Effect of Neck-Shaft Angle on the Stress Response of Femur Bone

Sridhar Adibhatla, Satya Devi. A, N.V. Swamy Naidu

Abstract: ***The neck region of femur is of great clinical importance and most general area which undergoes stress fractures. The femoral neck shaft angle (NSA) play major role to identify the structural deformities in femur. The present research is focused on stress analysis of femur with different NSA using finite element method (FEM). In order to identify the effects of NSA on stress response in the femur bone, two different femur geometries were considered and FE models were developed with NSA varying from 110^0-170^0. Two different porosity levels (50% and 75%) with isotropic material properties were considered for the stress analysis. The force on the femoral head was applied at 0^0 and 16^0 to the vertical axis in the frontal plane. Two different anteversion angles (12^0 and 24^0) were also considered. The results showed that there exists a direct relationship between stress and porosity. Also, there exists an inverse relationship of stress with NSA, anteversion and force inclination angle. It could be concluded that the subjects with lower NSA in combination with higher porosity are more prone to stress related fractures. Higher anteversion than normal, helps to reduce the stress magnitude when the rotation is internal***

Keywords: Anteversion, Femur, Neck-shaft angle, Porosity

I. INTRODUCTION

The structural deformities of femur depend on various factors. The main factors for these deformities could be osteoporosis (reduced bone porosity), congenital or growth-related problems and high energy trauma (as in the event of crash). Of these, the growth-related problems will lead to certain type of structural deformities in femur. The structural characteristics and strength of femur mainly depends on the neck shaft angle (NSA).

The NSA is the angle formed between the axis of the neck and shaft and the average angle is approximately 125^0 (Nordin and Frankel, 2001). Coxa vara, is a type of femur deformity, in which the NSA is less than 120^0 and in case of coxa valga, this angle is more than 130^0 (Yochum and Rowe, 2005). Femoral torsion (version or rotation) is a type of deformity in which the neck and head are rotated forward with respect to condyles. The normal torsion is about 12^0 internal rotation. If this angle is less than or more than 12^0 it is called as retroversion and anteversion respectively. These were shown in Fig. 1. and 2. respectively.

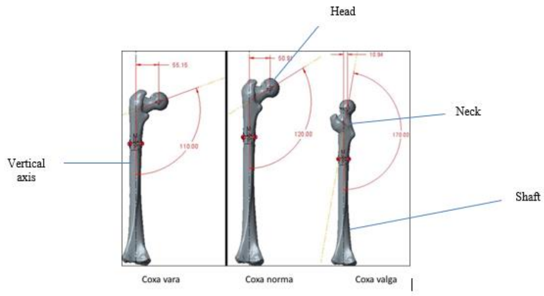

Fig. 1. NSA and moment arm

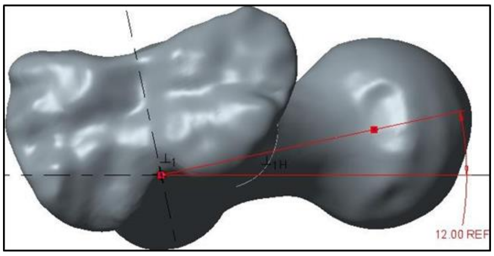

Fig. 2. Femoral bone with torsion

II. LITERATURE REVIEW

Gómez-Alonso et al. (2000) studied various femoral neck geometry attributes which could predict hip fracture. Their study concluded that reduction in bone mineral density (osteoporosis), higher neck width and increased NSA are the independent parameters for the risk of hip fracture. It was also concluded that, the combination of these three parameters predicted hip fracture more closely than the independent variables.

Qian et al. (2009) studied the effect of femur neck geometry and stress developed in the ward's triangle region. In this study NSA of 115^0 to 140^0 were considered. Their study concluded that as the NSA increases the stress in the neck region decreases.

Keyak et al. (2001) has studied the fractures in proximal femur region in single limb stance and impact due to fall. They predicted the fracture load using FE models. It was concluded that FE analysis could be used to predict the fractures.

Pinilla et al. (1996) conducted experiments to determine the effect of load direction in the failure of proximal femur in elderly people. It was reported that impact direction is a critical parameter in identifying the fracture risk and is independent of bone density.

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Past studies on relation between neck-shaft angle (NSA) and stress response of femur were done for a limited range of NSA. Very few studies have been done to establish the impact of anteversion and porosity along with NSA on femur strength.

The present work is focused on detailed stress response of femur by varying NSA (110^0 to 170^0), anteversion (12^0 and 24^0) and porosity levels (50% and 75%), with isotropic material properties.

III. FINITE ELEMENT ANALYSIS

A. 3D CAD model of femur

The geometry of two femurs have been obtained from online database 3D content central. The models were created using CT scan and converted into solid models in Solid works 2008. Both models had 135^0 of NSA and 10^0 of rotation initially. The geometry details of two femurs were shown in Table I.

Table I: Geometry details

Dimension (mm)	Femur1	Femur2
Head diameter	45.72	36
Shaft diameter (at mid-point of shaft)	10.9	9.5
Shaft length(L)	372.24	361.37
Inclined length(h)	58.24	56.46

The base models were modified to have NSA varying from 110^0 to 170^0 with anteversion (internal rotation) of 12^0 and 24^0. The models were prepared to have two different porosity levels (50% and 75%).

A load of 40 kg (392.4 N) was applied on femoral head, at 0^0 and 16^0 to long axis, in the frontal plane, to represent loading in standing position. The bottom surfaces (distal condyles) of femur were fixed in all degrees of freedom. The isotropic material properties (E=17000 MPa, ρ=1371.2 kg/m^3, μ=0.35) are applied. The geometry of femur, FE model along with load and boundary conditions were shown in Fig. 3 (left to right).

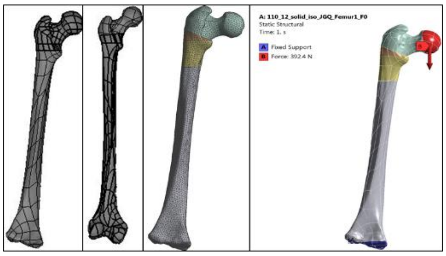

Fig. 3. Geometry and FE model details

B. FE modeling and validation of results

The mesh convergence study was performed and suitable element size was selected (0.75 and 0.71 mm for femur 1 and 2 respectively), which has produced approximately 100,000 nodes and 68,000 elements. The element type used was SHELL181. This element is used to analyze thin or moderately thick shell structures and suitable for linear, large rotation and/or nonlinear applications.

The 3-D model and representative 1-D model of femur was shown in Fig. 4. The approximate analytical solution for horizontal and vertical deflections at point B are derived using Castigliano's theorem (Gere and Goodno, 2009). These were given by equations 1 and 2 respectively.

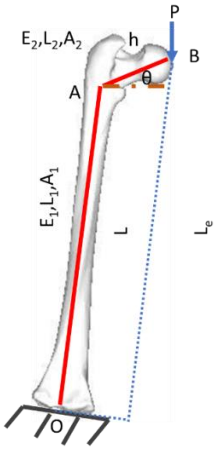

Fig. 4. 3-D model and representative 1-D model of femur

$$\delta_h = \frac{PL^3 \sin 2\theta}{2E_1 I_1} + \frac{PL^3 \cos\theta}{2E_1 I_1} - \frac{Ph \sin 2\theta}{2A_2 E_2} + \frac{Ph^3 \sin 2\theta}{6E_2 I_2} \dots (1)$$

$$\delta_v = \frac{PL}{A_1 E_1} + \frac{PL^3 \cos^2\theta}{E_1 I_1} + \frac{Ph \sin^2\theta}{A_2 E_2} + \frac{Ph^3 \cos^2\theta}{3E_2 I_2} \dots (2)$$

The maximum deflection, bending moment and stress in an eccentrically loaded column (approximately represents femur) are given by equations 3 – 5 respectively (Gere and Goodno, 2009).

$$y_{max} = e\left[\sec\left(\frac{l_e}{2r_g}\sqrt{\frac{P}{EA}}\right) - 1\right] \dots (3)$$

$$M_{max} = Pe \sec\left(\frac{l_e}{2r_g}\sqrt{\frac{P}{EA}}\right) \dots (4)$$

$$\sigma_{max} = \frac{P}{A}\left[1 + \frac{ec}{r_g{}^2}\sec\left(\frac{l_e}{2r_g}\sqrt{\frac{P}{EA}}\right)\right] \dots (5)$$

The comparison of results between analytical solution and 3-D FEA (of femur 1) are shown in Table II. The results of actual femur models (3-D FEA) showed deviation from the analytical results due to the effect of 3-D stiffness calculation, anteversion, continuous variation of area of cross- section and curvature, which were not incorporated in the analytical solution.

Table II: Horizontal Deflection

Horizontal Deflection (mm)			
Femur 1	Analytical	3D FEA	% Difference
110	4.394	3.828	12.873
115	4.644	3.789	18.404
120	4.810	3.721	22.644

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From equations 3-5 it could be observed that as the eccentricity increases (when the NSA decreases) the bending moment and stress will increase. The same phenomenon is observed in the graphs of reaction moment (obtained from FEA) versus other parameters like porosity, anteversion and force reaction.

IV. RESULTS AND DISCUSSION

The linear static analysis is performed using ANSYS 19.2, on two femur models with different (50% and 75%) porosity levels, force inclination angle and anteversion, by keeping the load and boundary conditions same. The details of load cases are shown in Table III.

Table III: Load cases details

Load Case	Force (applied angle)	Anteversion (internal rotation)	Geometry	Porosity (%)
LC1	0	12	Femur1 and Femur2	50% and 75%
LC2	0	24		
LC3	16	12		
LC4	16	24		

C. Porosity variation

Fig. 5 shows the effect of porosity on equivalent stress for different NSA. When porosity increases, the femur tends to become hollow and its wall thickness decreases. Therefore, models with higher porosity (independent of other parameters) will experience higher stress magnitude under the same conditions.

Femur 1 has lower stress values when compared with femur 2, since it has higher shaft diameter, than latter. Thus, even at higher porosity, it has more material to resist loading.

It could be observed that, the stress is sharply increased, when the NSA is reduced below 135^0 (at 75% porosity). This is due to the fact that as NSA reduces moment arm or eccentricity increases (Fig. 1.) which increases the bending moment (equation 2).

The stress increase is flat and linear at 50% porosity level, because it has more material to resist loading. The difference in stress magnitude between two models is gradually decreased as NSA is increased.

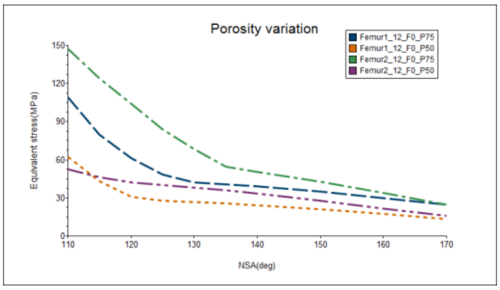

Fig. 5. Porosity variation

The change in stress could be attributed to change in moments as shown in Fig. 6.

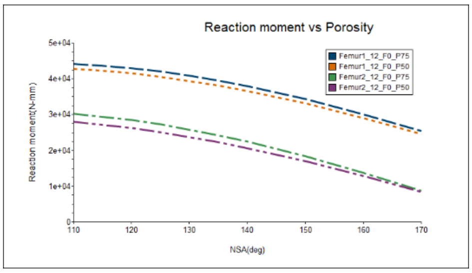

Fig. 6. Reaction moments at different porosity levels

D. Anteversion variation (LC1 and LC2)

From the results shown in Fig. 7. it could be observed that as the anteversion increases, the stress magnitude decreases. Also, as the NSA increases, the stress on the femur increases. This behaviour is same for both the femur models.

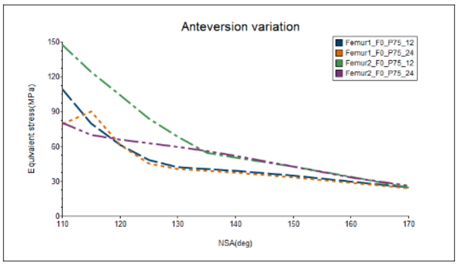

Fig. 7. Anteversion variation

As anteversion increased from 12^0 to 24^0 (the femur has been rotated internally), the moment arm got decreased. This reduced moment arm produces less bending moment, as shown in Fig. 8. which in turn produces less stresses.

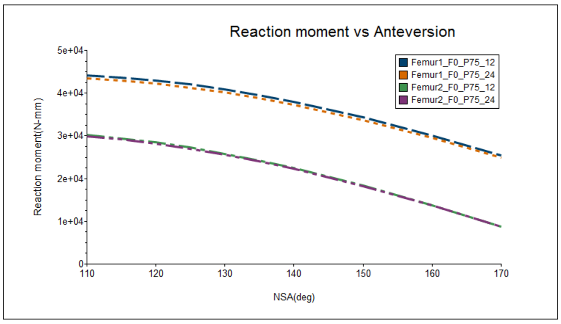

Fig. 8. Reaction moment at different anteversion angles

There is a steep rise in stress (Fig. 7.) when the NSA is reduced below 125^0, at both porosity levels. The dip in stress between 115^0 to 110^0 NSA, could be due to geometric changes for femur1.

The stress rise (Fig. 7) is very sharp (from NSA of 135^0 to 110^0) when anteversion is 12^0. When NSA has further increased (135^0 to 170^0) anteversion has very little effect on stress magnitude for femur 2.

E. Force inclination variation (LC1 and LC3)

It is observed that (Fig. 9), when the force is 0^0 to the vertical, the stress continuously decreased, when the NSA increased from 110^0 to 170^0 for both the models.

In the 16^0 to vertical case, the stress has decreased, with the increase of NSA from 110^0 to 150^0 and 110^0 to 135^0 for

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femur 1 and femur 2 respectively. The stress is observed to be increasing from 135^0 to170^0 as shown in Fig. 9.

As NSA increases, the head portion of femur moves up. This will cause the centre of head (pivot point of force application) to move into the body. This will reduce the moment arm (horizontal distance) and hence the stresses will reduce. This behaviour is same for both inclinations of force. The reaction moments obtained from FEA at different force inclination angles are shown in Fig. 10.

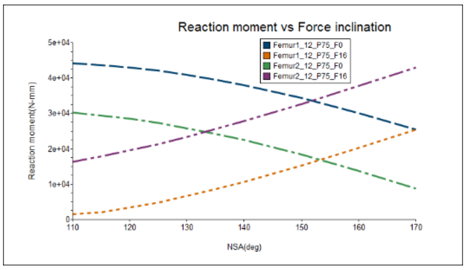

Fig. 9. Reaction moment at different Force inclination angles

But when the force is applied at an oblique angle (other than 0^0 to vertical), the force gets resolved into horizontal and vertical components. The horizontal component of force increases and vertical component of force decrease with the increase in NSA.

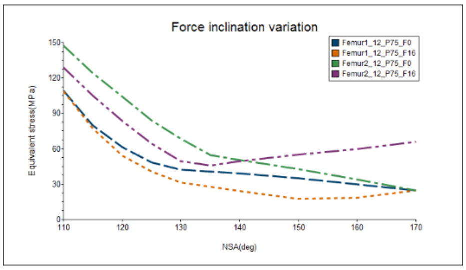

Fig. 10. Force inclination variation

These both force components will become equal when NSA is 135^0, and after that their signs gets reversed. This is the reason for increase in stresses, when the NSA is increased above 135^0.

As the force is applied at an offset distance to the vertical axis, the produced bending moment causes the medial side of femur to be in compression and the lateral side to be in tension.

When the NSA increased from 110^0 to 170^0, the compressive stress in the femur will increase with a corresponding decrease in tensile stress. These results for femur 2 at NSA of 110^0 and $170^0$are shown in Fig. 11. and 12 respectively. The similar behaviour is observed for femur 1 as well.

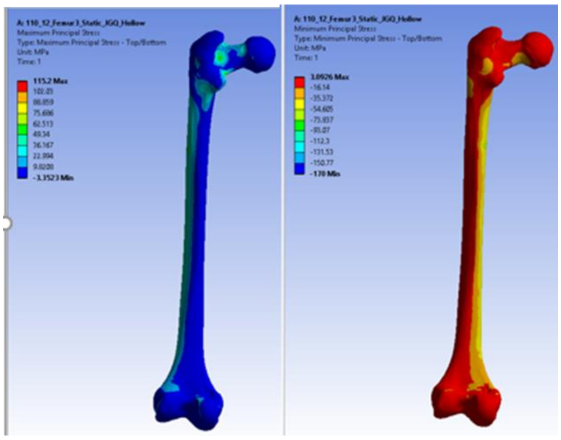

Fig. 11. Tensile and Compressive stress plots at NSA of 110^0

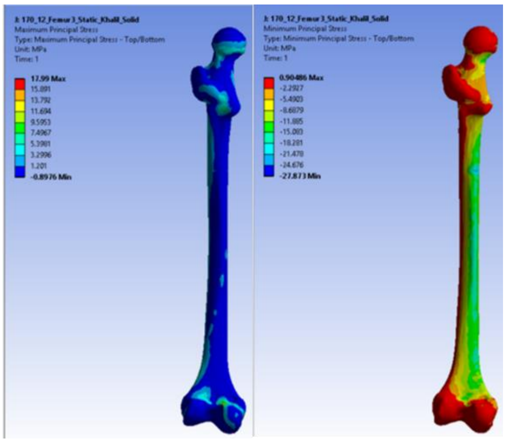

Fig. 12. Tensile and Compressive stress plots at NSA of 170^0

V. CONCLUSIONS

From the static structural analysis performed on two different femur geometries with different parameters the following conclusions could be drawn.

- As the NSA increases, the stress decreases when the force is applied at 0^0 to the vertical. But when the force is applied at 16^0 to the vertical, the stress decreases as the NSA changed from 110^0 to 135^0 and after that the stress increases till NSA is 170^0.
- It is hypothesized that due to increase in NSA, when the stress falls below the stress attractor stimulus, the stress should increase in order to maintain the bone mass balance. This is possible only when the load is applied at an inclination to vertical axis (16^0, in this study).
- The porosity has a direct relationship with the stress. As the porosity increases, the stress on femur will increase. It could be concluded that the subjects with lower NSA in combination with higher porosity are more prone to stress related fractures.
- Higher anteversion than normal, helps to reduce the stress magnitude when the rotation is internal.
- The geometric parameters of femur (length, shaft diameter etc) will impact the stress magnitude,

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though the response under loading is similar for different geometries.

- These results would be helpful in patient-specific therapy planning and provides a deeper insight in to the stress response of femur under different physiological parameters.

VI. FUTURE WORK

The future work should include simulations with different hyper elastic material models to assess the stress-strain response of femur more accurately.

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