International Journal of Recent Technology and Engineering (IJRTE)
ISSN: 2277-3878, Volume-8, Issue-1S4, June 2019

Applicability of Hyper Elastic Models for the Analysis of Femur Bone

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***Abstract:** The femur bone plays a key role in the locomotion activities of human beings. It is the load bearing and load transferring part in the lower extremity of bones. The stress-strain response of femur largely depends on the type of material and its properties. In the present study different incompressible hyper elastic material models (constants) were derived from the uni-axial compression test data (Evans, 1969) performed on both dry and wet femurs using curve-fitting techniques. Two different femur geometries were considered and FE models were developed with neck-shaft angle (NSA) varying from 110^0-170^0 and porosity level of 75%. The force on the femoral head was applied at 0^0 to the vertical axis in the frontal plane. The results of static structural analysis performed with different hyper elastic material models indicated that Ogden 3rd order model is able to predict the stress-strain response of femur in wet condition more accurately and in good agreement with the published experimental results. Also, it was observed that wet femur will have higher stress-strain response due to the presence of moisture and other contents in comparison to dry bone.*

***Keywords:** Femur, Hyper-elastic, Neck-shaft angle, Porosity, Ogden 3rd order*

1. INTRODUCTION

The selection of correct material model is of critical importance in assessing the load-deformation behavior of biological materials. These materials undergo large-deformations and behave non-linearly under applied loading. The classical isotropic material models would not be sufficient to predict this behavior. In the 20th century different hyper elastic material models were developed to understand the behavior of both soft and hard tissues to be able to perform computer simulations with improved accuracy.

2. LITERATURE REVIEW

MingleiJu et.al (2014) conducted different experiments on polyurethane foam under uni-axial compression/decompression with different hyper elastic and viscoelastic models. Their study concluded that Ogden three parameter model, polynomial models with two and three terms were able to predict the stress-strain response very well even under large compression.

Darijani. H et.al (2014) proposed a new hyper elastic model which contains second strain invariant term and compared its performance with other available models. They compared these models for both soft tissues and hard rubber. Their study reported that the new model is giving better performance when compared to 30 other models under different loading scenarios.

Rafael Tobajas et.al (2016) compared six different hyper elastic models to compare their performance against the test data obtained from santoprene polymer. Their study found that 5-parameter Mooney-Rivlin model is best suitable and in good agreement with test results for that given material.

Angela Mihai et.al (2015) studied the performance of different hyper elastic models applied to brain and fat tissues. They have assumed these material models to be isotropic and incompressible. Their study showed that Fung, Gent, neo-Hookean and Mooney-Rivlin models are inadequate to model the response of soft tissues used in their study. Ogden model was found to be suitable and in good agreement with the test results.

Beomkeun Kim et.al (2012) studied different hyper elastic models in application to chloroprene rubber. From their study it was concluded that Ogden 3rd order model is best suitable in comparison to neo-Hookean and Mooney-Rivlin models.

Hosseinzadeh et.al (2016) studied different hyper elastic models and their application to demineralized and deproteinized femur bone. Their results showed that Mooney-Rivlin and Ogden models were not able to predict the behavior in line with the experimental data. In contrast, general exponential and power law models gave results which are in good agreement with test data.

It could be summarized from the past literature that; selection of a particular hyper elastic material model depends on the type of tissue and type of loading. Also, there is no open literature available to assess the suitability of these material models applied to human femur.

In the present study, three different hyper elastic material models, namely Ogden 3rd order, Mooney-Rivlin 3rd order and polynomial 1st order models were chosen and applied to human femur bone to study the performance in comparison to the published test data.

3. MATERIAL MODELS

Following are the three hyper elastic material models used in the present study.

Mooney-Rivlin three-parameter model (MR3P): It

Revised Manuscript Received on June 10, 2019.

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is an improvement of neo-Hookean (NH) model. It has many variations, based on the number of material constants required. The strain energy density (SED) function is given by (Nomesh Kumar, 2016)

$$\varphi = C_{10}(\bar{I}_1 - 3) + C_{01}(\bar{I}_2 - 3) + C_{11}(\bar{I}_1 - 3)(\bar{I}_2 - 3) + \frac{1}{d}(J-1)^2 \dots (1)$$

Where C_{10}, C_{01}, C_{11} are material constants.

$d$material incompressibility parameter.

To have consistency with isotropic elasticity, the restrictions on material constants is

$$C_{10} + C_{01} \geq 0 \text{ and } C_{11} \geq 0 \dots (2)$$

$$\mu = 2(C_{10} + C_{01}) \text{ and } K = {}^{2}\!/_{d} \dots (3)$$

Where μ and K are initial shear and bulk modulus of the material respectively.

Ogden 3rd order model (OGD3): This model is used to model the stress-strain response of materials like rubber, biological tissues and polymer materials. The SED in terms of principal stretches is given by (ML Ju, et.al, 2013)

$$W(\lambda_1, \lambda_2, \lambda_3) = \sum_{p=1}^{N} \frac{\mu_p}{\alpha_p}(\lambda_1^{\alpha_p} + \lambda_2^{\alpha_p} + \lambda_3^{\alpha_p} - 3) \dots (4)$$

Where N, μ_p and α_p are material constants.

For incompressible materials, it changes to the form of

$$W(\lambda_1, \lambda_2) = \sum_{p=1}^{N} \frac{2\mu_p}{\alpha^2_p}(\lambda_1^{\alpha_p} + \lambda_2^{\alpha_p} + \lambda_1^{-\alpha_p}\lambda_2^{-\alpha_p} - 3) \dots (5)$$

The consistency condition for isotropic elasticity is given by

$$2\mu = \sum_{p=1}^{N} \mu_p \alpha_p \dots (6)$$

Polynomial 1st order model (POLY1):

The polynomial hyper elastic model is a generalized form of Mooney-Rivlin model. The SED is given by (Chang et.al, 1991)

$$\varphi = \sum_{i,j=0}^{\infty} C_{ij}(\bar{I}_1 - 3)^i (\bar{I}_2 - 3)^j + \sum_{k=1}^{\infty} \frac{1}{d_k}(J-1)^{2k} \dots (7)$$

Where C_{ij} are material constants and $C_{00} = 0$.

$d_k$is incompressibility parameter

In this study, the stress-strain curves for both dry and wet femurs are obtained from the published data of Evans (1969). These curves were generated from uni-axial compression test. The data points from the test (reference) curves were extracted using "web plot digitizer" [VII] tool. The graphs were redrawn for both dry and wet femurs as shown in Fig. 1. These data points were given as input to ANSYS. Material constants for the hyper elastic models discussed above are obtained.

These models are generally used to characterize rubber type of elastomeric materials. In the present study, these models are considered as incompressible, due to non-availability of volumetric test data.

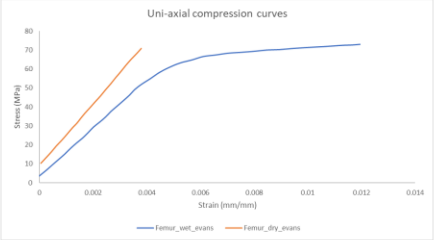

Fig. 1.Uni-axial compression curves (Evans, 1969)

4. FINITE ELEMENT ANALYSIS

A. 3D CAD model of femur

The geometries of two femurs were 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 nomenclature of femur geometry is shown in Fig. 2.

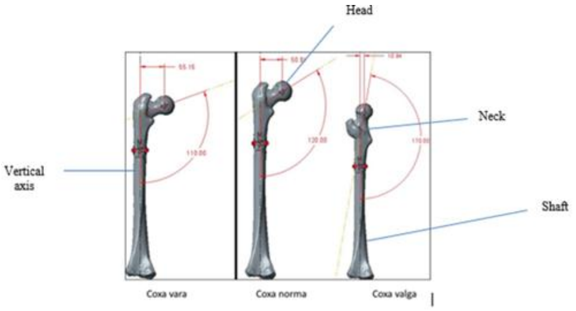

Fig. 2. Nomenclature of femur bone

The details of the geometry of the two femurs are 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. The models were prepared to have 75% porosity level.

A load of 20 kg (196.2 N) was applied on femoral head, at 0^0 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 geometry of femur, FE model along with load and boundary conditions are shown in Fig. 3 (left to right).

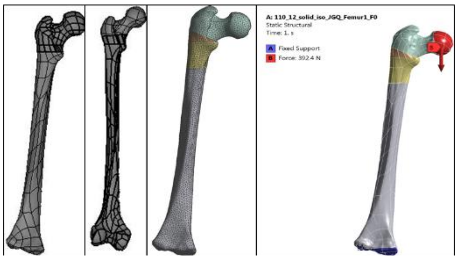

Fig. 3. Geometry and FE model details

B. FE modeling

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 was used to analyze thin or moderately thick shell structures and suitable for linear, large rotation and/or nonlinear applications.

5. RESULTS AND DISCUSSION

The linear static analysis is performed using ANSYS 19.2, on two femur models with 75% porosity, 00 force inclination angle (Fig. 4) and anteversion of 120 (Fig. 5) by keeping the load and boundary conditions same.

Fig 4. Force inclination angle

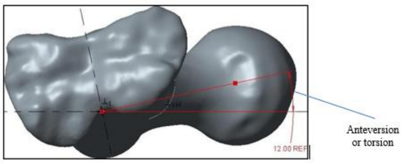

Fig 5. Femoral anteversion

The details of load cases are shown in Table II.

Table II: Load case details

Load case	Force inclination (angle)	Anteversion (internal rotation)	Porosity (%)	Condition (of bone)	Geometry
LC1	0	12	75	wet	Femur 1
LC2				dry	
LC3				wet	Femur 2
LC4				dry	

C. Analysis of Femur 1 (LC1 and LC2):

The results of equivalent strain and stress of femur 1 were shown in Fig 6 and 7 respectively. From the graphs it could be observed that Ogden (OGD3) model has produced higher strain results followed by Polynomial (POLY1) and Mooney-Rivlin (MR3P) models.

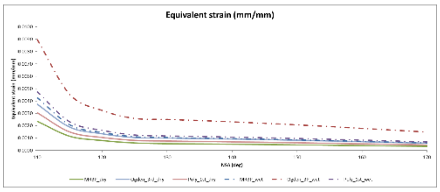

Fig 6. Equivalent strain for femur 1 (dry and wet)

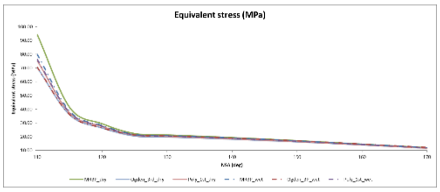

Fig 7. Equivalent stress for femur 1 (dry and wet)

Conversely, the order of stress is MR3P>POLY1>OGD3. In contrast to the linear elasticity, in this case the stress is not directly proportional to strain.

The similar behaviour was observed for femur 1 under wet condition, but the stress and strain values are higher than in dry condition.

D. Analysis of Femur 2 (LC3 and LC4):

The results of equivalent strain and stress of femur 2 were shown in Fig 8 and 9 respectively. The order of stress and strain are same as femur 1. But the magnitude of stress is less for femur 2 in comparison to femur 1.

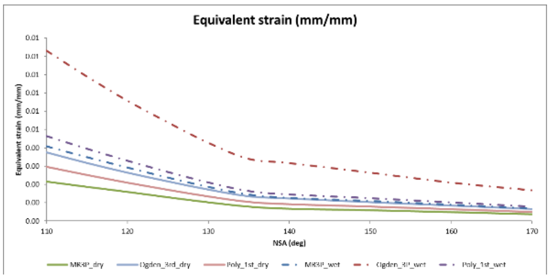

Fig 8. Equivalent strain for femur 2 (dry and wet)

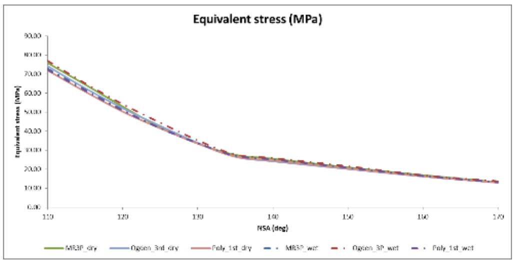

Fig 9. Equivalent strain for femur 2 (dry and wet)

From the graphs it could be observed that, Ogden 3rd order model produces higher results and the order of strain magnitude for the material models is OGD3>POLY1>MR3P.

This is because OGD3 model has principal stretch (strain) raised to the power of α_p, which produces higher strains. The stresses are less for the OGD3 model because in the non-linear zone, the increase in strain is more for a small increment of stress. Hence the order of stress magnitude is MR3P> POLY1> OGD3.

The response of OGD3 model in comparison to the experimental data was shown in Fig. 10. The curve with red circles indicates the experimental data, whereas the continuous blue line represents OGD3 model response.

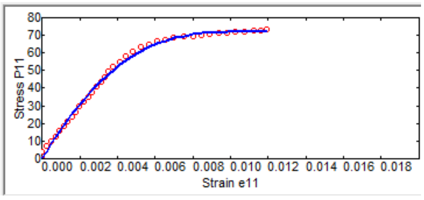

Fig 10. Experimental data (Evans, 1969) vs OGD3 model

6. CONCLUSIONS

The following conclusions could be drawn from the results presented above.

The OGD3 model predicts higher strain and lower stress magnitudes, when compared to the other material models considered in this study.

The difference in stress magnitude among different material models exists only up to the NSA of 120^0 to 130^0 only.

The difference in stress results is very minimal or insignificant when the NSA is increased from 130^0 to 170^0.

There is a considerable variation in the strain results throughout the entire range of NSA (110^0 to 170^0) considered, between different material models. The stress and strain behaviour is independent of the geometry considered (i.e. same for both femur 1 and femur 2).

The dry femur will result in lower stress and strain magnitudes as compared to wet femur, because wet femur will consist of moisture and bone marrow which yields non-linear stress-strain response.

In contrast, dry will have more ash content, which makes it brittle and hence the stress-strain response in almost linear.

For the given geometry and loading conditions, the OGD3 material is found to be suitable, because its response is in good agreement with the experimental data.

7. FUTURE WORK

The future work should include simulations with different hyper elastic material models to assess the dynamic response of femur.

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