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Probability of mechanical loosening of the femoral component in high flexion total knee arthroplasty can be reduced by rather simple surgical techniques

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ABSTRACT

Background: Some follow-up studies of high flexion total knee arthoplasties report disturbingly high incidences of femoral component loosening. Femoral implant fixation is dependant on two interfaces: the cement–implant and the cement–bone interface. The present finite-element model (FEM) is the first to analyse both the cement–implant interface and cement–bone interface. The cement–bone interface is divided into cement–cancellous and cement–cortical bone interfaces, each having their own strength values. The research questions were: (1) which of the two interfaces is more prone to failure? and (2) what is the effect of different surgical preparation techniques for cortical bone on the risk of early failure.?
Methods: FEM was used in which the posterior-stabilized PFC Sigma RP-F (DePuy) TKA components were incorporated. A full weight-bearing squatting cycle was simulated (ROM = 50°–155°). An interface failure index (FI) was calculated for both interfaces.
Results: The cement-bone interface is more prone to failure than the cement implant interface. When drilling holes through the cortex behind the anterior flange instead of unprepared cortical bone, the area prone to early interface failure can be reduced from 31.3% to 2.6%.
Conclusion: The results clearly demonstrate high risk of early failure at the cement–bone interface. This risk can be reduced by some simple preparation techniques of the cortex behind the anterior flange.
Clinical relevance: High-flexion TKA is currently being introduced. Some reports show high failure rates. FEM can be helpful in understanding failure of implants.

1. Introduction

With the introduction of high flexion total knee arthroplasty (TKA), at the beginning of this century, concerns have been raised regarding early aseptic loosening. In the “normal” flexion range TKA, aseptic loosening is the fourth reason for revision of all components after infection, instability and pain [1]. The revision rate for aseptic loosening in standard designs is less than 2% after 7 years [1]. Recent literature reports have shown that high-flexion designs sometimes show much higher revision rates due to femoral component loosening, ranging from 3.6% after 10.9 months up to 21% after 23 months [2–4]. It is thought that during high flexion excessive compressive forces are generated at the posterior femoral condyles, leading to distal shear and anterior tensile forces. This suggests that femoral implant fixation is a more apparent concern in high-flexion designs compared to the standard designs. Radiographs of loose femoral components show radiolucent lines behind the anterior flange. However, other studies report no difference in loosening between standard prosthetic designs and high-flexion designs [5,6].

A finite-element (FE) simulation by Zelle et al. [7], of the well performing Sigma RP-F (DePuy, Leeds) TKA, showed that the anterior flange was most at risk of failure, especially at high flexion angles. That study only simulated the cement–implant interface.

Obviously, in terms of prosthetic loosening, there are two interfaces to consider: the cement–bone interface and the cement–implant interface. Since the anterior flange covers both cancellous and cortical bone, the cement–bone interface can be divided in two; cement–cancellous and cement–cortical bone interfaces. More than 50% of the flange area can cover cortical bone, which has a relatively low interfacial strength [8]. This weak interface can be strengthened by relatively simple surgical preparation techniques such as removal of the periosteum, roughening the cortex and by drilling some small anchoring holes [8]. Strength values of the cement–cancellous bone interface are widely studied [9,10] and are much higher than those of the cement–cortical bone interface. In order to reduce long-term aseptic loosening of high flexion femoral components, the strength-to-stress ratios at both (cement–bone and cement–implant) interfaces

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behind the anterior flange should be considered, since both interfaces need a different approach to increase their strength. The cement–implant interface can be strengthened by application of different surface finishing techniques [11], whereas the strength of the cement–bone interface can be influenced by the preparation technique of the cortical bone [8].

The goals of this biomechanical study were:

1. To determine if the cement–bone interface was more prone to early failure than the cement–prosthesis interface in high flexion TKA.
2. To determine whether improvement of the cement–bone interface strength, as proposed by van de Groes et al. [8], would reduce the potential for prosthetic loosening.

2. Materials and methods

In this study FE techniques were used to assess the stress levels during high flexion at both interfaces (cement–implant and cement–bone interface). By comparing these stress levels to strength values as reported in earlier studies [7,8] we were able to assess the potential for mechanical failure at both interfaces and how this was affected by surgical preparation techniques of the cortical bone behind the flange.

2.1. FE knee model

The FE analysis performed in this study included two sub-models to improve computational efficiency: (1) a global FE knee model to determine the femoral loading during knee flexion and (2) a local femoral FE model to analyse the stress state at the cement–prosthesis and cement–bone interface (Fig. 1).

The global knee model has previously been described in detail [7] and consisted of a proximal tibia and fibula, high-flexion TKA components (posterior-stabilized PFC Sigma RP-F, rotating-platform TKA system, DePuy International, Leeds,UK), a quadriceps/patella tendon and a non-resurfaced patella. Knee flexion was achieved by application of the ground reaction force (=350 N, to represent ½ bodyweight) to the ankle joint and releasing the fixed quadriceps tendon slightly per increment of flexion, comparable to cadaveric loading setups such as the Oxford knee testing rig [12]. A weight-bearing deep knee bend up to 155° was simulated. Thigh-calf contact, occurring during knee flexion beyond 130°, was integrated in the knee model to account for the joint relieving effect of posterior soft-tissue compression during high flexion [13]. The FE knee model was relatively unconstrained and free to seek its own kinematics.

Subsequently, the femoral loading conditions per node derived from the global FE knee model were applied to matching local femoral FE models. The local FE models included a femoral component, implant–cement interface elements, a 1 mm thick bone cement layer, cement–bone interface elements and a distal femur. The Young's modulus of the bone was in the range of 26.3–14,500 MPa (based on bone mineral density (BMD) on CT-scan), bone cement 2200 MPa and the femoral component 210,000 MPa. Except for the implant–cement and cement–bone interface, four-noded tetrahedral elements were used to generate the FE model. Cement pockets in the femoral component were neglected to avoid edge artefacts and simplify the interface analysis. The geometry of the distal femur was obtained from a femoral CT-scan of an 81 year old male (t-score = −1.9) using modelling software (Mimics 11.0, Materialise, Leuven, Belgium). The femur was CT-scanned using a calibration phantom and material properties were mapped to the femur using BMD information derived from the calibrated CT-scan according to Keyak and Falkinstein [14]. Bone cement was modelled as a linear elastic material. FE simulations were performed using MSC.MARC (MSC Software Corporation, Santa Ana, CA, USA).

2.2. Cement–bone and cement–implant interface

Zero-thickness six-noded cohesive elements were used to model the cement–bone and cement–implant interface, which were the regions of interest and indicated to be at risk during deep knee flexion [2]. Interface loading was expressed in terms of normal (σ_n) and shear stresses (σ_s). Since the analysis of the stress conditions and failure potential of the cement–bone interface compared to the implant–cement interface was the main objective of this study, actual debonding was not simulated and only linear elastic behavior was applied to the interface elements.

2.3. Cement–implant interface

The tensile ($S_t = 2.09$ MPa) and shear ($S_s = 3.89$ MPa) strengths of the cement–implant interface were based on the (arithmetic) average surface roughness of the femoral components ($R_a = 1.593$ μm) and experimental data of interface specimens with varying surface roughness [15]. The interface stiffness in tensile and shear direction ($K_t = 57.3$ MPa/mm; $K_s = 151.4$ MPa/mm) as well as the compressive

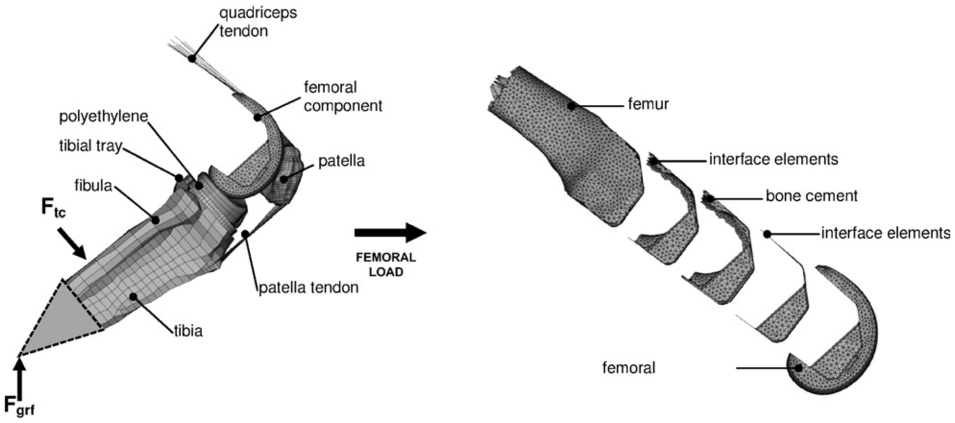

Fig. 1. The global FE knee model (left) utilized in this study to determine the femoral loading conditions during deep knee flexion and the local femoral FE model (right) to subsequently analyze the loading of the femoral fixation site. The global knee model contained osseous tissues (femur, tibia, fibula and patella), soft-tissues (quadriceps, patella tendon and PCL) and high-flexion TKA components. The boundary conditions applied to the FE models, such as the ground reaction force F_{grf} and the thigh-calf contact force F_{tc}, are shown as well.