Clinical Biomechanics 25 (2010) 1018–1024

Contents lists available at ScienceDirect

Clinical Biomechanics

journal homepage: www.elsevier.com/locate/clinbiomech

Intraoperative impaction of total knee replacements: An explicit finite-element-analysis of principal stresses in ceramic vs. cobalt–chromium femoral components

Daniel Kluess *, Wolfram Mittelmeier, Rainer Bader

Department of Orthopaedics, University of Rostock, D-18057 Rostock, Germany

ARTICLE INFO

Article history:
Received 7 May 2009
Accepted 2 August 2010

Keywords:
Total knee replacement
Impaction
Finite-element-analysis
Ceramics
Femoral component

ABSTRACT

Background: In connection with technological advances in the manufacturing of medical ceramics, a newly developed ceramic femoral component was introduced in total knee arthroplasty. We generated an explicit finite-element-model to calculate the stresses developed under the highly dynamic intraoperative impaction with regard to cobalt–chromium and ceramic implant material as well as application of a silicone cover in order to reduce stress.

Methods: The impaction was calculated with the hammer hitting the backside of the impactor at previously measured initial velocities. Subsequently the impactor, consisting of a steel handhold and a polyoxymethylene head, hit the femoral component. Instead of modelling femoral bone, the implant was mounted on four spring elements with spring constants previously determined in an experimental impaction model. The maximum principal stresses in the implants were evaluated at 8000 increments during the first 4 ms of impact.

Findings: The ceramic implant showed principal stresses 10% to 48% higher than the cobalt chromium femoral component. The simulation of a 5 mm thick silicone layer between the impactor and the femoral component showed a strong decrease of vibration resulting in a reduction of 54% to 68% of the maximum stress amounts. The calculated amounts of principal stress were beneath the ultimate bending strengths of each material.

Interpretation: Based on the results, intraoperative fracture of femoral components in total knee replacement may not be caused solely by impaction, but also by contributing geometrical factors such as inadequate preparation of the distal femur. In order to minimize the influence of impaction related stress peaks we recommend limiting the velocity as well as the weight of the impaction hammer when inserting femoral components. The silicone cover seems to deliver a strong decrease of implant stress and should be considered in surgery technique in the future.

1. Introduction

The number of primary total knee replacements (TKR) in the United States of America increased from 129,000 in 1990 to 381,000 in 2002 (Kurtz et al., 2005). According to the Swedish knee arthroplasty register (Robertsson et al., 2001), the most prevalent complication encountered in primary TKR is implant loosening (approximately 44%), which is directly connected to osteolysis. Wear particles generated in the articulating surfaces have adverse effects on osteoblast function and stimulate osteoclast recruitment. The expression of cytokines and matrix metalloproteinase is concurrently increased in the presence of wear particles (Choi et al., 2005). The evidence linking osteolysis and aseptic loosening with metal sensitivity is circumstantial: causes and effects are discussed controversely (Jacobs and Hallab, 2006; Bader et al., 2008).

A solution to avoid sensitivity against metallic materials and to reduce wear debris is found in the application of ceramic implant components (Hannouche et al., 2005; Fisher et al., 2006; Kluess et al., 2008). In total hip replacement (THR), the use of ceramic components revealed promising results in increased wear resistance and long-term survival (Hannouche et al., 2005). Initial steps to introduce ceramics in TKR were realized firstly in the form of a non-cemented tibial tray by Langer et al. in 1972 (Langer, 2002). The extension of alumina ceramic to a femoral component was realized by Oonishi et al. in 1982 (Bal and Oonishi, 2003). Further developments included the implementation of a polyethylene tibial inlay for improved articulation as well as advanced cement fixation with ceramic beads on the implant surface (Bal and Oonishi, 2003). However, these ceramic femoral components did not succeed worldwide.

At present, a new Biolox® delta ceramic femoral component integrated in the Multigen Plus total knee system (Lima-LTO, San Daniele, Italy, Fig. 1) is tested clinically in a multi-center study (Mittelmeier et al., 2006). Approval of the ceramic component for clinical testing was gained following extensive experimental testing

* Corresponding author. Department of Orthopaedics, University of Rostock, Doberaner Strasse 142, D-18057 Rostock, Germany.
E-mail address: daniel.kluess@med.uni-rostock.de (D. Kluess).

0268-0033/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.clinbiomech.2010.08.002

Fig. 1. Multigen Plus total knee replacement with ceramic femoral component (Lima-Lto, San Daniele, Italy).

considering quasi-static and dynamic in-vivo loads. Facing the brittleness and the relatively low fracture toughness of ceramics, the risk of fractures caused by stress peaks has to be examined intensely. Apart from the postoperative in-vivo loads, intraoperative impaction of ceramic components using an impactor and a hammer poses a significant challenge to the implant material. Two fractures of the Biolox® Delta ceramic femoral condyle during impaction were observed at the beginning of the clinical multi-center study (Bergschmidt et al., 2009). It is suspected that the hammer velocity had a major influence on these fractures.

The Finite-Element-Method (FEM) proved as a powerful analytical tool in orthopaedic research to predict the biomechanical behaviour of load-bearing implants. A series of FE-analyses into the biomechanics of the distal femur have been published recently. Completo et al. (Completo et al., 2007) calculated the bone strains at the stance phase of gait in synthetic femurs with different total knee replacements and compared the results with experimental measurements. On this basis, FE-analysis of revision knee endoprostheses followed (Completo et al., 2009). D'Lima et al. (D'Lima et al., 2008) measured the tibial forces during gait using an instrumented knee endoprosthesis and utilized these forces for FE-analyses of contact stresses in a total knee replacement. A FE-study focussing on the surgery technique deals with notching of the cortex during preparation of the distal femur (Zalzal et al., 2006), which was found to cause high stress peaks under load during gait.

Compared to the quasi-static loads during gait, the intraoperative impaction of ceramic components which is being analysed in the present paper is a highly dynamic process. Consequently, an analysis of the impaction behaviour necessitates the consideration of time-dependent damping forces and inertial forces.

The objective of developing a numerical model of the intraoperative impaction of total knee components was to compare the principal stresses in cobalt–chromium vs. ceramic femoral components analysing the safety against failure and breakage of the new ceramic implant. Thereby, the impaction velocity shall be evaluated.

2. Methods

2.1. Generation of the finite-element-mesh

The ceramic and metallic femoral component of the Multigen Plus knee and the impactor were provided as computer-aided-design (CAD) files from the manufacturer. All components were meshed with hexahedral elements using the software GEOMAGIC (Raindrop Geomagic, NC, USA) and the pre-processor software PATRAN (MSC, CA, USA). In order to allow for automatic hexahedral mesh generation, the surfaces of the CAD-files from the manufacturer were rearranged such that the whole implant consisted of oppositely located quadrilateral NURBS-surfaces. Afterwards, the quadrilateral surfaces were assembled in hexahedral solids. Finally, automatic hexahedral mesh generation was performed based on the isomesher included in PATRAN (Fig. 2). Following a convergence study, the components were meshed with approximately 55,500 elements (element-type:

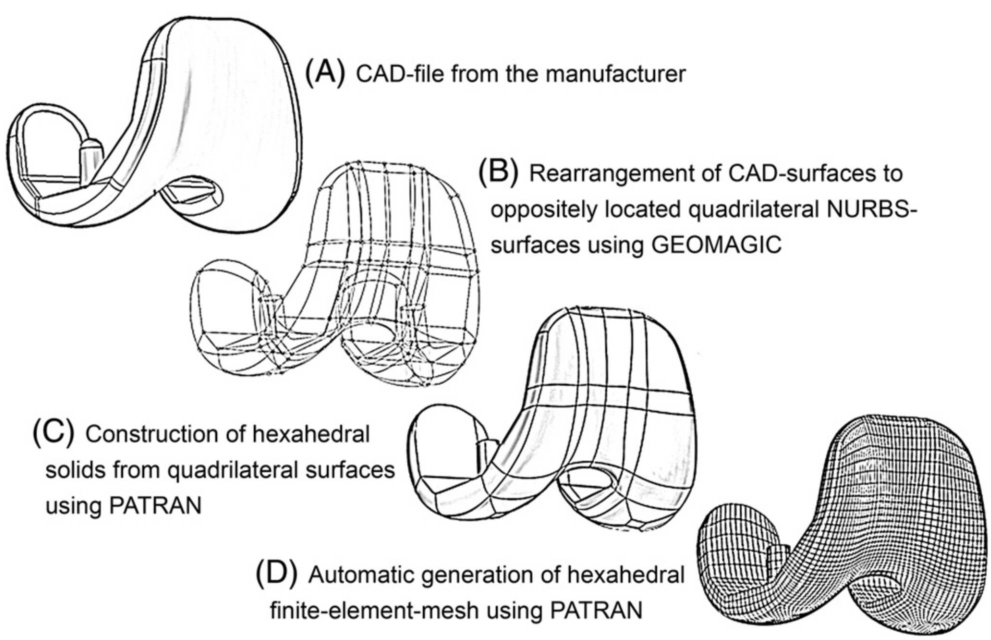

Fig. 2. Hexahedral meshing of the femoral component partially based on the algorithm proposed by Kluess et al. (Kluess et al., 2009).