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FINITE ELEMENT ANALYSIS OF FEMORAL BONE UNDER VARYING BONE DENSITY CONDITIONS

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Abstract

Understanding the biomechanical response of a femoral bone under physiological loads is critical for assessing bone health and fracture risk, particularly in aging populations affected by osteopenia and osteoporosis. This study investigates the mechanical behavior of the femoral bone under standing loading conditions across three bone states: healthy bone, bone with osteopenia, and bone with osteoporosis. In-house finite element solver, PAK, was used to calculate von Mises stress and displacement values for each condition. The influence of reduced bone density on structural integrity was examined by comparing results among the three models. Displacement values increased from 0.724 mm in the healthy model to 1.02 mm in bone with osteopenia and 1.6 mm in bone with osteoporosis. For von Mises stress, the values indicate a slight decrease in stress values with bone density loss. Results obtained by the in-house solver were validated against those obtained from the commercial solver Nastran, showing strong agreement in both stress and displacement values. The findings highlight the importance of early diagnosis of bone diseases and suggest that material properties based on patient-specific data could further enhance the predictive power of such simulations.

Keywords: Femur, Finite Element Analysis, Osteoporosis, Osteopenia, Bone Biomechanics

1. Introduction

The femoral bone has a crucial biomechanical role in supporting the axial skeleton and allowing movements of the body. During daily activities, it must absorb and transmit considerable forces. That ability is dependent on its geometry and material composition. If these characteristics are compromised, which can happen due to osteopenia or osteoporosis, the risk of fractures increases significantly, especially in elderly populations.

One of the most common age-related skeletal conditions is osteoporosis, characterized by a progressive loss of bone density and mass, as well as bone microarchitecture deterioration leading to increased fragility and fracture risk (Clynes et al., 2020). Osteopenia, a precursor to osteoporosis, involves a moderate decrease in bone density and is similarly associated with increased fracture risk (Eriksen, 2012). These conditions alter the load-bearing capacity of bone, meaning that understanding of their progression is critical for clinical risk assessment and intervention.

In recent decades, finite element analysis (FEA) has become indispensable as a tool in the study of bone mechanics. FEA provides a non-invasive approach for analyzing stress distributions, strain patterns, and displacement fields in bone structures under various physiological and pathological conditions. It is used for applications such as surgical planning, implant design, fracture risk prediction and personalized treatment strategies (Ahirwar et al., 2021; Singh and Singh, 2021; Bazyar et al., 2023; Falcinelli et al., 2023).

The accuracy of FE simulations relies heavily on several factors, including the geometric model, appropriate material properties, definition of loading and boundary conditions, and the numerical method employed. Commercial solvers are widely used due to their robustness and reliability. However, there is a growing interest in the development and use of in-house solvers, which offer flexibility, integration with custom workflows, and often improved computational efficiency for specific problem domains. PAK is an in-house solver that has been used for several decades for the numerical simulations of solid structures, including bone biomechanics (Ranković et al., 2007; Kalanović et al., 2010; Vulović et al., 2011).

This study focuses on evaluating the biomechanical behavior of the femoral bone under standing loading conditions in three bone health states: healthy, bone with osteopenia, and bone with osteoporosis. Using in-house finite element solver - PAK, we assessed how decreasing bone density affects stress distribution and displacement across the femoral structure. The primary aim was to quantify the mechanical response of the bone in each condition and to evaluate the impact of reduced material stiffness due to bone loss.

By simulating and analyzing changes in mechanical behavior across different bone density states, this work contributes to a better understanding of bone structural degradation and its effects on mechanical behavior. It also highlights the role of computational modeling in early diagnosis and prevention of fragility fractures, particularly in populations at risk for osteoporosis. Furthermore, the study underscores the potential of patient-specific modeling as a future direction for improving the physiological relevance of FE simulations in orthopedics and rehabilitation.

2. Materials and Methods

2.1 Femoral bone 3D model

The aim of this study was to assess the effect that different values of density and elasticity modulus have on the stress and displacement distribution. In order to achieve that, anatomical 3D femoral geometry was created from the CT images (Fig. 1). In total, 400 2D images in DICOM format, with resolution 512 x 512 pixels and pixel size 1mm were used. The distance between two slices and the slice thickness were 1mm (Vulović and Filipovic, 2021).

A) Coronal plane B) Transverse plane

Fig. 1. Femoral bone CT scans.

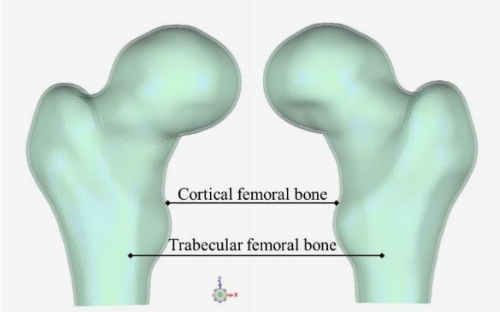


Fig. 2. Femoral bone model.

For the presented model, the number of nodes and elements was 10195 and 42982, respectively.

2.2 Material properties and Boundary Conditions

A reduction of bone density is associated with several health conditions, most notably osteopenia and osteoporosis, which significantly increase the risk of fractures and compromise structural integrity. The aim of the paper was to assess the effect that bone density has on displacement and stress distribution. Both cortical and trabecular femoral bones were considered linear elastic, isotropic and homogeneous. Material properties (elasticity modulus and Poisson's ratio) for trabecular femoral bone were taken from the literature, while for the cortical bone, Poisson's ratio was taken from the literature, and the elasticity modulus was calculated based on the known relations available in the literature. In the study, three different apparent density values were considered as a way to analyze how much stress changes between healthy bone, bone with osteopenia, and bone with osteoporosis. Based on these density values, the elasticity modulus was calculated using the following equation (Knowles et al., 2016):

$$E(MPa) = 14664 \cdot \rho_{\alpha}^{1.49} \tag{1}$$

where ρ_α is ash density.

The correlation between ash density and apparent density is (Knowles et al., 2016):

$$\frac{\rho_{\alpha}}{\rho_{app}} = 0.6 \tag{2}$$

Based on this, we have obtained the following elasticity modulus for normal femoral bone, femoral bone with osteopenia and femoral bone with osteoporosis (Table 1).

Femoral bone material properties – elasticity modulus				
	Cortical femoral bone		Trabecular femoral bone	
	Apparent density [g/cm^3]	Elasticity modulus	Value	Reference
Healthy bone	2	19241,22	600 MPa	(Perez et al., 2008)
Bone with osteopenia	1.5	12533,54		
Bone with osteoporosis	1	6850,11		

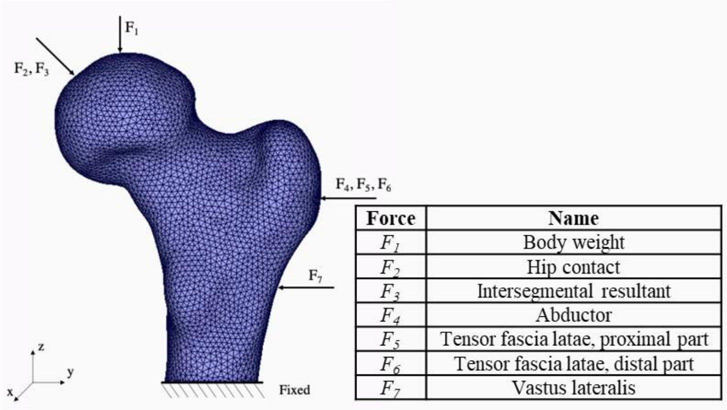
Table 1. Elasticity modulus

Constant values for Poisson’s ratio were considered for both types of bones, and the values are given in Table 2.

Femoral bone material properties – Poisson’s ratio				
	Cortical femoral bone		Trabecular femoral bone	
	Value	Reference	Value	Reference
Poisson's ratio	0.3	(Dhanopia and Bhargava, 2017)	0.2	(Perez et al., 2008)

Table 2. Poisson’s ratio

The considered boundary conditions were adapted from the literature and corresponded to the physiological conditions when a person is standing. The bottom of the femoral bone was fixed, while all other nodes were not constrained. The simulations considered the effect of seven forces on the femoral bone, shown in Fig. 3. The force values were taken from (Chalernpon et al., 2005).



Force	Name
F_1	Body weight
F_2	Hip contact
F_3	Intersegmental resultant
F_4	Abductor
F_5	Tensor fascia latae, proximal part
F_6	Tensor fascia latae, distal part
F_7	Vastus lateralis

Fig. 3. Applied boundary conditions for the numerical simulations.

A proprietary solver PAK C, developed at the Faculty of Engineering University of Kragujevac (Kojic et al., 1998), was employed for the static finite element analysis of the femoral bone. To ensure the accuracy and validity of the simulations, the results obtained from PAK were compared with results from Nastran, which is one of the commonly used commercial solvers. This comparative analysis allowed us to assess the reliability of the in-house solution and determine whether it can serve as a viable tool for biomechanical investigations of bone structures.

3. Results and Discussion

The aim of this study was to assess the changes in the stress and displacement distribution with different values of density and elasticity modulus of the cortical femoral bone. This part of the paper presents both stress and displacement distributions and their comparison with the commercial solver Nastran. Figures 4-6 show displacement distributions for all three scenarios. As it was expected, there was a noticeable difference between calculated displacement values.

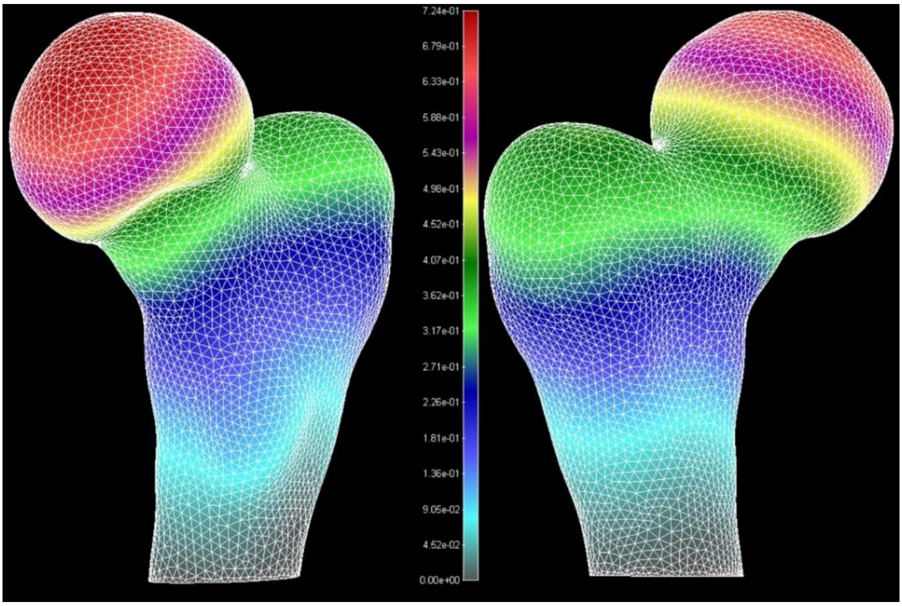


Fig. 4. Femoral bone displacement – healthy bone (unit mm)

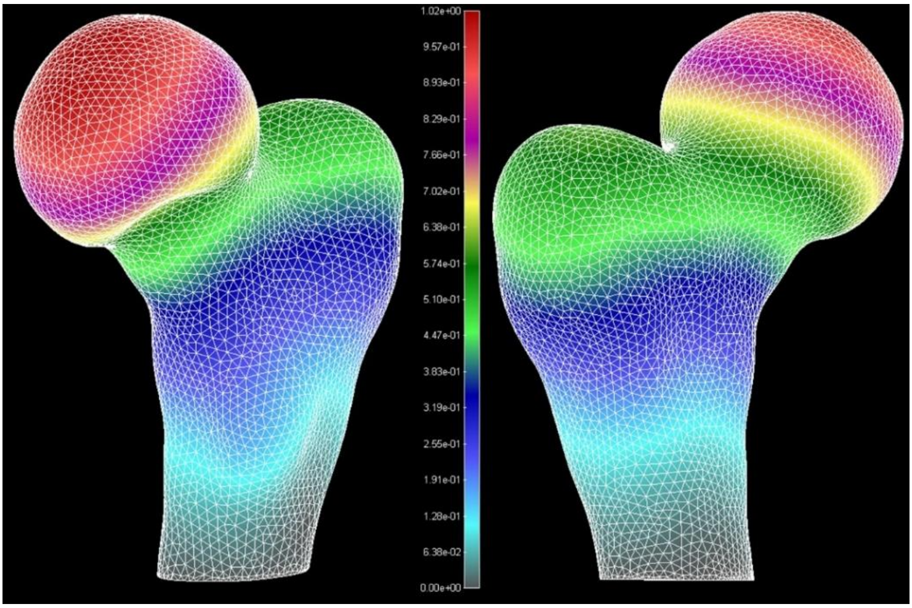


Fig. 5. Femoral bone displacement –bone with osteopenia (unit mm)

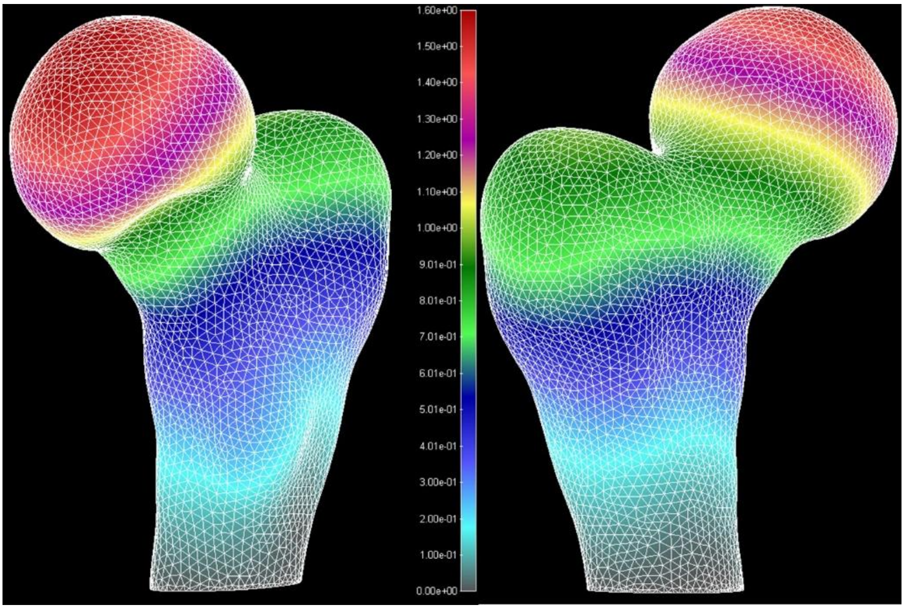


Fig. 6. Femoral bone displacement –bone with osteoporosis (unit mm)

The maximum displacement value of the femoral bone increased with decreasing bone density. Table 3 shows that the percentage of displacement values increases for a bone with disease compared to a healthy bone.

	Healthy bone	Bone with osteopenia	Bone with osteoporosis
Maximum displacement [mm]	0.724	1.02	1.6
Percentage change compared to healthy bone	/	40.88%	120.99%

Table 3. Displacement values

The obtained results indicate a clear correlation between bone mineral density and the structural stiffness of the femoral bone, with displacement increasing as bone health deteriorates. The maximum displacement increased from 0.724 mm in a healthy bone to 1.6 mm in osteoporotic bone, representing more than a 120% increase. The increase in displacement values suggests that bones with lower density deform more under the same physiological loading conditions, which is consistent with the known material behavior of osteoporotic bone.

The difference between healthy and bone with osteopenia (from 0.724 mm to 1.02 mm) already shows a significant drop in mechanical performance, suggesting that intervention during osteopenia could be critical in preventing the progression to osteoporosis and associated fracture risk.

Figures 7-9 show stress distributions for all three scenarios. The results show a decreasing trend in maximum von Mises stress as bone density decreases.

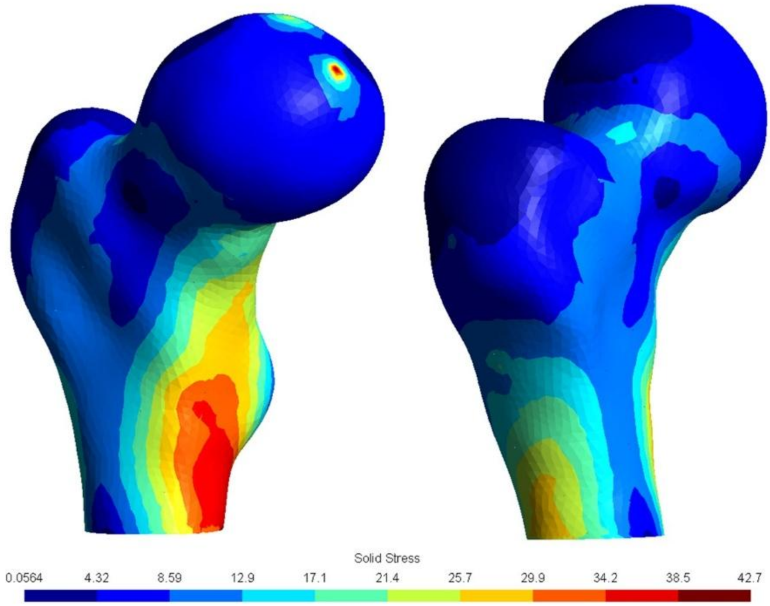


Fig. 7. Femoral bone von Mises stress – healthy bone (unit MPa)

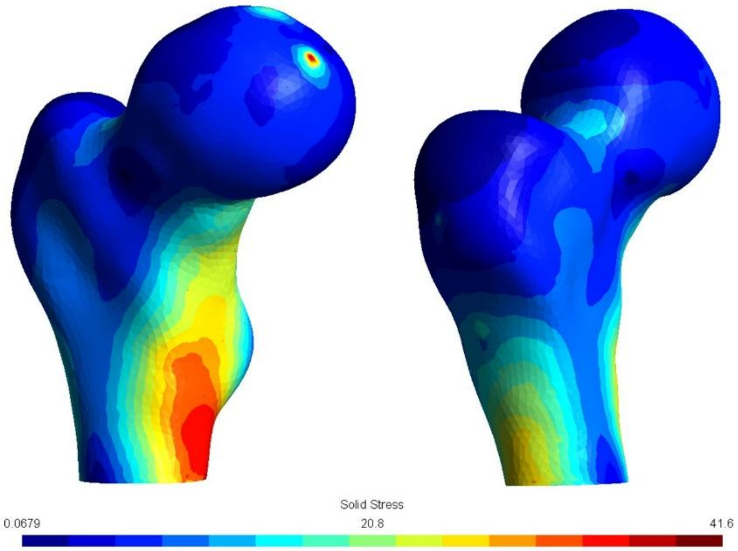


Fig. 8. Femoral bone von Mises stress – bone with osteopenia (unit MPa)

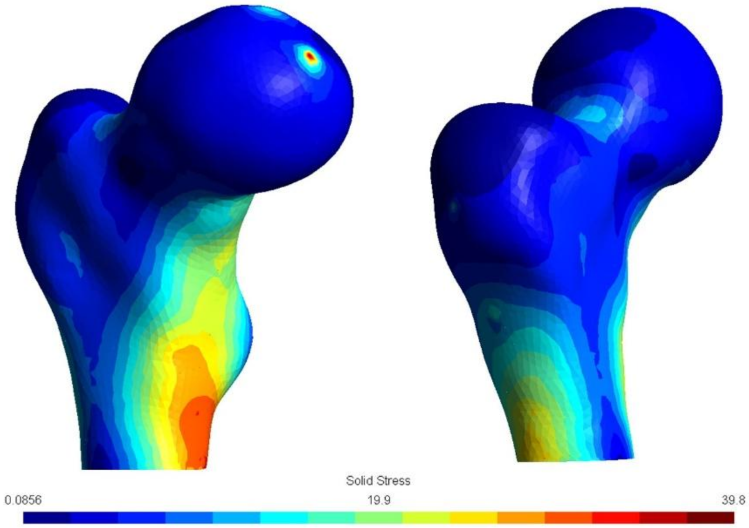


Fig. 9. Femoral bone von Mises stress – bone with osteoporosis (unit MPa)

Table 4 shows the percentage of stress values decrease for a bone with disease compared to healthy bone.

	Healthy bone	Bone with	Bone with

		osteopenia	osteoporosis
Maximum stress [MPa]	42.7	41.6	39.8
Percentage change compared to healthy bone	/	-2.58%	-6.79%

Table 4. Stress values

The obtained von Mises stress values show a reduction in stress-bearing capacity in bones with decreased mineral density. The maximum stress values decreased from healthy bone to osteopenia and further to osteoporosis. This is primarily attributed to the reduction in bone stiffness and elastic modulus. The lower stress values in bones with osteopenia and osteoporosis, were likely the result from the bone's inability to resist deformation, leading to increased risk of bone fracture under relatively low loads. Under standing conditions, the femur is subject to relatively moderate loads, which is the reason why the differences in stress values are not too high. However, under more demanding conditions, such as jumping, it is likely that the mechanical limitations of osteoporotic bone would become much more pronounced.

3.1 Comparison with commercial solver Nastran

Tables 5 and 6 present a comparison of the minimum and maximum displacement and von Mises stress values obtained using both the in-house solver PAK and the commercial solver Nastran.

	PAK		Nastran	
	Minimum [mm]	Maximum [mm]	Minimum [mm]	Maximum [mm]
Healthy bone	0	0.724	0	0.724
Bone with osteopenia	0	1.02	0	1.021
Bone with osteoporosis	0	1.6	0	1.602

Table 5. Comparison of displacement values between PAK and Nastran

	PAK		Nastran	
	Minimum [MPa]	Maximum [MPa]	Minimum [MPa]	Maximum [MPa]
Healthy bone	0.0564	42.7	0.0313	42.74
Bone with osteopenia	0.0679	41.6	0.0393	41.57
Bone with osteoporosis	0.0856	39.8	0.0498	39.75

Table 6. Comparison of stress values between PAK and Nastran

The results show a high degree of consistency between PAK and Nastran for all bone conditions. The maximum difference for displacement value was 0.002 mm, and for the von

Mises stress it was 0.05 MPa, which were within acceptable numerical tolerances. These small deviations in the results can be related to differences in solver algorithms and numerical precision. This confirms the robustness of PAK in capturing the mechanical response of femoral bone under physiological loading. The obtained results validate PAK as a reliable in-house alternative to commercial solvers for modeling bone mechanics.

4. Conclusions

This study highlights the biomechanical implications of decreasing bone mineral density by analyzing the femoral bone under standing loading conditions in healthy bone, bone with osteopenia, and bone with osteoporosis. The observed trend of increasing displacement and decreasing maximum von Mises stress with bone degeneration underscores the loss of structural stiffness and integrity in compromised bone tissue. The reduction of stress values shows the bone's diminished ability to resist deformation. The results emphasize the critical need for early diagnosis and intervention in patients with osteopenia or osteoporosis.

The current study is based on simplified material properties, using homogeneous and isotropic elasticity modulus, while bone is a highly heterogeneous and anisotropic tissue. As such, future work would benefit from incorporating patient-specific material mapping from imaging modalities, allowing for region-dependent assignment of mechanical properties. This would improve the accuracy of simulations and provide more personalized predictions of bone strength and fracture risk.

The obtained results not only validate the use of computational tools like the in-house solver PAK for bone biomechanics research but also highlight the clinical relevance of biomechanical modeling in understanding, diagnosing, and ultimately preventing the consequences of age- or disease-related bone deterioration.

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