Orthopaedics & Traumatology: Surgery & Research 101 (2015) 667–673

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Original article

Primary cup stability in THA with augmentation of acetabular defect. A comparison of healthy and osteoporotic bone☆

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ARTICLE INFO

Article history:
Received 6 March 2015
Accepted 7 July 2015

Keywords:
Arthroplasty
Replacement
Hip prosthesis
Bone cements
Osteoporosis

ABSTRACT

Background context: Reconstruction of acetabular defect has been advocated as standard procedure in total hip arthroplasty. The presence of bony defects at the acetabulum is viewed as a cause of instability and acetabular wall augmentation is often used without proper consideration of surrounding bone density. The initial cup-bone stability is, however, a challenge and a number of studies supported by clinical follow-ups of patients suggested that if the structural graft needs supporting more than 50% of the acetabular component, a reconstruction cage device spanning ilium to ischium should be preferred to protect the graft and provide structural stability. This study aims to (1) investigate the relationship between cup motion and bone density and (2) quantify the re-distribution of stress at the defect site after augmentation.
Hyphotesis: Paprosky type I or II, acetabular defects, when reconstructed with bone screws supported by bioabsorbable calcified triglyceride bone cement are significantly less effective for osteoporotic bone than healthy bone.
Materials and methods: Acetabular wall defects were reconstructed on six cadaveric subjects with bioabsorbable calcified triglyceride bone cement using a re-bar technique. Data of the specimen with higher bone density was used to validate a Finite Element Model. Values of bone apparent density ranging from healthy to osteoporotic were simulated to evaluate (1) the cup motion, through both displacement and rotation, (2) and the von Mises stress distribution.
Results: Defect reconstruction with bone screws and bioabsorbable calcified triglyceride bone cement results in a re-distribution of stress at the defect site. For a reduction of 65% in bone density, the cup displacement was similar to a healthy bone for loads not exceeding 300 N, as load progressed up to 1500 N, the reconstructed defect showed increase of 99 μm (128%) in displacement and of 0.08° in rotation angle.
Conclusions: Based on the results, we suggest that an alternative solution to wall defect augmentation with bone screws supported by bioabsorbable calcified triglyceride bone cement, be used for osteoporotic bone.
Level of evidence: Level IV, experimental and cadaveric study.

1. Introduction

The number of primary hip replacements has increased substantially in the United States between 1990 and 2002 [1]. Understanding initial cup stability is especially important in a total hip replacement (THR) done in the presence of defects on the acetabular wall. The stability and fixation can be compromised due to deficiencies on the posterior or anterior acetabular walls [2]. A number of corrective methods for stabilizing the wall prior to cup implantation are currently in use, such as bone grafting [3,4] or screw fixation [5]. A number of studies supported by clinical follow-ups of patients suggested that if the structural graft supports more than 50% of the acetabular component, a reconstruction cage device spanning ilium to ischium should be used to protect the graft and provide structural stability [6]. Noted is a complication rate of 21.2% in the mid to long-term of these procedures. It has also been suggested that cementless components be used to treat major acetabular bone loss [7–9]. Winkler et al. [10] investigated defects augmentation with an antibiotic compound for 37

☆ This work was partially supported by Aurelio M. Caccomo family foundation.
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http://dx.doi.org/10.1016/j.otsr.2015.07.007
1877-0568/

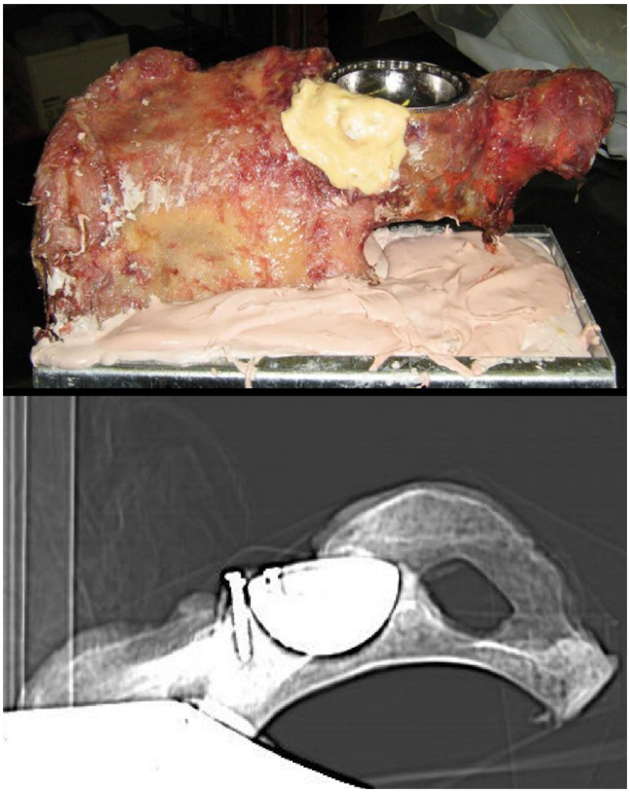

Fig. 1. CT Scout image and actual picture of the implanted pelvis after acetabular augmentation.

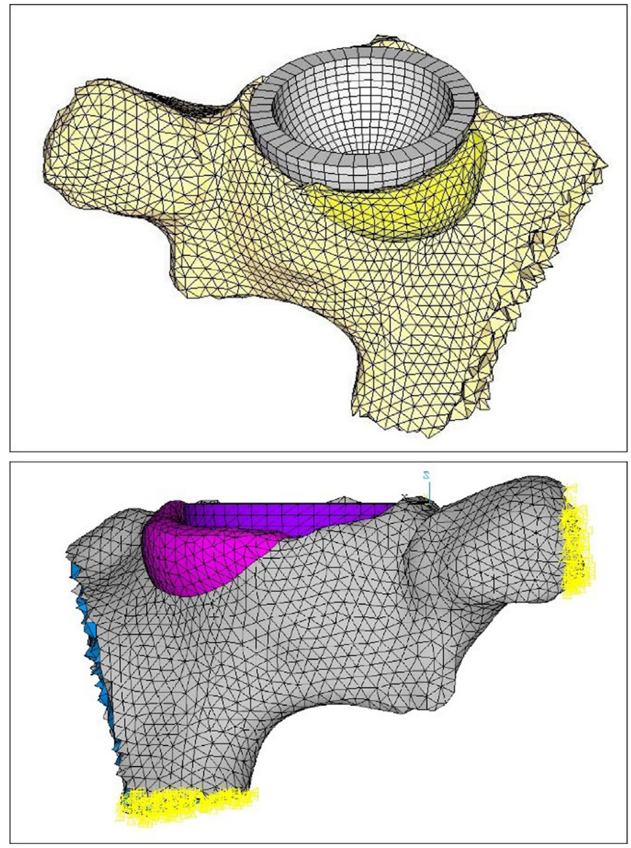

Fig. 2. 3D reconstruction of the hemi-pelvis following defect creation and cup placement and Boundary condition adopted.

patients with success rate of 92 % after 4.4 years. There are several ways to measure and evaluate the defect and hence their classification and method of repair might not be unique [11,12]. Because defects may also occur in conjunction with various levels of osteoporosis characterized by reduced bone density, we hypothesized that Paprosky type I or II, acetabular defects, when reconstructed with bone screws supported by bioabsorbable calcified triglyceride bone cement are significantly less effective for osteoporotic than for healthy bone. This hypothesis was tested using a validated Finite Element Model simulated with different bone apparent densities and both cup displacement and rotation were evaluated as measure of cup motion. Furthermore, the von Mises stresses for all three cases were analyzed to identify threshold limits of stress distribution. This study aims to:

- investigate the relationship between cup motion and bone density;
- quantify the re-distribution of stress at the defect site after augmentation.

2. Material and methods

2.1. Material

The present study is based on six cadaveric subjects with age of 79.4 ± 7.8. We harvested one pelvis side from each subject and measured for all, the distance from the Posterior (PSIS) to the Anterior (ASIS) iliac spines of 162.9 ± 7.66 mm. To develop the 3D FEM, a specimen characterized by a rim circumference of 135 mm, a femoral head diameter of 38.6 mm and a distance ASIS-PSIS of 160.3 mm was selected. The latter is characterized by the highest Hounsfield unit values measured in area 2 (posteroinferior acetabular quadrant) as described by Dalstra et al. [13] and located on the opposite side of the defect.

2.2. Defect reconstruction

For an intact pelvis, an artificial defect with length of 41.5 mm and depth of 12.5 mm was created on the posterior acetabular wall using a bone rongeur. The resulted acetabular wall defect was less than 50% and was reconstructed with bone screws supported by bioabsorbable calcified triglyceride bone cement (Kryptonite™ Bone Cement, Doctors Research Group, Oxford, CT) [14]. The reconstruction was reinforced by three Zimmer 2.7-mm Cortical Screws (Zimmer, Inc. Warsaw, IN) with length of 22 mm and hex size of 2.5 mm located equidistant from one another within the defect. After the defect reconstruction, a 54-mm DePuy Pinnacle acetabular cup (DePuy, Warsaw, IN) was press-fit with 1 mm of under-reaming. Considering that the cup inclination doesn't influence the migration [15], the cup was oriented with an anteversion of 12° to help with sensors placements (Fig. 1).

2.3. Finite element model

Diagnostic images obtained through a CT scan using a BrightSpeed (GE Medical Systems, Little Chalfont, UK) scanner (slice thickness of 0.625 mm, pixel size of 0.422 mm, field view of 216 mm) were taken of the complete hemi-pelvis from the selected cadaveric female subject prior to cup implantation in order to develop a 3D reconstruction of the hemi-pelvis. The 3D reconstruction of the hemi-pelvis was constructed and thresholding done on the Hounsfield scale to allow for material property segmentation [16,17]. A Boolean subtraction was used to simulate reaming of the acetabulum with a diameter of 53 mm (Fig. 2).

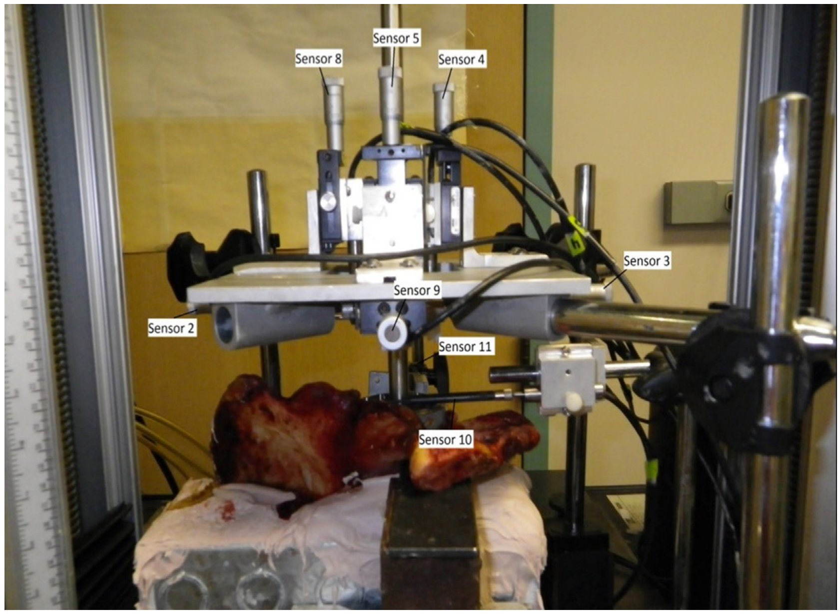

Fig. 3. Experimental apparatus.

All the materials were modeled as isotropic [18] with Poisson's ratio of 0.3. For the trabecular bone, we used a constant value of 70 MPa for the Young's Modulus [19]. The cortical and subchondral bones were taken into account adapting the elastic modulus-apparent density relations proposed by Wirtz et al. [20] and assigning a Young's modulus of 17 GPa [18,21] to the highest value of density found in the identified volume. The Young's modulus of the Bone screws and of the acetabular Cup are assumed to be 115 GPa, equivalent to Titanium [19], and the bioabsorbable calcified triglyceride bone cement modulus was approximated to be 830 MPa for stress value up to 20.5 MPa, from experimental data provided by the manufacture company (Doctors Research Group, Oxford, CT). Between the cup and the bone, a non-linear, asymmetric, frictional, surface-to-surface contact interface was created with a coefficient of friction of 0.5 [21,22] and the augmented Lagrange method was selected for the solution.

2.4. Model validation

The model was validated using the experimental setup already discussed in previous studies developed by our Lab [23–25]. An Instron electromechanical tensile-testing Machine 5569 (Instron^{TM}, Norwood, MA) was set to apply a compressive load, perpendicular to the plane of the cup, with a moment arm of 30 mm placed on the cup in the posterior-anterior direction. Forces ranging from 100 N to 1500 N, calculated for the subject body weight considering the peak load recorded by Bergmann et al. [26] for fast walking, were applied in a cycle of 5 repetitions for each loading case. Loading speed was set to 4 mm/sec. Displacement values were recorded during the entire loading phase 0 to 1500 N, using linear variable differential transformer LVDT sensors with a resolution of 25 μm (Fig. 3).

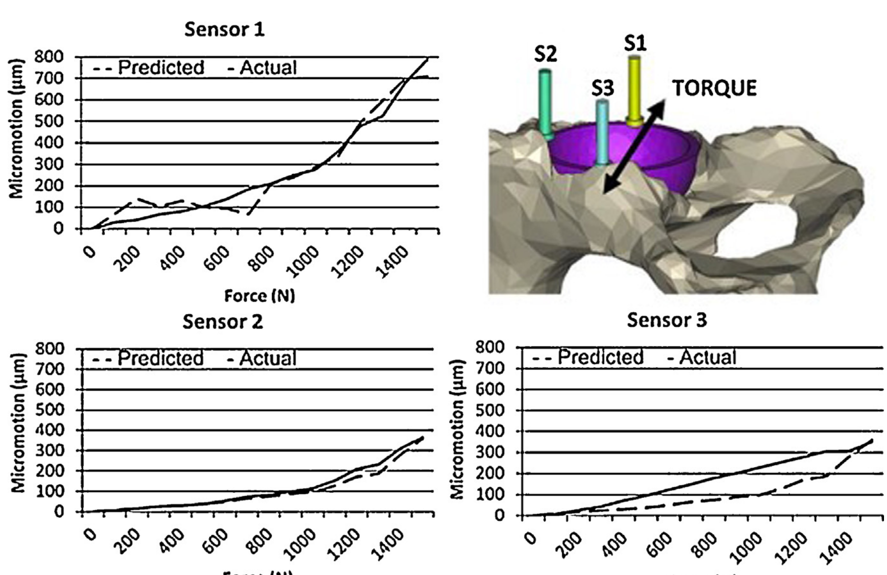

Fig. 4. Sensor micromotion and calculation of net cup/bone interface displacement. Comparison of predicted and actual values from 0 to 1500 N of loading for model validation.

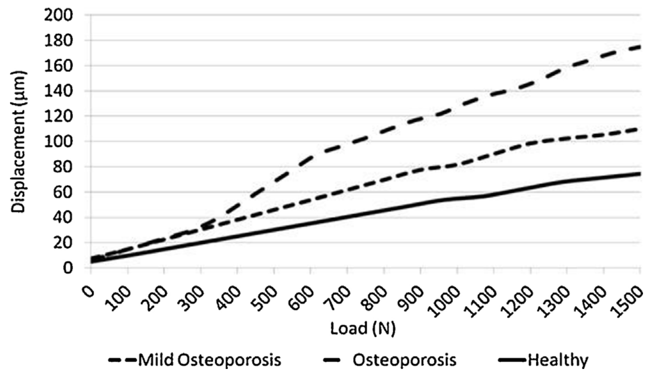

Fig. 5. Displacement of the center of the acetabular cup along the z-axis into the acetabulum over loading for various levels of osteoporosis in the presence of a reconstructed acetabular defect.

Loading was simulated in three phases. The first phase simulated cup insertion. The second phase was regarded as an equilibrium phase where all constraints were removed from the cup and it was allowed to rebound to a position of equilibrium. The third phase replicated the loading condition of the experiment, where a compressive load of 1500 N was applied. In the final load step, the micromotion values of three nodes located in the same position as Sensors 1, 2, and 3 from the in-vitro experiment were used for validation (Fig. 4). The final values of cup displacement at 1500 N for the three nodal points representing sensors 1, 2 and 3 were predicted with a percent error of 11%, 12%, and 2%, respectively.

2.5. Model's osteoporosis

Mechanical testing of the trabecular bone of the femoral neck in one study revealed that the percent difference of apparent density between healthy bone and one affected with was approximately 35% [27–29]. Another study found that the average apparent density of a healthy trabecular pelvic bone is 0.248 g/cm^3 with values ranging from 0.109–0.959 g/cm^3 [13]. According to another study, the apparent density of cortical bone may range from 1.5 g/cm^3 to 2 g/cm^3 [20]. The osteoporotic configuration was characterized with Young modulus of the cortical bone calculated using the relationships found by Wirtz et al. [20] for apparent density values of 1.5 g/cm^3 and assuming 24 MPa for the trabecular bones with apparent density of 0.109 g/cm^3 [13]. An intermedia configuration characterizing the moderate osteoporotic bone was simulated assuming values reported in Table 1.

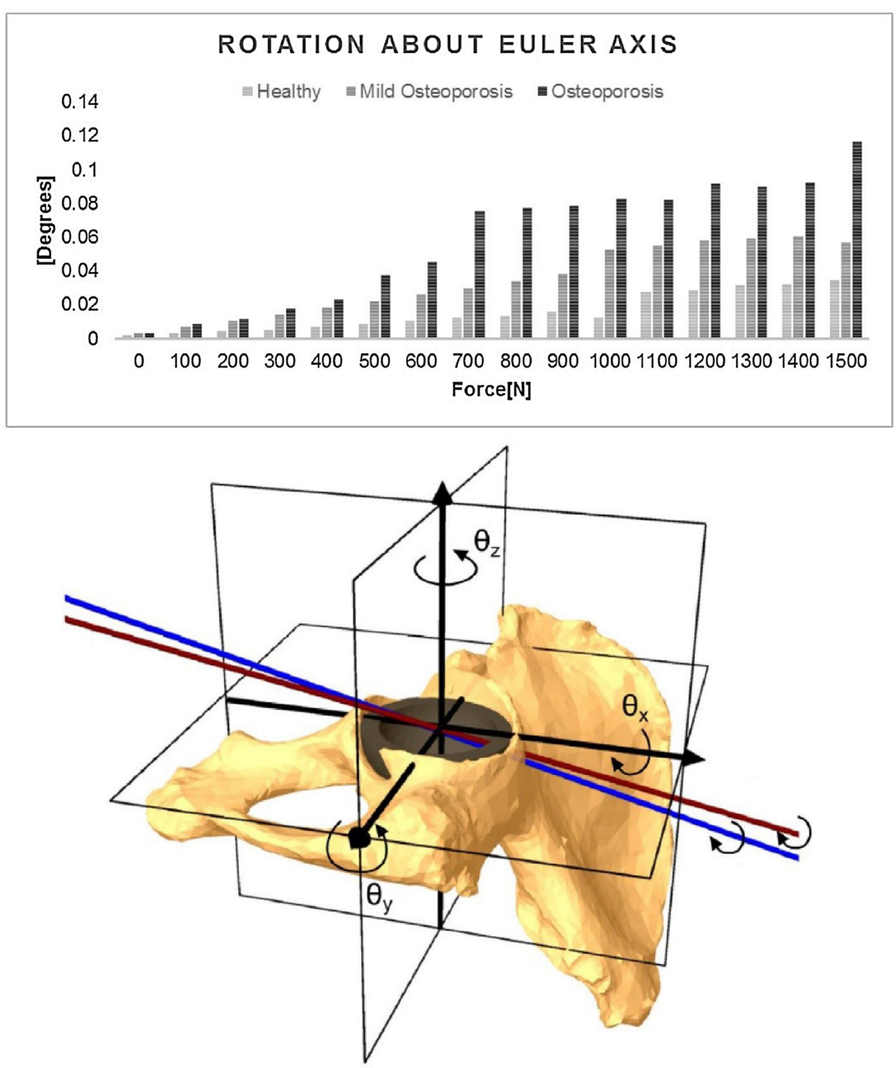

Fig. 6. Euler rotation angle of the acetabular cup for various levels of osteoporosis with a reconstructed acetabular defect.

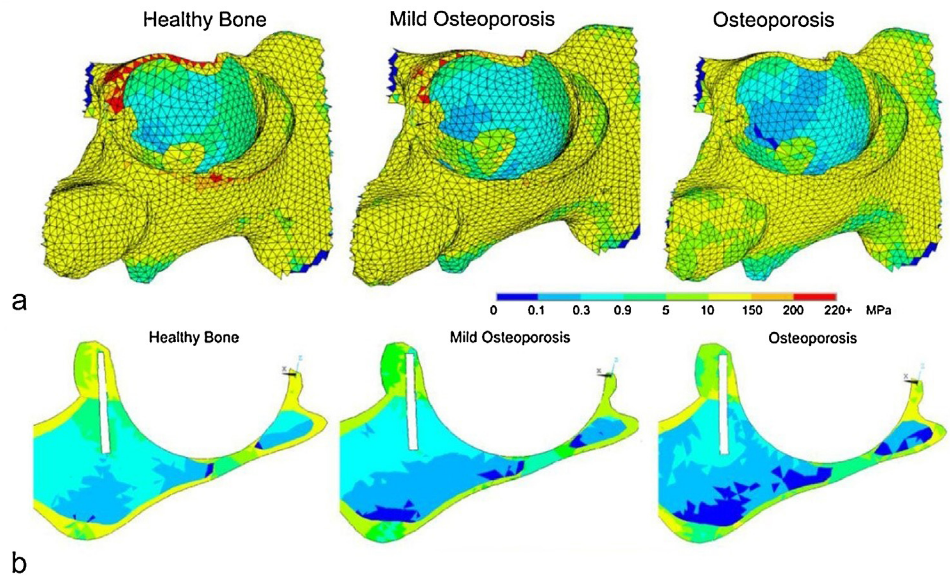

Fig. 7. a: resulting von Mises stress (MPa) on healthy hemi-pelvis and bone cement with reconstructed defect during postoperative loading; b: cross-section showing the resulting von Mises stress (MPa) on healthy hemi-pelvis and bone cement with reconstructed defect during postoperative loading.

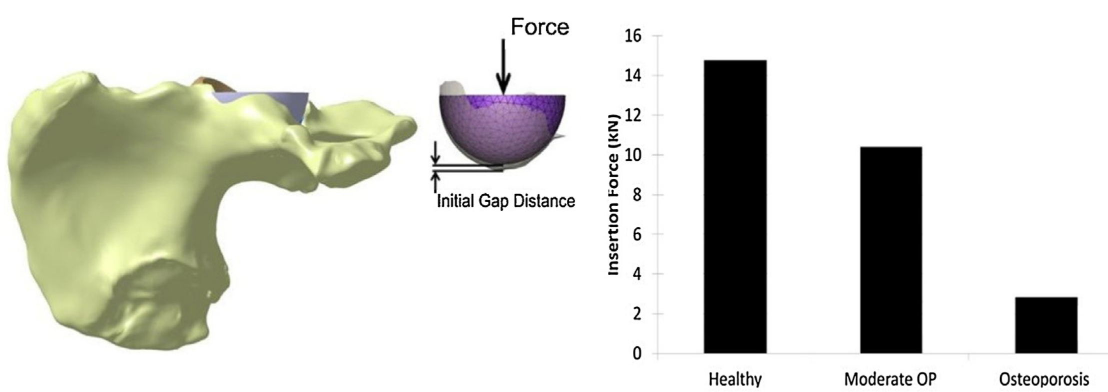

Fig. 8. Force needed to press-fit insert the acetabular cup in the presence of a reconstructed acetabular wall defect and varying levels of osteoporosis.

Table 1
Bone material properties for healthy, moderate and severe osteoporosis [13,20,27–29].

Type of bone	Young's Modulus (GPa)		
	Osteoporosis	Moderate OP	Healthy
Cortical bone	5.89	10.59	17.00
Cancellous bone	0.024	0.047	0.07

2.6. Methods of assessment

The cup motion has been calculated through displacement and rotation around the calculated Euler Axis for each configuration, every 100 N. The stress distribution has been evaluated by the percentage of elements under the value of 55 MPa reported by Kotha and Guzelsu [30] as value for change in slope in stress-strain characteristic of damaged bone tissue and by the location of the peak values calculated in the model.

2.7. Statistical analysis

Wilcoxon signed-rank tests at the 5% significance level were performed between each osteoporotic configurations and the healthy using Matlab^{TM} R2012b (Mathworks, Natick, MA, USA) comparing the cup displacements and rotations of the cup at every 100 N of load increments for the specified load range. Von Mises stress values are reported for the maximal simulated load for direct comparison.

3. Results

For a compressive load lower than 300 N, the healthy bone has a cup displacement of 21.13 μm, lower than the severe osteoporotic which has a displacement of 33.1 μm and the moderate osteoporotic showing 30.9 μm. Starting at 300 N, we see a divergence in terms of displacement or micromotion of the cup. The maximal displacement for a healthy bone at 1500 N is 78 μm and is 33 μm (43%) and 99 μm (128%) higher for moderate and severe osteoporosis (Fig. 5). The cup micromotion was also analyzed by computing the Euler rotation angle (Fig. 6) where an increased rotation of 0.08 degrees at 1500 N is seen when the bone apparent mass density decreased to osteoporotic level.

The relative displacement of the cup for both Moderate and Severe osteoporosis are significantly different from the displacement calculated for the healthy bone ($P = 0.00004$ both). Identical $P = 0.00004$ value was observed for the relative rotations of the cup were found.

Von Mises stress did not exceed 55 MPa in 90%, 95%, and 98% of the bone, for the different cases respectively. The corresponding stresses ranging from 25 MPa to 226 MPa are strongly affected by the grade of osteoporosis, noted primarily on the cortical bone near the peripheral rim of the acetabular cup. Average values of 102 MPa and 123 MPa for severe and moderate osteoporosis are found for both cases respectively (Fig. 7a). Near the site of the screw sites (Fig. 7b), higher resulting stress values of 10 and 7 MPa remain below the yield limit for both bioabsorbable calcified triglyceride bone cement and bone for all cases.

The results also show that for an otherwise healthy bone with a reconstructed acetabular wall defect the estimated cup insertion force is 14.8 kN. For a reconstructed defect in the presence of osteoporosis, the amount of force needed to seat the acetabular cup decreased by 4.4 kN (29.8%) from moderate osteoporosis to 11.9 kN (80.8%) for osteoporotic bone (Fig. 8).

4. Discussion

This study investigates the initial stability and fixation of the acetabular cup in the presence of an acetabular wall defect reconstructed with bone screws and augmented with bioabsorbable calcified triglyceride bone cement. Because defects may also occur in conjunction with decreased apparent bone density, the FE model has been used to evaluate the efficiency of an imposed defect reconstruction for various levels of simulated osteoporosis. The analysis shows that for decreasing levels of apparent density of bone, displacement of the acetabular cup increases with increasing load. The changes in slope from the healthy configuration ($R^2 = 0.998$) to the moderate ($R^2 = 0.994$) and severe ($R^2 = 0.991$) osteoporotic configurations are respectively 49.6% and 151.4%. The maximal displacement values of 78 μm and 111 μm found for the healthy and moderate osteoporotic bone configurations are below the generally assumed critical threshold of 150 μm for osseo-integration [31,32] while for the severe osteoporotic bone, we found displacement of 177 μm. The strongest limitation of this study must be in the adopted material properties that are based on the formulation proposed by Dalstra et al. [13] for trabecular bone with a coefficient of 0.58. Another limitation of the study may be seen in the number of points (nodes) used in the validation of the FE model. Additional sensors and experimental data points will enhance the validity of the model with maximal displacement values of 782 μm, 374 μm and 352 μm, higher than the values obtained by Clarke et al. [33] that were ranging from 69.1 μm to 318 μm, according to the particular position on the cup, but a direct comparison of these values is limited by the fact that we used a cadaveric subject that was further altered by the reconstructed defect.

The majority of peak stresses were located in the cortical bone around the peripheral rim of the acetabular cup opposite of the reconstructed defect location. The distribution of stress is further altered due to the reconstructed defect, particularly in the trabecular bone due to the addition of bone screws. The estimated cup insertion force of 14.8 KN is comparable to that seen in previous studies [34] where a mean value of 16.7 KN has been calculated from the impact peak forces measured without defect present. Because a safe margin higher than the limitations exposed the proposed hypothesis should be accepted. Further testing of various repairs techniques are needed to gain a better understanding of cup bone stability.

5. Conclusion

Reconstruction of Paprosky type I or II, acetabular defects with bone screws supported by bioabsorbable calcified triglyceride bone cement during THA, are less effective in osteoporotic bone. For pelvic bone with apparent densities values of 0.109 g/cm^3 for trabecular and 1.5 g/cm^3 for cortical bones, a different technique for defect reconstruction is recommended.

Disclosure of interest

The authors declare that they have no conflicts of interest concerning this article.

Acknowledgments

This work was partially supported by Aurelio M. Caccomo family foundation.

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