

Femoral head necrosis: A finite element analysis of common and novel surgical techniques

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ABSTRACT

Background: Femoral head necrosis is a common cause of secondary osteoarthritis. At the early stages, treatment strategies are normally based on core decompression techniques, where the number, location and diameter of the drilling holes varies depending on the selected approach. The purpose of this study was to investigate the risk of femoral head, neck and subtrochanteric fracture following six different core decompression techniques.

Materials: Five common and a newly proposed techniques were analyzed in respect to their biomechanical consequences using finite element analysis. The geometry of a femur was reconstructed from computed-tomography images. Thereafter, the drilling configurations were simulated. The strains in the intact and drilled femurs were determined under physiological, patient-specific, muscle and joint contact forces.

Findings: The following results were observed: i) - an increase in collapse and fracture risk of the femur head by disease progression ii) - for a single hole approach at the subtrochanteric region, the fracture risk increases with the diameter iii) - the highest fracture risks occur for an 8 mm single hole drilling at the subtrochanteric region and approaches with multiple drilling at various entry points iv) - the proposed novel approach resulted in the most physiological strains (closer to the experienced by the healthy bone).

Interpretation: Our results suggest that all common core decompression methods have a significant impact on the biomechanical competence of the proximal femur and impact its mechanical potential. Fracture risk increases with drilling diameter and multiple drilling with smaller diameter. We recommend the anterior approach due to its reduced soft tissue trauma and its biomechanical performance.

1. Introduction

Insufficient blood supply may lead to osteonecrosis of the femoral head. It is often characterised by persistent progression despite treatment, resulting in painful disabling arthritis, subchondral fracture or collapse of the femoral head (Glimcher and Kenzora, 1979; Pierce et al., 2015). The socioeconomic impact of this disease is dramatic since advanced osteonecrosis with secondary osteoarthritis is reported in 5 to 10% of all total hip replacements (Mankin, 1992). This disease commonly affects young patients around the age 20–40 years which further emphasises the importance of early treatment so that the patients can undergo a joint-preserving operative treatment (Mont and Hungerford, 1995).

In early stages of the disease (Association Research Circulation

Osseous (ARCO) stage 1 and 2) a joint-preserving technique is preferred (Arlet, 1992). The most common technique is core decompression with or without grafting of bone substitutes (Amanatullah et al., 2011). Core decompression gains access to the necrotic femoral head lesion through the lateral subtrochanteric region towards the femur neck. A major remaining concern of surgeons regarding this technique is the structural defect at the lateral cortex of the femur, which is a predetermined location for a fracture. In the literature, the incidence of post-decompression subtrochanteric fractures varies between 0 and 5% (Aluisio and Urbaniak, 1998; Fairbank et al., 1995; Markel et al., 1996; Song et al., 2007; Steinberg et al., 2001). Certain predisposing factors such as location and size of the osteonecrosis have been described in the literature (Mantes et al., 2009; Sadile et al., 2016). In particular, the size in relationship to the weight-bearing portion of the femoral head is

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decisive for osseous complications (Brown et al., 1993). Several approaches exist that differ in the number of entry points, the drilling diameter or the location of the entry point (Cao et al., 2016; Lieberman, 2004), leading to different biomechanical conditions of the femur and therefore different grades of bone fracture risk.

FE techniques have been previously used to investigate the risk of femoral fracture following core decompression (Floerkemeier et al., 2011; Ji et al., 2013; Lutz et al., 2011; Tran et al., 2014a, 2014b), however insufficient data exists concerning the stability of the bone after decompression although fracture remains the main concern of the surgeons (Tran et al., 2014a, 2014b) (Testi et al., 1999) (Cao et al., 2016). In addition, failure loads of these studies were based on peak stress/strain values induced within the bone, which could be insufficient to determine the complex mechanical environment (Sadile et al., 2016). Furthermore, an exhaustive analysis of the risk of collapse and fracture for different femoral regions has not been performed; the analyses were just based on the femoral head or the region around the drilling entry points. In total hip arthroplasty, the minimally invasive anterolateral approach has several advantages over the classical direct lateral approach. It leads to a decreased approach-related muscle injury resulting in an increased post-operative function (Müller et al., 2011a, 2011b). However, it has not been studied in the field of core decompression of patients with femoral head necrosis. In this patient population, the incision can be even smaller and less invasive. Therefore, the present study evaluates the risk of femoral head, femoral neck and subtrochanteric fracture after core decompression, considering the advance of the disease at the moment of surgery and various clinical drilling techniques including a minimally invasive anterolateral approach. The aim of this study is to investigate changes in the maximum absolute principle strains (equal to the highest principle strain in absolute value) of the femur between the intact and post-decompression situations using FE numerical techniques.

2. Methods

2.1. Finite element model

Three-dimensional (3D) FE models of the intact and treated femur were developed using the commercial finite element software ABAQUS 6.12 (Dassault Systemes, Vélizy-Villacoublay, France). The bone geometry corresponds to a right femur selected out of a larger analysis of 100 patients who experienced a Total Hip Arthroplasty (THA) in our clinic^{38, 41}. In the large cohort, proximal bone remodeling was analyzed using a combined quantitative computed tomography (QCT) and bone remodeling analysis approach (Szwedowski et al., 2012; Taylor et al., 2012). The selected bone corresponds to a representative patient with median bone density whose geometry was reconstructed from Computed Tomography (CT) scan images (Fig. 1). Second-order, ten-node, tetrahedral elements with a typical edge length of 2 mm were used to mesh the bone. However, as Fig. 1 shows, a finer mesh size was used around the holes (typical local element length edge of 0.1 mm for the areas around holes). Sensitivity analyses of the mesh were performed with an emphasis on the local region surrounding the holes, in addition to overall femur. The element size was decreased until convergence, that is, until a change of no more than 5% in the predicted strains within the femur was achieved. It led to approximately 180,000 elements with 210,000 nodes (Fig. 1). For further details about mesh, see the Supplementary Data. Bone was modelled as a linear elastic and heterogeneous material. Heterogeneous material properties were derived from grey-scale values from the CT scan data set of the healthy femora. The bone mass density distribution was calculated from the CT data using the empirical approach described by Helgason et al. (Helgason et al., 2008) (Fig. 1). A calibration phantom consisting of five mixtures of calcium carbonate and polymer with known densities was used. This phantom was recorded at the same time as the acquisition of the patient-specific CT (Ciarelli et al., 1991; McBroom et al., 1985).

Then, the apparent density was calculated based on the ash density values taken from the patient-specific CT scan following Keyak et al. (Keyak et al., 1994; Morgan et al., 2003). Finally, the correlation defined by Morgan et al. (Morgan et al., 2003) for the human femur was chosen to determine the elasticity–density relationship,

$$E = 6.850 \rho_{\text{app}}^{1.49},$$

where E is the Young's modulus in GPa and ρ_{app} represents the apparent density measured in g/cm^3 .

To simulate the advance of the osteonecrosis disease, a necrotic region was defined in the femoral head (Ji et al., 2013). In this region, material properties were assigned as two-thirds of the healthy femur material properties from the patient to simulate the disease, (Yuehwei and Draughn, 1999). The material properties came from a patient who has not femoral head necrosis.

Physiological boundary conditions were set to minimise the reaction forces at the constrained nodes (Speirs et al., 2007) (Fig. 1). Finally, in-vivo, patient-specific muscle and joint contact forces were calculated while the selected patient performed a walking gait cycle using a validated musculoskeletal model (Trepczynski et al., 2012). Applied joint and muscles loads were taken from the frame in which the highest calculated hip contact force occurred (45% of the gait cycle). Muscle loads were applied at a set of nodes representing the location of the muscle attachment (see the Supplementary Data for further details about the muscle forces and contact forces). Therefore, it should be highlighted that the contribution of the most important muscles was considered in the models. In addition, a uniform pressure at the top of the femur head surface was considered in order to simulate the contact reaction as well as the dynamic forces at the hip.

2.2. Modelling core decompression approaches

Six different core decompression approaches were modelled which differed in the number of drilling cores, the drilling diameter and the location of the entry point(s) (Fig. 2). Models were developed using the Boolean operations (subtraction) as virtual surgical approaches. The six drilling techniques that were included in this systematic assessment are shown in Table 1:

2.3. Data analysis

Six core decompression approaches in a healthy and necrotic bone were investigated. For each case, the percentage change in the mechanical conditions of the treated femur in relation to the intact condition was evaluated in three different regions: 1) femoral head, 2) femoral neck and 3) trochanteric and subtrochanteric regions (Fig. 3).

An additional parameter was defined to quantify the Risk of Fracture (ROF) of the entire femur (Schileo et al., 2008; Testi et al., 1999):

$$\text{ROF} = \varepsilon / \varepsilon_{\text{lim}}$$

where ε is the maximum absolute principal strain at each element of the femur (either compressive or tensile) and ε_{lim} is the corresponding ultimate strain (ultimate compressive strain: 0.0104 and ultimate tensile strain: 0.0073) (Bayraktar et al., 2004; Ford et al., 1996).

Towards this aim, the maximum absolute principal strains was determined at each element for each of the healthy femur. These elements were classified in four groups with the same number of elements, this corresponds to the four statistical quartiles which were named as small, medium, high and very high values for first, second, third and fourth quartile, respectively (Cilla et al., 2017). Then, the maximum absolute principal strains at each element for the rest of the modes were determined. For each model, these strain values were classified according to the aforementioned groups/quartiles. Thereafter, the number of elements falling into the different strain categories was quantified in the drilled models and compared to those of the intact for the same

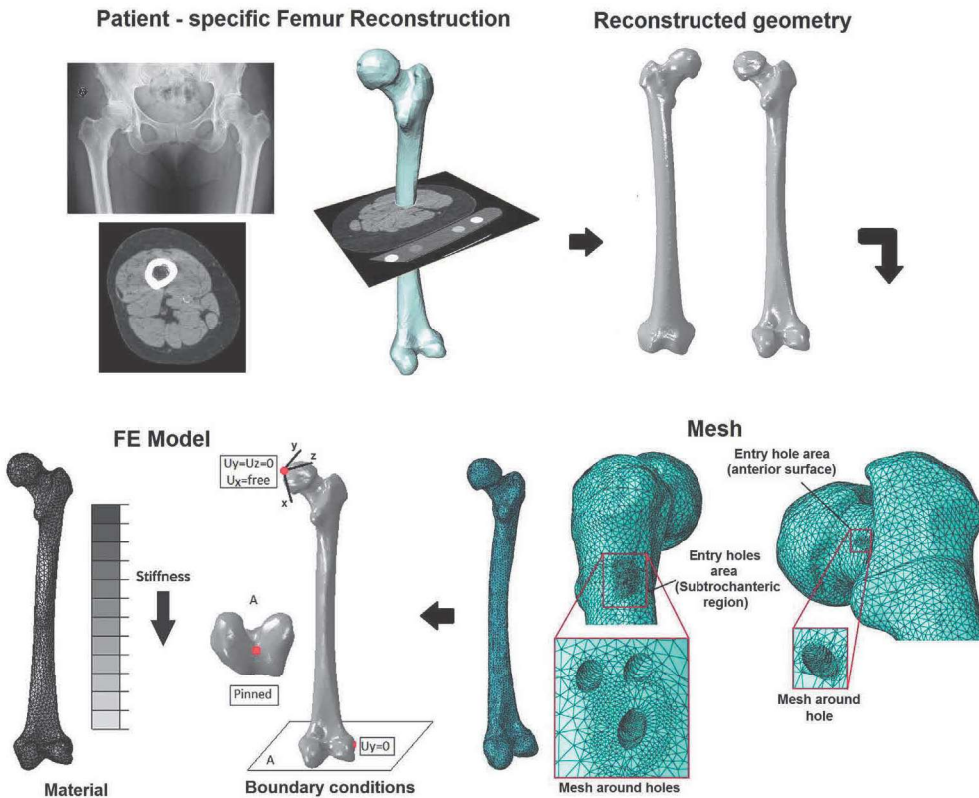


Fig. 1. Steps for building patient-specific musculoskeletal models of the femur: Femur reconstruction from CT clinical images, femur reconstructed geometry, mesh of the model and mesh detail around the entry holes and features to build the FE model (heterogeneous material properties distribution and physiological boundary conditions constrained in the model).

location. It should be noted that the actual numbers corresponding to the quartile boundaries are different for the different studied areas (head, neck and associate fracture risk). Following this approach, a drilled model has an increased risk when the percentage of elements under low strain magnitudes decreases, and consequently, the percentage of elements under high strains increases. Moreover, the ROF scalar value for each element of the different drilled model was assessed and the percentage of elements which have a ROF greater than 1 was compared for the different models in order to measure the overall risk of fracture.

In addition, the differences of strains between the drilled models and the intact femur in each single element were determined. For the purpose of comparison, the model with a single 3 mm diameter hole at the subtrochanteric region was chosen as reference. In this case, the elements of this reference model were divided into four groups (small, medium, high and very high) containing the same number of elements attending to the magnitudes of the differences in strain with the intact femur. The elements of the other drilled models were divided into this group classification for comparison.

3. Results

The complex musculoskeletal loading resulted in bending of the proximal femur, with the lateral side being under tension and the medial side under compression. In general, drilling of the bone resulted in an increase in the strains of the bone in the vicinity of the holes, (Fig. 4b) which was more pronounced in the bone with necrotic material properties in the femoral head (Fig. 4a).

In all configurations, the entry point was located in an area working under tension, except for the configuration with a single entry point in the anterior surface, which works under compression (Fig. 4b).

In the head region, with properties of healthy bone, we observed a slight increase in the number of elements under high maximum absolute principal strains in the drilling procedures using a single hole of 8 mm and 3 holes of 3 mm, both with the same and different entry points, at the subtrochanteric region. Moreover, in a bone with necrotic material properties, an increase in the number of elements under high strain values was detected in all drilling procedures (Fig. 5). There was a moderate influence of quality of the bone (healthy versus necrotic head) on fracture risk for the neck collapse compared to the head collapse. The procedures with the highest increase in the risk of fracture

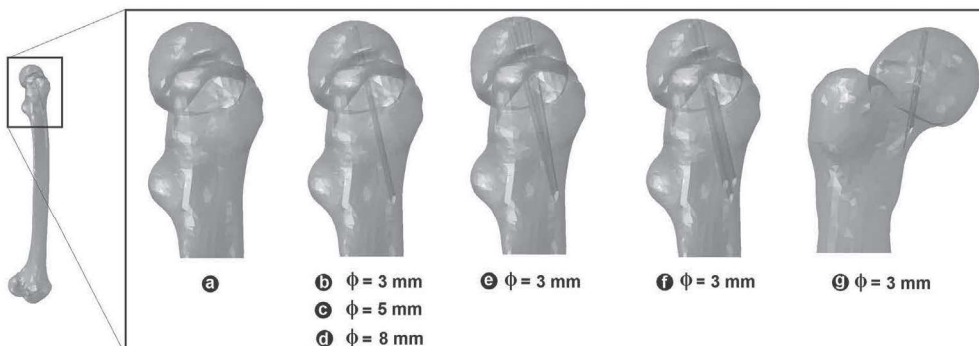


Fig. 2. Geometric models of the necrotic femur after multiple drilling operations.

Table 1
Summary of the six drilling techniques studied.

Model	Position	# Holes	# Entry points	Hole ϕ
Model b (Ramesh, 2009)	Subtrochanteric region towards the head of the femur	1	1	3 mm
Model c (Ramesh, 2009)	Subtrochanteric region towards the head of the femur	1	1	5 mm
Model d (Ramesh, 2009)	Subtrochanteric region towards the head of the femur	1	1	8 mm
Model e	Subtrochanteric region towards the head of the femur	3	1	3 mm
Model f	Subtrochanteric region towards the head of the femur	3	3	3 mm
Model g	Anterior surface	1	1	3 mm

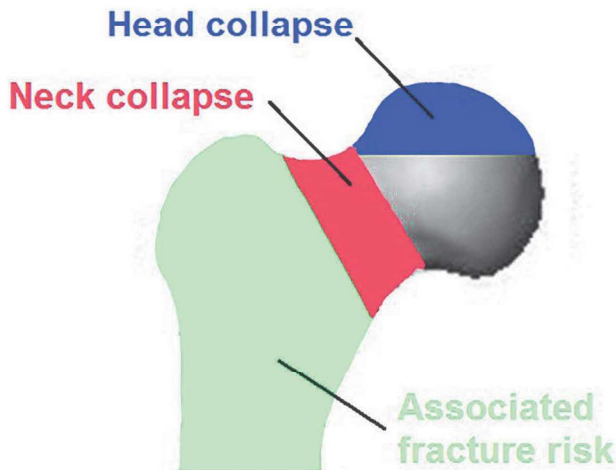


Fig. 3. Regions considered for neck collapse, head collapse, and associated fractures.

were those with a single hole of 5 and 8 mm at the subtrochanteric region. As expected, the model with a single hole of 8 mm at the subtrochanteric region again shows the worst results at early stages of the disease (Fig. 5). Finally, regarding the collapse risk of the subtrochanteric region, the material properties of the femur were not influential since similar results were found for both healthy and necrotic models. Once more, a single 8 mm hole at the subtrochanteric region and multiple drilling were shown to be the riskiest operations (Fig. 5).

Comparing the different approaches in terms of their % difference in the maximum absolute principal strain relative to the intact femur, a

single hole at the anterior surface of the femur was found to produce less mechanical alterations in the femur in the three regions for both healthy and necrotic models (Fig. 6). This drilling option resulted in more physiological strains than the other approaches considered. In addition, a model with a single hole of large diameter at the subtrochanteric area was found to be the most prone to fracture (Fig. 6). In a comparison of the multiple drilling options, the overlapped holes showed a better performance than the parallel holes, at least for this combination of three drilling holes (Fig. 6). Regarding the material properties of the femur, the advance of the disease is once again critical for the fracture risk, especially in the head region. Finally, it was observed that for the models with a single hole at the subtrochanteric region, the risk of fracture increases as the diameter of the holes increases.

Fig. 7 shows the percentage of elements of the entire femur model with a ROF higher than 1. The advance of the disease (necrotic femur) increases the risk of fracture since the number of elements prone to fracture increases. In agreement with the results of Fig. 6, the model with a single hole at the anterior surface of the femur has less elements prone to fracture for both healthy and necrotic models. The fracture risk for the models with a single hole at the subtrochanteric area increases as the diameter of the holes increases and the bigger diameter is the most prone to fracture (Fig. 7). Finally, a slightly lower risk fracture is obtained for the overlapped holes than for the parallel holes.

4. Discussion

In this study, FE models were used to investigate the influence of different core decompression techniques for the treatment of femoral

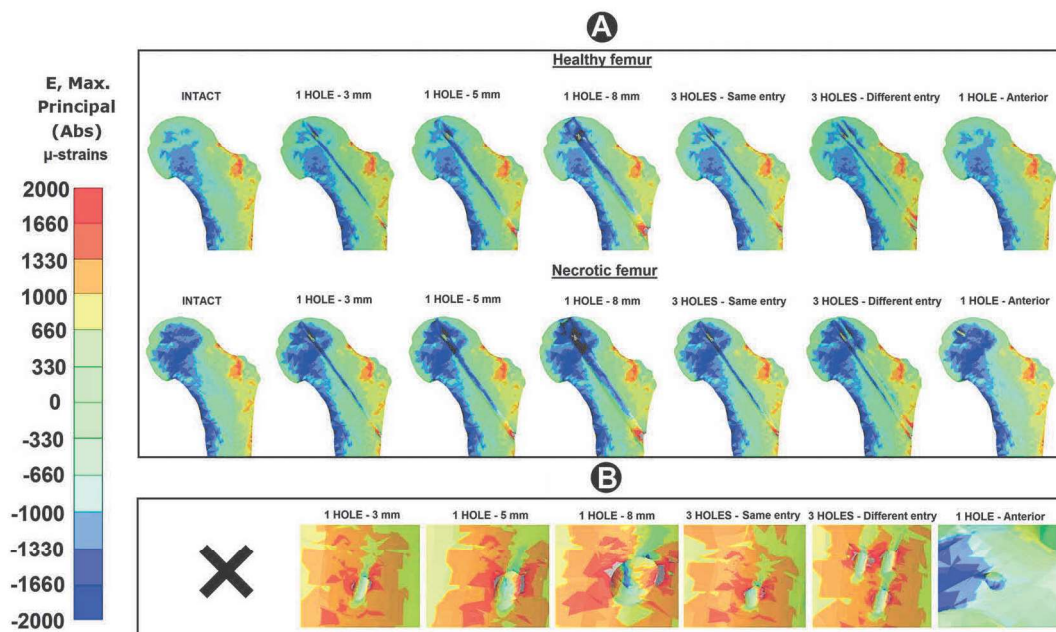


Fig. 4. Contour maps of the absolute value of maximum principal strains (a) at the transversal cross section (at the hole center) of the femur for healthy and necrotic models, and (b) at the region around the entry points for each drilling operation in the femur.

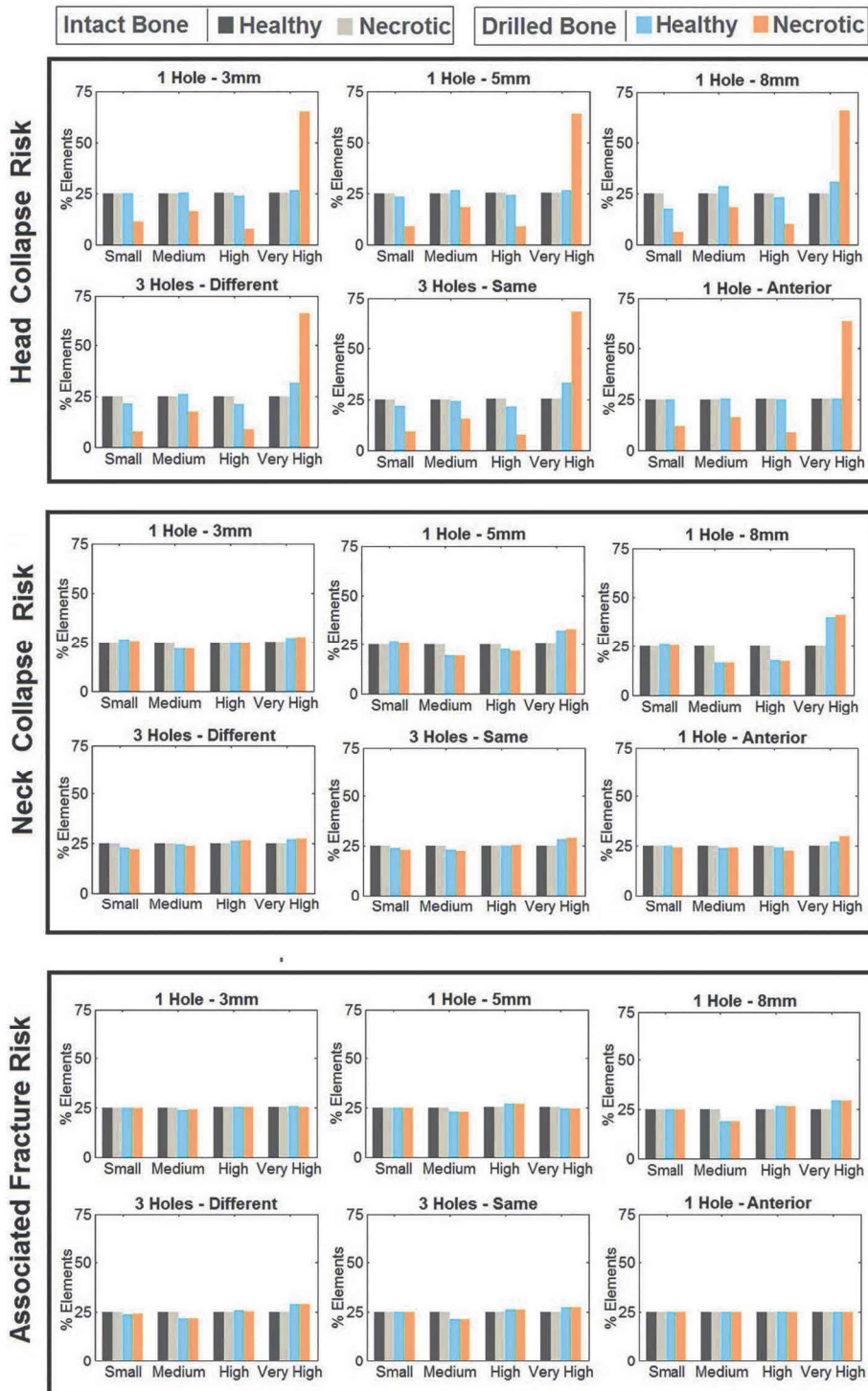


Fig. 5. Comparison of the head and neck fracture and associated fracture risk of the drilled models considered in relation to the intact femur.

head necrosis on the biomechanical behaviour of the proximal femur. The mechanical stability of the proximal femur varies dramatically, depending on the technique. Drilling number and diameter had an effect on the risk of fracture as well as the quality of the treated bone. We proposed a novel drilling technique consisting of an anterior entry point, which reduces the risk of fracture compared to traditional drilling approaches based on a lateral entry point.

Our FE results show that all conventional techniques weaken meaningfully the bone. However, the proposed novel approach based on an anterior entry point for core decompression showed a decreased fracture risk compared to the common techniques used in current clinical practice (Figs. 6 and 7). The anterior approach resulted in

maximum absolute principal strain within the bone, which were closest to the physiological strains when compared to traditional approaches. In conventional drilling configurations, the entry point is located in an area working under tension. In our novel approach the entry point is in an area working under compression (Fig. 4b). The entry point is accessed through an antero-lateral approach, followed by external rotation of the leg. The necrotic femoral head area can be addressed by drilling horizontally. Due to their physiology, bones are stronger in compression and weaker in tension and shear (Manaster et al., 2013), which strengthens the use of the proposed novel approach as a successful technique for femoral head osteonecrosis. In finite element studies, various authors investigated different treatment options.

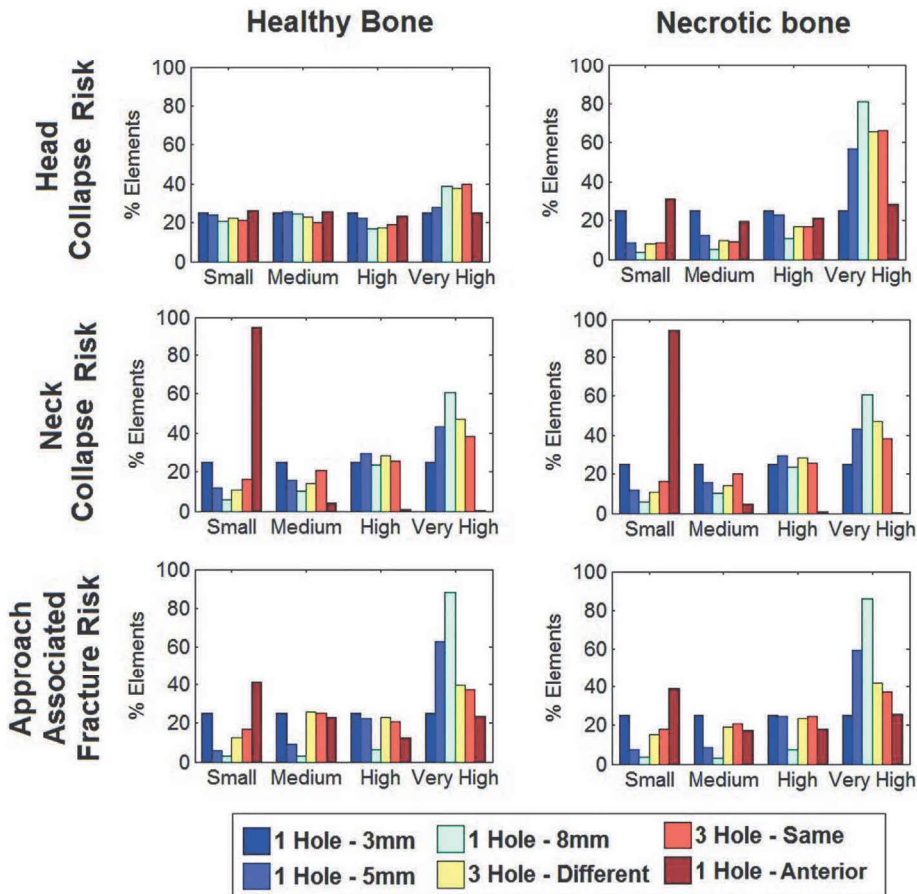


Fig. 6. Difference of strains between the drilled models and the intact femur. Comparison of the head collapse, neck fracture and associated fracture risk.

However, all of these altered the mechanical environment of the proximal femur to a greater extent than our novel drilling approach, especially in regards to the prediction of femoral head collapse (Volokh et al., 2006) and subtrochanteric fractures (Ji et al., 2013; Lutz et al., 2011).

Furthermore, our results show that the most unfavourable drilling techniques were the 8 mm single hole at the subtrochanteric region and multiple drilling holes. One entry point with three drilling directions was slightly safer than three entry points with one drilling direction each. In addition, the advance of the disease is an important factor to consider since it drastically increases the collapse and fracture risk, especially at the femoral head.

Although previous finite element modelling studies have

investigated the effect of drilling diameter or number of drilling holes on the biomechanical behaviour of the bone (Floerkemeier et al., 2011; Lutz et al., 2011; Song et al., 2007; Ji et al., 2013), they only focused on determining the peak strains or stresses induced around the entry points, without considering the strains and stresses within the femur or the neck fracture risk. In addition, they used simplified loading conditions without taking into account muscle loads. Our study uses patient-specific joint and muscle forces to determine alterations in the maximum absolute principal strain state of the bone after different core decompression techniques.

Some remaining limitations of this study need to be stated and taken into account. First, we only investigate normal walking loading conditions. Other demanding activities, such as stair climbing or stumbling,

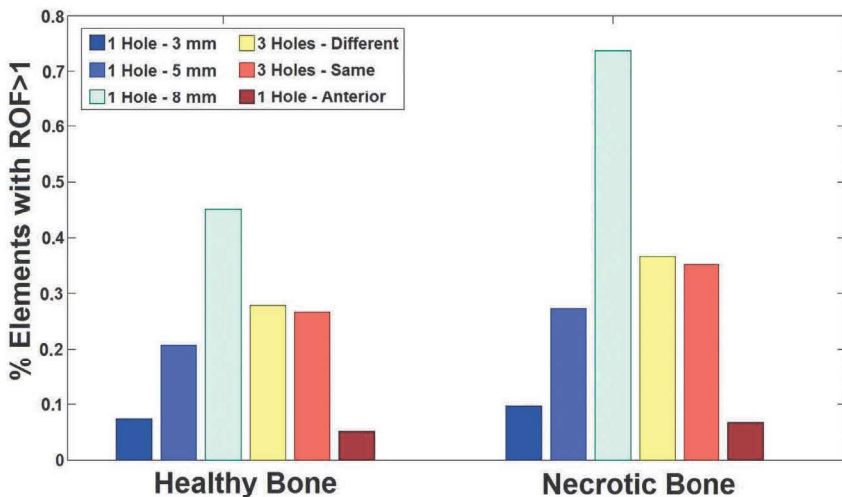


Fig. 7. Percentage of elements with ROF greater than 1. Comparison of the risk to collapse for the different drilled models considered.

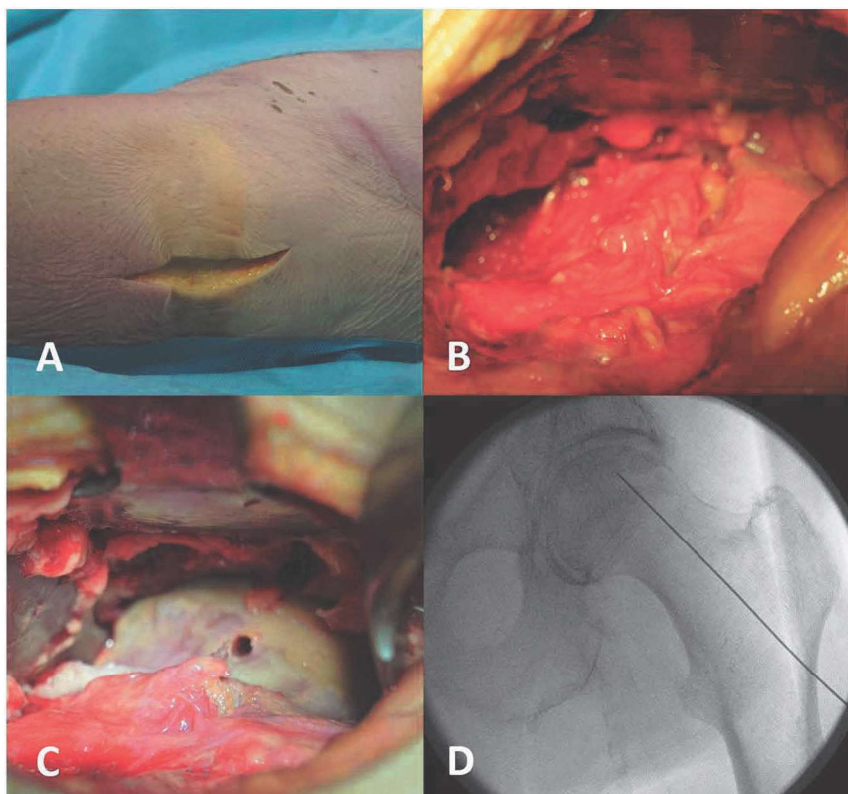


Fig. 8. Anterior entry point approach to the femoral head (A = curved skin cut over the trochanteric region; B = view on the incision of the anterior capsule; C = anterior view at the bone-cartilage intersection of the femoral head; D = AP X-ray of a k-wire directed towards the area of interest).

could play an important role in the risk of fracture and should be investigated in the future. In addition, loading conditions were derived from the gait of a hip replacement patient using a validated musculoskeletal model. To the best of our knowledge, no data exists on the gait pattern of osteonecrotic patients. Similarly to hip joint replacement patients, it is expected that osteonecrotic patients would place lower level of loading on their joints as do age-matched healthy subjects (Stansfield, 2002). To reduce the influence of the loading conditions on our conclusions, we determined relative differences in strain distributions between non-treated and treated (drilled) femurs assuming the same loads in both models. Although the absolute strain values cannot be assured, we can conclude about the influence of the different drilling techniques on the biomechanical behaviour of the femur. Second, we used a maximum principal strain criterion, including asymmetry in the tensile/compressive limit values, following Schileo et al., 2008. Other failure criteria based on principle stress, maximum shear stress or maximum distortion energy have shown small differences in their prediction potential (Keyak and Rossi, 2000). Thirdly, although the novel approach may have advantages over the common core decompression techniques, the approach could be surgically more challenging. Furthermore, due to the angulation and operative approach, the novel access is limited to necrotic defects in the typical anterolateral location. Although the entry point of the bone is not directly subcutaneously palpable, a straight anterior mini-open approach to the hip can be performed by an experienced orthopaedic surgeon (Fig. 8).

5. Conclusions

Despite these limitations, this study can be considered as an additional step towards understanding core decompression techniques and it could represent a reference point for the development and application of the proposed drilling technique. The mechanical stability of the proximal femur varies dramatically, depending on the technique. Alterations to the lateral cortex of the femur should be avoided, especially entry holes greater than 5 mm. From a clinical stand point we

recommend the anterior approach due to its reduced soft tissue trauma and its superior biomechanical performance. However, clinical investigations are warranted in order to provide sufficient evidence of this technique.

Conflict of interest

There are no conflicts of interest related to this manuscript.

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