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Experimental and computational studies on the femoral fracture risk for advanced core decompression

T.N. Tran [a,b], S. Warwas [a], M. Haversath [a], T. Classen [a], H.P. Hohn [c], M. Jäger [a], W. Kowalczyk [b], S. Landgraeber [a,*]

[a] Department of Orthopaedics, University Hospital Essen, University of Duisburg–Essen, Hufelandstr. 55, 45147 Essen, Germany
[b] Chair of Mechanics and Robotics, University of Duisburg–Essen, Lotharstr. 1, 47057 Duisburg, Germany
[c] Department of Anatomy, University Hospital Essen, University of Duisburg–Essen, Hufelandstr. 55, 45147 Essen, Germany

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ABSTRACT

Background: Two questions are often addressed by orthopedists relating to core decompression procedure: 1) Is the core decompression procedure associated with a considerable lack of structural support of the bone? and 2) Is there an optimal region for the surgical entrance point for which the fracture risk would be lowest? As bioresorbable bone substitutes become more and more common and core decompression has been described in combination with them, the current study takes this into account.

Methods: Finite element model of a femur treated by core decompression with bone substitute was simulated and analyzed. In-vitro compression testing of femora was used to confirm finite element results.

Findings: The results showed that for core decompression with standard drilling in combination with artificial bone substitute refilling, daily activities (normal walking and walking downstairs) are not risky for femoral fracture. The femoral fracture risk increased successively when the entrance point is located further distal. The critical value of the deviation of the entrance point to a more distal part is about 20 mm.

Interpretation: The study findings demonstrate that optimal entrance point should locate on the proximal subtrochanteric region in order to reduce the subtrochanteric fracture risk. Furthermore the consistent results of finite element and in-vitro testing imply that the simulations are sufficient.

1. Introduction

Core decompression (CD) represents an established technique for treatment of early stage osteonecrosis and most commonly used for disease that affects the hip joint. The procedure is designed to decrease pressure within the bone by restoring blood flow to the bone (Steinberg, 2000; Veillette et al., 2006). CD consists of drilling one or more small channels into the dead bone (necrotic lesion) from the lateral subtrochanteric region of femur (Mont et al., 2004). This is associated with a lack of structural support of the bone. Subtrochanteric stress fractures at the surgical entrance point of the core track were regularly described as a complication of conventional core decompression with a rate of about 1–2% (Schneider et al., 2000; Smith et al., 1995; Steinberg, 1995; Steinberg et al., 1995). Camp and Colwell (1986) found an even higher fracture rate. That's why patients normally are requested to be partial weight bearing for several, normally six weeks due to the risk of fracture (Shuler et al., 2007; Veillette et al., 2006). Stronach et al. (2010) stated that a more proximal entrance point might prevent subtrochanteric fracture. However, these recommendations are mainly based on clinical experience. So there is a need for rigorous studies to determine specific indications for this kind of treatment.

The so-called "advanced core decompression" (ACD) is a modified technique of core decompression that may allow better removal of the necrotic tissue by using a new percutaneous expandable reamer and refilling of the drill hole and the defect with an injectable, hard-setting, composite calcium sulfate ($CaSO_4$)–calcium phosphate ($CaPO_4$) bone graft substitute (PRO-DENSE®, Wright Medical Technology™, Inc., Arlington, TN, USA) (Civinini et al., 2012). In a former study it was shown by biomechanical in-vitro tests that the load-bearing capacity of femur treated by ACD was the same as that of the untreated femur of the contralateral side from the same body donor (Landgraeber et al., 2012). These tests were performed using the standard entrance point at the tuberculum innominatum, under the assumption that this is the optimal entrance point. In the current study it should be evaluated what influence variations of the entrance point may have on the structural support of the bone. For that purpose finite element method is used in addition to biomechanical testing.

The finite element (FE) method has recently become a gainful and powerful technique for numerical simulation in orthopedic biomechanics (Lee et al., 2006; Lian et al., 2008; Volokh et al., 2006; Yang et al., 2002). Given the structural nature of the femur, finite element model

* Corresponding author at: Department of Orthopaedics, University Hospital Essen, University of Duisburg–Essen, Hufelandstr. 55, D-45147 Essen, Germany.
E-mail address: stefan.landgraeber@uni-due.de (S. Landgraeber).

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derived from the reconstruction of CT or MRI images may help to effectively simulate the influences of CD on the mechanics of femur. Floerkemeier et al. (2011) performed a finite element analysis of CD using a 10-mm drill and CD via multiple small drillings without bone grafting as well as CD combined with the insertion of a tantalum rod. They suggested that CD using small drillings should be preferred since it was associated with a lower fracture risk compare to conventional CD using a 10-mm drill.

The aim of this study was to develop a model for bones treated by core decompression to answer two questions which are often addressed by orthopedic surgeons regardless if bone substitutes are used or not: 1) Is the core decompression procedure associated with a considerable lack of structural support of the bone? and 2) Is there an optimal region for the surgical entrance point for which the fracture risk would be lowest. The results of the model were verified by comparing with data from an established biomechanical in-vitro test. As core decompression in combination with bone substitutes becomes more and more common, we performed this study for the ACD.

2. Methods

2.1. Finite element simulation

A three-dimensional computer aided design model of a full left femur of a male donor was generated from a MRI scan data set of about 350 slices using the software Avizo® (VSG). The procedure included first a segmentation process that assigns the bone region to pixels of the image. A triangular surface model was then extracted from segmentation results based on surface reconstruction techniques. The last step was the generation of the model volume enclosed by the surface. A necrosis domain was supposed to be located in the cranioventral part of the femoral head as it mostly does. In our study, this necrotic lesion was supposed to be completely removed after the ACD using the cutting instrumen X-ream™ (Wright Medical Technology, Inc.). Therefore, a spheroid form similar to the working domain of the X-ream™ was chosen with minor and major axes of 11 and 21 mm, respectively. A drilling channel of 9 mm diameter was created from an entrance point on the lateral subtrochanteric region penetrating through the necrotic domain. We defined a coordinate system (t, d) in which t and d correspond to the posterior and distal directions, respectively. The origin of the coordinate system was located at the inferior border of the greater trochanter in the subtrochanteric lateral cortex as the position of the supposed standard entrance point. Ten different entrance point positions were chosen corresponding to ten models: (0, −10), (0, 0), (0, 10), (0, 20), (0, 30), (5, −10), (5, 0), (5, 10), (5, 20), and (5, 30) (Fig. 1, left) in which all coordinates were measured in mm. It means that the models (0, 30) and (5, 30) have the farthest distal entrance point (Fig. 1, right) and the models (0, −10) and (5, −10) have an entrance point near the greater trochanteric region (Fig. 1, middle). The drilling channel and the necrosis domain were filled with the bone substitute PRO-DENSE® (Wright Medical Technology, Inc.). Contact between PRO-DENSE® and bone was supposed to be bonded.

The Poisson ratio of PRO-DENSE® was supposed to be similar to cancellous bone and the Young's modulus of PRO-DENSE® was determined from an axial compression test. Six cubic specimens of $2 \times 2 \times 1$ cm were tested on a testing machine which had a maximum working load of 10 kN. The force–displacement curves were converted to stress–strain curves for each specimen. The main portion of the stress–strain curve for each specimen was then fitted by a straight line in the nonlinear least squares sense and the Young's modulus was the slope of this line. The Young's modulus of PRO-DENSE® was the mean of six calculated values and given in Table 1.

Finite element meshes were generated using 4-node tetrahedron element (Fig. 2, right). A mesh refinement was performed in the drilling region to better capture the mechanical behavior of the hole. A linear elastic model that consists of a superficial cortical bone layer with uniform thickness of 3 mm and an internal cancellous bone was considered. The corresponding material properties were given in Table 1 according to Lutz et al. (2011), Keyak et al. (1998), and Keaveny et al. (1994).

To estimate the fracture risk, peak loads of hip joint force representing daily activities were investigated for two cases: normal walking and walking downstairs. The loads were extracted from the patient data set "HSR" (Bergmann et al., 2001) and details of the load components were given in Table 2. In each analysis, the applied load was distributed over nodes on the femoral head within a radius of 10 mm to avoid stress concentration. The distal end of the femur was fully constrained (Fig. 2, left). FE analysis was performed using ANSYS v14.

A mesh convergence analysis was studied for the model (0, 0) in the case of normal walking load condition. First, three different meshes with maximum element lengths of 1, 2 and 3 mm were generated. The element numbers for each mesh were 1,846,310, 690,198 and 497,915 respectively. Second, three additional meshes were created from the three above meshes in which 10-node tetrahedron element was used instead of the 4-node one. The element numbers for 10-node tetrahedron element meshes were kept unchanged as those for 4-node meshes. The total strain energy and the maximum value of the first principal

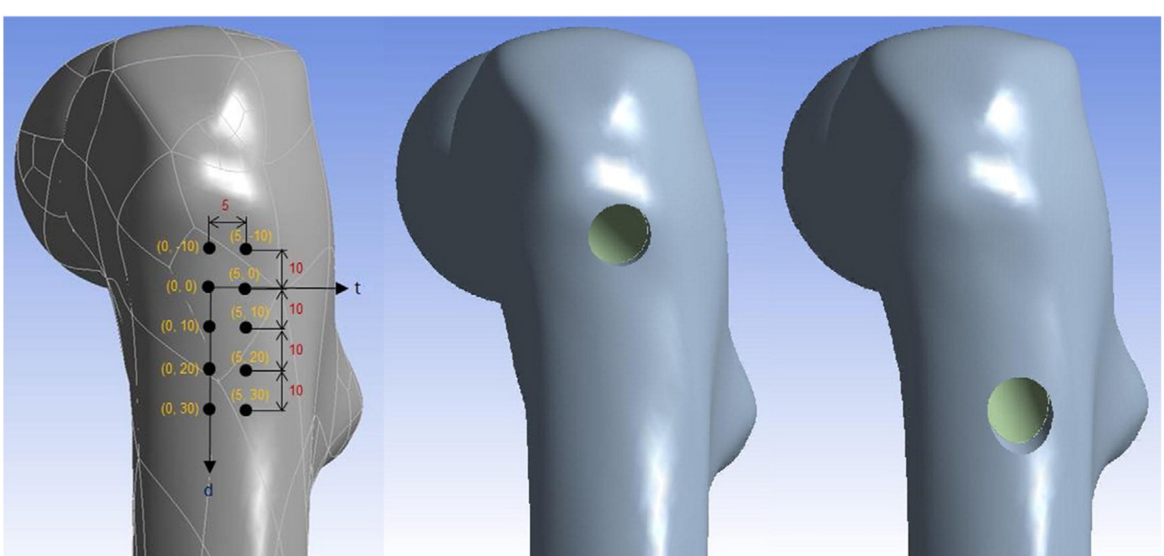

Fig. 1. Ten different entrance point positions (left), model with the most proximal drilling channel (middle) and model with the most distal drilling channel (right).