

# Long anatomical femoral stem reduces stress concentrations on femurs with lateral bowing deformity: A finite element analysis

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## Abstract

**Aim:** Femoral morphology varies widely among different ages and sexes. Lateral bowing is a variance of the femur described in elderly females from Asian race. This bowing deformity is usually underestimated in patient evaluation and planning the most suitable treatment. In this study we aimed to evaluate the stress distribution around femoral prosthesis in femurs with lateral bowing deformity, using a finite-element (FE) method. The main objective of our study was to compare stress concentrations around five different stem models.

**Material and Methods:** A lateral femoral bowing deformity model was obtained from the post-operative CT data of a 69-year-old woman, using a software (3D-Slicer). Straight and anatomical femoral stem models with different lengths are designed on the model of von Mises stress concentrations of five different stem models are evaluated.

**Results:** The long anatomic stem did not lead to excessive stress concentrations on any area of the femur and a uniform stress distribution was obtained. The maximum von Mises stress for long anatomical stem (29,197 MPa) was lower than any other model. Highest stress concentrations were observed in medium straight stems (43,147 MPa).

**Conclusion:** For patients with a lateral bowing deformity, longer anatomical femoral stems may overcome the excessive stress shielding, providing stress distribution over a wider region of the femur.

**Keywords:** Femoral Lateral Bowing; Finite Element; Anatomical Stem; Hip Arthroplasty.

## INTRODUCTION

Total hip arthroplasty (THA) is one of the most common elective surgeries performed in older adults. As life expectancy in developed nations continues to increase; the ratio of the population older than 65 years old also rises, leading to more frequently performed THA surgeries. It is estimated that approximately 1-3% of the population older than 65 years will undergo THA at some point, with an average age of 66 (1). When the epidemiology of both primary and revision total hip replacement in the U.S. Medicare population is evaluated the rates of THA procedures were found to be higher among women than men (2). The number of revision THAs is also expected to increase significantly secondary to both the increasing life expectancy and the increasing number of primary THAs (3). As a result the incidence of periprosthetic fractures are

expected to rise; especially after revision surgeries (4-6).

The geometry and size of femoral stem is an important factor which affects the pattern of stress transferred to the femur. It has been known that a precise fit of the femoral stem in the femur minimizes stress shielding and for this purpose custom made implant designs have been suggested (7), owing to the fact that femoral structure and morphology varies widely among different ages and sexes (8).

Lateral bowing is a morphologic variance of the femur especially in elderly females from Asian race (9). During our clinical practice, we also have encountered a remarkable number of such patients in our institution. However to the best of our knowledge, there are no studies about the prevalence or biomechanical properties of this deformity. On the other hand, this bowing deformity is usually

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underestimated in evaluation and treatment planning; for instance, anterior bowing of the femur has been taken into account during the design of long-stemmed prosthesis, however lateral bowing deformity is neglected. Furthermore, the effect of longer femoral stems on femurs with lateral bowing has not been studied before.

Therefore, we performed this study using a finite-element (FE) method. The research question of our study was 'what is the optimal length and curvature of the femoral stem to reduce stress shielding over femurs with lateral bowing deformity?' Our hypothesis was longer stems with anatomical curves on both sagittal and coronal planes would achieve a uniform stress distribution. We aimed to evaluate and compare the stress concentrations around five different stem models (short/medium/long straight and medium/long anatomical) in femurs with lateral bowing deformity.

Independent variables of our study was the length and shape of femoral stems. Dependent variables consisted of von Mises stress values caused by these different stem models.

### Geometrical Definitions

The CT-based finite element method is used to evaluate the effect of stem length and stem geometry on patients with bowing deformity in the coronal plane. A CT data of lateral femoral bowing deformity were obtained from the post-operative CT of a 69-year-old woman, who had undergone revision hip arthroplasty using a 17mm X 150mm sized straight femoral stem (Arcos® Modular Femoral Revision System, Biomet Orthopedics, LLC, Warsaw, Indiana USA). The implant applied to this patient ended nearly on the apex of lateral bowing deformity (intersection of two femoral axes) and this data was used for creating the middle length straight stem model (Figure 1a). To compare different stem size effects accurately, implant geometry was simplified with some measurements (head diameter, neck-shaft angle, stem length and diameter) manually and remodeled. 3D bone geometries were obtained using free and open-source software 3D-Slicer (10) and all parts were segmented manually. Cortical and cancellous bone were modelled as separate sections. The femur was positioned with the center of the implant head coinciding with the origin of the global reference system and the x, y and z axes defined according to HIP 98 (11) (Figure 1b). In addition, lateral bowing deformity angle measured with an intersecting proximal and distal femoral axis (3 points: lower edge of the lesser trochanter, middle, and 100 mm proximal to the distal end) (12). A cross-sectional 2D model created from XZ plane. Intersecting point of the proximal and distal axis defined as point C, proximal and distal points were defined point A and point B respectively. The angle between these axes was defined as femoral bowing angle (FBA)  $9.33^\circ$  shown in Figure 1b. Two groups of different types of femur models are created. In the first group, straight stems with three different lengths were modelled as seen in Figure 2a, Figure 2b.

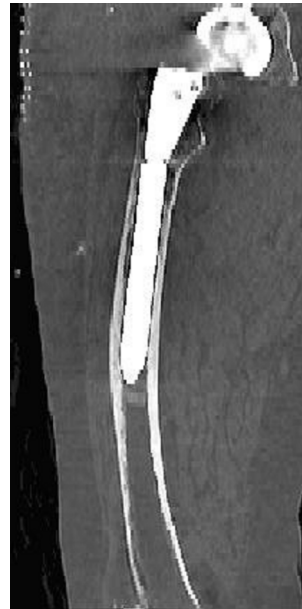


Figure 1a . CT coronal view,

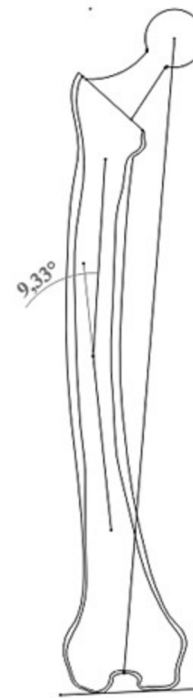


Figure 1b. Femoral bowing angle measurement in coronal plane

All models were designed manually with reference to the geometry of stem in our patient's CT data, which was considered as the middle length straight stem model. In the first model, stem ended proximal to the point C, intersection of two femoral axes, and stem longitudinal axis remained same with CT-data. In the second model, stem geometry remained same and ended nearly on point C. In the last model, stem was positioned in the cancellous bone, distal to point C, so that penetration into cortical bone was minimal. In the second group, two anatomical shaped implants with two different sizes were used. Stem geometries of these implants were created using femoral shaft curvature created with three points in Figure 3a and Figure 3b. In all models, femoral offset distance remained same for an accurate assessment.

**Mesh and Boundary Conditions**

All femur and implant geometries meshed with second order tetrahedral elements with a global element size of 3 mm were used for the FE models. All contact surfaces were accepted fully bonded. Distal faces of lateral and medial condyle were fixed in all displacement. For boundary condition, static loads were applied to the FE models, which was based on the study by Heller et al. (13,14), consist of the hip contact load and a set of simplified muscle forces (abductor, vastus lateralis, and vastus medialis), and the distal end of the femur was fully fixed as shown in Figure 4.



Figure 2a. Frontal views of straight stem models,



Figure 2b. Sagittal views of straight stem models



Figure 3a. Frontal views of anatomic stem models



Figure 3b. Sagittal views of anatomic stem models

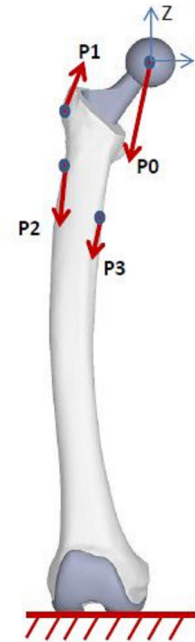


Figure 4. Boundary conditions and material properties

The hip contact and muscle forces were applied as a percentage of the body weight (%BW) to simulate the peak load during stair climbing, which is the most critical load affecting the stability of the femoral stem among all daily activities. All material settings were based on literature values (Table I).

Table I. Young modulus and Poisson ratio values according to material properties				
Force (%body weight)	x	y	z	point
Hip contact	-72.3	-88.6	-333.4	P0
Abductor	83	35.6	77.3	P1
Vastus lat	-2.2	22.4	-135.1	P2
Vastus med	-8.8	39.6	-26.7	P3
	Young Modulus		Poisson Ratio	
Cortical bone	18		0.33	
Trabecular	1		0.2	
Ti-6Al-4V	113.8		0.33	
Knee Component	210		0.33	

Cortical and trabecular bone geometries of orthotropic materials were used. Young's modulus and Poisson's ratio were taken to be 1000 N/mm<sup>2</sup> and 0.2 for the trabecular bone, and 18,000 N/mm<sup>2</sup> and 0.3 for the cortical bone

in axial (Z) direction (15) and for other directions young modulus and all shear modulus and Poisson ratios were calculated from equations (16). All finite element analysis are static and solved in ANSYS Workbench.

Von mises stresses concentrations in straight and anatomical stem models are given in figure 5a, 5b, 5c and figures 6a, 6b respectively Maximum von mises stresses for the short straight stem are concentrated over the area between the apex of lateral femoral curvature and the tip of the stem (Point C).

Likewise, for the middle straight stem, stresses are maximum on the narrow area between the tip and apex. Whereas in the long straight stem model maximum stress value decreased and concentration area shifted distally. Compared to the middle straight stem model, middle anatomic stem showed a lower maximum stress value, with a similar stress distribution pattern. However, the long anatomic stem did not lead to stress concentrations on any area of the femur and a uniform stress distribution was obtained. Besides maximum von Mises stresses for the long anatomical stem was found to be lower than any other model.

Principle stress concentrations on the lateral side of the femur for each model are given in Figure 7a-e. Maximum principle stresses on lateral mid-shaft, where two axes intersect (Point C) are given in Figure 8.

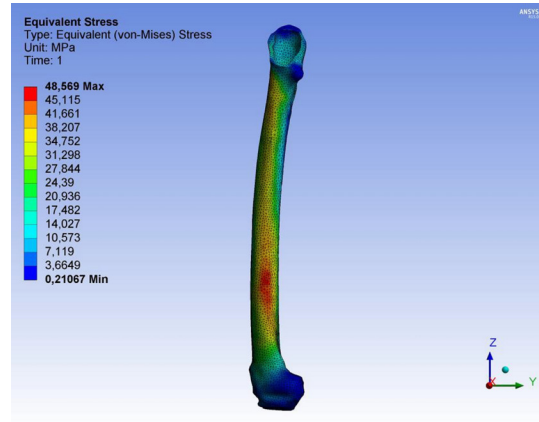


Figure 5c. long respectively

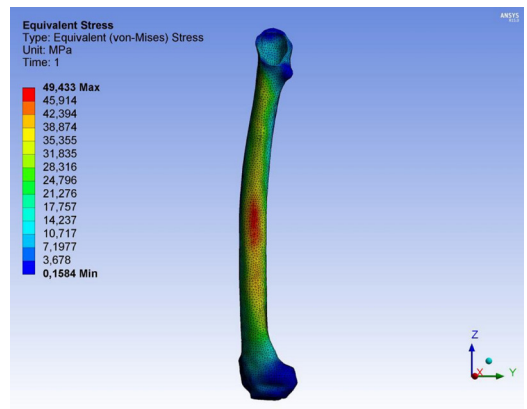


Figure 6a. Max von Mises stresses on anatomical shaped implants aMedium

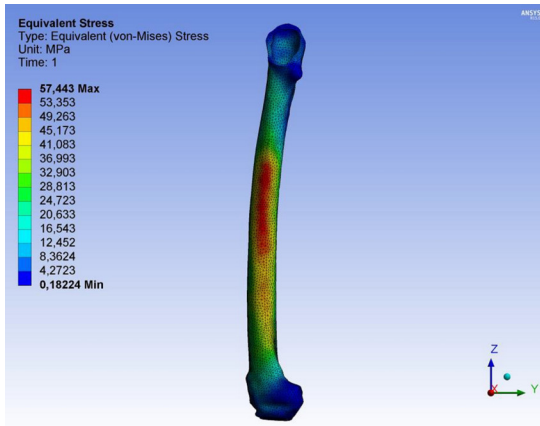


Figure 5. Von Mises stresses concentrations in straight stem models, a. Short

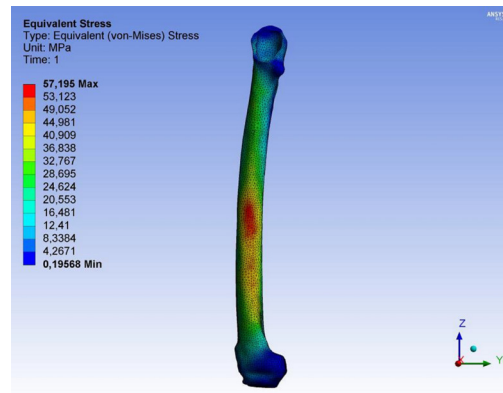


Figure 6b. Long respectively

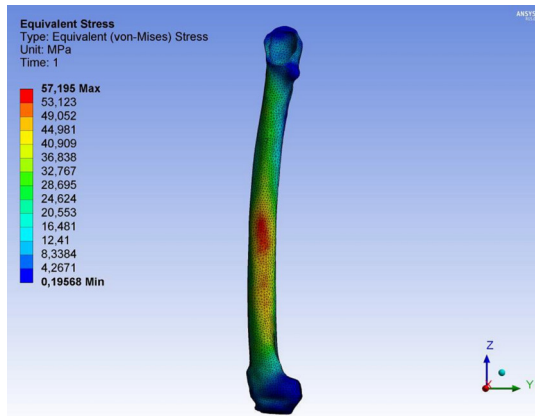


Figure 5b. medium and

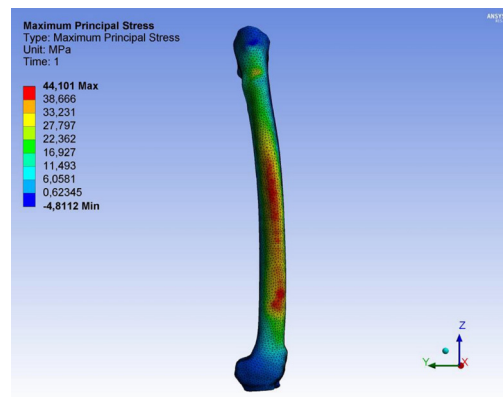


Figure 7. Principle stress concentrations on lateral side a. short

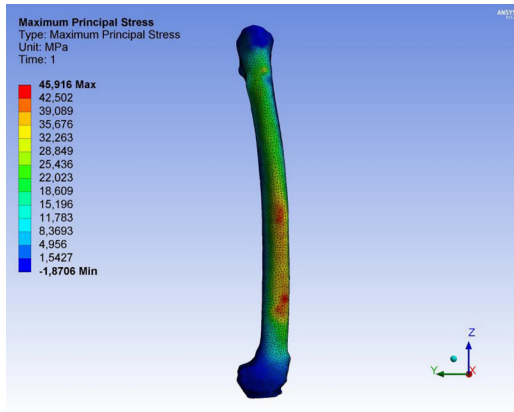


Figure 7b. Medium

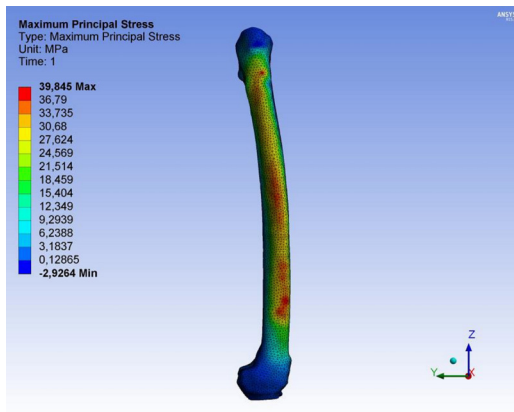


Figure 7c. Long straight stem

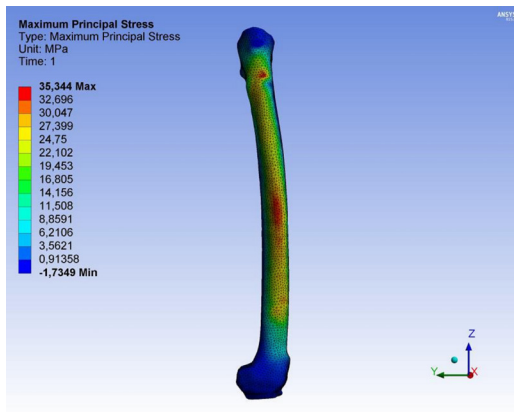


Figure 7d. Anatomic medium size e. anatomic long size

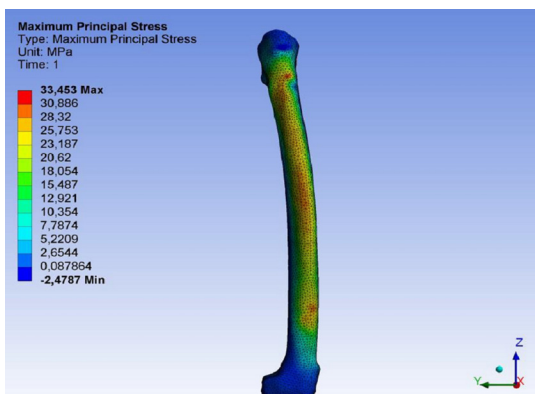


Figure 7e. Anatomic long size

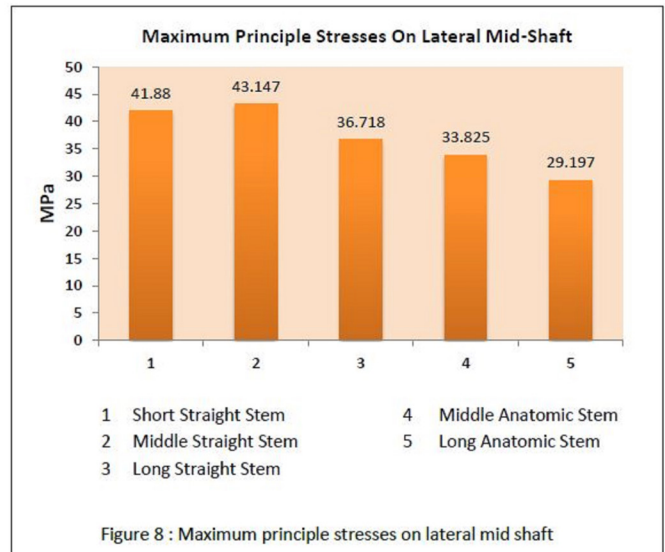


Figure 8. Maximum principle stresses on lateral mid shaft

## DISCUSSION

The most important finding of this study was that the longer femoral stem with lateral bowing provided a uniform stress distribution over the femoral shaft. Also this longer anatomical stem model achieved lower stress concentration values compared to straight models at the same length.

The geometry, size and the material properties of the prosthesis along with technique and extent of fixation have been recognized as important factors which affect the pattern of stress transferred to the femur; determining the stress shielding over the bone. Stress transfer to the femur is beneficial as it ensures a stimulus for maintaining bone mass and protects the bone against disuse osteoporosis. It has been known that a precise fit of the femoral stem in the femur minimizes stress shielding and the beneficial effects of custom-made implants which provide a precise fit, has been emphasized in the literature. (7,17) Corresponding to the literature, in our study we also observed that the model that most fits to the bowed femur, ensured minimum stress values.

In the quest to establish the optimum length of the femoral stem, the geometry and size of the patient's femoral canal come forward as the most determining two factors. Currently, stems with lengths of varying from 120 to 150 mm are routinely used (18). With the results achieved in this study, longer stems seem to more suitable and safer for bowed femurs. On the other hand longer stems reaching to the isthmus have disadvantages such as technically harder placing with a tendency towards varus malposition, putting the anterior femoral cortex into risk of perforation due to anterior femoral bowing and insufficient cementing beyond the isthmus. However, in cases of fractured or weakened femoral cortex especially in revision surgery, longer stems are essential.

The femoral structure and morphology vary widely among different ages and sexes. Lateral bowing is one of these

morphologic variances of the femur especially seen in elderly females from Asian race (9). These variations in femur morphology increase with age, as well as the incidence of proximal femoral fractures. On the other hand, most prosthesis currently used (including the straight femoral stem used in our study) are designed based on the normal femoral structure, neglecting the age-dependent variations. Changes of both bone structure (osteoporosis) and lower extremity biomechanics in elder patients are considered to cause alteration of stress distribution, which may lead to periprosthetic fractures around the femoral stem. Due to the increased comorbidities of elder patients such as diabetes, hypertension, heart failure, etc. multiple revision surgeries could lead to extra costs in addition to morbidity. Considering the life-threatening outcomes of revision surgeries, every effort should be made to refrain from this intricacy (6). With this point of view; the potentially higher costs of custom made prosthesis that fits to bowed femurs should be embraced, in order to avoid any kind of secondary interventions.

In addition to the increase in life expectancy, the number of younger patients undergoing hip replacement is also rising. With the potential risk of trauma and infection, revision surgeries are expected to increase consequently. Surgeons may consider short femoral components as safer options in hip replacement; however it is not clearly proven whether shorter femoral stems provide better outcomes or easier revision surgeries (19). The decision making process for the specific length of femoral stem should include; optimal stress distribution over the proximal femur; and maximum bone preservation combined with optimum stability. While opting for the most suitable femoral component type; surgeons should keep in my mind that depending on the variable patient specific factors such as femoral morphology or bone mineral density; different femoral stems with varying lengths and designs may provide the optimum long lasting outcomes (19).

There are some major limitations of our study which includes the lack of comparison of our deformity model with a normal shaped femur model. Also our model was created using CT data of only one patient with lateral bowing deformity. Further clinical and biomechanical studies are needed to understand the true prevalence especially in older population of this deformity and its role on periprosthetic fractures. Besides, cemented femoral components are also commonly applied for the elderly osteoporotic patients. Not involving cemented models for comparison to evaluate the different stress distribution and load transfer patterns between cement and bone interface, is also a limitation of the current study. The number of cases in which the existing stems cannot be used, or the prevalence of lateral bowing deformities among our population would be of great value for reflecting findings of our work into the clinic.

## CONCLUSION

In our study, we focused on the stress distribution around

long stemmed femoral prosthesis in patients with lateral femoral bowing deformity which is usually not taken into account despite its remarkable prevalence, especially among older females. Our study revealed that particularly for patients with a lateral bowing deformity longer anatomical femoral stems may overcome the excessive stress shielding arising from shorter stems. In selected cases with lateral femoral bowing deformity, after evaluation of the femoral geometry with CT, application of custom-made longer anatomical femoral stems may provide stress distribution over a wider region of the femur.

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