# The modelling and mechanical consequences of fibrous-tissue formation around femoral hip prostheses

# THE MODELLING AND MECHANICAL CONSEQUENCES OF FIBROUS-TISSUE FORMATION AROUND FEMORAL HIP PROSTHESES

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## Introduction

The Finite Element Method (FEM) is used with increasing frequency for analyses of load-transfer and stress patterns in bone/prostheses structures, to assess the adequacy of prosthetic designs (Huiskes and Chao, 1983). The FEM models applied are usually descriptive of idealized, immediate post-operative configurations, assuming complete interface bonding. On the longer term, bone resorption around the prosthesis may occur, at least when acrylic cement is used for fixation, resulting in a soft fibrous tissue layer between cement and bone. The purpose of the present study was to incorporate this soft-tissue layer in the FEM models, and to study its effects on the load transfer.

The fibrous tissue layer usually consists of parallel fibred collagen within a soft matrix, with a highly nonlinear, visco-elastic compliance in compression, and little resistance against tension and shear (Draenert, 1986; Hori et al., 1982a). The mechanical behavior of a fibrous-tissue interface connection will therefore be governed by the following effects: 1) reduced compliance; 2) material nonlinearity of the tissue itself; 3) loosening on tension; 4) slip in shear; 5) time dependency. The consequences of the first effect was analysed previously by Brown et al. (1986), in a (linear) 3-D FEM model of femoral stem fixation. Vroemen et al. (1986) investigated a combination of the first, third and fourth effects in a (nonlinear) 2-D FEM model of femoral surface replacement. Hori et al. (1982b) and Vanderby et al. (1985) studied a combination of the first, second and fifth effects in (non-linear) models of tibial knee replacements.

In the present analysis, a (nonlinear) 2-D FEM model (using quasi 3-D structural characteristics) of femoral hip replacement was used to study the consequences of the effects 1 through 4 on the load-transfer mechanism, the stress patterns and the relative motions occurring between implant and bone.

## Methods

The front plate of the FE model applied is shown in Fig. 1. In order to account for the 3-D structural characteristics of the bone, a side plate was used, superimposed over the front plate. This modelling approach gives a reasonably accurate discription of stress patterns in the frontal plane (Huiskes, 1980, Huiskes et al. 1986). The orientation of the hip-joint force is indicated in Fig. 1. The prosthetic shoulder is assumed not to be in contact with the bone of the calcar.

The effect of a fibrous tissue layer of 1 mm thickness, extending along the full medial and lateral cement/bone interfaces, whereby 1 mm of bone was removed, was studied in a step-by-step approach, as shown in Table I.

Table I: Characterization of the FE models applied.

| Nr. | Type of model | interface layer | layer material | E-modulus (MPa) | Interface connection |
|---|---|---|---|---|---|
| i | linear | no | - | - | bonded |
| ii | linear | yes | lin. elastic | 17,000 | bonded |
| iii | linear | yes | lin. elastic | 170/10 | bonded |
| iv | nonlinear | yes | lin. elastic | 10 | loose |
| v | nonlinear | yes | nonlinear | - | loose |

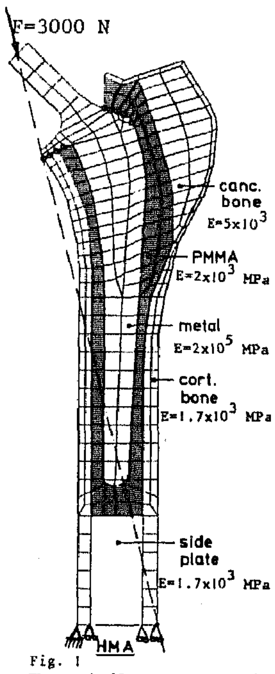


Fig. 1
The mesh (front plate only) used in the analysis. The elements of the front plate are of non-uniform thickness. Poisson's ratio is 0.3 for all elements.

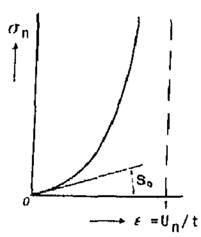


Fig. 2 Nonlinear material behavior for interface under pressure.

Because of the thickness of the layer, and potential problems with small element aspect ratios, an alternative modelling approach was implemented. In the case of a linear elastic layer, bonded to bone and cement, force-displacement relations between neightbouring nodes in the normal and tangential directions were assumed. The effect of this description is, that the normal stress ($\sigma_n$) and the shear stress ($\sigma_{np}$) across the layer are uniform, and the parallel (bending) stress ($\sigma_p$) in the layer is neglected. Normal and shear strains across the layer are related to the stresses by

$$\sigma_n = E\varepsilon_n \quad \text{and} \quad \sigma_{np} = (E/2(1+\nu))\gamma_{np} \qquad (1)$$

where E and $\nu$ are the elastic modulus and Poission's ratio of the layer, respectively.

The model (ii) was used to test this approach, relative to a conventional description (i). Model (iii) was used to test the applicability of a linear approach, assuming the interface layer to be soft, but linear elastic and bonded to cement and bone, as done previously by Brown et al. (1986).

Model (iv) was applied to evaluate the effects of tensile loosening and slip between the (linear elastic) interface layer and bone. For this purpose, nonlinear gap elements were introduced in addition to the above interface description.

Model (v) combines the nonlinear bonding conditions applied in model (iv) with a nonlinear elastic description of the fibrous material, assuming

$$\sigma_n = \frac{S_o}{n}\left\{\frac{1}{(1-\varepsilon_n)^n} - 1\right\} \qquad (2)$$

The values of $S_o$ and $n$ are varied to study the effects of differences in layer compliance. This material behaviour is illustrated in Fig. 2.

In the case of nonlinear assumptions (models iv and v), the force was increased from zero to 3000 N in steps, using Newton-Raphson interation to find a solution after every step. The models were analysed with the MARC FEM code (MARC Analysis Corporation, Palo Alto, CA).

## Results

The stress patterns found for model (ii) were virtually equal to those of model (i), indicating that the modeling approach for the intermediate layer is reliable.

Fig. 3 shows an example of (bending) stress patterns along the medial bone cortex and the lateral prosthetic surface as found in the models (ii) - (v).

The linear soft-interface model (iii) results in increased bone and stem (bending) stresses, similar to effects reported by Brown et al. (1986). Load-transfer stresses in cement and at interfaces were more evenly distributed as compared to the intact model (ii). By assuming a modulus of 170 MPa in stead of 10 MPa for the layer, the effects were somewhat reduced, but not to a very large extent.

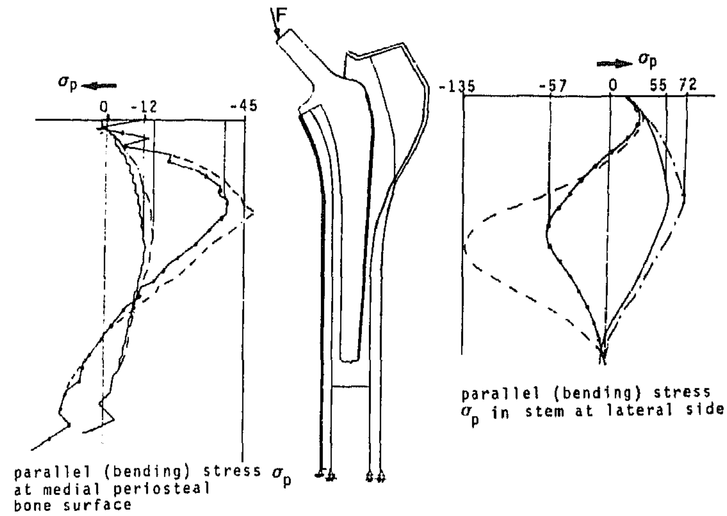


Fig. 3 Bending stresses in medial bone and lateral stem.
——— linear analysis, calculation ii
—·—· linear analysis, calculation iii , E=10 MPa
– – – – nonlinear analysis, calculation iv
–•——•– nonlinear analysis, calculation v

Very dramatic effects on the stress patterns were obtained when the interface connection was assumed loose (model iv), as evident in Fig. 3. Bending stresses in the medial cortex increased fourfold, the bending of the stem even changed its orientation. These effects are caused by a completely altered load-transfer mechanism, whereby implant/bone stresses are concentrated in the proximal/medial and midlateral areas, supporting the stem practically in three-point bending (Fig. 4).

The additional aspect of nonlinear elastic properties of the tissue layer (model v) changed the stress patterns relative to model (iv) only in a gradual sense. The general trends were equal. The concentrated implant/bone stresses, occuring in model (iv) are somewhat less pronounced in model (v). Fig. 4, shows normal stresses at the cement/stem interface as found in the linear calculation (i) and as calculated for the loose non-linear tissue case (v).

## Discussion

The present analysis indicates dramatic effects of a fibrous-tissue layer at the cement/bone interface on the load-transfer mechanism in femoral bone/prosthesis structures, to the extent that stress pattern in the whole system are completely changed. The soft layer causes the prosthesis to sink, and find support at a few locations, where very high stress concentrations occur, which must compensate for the loss of interface-shear resistance. In earlier analyses it was found that interface loosening by itself does not have such a dramatic effect (Huiskes, 1980; Huiskes et al., 1986). The present results (model iii) show that the low compliance of the layer does not have such a dramatic effect by itself either. Hence, the cause must be found in the combination of loosening and low compliance.

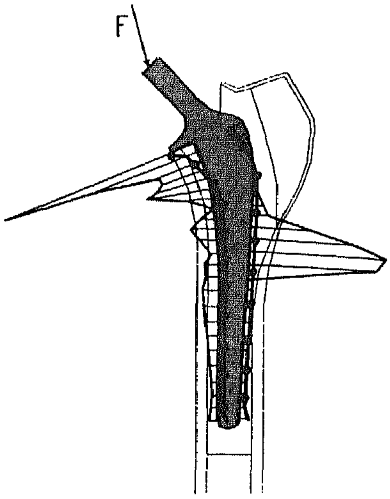


Fig. 4 Normal stress in cement layer perpendicular to the stem-cement interface.
linear analysis, calculation i
nonlinear analysis, calculation v

These findings indicate, that the effects of fibrous tissue interfaces can not be modeled reliably by using a linear approach. However, if the nonlinear contact conditions are adequately represented, a reasonable approximation, in a qualitative sense, can be obtained by assuming the layer to act as a soft, linear elastic material. Assuming the material to act nonlinear is more realistic. However, the results are not very sensitive to the precise constituitive equation, as was found from parametric analysis with model (v).

The mechanical behavior of the implant surrounded by a fibrous tissue also clearly demonstrates, that the stress patterns depend very heavily on the actual geometry of the interface. This indicates, that a completely different behavior can occur if the layer does not extent along the whole interface, if its thickness varies, or if the geometrical configuration of the cement/bone composite is different. This implies, that the present analysis, using a 2-D model of a particular geometry, can only serve as a demonstration of the fibrous-tissue interface effects in a general, qualitative sense.

Acknowledgement: Sponsored in part by Grant 95-189 from the Netherlands Organisation for the Advancement of Pure Research (ZWO).

**References**

Brown, T.D., Pedersen, D.R., Radin, E.L., Rose, R.M.,"Global mechanical consequences of bone/cement interface degradation in proximal femoral arthroplasty", Trans. of the 32nd Ann. Mtg., Orth. Res. Soc., 1986, p. 467.

Draenert, K., "Histomorphological Observations on Cemented Standard and Press fit Prosthesis", Symposium on Orthopaedics and Surgery of Bone and Joints, 28/29-11-1986, Institute of the Histomorphological Study Group, München.

Hori, R.Y., Lewis, J.L., Hammer, R.S., Askew, N.J., "The effect of a fibrous tissue liner between bone and cement on finite element models of bone prosthesis structures", Trans. of the 28th Ann. Mtg., Orthop. Res. Soc., 1982b, p. 146.

Hori, R.Y., Lewis, J.L., "Mechanical properties of the fibrous tissue found at the bone-cement interface following total joint replacement", J. Biom. Mat. Res. 16:911-927, 1982a.

Huiskes, R., "Some fundamental aspects of human joint replacement", Acta Orthop. Scand. Suppl. 185: 1-209, 1980.

Huiskes, R., Chao, E.Y.S., "A survey of finite element methods in orthopaedic biomechanics", J. Biomech. 16:385-409, 1983.

Huiskes, R., Snijders, H., Vroemen, H., Chao, E.Y.S., Morrey, B.F., "Fixation stability of a short cementless hip prosthesis". Trans. of the 32nd Ann. Mtg., Orthop. Res. Soc., 1986, p. 466.

Vanderby, R., Lewis, J.L., Chapman, S.M., "Biphasic modeling of fibrous tissue at the bone prosthesis interface in total joints", Trans. of the Winter Ann. Mtg. of the ASME, 1985, pp. 22-23.

Vroemen, W., Huiskes, R., Strens, P., Slooff, T.J., "A nonlinear finite element simulation of interface loosening and bone resorption after hip resurfacing" Trans. of the 32nd Ann. Mtg., Orthop. Res. Soc., 1986, p. 453.