BIOMECHANICAL PARAMETERS RELEVANT TO THE SUCCES OF HIP PROSTHESES: CLINICAL FOLLOW-UP AND FE MODEL STUDY

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Abstract: Long-term functionality of non-cemented hip prostheses is influenced by several factors. Among these, the initial fixation stability and the adaptive bone response in the long term are deemed most important. The initial fixation of the prosthesis and the immediate postoperative biomechanical conditions will strongly influence the stress and strain distribution in the surrounding bone tissue, which in turn governs the bone biological reactions in its adaptive response. This paper presents the main topics in the development of a parametric model to analyse individual retrospective clinical data of cementless hip prosthesis cases. The long term goal is to develop a predictive tool for cementless Total Hip Replacement (THR) outcome, to allow close monitoring of patients at increased risk of loosening, allowing corrective measures in an early stage of the loosening process. The aim of the reported preliminary study was to find out which of five specific biomechanical parameters most affect the stress-strain distribution in the bone after a mid-term follow-up. The surface area against rotation seems to be the most critical regarding the average stress distribution, though the effect of press-fit rings and hydroxyapatite coating are relevant and interesting for further study of density distribution changes over time.

Introduction

Cementless implants rely on the biologic reaction of surrounding bone tissue to ensure a lasting fixation. The established interface conditions during surgery, the bone quality and prosthesis geometry among others will strongly influence the stress and strain distribution in the surrounding bone tissue, which in turn governs the bone biological reactions in its adaptive response [1-3]. The immediate postoperative biomechanical conditions will influence the long-term behaviour of a robust implant-bone interface, which is the ideal condition.

For our study, clinical data from several hip replacements were provided by the orthopaedics department where about 500 THRs are performed annually. The system of intra-operatively custom-made THR stems, used in this orthopaedic department, is based on the hypothesis that a better “fit and fill” of the prosthesis in the femoral cavity will prevent the mechanical problems of subsidence and breakdown of the interface, with loosening and bone destruction as consequence [4]. However, the role of many other biomechanical parameters in the outcome of cementless THR is not yet well understood.

The reported work is part of a larger research project to establish a relationship between biomechanical parameters, more specificly the load bearing capacity of an implant and the surrounding bone as well as the load during functional activity, and the quality of the initial fixation of the implant.

This paper presents the main topics in the development of a parametric model to analyse individual retrospective clinical data of cementless hip prosthesis cases. Various biomechanical parameters are hypothesised as determinant in the load transfer mechanism during the initial fixation i.e. stem length, a plasma sprayed hydroxyapatite (HA) coating and press-fit rings in the proximal part of the stem.

The long term goal is to develop a predictive tool for cementless Total Hip Arthoplasty (THA) outcome, to allow close monitoring of patients at increased risk of loosening, allowing corrective measures in an early stage of the loosening process. The aim of the reported preliminary study was to find out which of five specific biomechanical parameters most affect the stress-strain distribution in the bone after a mid-term follow-up.

Materials and Methods

In this study, clinical data from an intra-operatively produced prostheses are used [5]. These personalised prostheses are designed to obtain a rapid and optimal bony integration by a complete and close contact between the endosteal bone and implant surface. This technique is used in primary hip surgery or revision with deformed femoral cavity geometry, see figure 1.

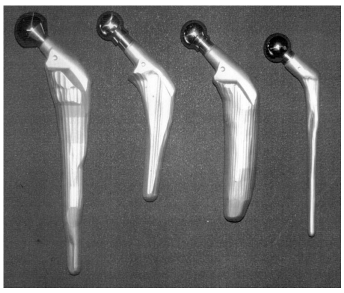

Figure 1: Various geometries of personalised intra-operatively produced prostheses.

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An optimal close match between the femoral component and the cavity is obtained on the basis of a mould or imprint of the femoral canal. Based on the measurements of the mould, the dimensions of the implant are calculated. Although full contact is aimed for, there are some zones creating volumetric interference when introducing the prosthesis and these have to be eliminated, which is illustrated in figure 2.

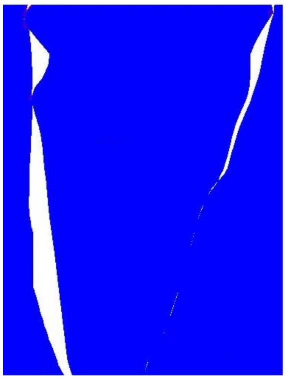

Figure 2: Sagittal view in the antero-posterior plane showing void spaces between prosthesis and bone in white. These spaces are created when material from the prosthesis has to be removed to make the prosthesis introducible in the cavity.

With a CAD-CAM system, the implant is manufactured during surgery and material is machined away in these interference volumes, preventing full contact. For all patients in this study, the 3D geometry of the reamed cavity and of the custom-made implant is fully documented and was provided by the hospital in STL format, figure 3.

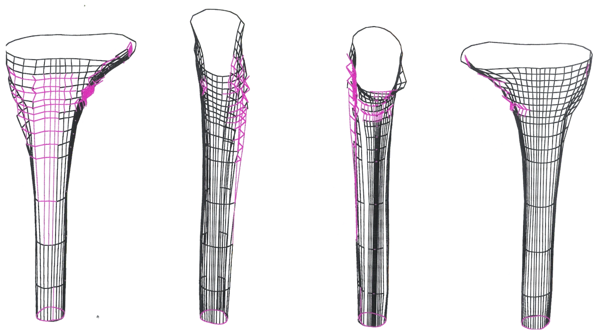

Figure 3: Three dimensional surface of the prosthesis showing in pink the interference areas preventing full contact between prosthesis and bone

Based on these geometries, an average case (a) was selected and four parametric variations of prosthesis and cavity were modelled to study which of those biomechanical parameters is more influential in the outcome of the stress and strain distributions of the initial fixation. These geometries are depicted in figure 4. Variations are:

- Press-fit rings (b) in the proximal part of the stem are added according to actual geometrical data from the hospital.
- Stem length (c) is enlarged in the distal third 10% from the basic geometry.
- Area against rotation or antirotation effect (d) is simulated reducing 10% of the shortest axis of the elliptical cross section of the stem.
- Hydroxy-apatite (HA) coating (e) in the proximal third of the stem is simulated using literature values of friction in the contact region.

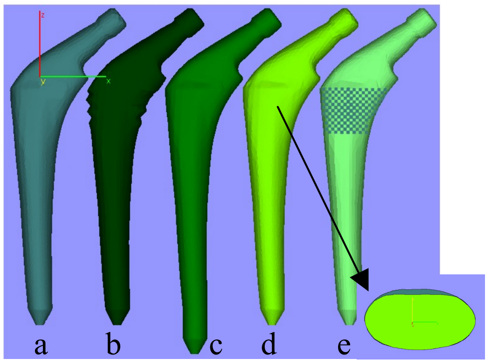

Figure 4: Geometric variations simulating biomechanical parameters affecting stability: (a) base case, (b) press-fit rings, (c) stem length enlarged, (d) area against rotation increased and (e) HA coating.

To study the antirotation effect, not only the influence of the transversal elliptical area was varied with respect to the control model (a). The effect of grooves in the vertical direction of the stem created by the machining tool was studied as well. These grooves are created by a milling tool of diameter (11.5±0.5) mm, creating an angulated cross section as depicted in figure 5.

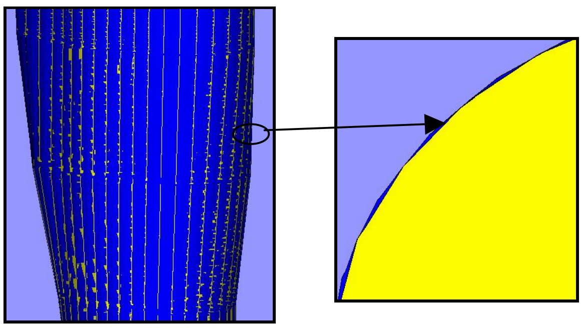

Figure 5: Detail of vertical grooves creating a different transversal area (right) in the stem of the prosthesis

To compare the various results, a cylinder simulating bone was used to introduce the prostheses. The model considers specific contact conditions and muscular forces [6, 7]. Tetrahedral elements were used and calculations performed with MARC/Mentat and Patran finite element (FE) software (MSC.Software, NL). Control nodes in each model were defined in order to compare and analyze results in the anterior, posterior, lateral and medial zones of the simulated bone (cylinder).

Table 1: Mechanical characteristics used for bone and titanium

	Young's modulus (N/mm^2)	**Poisson coefficient**
Bone	19000	0.3
Prosthesis	114000	0.3

Pre- and post-operative radiographs were available for all cases.

Results

Immediately post operative strain and stress distributions around the bone were calculated and compared among the various geometries. Results were compared as well with general tendencies observed in the clinical data provided by the hospital.

Volumes of the prosthesis and the reamed cavity are not always exactly the same, introducing peak contact zones along the stem, the proximal press-fit rings (b) being the most critical case as shown in figure 9.

A common pattern of stress distribution among all the models studied was observed. The pattern followed higher stress concentrations in the proximal part with respect to the distal zone (x=0 representing the proximal part of the stem in figure 6).

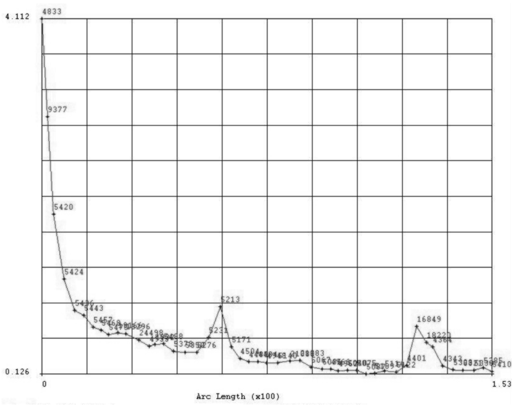

Figure 6: Von Misses stress pattern followed by the models; higher stress concentrations in the proximal part with respect to the distal zone (x=0 representing the proximal part of the stem).

No appreciable differences in stress or strain values and distribution were obtained in the case with a longer stem.

The model simulating the antirotation effect showed 15% higher stress concentration in the posterior zone of the bone compared to all the other models, see figure 7.

HA models showed a high stress concentration in the border between the coating and the non coated surface of the stem, see figure 10.

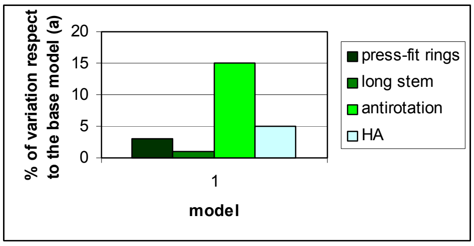

Figure 7: Percentage changes in Von Misses stress in the posterior zone among the model variations.

The vertical grooves did not output a significant effect in the stress and total strain values, see figure 8. Less than 4% variations were observed between the cases with and without grooves.

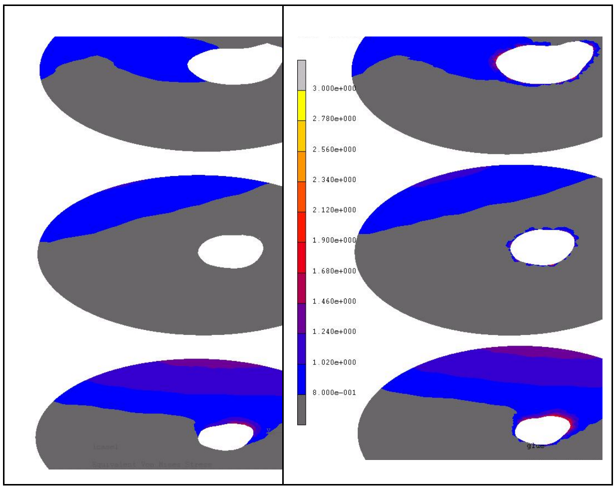

Figure 8: Von Misses stress distributions (MPa) in the cross section around the grooves in the stem. Left: case without the grooves, right: with the grooves.

Discussion

Contact peaks introduced by the press-fit rings might be related to the "bony bridges" observed in the radiographs of some patients with this type of anchorage, see figure 9.

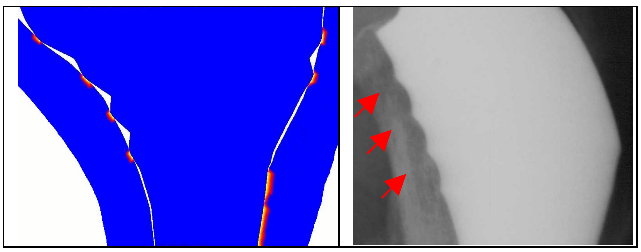

Figure 9: Left: high contact zones introduced by the press-fit rings in the proximal zone. On the right side the radiograph showed the formation of 'bony bridges' (marked with red arrows) at those locations.

The fact that no differences were found in the stress and strain distributions for the changes in the stem

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length can be attributed to the contact conditions. By definition, this type of prosthesis is aimed at establishing a very good proximal anchorage and contact between the bone and the prosthesis. Even if the distal part is considered as well for the total contact principle, in some situations, due to the cleared interference already explained, it is not possible to reach the homogeneous and good load transfer over the entire interface surface. Then the proximal part of the simulated bone is more sensitive to the changes modelled by the press-fit rings, the changes in surface against rotation or the HA coating, instead of changes concerning the distal zone of the prosthesis.

Regarding the results of the changes in the resistance against rotation induced by reducing 10% of the shortest axis of the transversal area, the differences were appreciable in the posterior zone only. This result is limited to this specific simulation. To establish a general conclusion about the beneficial effect of this parameter, further comparisons should be done with two cases where the antirotation effect is more pronounced. Clinical data should then be used to interpret the results.

The high stress concentration in the HA coating transition zone in the stem shows a result coherent with the observations in the radiographs, where the presence of an incremented bone ingrowth in that specific zone is depicted, figure 10.

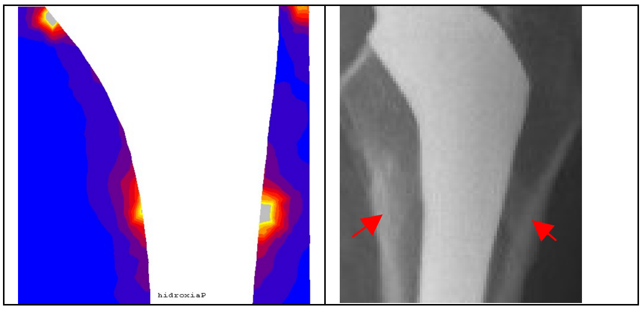

Figure 10: Left: FE simulation results for the HA coating. Good correlation is found with the radiographs (right) showing bone ingrowth marked with red arrows.

This result can be expected since the contact conditions are changing in those specific regions because of the friction coefficient. This implies a more complex situation in the stress and strain distributions. The interesting point is the way bone is positively responding to this condition and bone growth is stimulated as observed in the clinical data in figure 10. The effect of the vertical grooves was considered negligible with respect to the effect of the changes in the elliptical cross section generating resistance to rotation.

Conclusions

Strain and stress distributions around the bone were studied and compared among the various biomechanical parameters simulated.

Actual contact conditions between the prosthesis and the cavity in the bone appeared to be critical in the general results.

When comparing the immediate post operative load transfer mechanism with the long term stability results of the clinical data (radiographs) a quite coherent qualitative stress distribution is obtained.

From the simulation of the various geometrical stability criteria in this study, the surface area against rotation seems to be the most critical regarding the average stress distribution, though the effect of the press-fit rings and the hydroxyapatite coating influence are relevant and interesting for further study regarding bone density distribution changes over time.

Acknowledgment

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