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Femoral loosening of high-flexion total knee arthroplasty: The effect of posterior cruciate ligament retention and bone quality reduction

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ABSTRACT

High-flexion total knee arthroplasty (TKA) may be more sensitive to femoral loosening than conventional TKA as the knee joint force increases during deep flexion. The objective of this study was to evaluate whether the probability of femoral loosening is equal in posterior cruciate ligament (PCL) retaining and substituting high-flexion knee implants and whether loosening is related to femoral bone quality. A three-dimensional finite element (FE) model of the knee was developed and a weight-bearing deep knee bend up to 155° was simulated. PCL conservation considerably increased the compressive tibio-femoral joint force as a maximal force of 4.7–6.0 × bodyweight (BW) was found, against a maximal force of 4.0 × BW for posterior-stabilized TKA. Roughly 14% of the fixation site beneath the anterior femoral flange was predicted to debond on the long-term in case of cruciate-retaining TKA compared to 20% in case of posterior-stabilized TKA. Reducing the femoral bone quality to 50% of its original bone mineral density increased the amount of potential anterior failure for cruciate-retaining TKA to 22% and posterior-stabilized TKA to 24%. We therefore conclude that the femoral fixation site has a similar failure potential for both cruciate-retaining and posterior-stabilized high-flexion TKA.

1. Introduction

High-flexion knee replacements have recently been developed to facilitate a larger range of motion (ROM > 120) than standard total knee arthroplasty (TKA). High-flexion implants are often based on successful conventional TKA designs of which the posterior tibio-femoral conformity has been improved to avoid edge loading [1] and accommodate the increased joint load occurring during deep knee flexion [2,3]. Both cruciate-retaining and cruciate-substituting high-flexion TKA designs have been introduced.

Preservation of the posterior cruciate ligament (PCL), as practiced during cruciate-retaining TKA, is one of the most debated items in knee arthroplasty. Proponents of PCL conservation argue that sparing the PCL leads to more physiological knee kinematics, less intra-operative femoral bone loss, lower shear loads on the tibial component and maintenance of proprioception [4]. In cruciate-substituting TKA, the PCL is excised and substituted by a post-cam mechanism, which is referred to as posterior-stabilized TKA. An important function of the PCL is to pull the femur posteriorly during knee flexion (=femoral rollback), which is essential to avoid posterior tibio-femoral impingement and maximize knee flexion [5]. A tight PCL leads to more posterior femoral rollback than a slack PCL, at the expense of an increased joint compression and potential polyethylene wear [6,7].

Recent studies are showing evidence for potential femoral fixation problems in high flexion TKA. Firstly, a recent follow-up study reported a disturbingly high incidence of early femoral loosening for cemented high-flexion TKA [8]. Aseptic loosening of the femoral component was observed in 38% of the operated patients at a mean follow-up time of 23 months. Implant loosening primarily occurred at the femoral implant–cement interface and the incidence appeared to be associated with the maximal post-operative flexion angle. Secondly, in another clinical study considering cementless high-flexion TKA, radiographic loosening of the femoral component was observed in 36% of the knees implanted and analyzed after on average 50 months of in vivo functioning [9]. By reason of severe pain complaints 8.3% of the loosened knees were revised within the follow-up period.

Finite element (FE) analysis is a good method to evaluate knee mechanics and to perform comparative mechanical analyses, provided that enough emphasis is put on the validation of the results. FE models have been used to study implant loading for both standard and high-flexion TKA components [1,10]. In a previous FE study [11] we found critical tensile and shear stress conditions at particularly the femoral fixation site beneath the anterior flange

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during deep flexion. The FE knee model used in that study only included a posterior-stabilized high-flexion knee implant and, to the authors knowledge, no studies have yet been published about the effect of PCL conservation on the loading of the femoral fixation site during deep flexion. PCL tension may increase the tibio-femoral load during deep flexion [7] and further increase the risk of implant loosening.

The objective of the present study was to evaluate the effect of PCL retention on the loading of the femoral fixation site during weight-bearing deep knee flexion (ROM ≤ 155°). A three-dimensional FE knee model was developed including high-flexion prosthetic components. The loading condition of the femoral fixation site was evaluated for both a cruciate-retaining and a posterior-stabilized high-flexion knee replacement. Furthermore, we investigated the effect of variations in PCL functioning and inadequate support of the femoral implant due to poor bone quality on the predicted femoral loosening potential.

The hypotheses tested in this article are:

1. PCL retaining prostheses increase the tibio-femoral load during deep flexion and further increases the risk of implant loosening, compared to PCL substituting protheses.
2. An increase in PCL tension will increase the risk of implant loosening.
3. Reduction of bone mineral density of the femur will increase the risk of implant loosening.

2. Materials and methods

2.1. Finite element knee model

The FE analysis performed in this study included two sub-models to improve computational efficiency while varying patient-specific properties: (1) a global FE knee model to determine the femoral loading during knee flexion and (2) a local femoral FE model to analyze the stress state at the femoral fixation site (Fig. 1). The global knee model has previously been described in detail [11] and consisted of a proximal tibia and fibula, high-flexion TKA components, a quadriceps/patella tendon, a non-resurfaced patella and a PCL in case cruciate-retaining TKA components were evaluated. Knee flexion was achieved by application of the ground reaction force (=350 N) to the ankle joint and releasing the fixed quadriceps tendon slightly per increment of flexion, comparable to cadaveric loading set-ups such as the Oxford knee testing rig [12]. Hence, 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 unconstraint and free to seek its own kinematics. Femoral loading conditions derived from the global knee model were applied to the local femoral model. The local FE model included a femoral component, implant–cement interface elements, a 1 mm thick bone cement layer and a distal femur. High-flexion TKA components of the cruciate-retaining PFC Sigma CR150 and posterior-stabilized PFC Sigma RP-F, both rotating-platform TKA systems (DePuy International, Leeds, UK), were incorporated in the FE models to evaluate the effect of PCL conservation. FE simulations were performed using MSC.MARC (MSC Software Corporation, Santa Ana, CA, USA).

The number of elements and material properties assigned to different parts of the local femoral FE model are given in Table 1. Except for the implant–cement interface, four-noded tetrahedral elements were used to generate the FE model. Cement pockets in the femoral component were neglected to avoid edge artifacts and simplify the interface analysis. The geometry of the distal femur was obtained from a femoral CT-scan of an 81 years old male (*t*-score = −1.9) using modeling 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 bone mineral density (BMD) information derived from the calibrated CT-scan according to Keyak and Falkinstein [14]. Bone cement was modeled as a linear elastic material (E = 2200 MPa).

2.2. Femoral implant–cement interface

Zero-thickness six-noded cohesive elements were used to model the femoral implant–cement interface, which was the region of interest and indicated to be at risk during deep knee flexion [8]. 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 at the femoral 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. The tensile (S_t = 2.09 MPa) and shear (S_s = 3.89 MPa) strengths 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 interface strength (S_c = 70 MPa) were obtained from literature [16,17]. The stiffness of the interface under compression was set very high compared to tension ($K_c = 100 \cdot K_t$).

The multi-axial Hoffman failure criterion [18] was used to determine the locations where the femoral implant–cement interface would debond based on the local normal and shear stresses (Fig. 2a). The Hoffman criterion uses a failure index (*FI*) to describe the risk of interface failure when exposed to a certain stress state based on a quadratic relation between the interface strength in pure normal and shear direction. Static interface debonding is expected to occur in case $FI \geq 1$ and long-term fatigue failure is likely in case $FI \geq 0.5$ [19]. Since we experimentally have demonstrated that the strength of the implant–cement interface under mixed-mode tensile and shear loading conditions does not comply with the traditional quadratic Hoffmann failure formulation [15], the Hoffmann criterion was modified for tensile normal loading conditions (Eqs. (1) and (2)):

$$\text{Normal tensile stress}: \quad \sigma_n \geq 0 \rightarrow FI = \frac{1}{S_s}\sigma_s + \frac{1}{S_t}\sigma_n = 1 \tag{1}$$

$$\text{Normal compressive stress}: \quad \sigma_n < 0 \rightarrow FI = \frac{1}{S_t S_c}\sigma_n^2 + \left(\frac{1}{S_t} - \frac{1}{S_c}\right)\sigma_n + \frac{1}{S_s^2}\sigma_s^2 = 1 \tag{2}$$

2.3. Femoral fixation analysis

Because the mechanical properties of the PCL, such as its stiffness, are known to vary per patient [20] and directly affect the PCL force and joint load, the loading of the femoral fixation site was evaluated for a varying PCL stiffness. Similarly as described in an earlier FE study considering cruciate-retaining TKA [7], three typical PCL responses were derived from experimental data [21]: a relatively stiff PCL (P1), an average PCL (P2) and a relatively compliant PCL (P3). Both the tibio-femoral joint force and the PCL tension were determined using the global FE knee model to establish at which flexion angle the highest interface loading was generated. All joint forces acting within the knee were normalized for bodyweight (BW). The anterior, posterior and distal femoral interface areas were selected as separate regions of interest as these interface