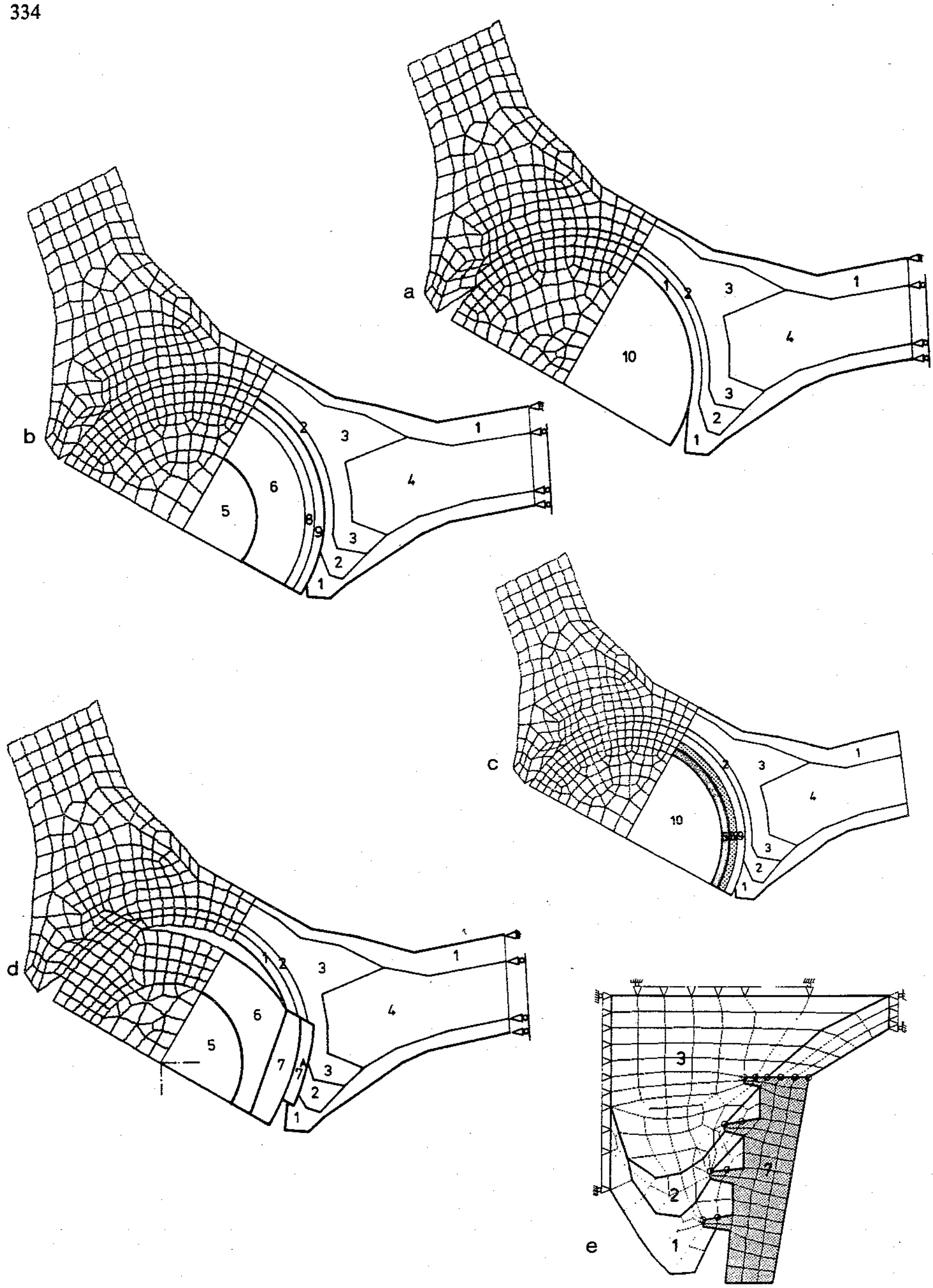


FIGURE 1: FE meshes used in the analyses, with femoral head included, contact coupled to the acetabulum (compressive stress only).
a: Natural acetabulum; b: conventional sockets;
c: surface replacement; d: CLW threaded cup;
e: local model (2-D) for CLW cup.

threaded cup, conventional polyethylene cups, and a surface replacement cup. As in the model of Pedersen et al. (1982), axisymmetric solid elements were used, but in this case the femoral head was included in the models, contact coupled to the acetabular cup (Brown and Digioia, 1984; Rapperport et al., 1985). As a penalty for this inclusion, only symmetric loads could be taken into account. In addition, calculations were carried out, whereby a non-axisymmetric load was assumed (Fourier expansion), without the femoral head. The CLW reconstruction (being the most rigid of the cups analysed) and the surface replacement cup (being the most flexible one) were also analysed with 2-D plane-strain elements.

In the global CLW reconstruction model (Fig.1), the region of the threads was modelled as a composite material of bone and metal. The detailed stress patterns in and around the threads were analysed with a local, refined model, for which the boundary conditions were derived from the global model (Fig.1). The material of the metal ring in the CLW model was varied between CoCrMo alloy and c.p. titanium.

The conventional cup model was analysed with several variations, including cemented UHMWPE, with and without metal backing, with and without subchondral reaming, and noncemented UHMWPE with subchondral reaming. Elastic moduli used are shown in Table I (see also Fig.1).

Nr.	Material/Variation	E(MPa*10^4)
1	Cortical bone	1.7
2	Cancellous bone	0.3
3	Cancellous bone	0.15
4	Cancellous bone	0.1
5	CoCrMo alloy	20.0
6	UHMWPE	0.07
7	Titanium; CoCrMo alloy	11.0; 20.0
7a	Composite bone/metal	5.5; 10.0
8	UHMWPE; CrCoMo alloy; PMMA	0.07; 20.0; 0.3
9	UHMWPE; PMMA; cortical bone	0.07; 0.3; 1.7
10	Cancellous bone	0.5

TABLE I: Elastic moduli used in the models; bone moduli according to Pedersen et al. (1982).

All materials were assumed linear elastic, homogeneous and isotropic. In the axisymmetric models, quadrilateral 8-node isoparametric elements were used. Plane strain quadrilaterals, also 8-node, were used in the 2-D models. In the case of non-axisymmetric loading, ten Fourier terms were applied. All materials were assumed rigidly connected, except for the femoral head/cup bond, where only compressive stress was allowed. Stress results are presented per unit of applied force.

3. RESULTS

3.1. Effects of the femoral head

The femoral head presents a restraint for the deformation of the cup. This is illustrated in Fig.2, showing cup deformations for the case that the head is included, and for the case that a distributed load is directly applied to the polyethylene socket. It is also evident from this figure that the metal CLW ring behaves almost like a rigid body, relative to the socket and the bone.

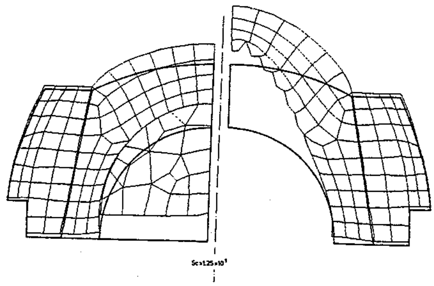


FIGURE 2:
Deformations of the CLW-cup;
left: femoral head included,
right: load application directly
to inner polyethelene boundary.

The head/socket interaction causes the compressive-stress distribution at the inner socket to depend on the elastic characteristics of the acetabular reconstruction (Fig.3). This dependency also has an effect on the stress patterns in the cup, the bone and at the cup/bone interface. However, when a relatively rigid reconstruction is used, as in the case of the CLW cup, the bone stress patterns only depend on the direction of the external force, and not on the precise pressure distribution at the inner cup boundary.

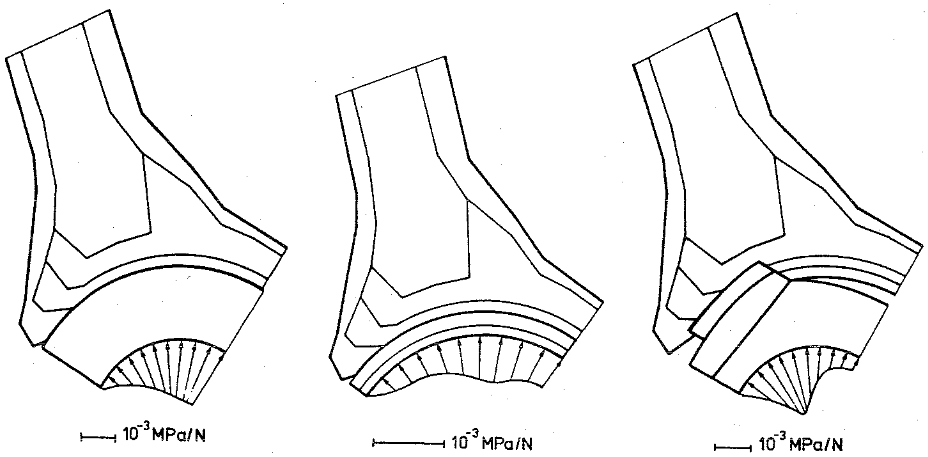


FIGURE 3: Pressure distributions at the head/cup boundary calculated for the cemented polyethelene cup (left), the surface-replacement cup (middle), and the CLW cup (right).

3.2. Solid versus 2-D models

The differences in the stress patterns between the axisymmetric solid models and the 2-D plane strain models are the more pronounced in the case that the reconstruction is more flexible; i.e. the actual quantitative differences are greater in the latter case (Fig.4). In the 2-D surface replacement model the element thickness was taken as 50 mm, which results in approximately equal compressive stress distributions at the inner socket boundary in the frontal plane, in both the 3-D and 2-D cases. Evidently (Fig.4), the stresses in the 2-D model are grossly overestimated. This overestimation is more extensive the farther away from the cup. Although the stress patterns are qualitatively similar, the 2-D model underestimates the contribution of the cortical bone layer surrounding the acetabulum, in particular at the lateral rim (hoop stress) and the medial wall. It overestimates the contribution of the superior cancellous bone.

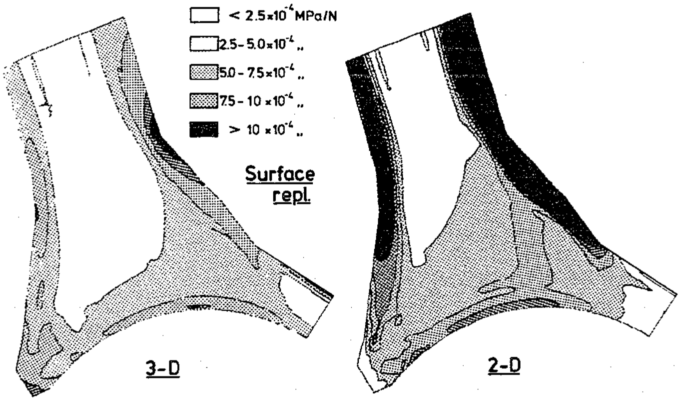


FIGURE 4: Comparison of von Mises equivalent stress patterns in the frontal bone section of a 3-D (axisymmetric) and a 2-D model of the surface replacement cup reconstruction.

3.3. Effect of symmetric versus asymmetric load

Fig.5 shows von Mises stress patterns in the bone of the CLW reconstructed acetabulum, assuming a one legged stance maximal force orientation (Pedersen et al., 1982), and a symmetric force, in both cases distributed over the cup boundary. The femoral head was included in neither of these models which has, in the case of a relatively rigid reconstruction, no concequences for the bone stresses (sect. 3.1.). The general effect of the medially rotated force is an almost uniform increase of stresses in the superior, lateral bone part, and a corresponding decrease in the inferior, medial part. This indicates that the symmetric load is adequate to analyse general trends in the bone stress patterns.

In a more flexible reconstruction, the differences may be more pronounced. However, the present findings for the conventional cup reconstructions, using a symmetric load, compared to the corresponding results of Pedersen et al. (1982), who used a one legged stance load, indicate that also in this case the differences are not dramatic in terms of general trends.

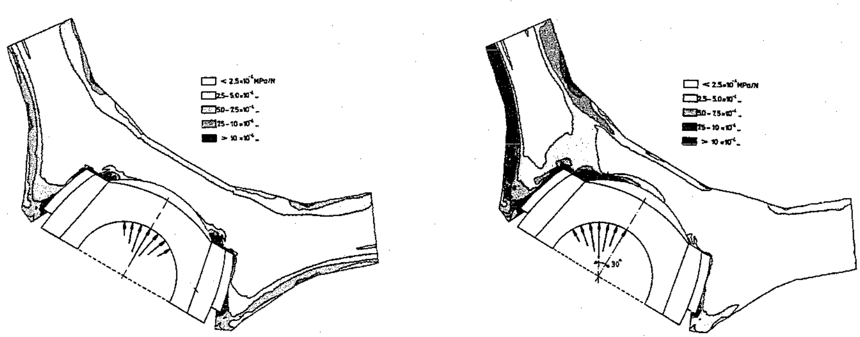
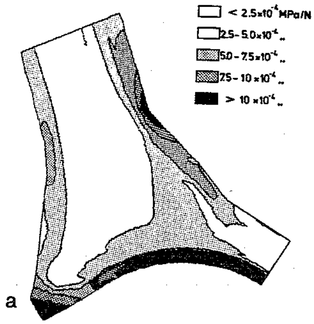


FIGURE 5: Von Mises equivalent stress patterns in the frontal bone section, as determined for the CLW-cup model. Left a symmetric load, right an asymmetric load.

3.4. Effects of cup design and fixation technique

The effects of cup design and fixation technique on the stress patterns in the bone are evaluated relative to the natural case, shown in Fig.6a. In this comparison, only the models with the femoral head included (symmetric load) are considered.



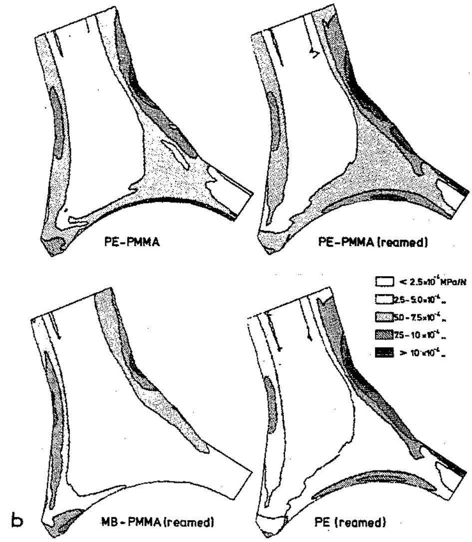


FIGURE 6:
Von Mises equivalent stress patterns in the frontal bone sections of various models.
a: natural acetabulum;
b: conventional cup reconstructions with and without PMMA, subchondral reaming and metal backing.

As evident from Fig.6.b, there is hardly any difference at all between the stress patterns in the acetabulum with the cemented and the noncemented UHMWPE cups. Although the cement elastic modulus is more than 4 times higher than the one of UHMWPE, the cement layer is relatively thin, hence, these reconstructions are structurally about equally stiff. Relatively to the natural case, stress concentrations occur at the superior cup/bone interface. More load is transferred through the central cancellous bone directly to the medial/superior cortex, than via the cortical shell.

Conversely, when the subchondral bone layer is left intact (Fig.6.b), the stress patterns are very similar to those in the natural case (Fig.6.a); the stress concentration at the interface, ocurring in the reamed model, has disappeared.

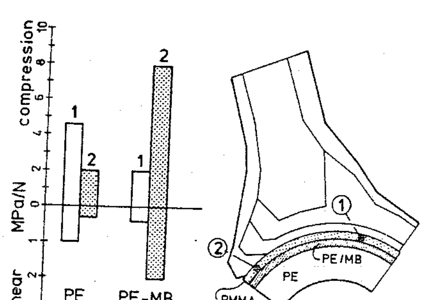


FIGURE 7:
Compressive and shear stresses at the cup/cement interface in two regions (1 and 2), with and without metal backing (MB).

When metal backing is applied on a cemented polyethylene cup (Fig.6.b), the central cancellous bone region is stress-shielded relative to the natural acetabulum, to a considerable degree. In this case, even more load is transferred directly to the lateral cortical shell and less load is transferred through the superior cup/bone interface. As a result, the central interface and cement stresses in relation with the metal backed cup are much lower than in the non-metal backed case (area 1 in Fig.7). This mechanism, described earlier (Pedersen et al., 1982; Carter et al., 1982), has been considered as the mechanical advantage of metal backing. However, this advantage has a penalty in increased interface and cement stresses close to the lateral cup rim (area 2 in Fig.7), both in shear and in compression. The gain in area 1 (in the superior region) from metal backing is in these models even less than the loss in area 2 (near the cup rim).

The bone stress patterns in the surface-replacement model (Fig.4, 3-D) are not very different from those in the conventionally reconstructed acetabulum (Fig.6.b, PE (reamed)). The cement/bone interface stresses are even better spread in the former case, and more load is directly transferred to the latter cortical shell. This seems surprising in view of the higher flexibility of the surface-replacement cup. In fact, this is the result of the deformation restraining action of the stiff femoral head, which is relatively large in this case.

In the case of the threaded cup reconstruction (Fig.5, symmetric load), stress shielding of the central cancellous bone relative to the natural case (Fig.6.a) is evident. Also in this case more load is transferred directy to the lateral cortical shell. Stress concentrations occur in small areas near the inferior and the superior parts of the threaded ring. From the stress patterns in and around the threads, determined in the local FE model (Fig.1) it is found that most of the load is transferred through the first and the last threads.

4. DISCUSSION AND CONCLUSIONS

In earlier FE analyses of acetabular reconstruction (Pedersen et al., 1982; Carter et al. 1982; Oonishi et al., 1986), the external load was directly applied at the inner cup boundary. In the present analysis it was found that this is an unrealistic assumption, because of elastic coupling between the femoral head and the socket. When the cup has a relatively stiff metal backing, the effect of the coupling is limited to the direct (polyethylene) environment of the head, but in the case of a flexible reconstruction the bone stress patterns are affected also.

The effect of the femoral head restraint is the most pronounced in the case of the surface-replacement reconstruction. It could be said, that the femoral head, in this case, acts like a 'pseudo metal backing', thereby reducing the negative effects of the high cup flexibility. It is possible, therefore, that the relatively unfavorable clinical results of surface replacement cups are the effects of friction, rather than cup flexibility.

Because the head/socket contact pressure distribution depends on the elastic characteristics of the reconstruction, the head/socket friction will also be susceptible to the elastic characteristics, and thus vary with prosthetic design.

In a generic way, the use of symmetric loads versus asymmetric loads or 2-D models versus solid FE models can be useful and appropriate to evaluate trends in the stress patterns comparatively. The effects of these simplifying assumptions, however, depend on the flexibility of the reconstruction: the more rigid the cup, the less the bone stress patterns are susceptible to the modelling characteristics. In all cases, however, the stress values are grossly overestimated in 2-D models, depending on the assumed thickness of the 2-D elements.

The acetabulum behaves like a 'sandwich' structure, in the sense that most of the load is transferred through the cortical shell, and the inner cancellous bone basically serves to keep these shells apart (Jacob et al., 1976). This behavior is also evident in the normal stress patterns (Fig.6.a). The reconstructions can be divided according to those which violate this behavior (the flexible ones like all conventional cups with subchondral bone layer reamed) and those which essentially leave the structural integrity intact (the stiffer ones like the CLW cup, metal-backed cup, or any cup with an intact subchondral layer). The latter category seems to be the favorable one, although there is a penalty in all cases: local bone stress concentrations in the CLW cup, increased cement stresses with the metal backed cup in the lateral rim region (Fig.7), and the difficulty of cement/bone interlocking when the subchondral bone layer is retained.

It is well feasible that optimal designs could be developed, based on compromises between the various conflicting aspects. Eventually, these compromises must be based on a better understanding of the three-dimensional mechanical characteristics of the acetabulum, in particular in cases which are representative for the patient population.

ACKNOWLEDGEMENT:
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