IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)
An International Open Access, Peer-reviewed, Refereed Journal

Finite element material models for nonlinear analysis of cortical bone – A Systematic Review

Nikhil BN[1], Dr. Chandrashekhar Bendigeri[2]

[1]Research Scholar, Department of Mechanical Engineering, University Visvesvaraya College of Engineering, Bangalore, Karnataka, India

[2]Professor, Department of Mechanical Engineering, University Visvesvaraya College of Engineering, Bangalore, Karnataka, India

Abstract: Bone tissue is a material with a complicated structure & mechanical property. Repetitive loads or diseases can produce microfractures to appear in the bone tissue, which results in a worsening of its mechanical properties. On the other hand, bone is a constantly evolving tissue, adapting its density to the loading conditions it is subjected to. The advantage of the computational or the numerical method is that a wide range of loading and impact conditions can be easily reconstructed and analyzed. Current FE models are limited due to assumptions for the geometric and time-dependent material properties inherent in the anisotropic and anatomic constraints associated with joint stability and the static conditions inherent in the analysis. This systematic review will give a very good overview of latest research in the field of Computational Biomechanics, Material model development, Finite element simulation of Human cortical Bone collected from various international journals.

***Index Terms* – Finite element Modelling, Trabecular Bones, Remodeling, material model.**

I. INTRODUCTION

The trabecular bone exhibits a very complicated non-linear material behaviour. The three stages of the bone failure are softening after the yield point, plateau, and densification stage, which are observed during compression. Soft tissues exhibit mechanical properties and behaviour with higher complexity than most engineering materials and structures. The current commercial FEA software are not designed for studying the behaviour of hard tissues & is not well suitable to solve highly non-linear geometry and material properties like human hard tissues.

On the other hand, there are very less data available on the mechanical properties of Human bones, age related degradation and theory of failures or the damage prediction methods. Since the availability of fresh cadavers, The quality of the bones, the difficulty in storage and experimental infrastructure difficulties Authors have either referred to existing works of literature, testing of Animal bones, testing of bone similar materials Or performed material property measurements using micro Computational tomography scans of the bones.

II. MATERIAL AND MATERIAL MODELS

Osteoporosis is a prevalent bone condition that causes bone mineral density reduction over time, increasing the risk of fracture. Fractures caused by osteoporosis are especially common in trabecular-rich locations like femoral heads and vertebrae. The important feature of trabecular bones are the remodeling phenomena, where the bones adapt the internal trabecular structure based on the loading condition and aging. The remodeling or evolution of the material properties affects the mechanical properties of human cortical bone but this phenomenon is very difficult to measure in-vivo.

(Du, Li and Silberschmidt, 2020) have used bone mineral density values for finite element simulation. Bone mineral density has been obtained from Micro CT Scan. Based on the Hounsfield Unite in the CT scans the Bone mineral density has be approximated. Authors have used bovine femoral head, the sample was scanned at 60µm resolution and the region of interest with height of 5mm was extracted digitally from the trabecular region of the CT Scan. The young’s modulus was calculated based on the relationship proposed by Currey.

The relationship of young’s modulus and BMD is given by:

$$E^i = C_e\left(\rho_t^i\right)^b$$

ρ_t^i is the BMD in the element ‘i’ at simulation time ‘t’, ‘b’ is set to 1.54 and C is a constant which is set to 4621.84.

Mechano-state theory has been used to study the remodeling phenomenon. The bone adaptive activities were categorized into three stages with respect to the magnitude of mechanical stimuli, which represents resorption and formation. In this study sensitivity of remodeling was investigated and The results from this study was, trabecular structures with both multi and single material models were simulated. It is observed the bone volume fraction was higher in the multi material model. These outcomes indicate that single material properties can still be used.

(Johnson, Socrate and Boyce, 2010) have described many previously published widely cited theories. One of the theories include by *Wood* has developed a regression equation for calculating Youngs modulus using the strain rates. This equation has given good fit for the experimental data but not reliable for the extremely low strain rates.

$$E = [16.0 + 1.93 \log(\dot{\varepsilon})] GPa$$

The next theory is proposed by Tennyson et al which is based on Split Hopkinson Pressure bar technique to study the effect of post mortem age on bovine femoral under compressive loads, the regression equation is:

$$\sigma = E\varepsilon + \eta\dot{\varepsilon}$$

Where E is the long-term elastic constant and the value is considered as 18.1GPa and Viscosity, η is considered as 2.4 x 10^4Pa s. To present the model development authors have explained the model in rheological form. The Rheological form consists of visco-elastic and visco-plastic components. The rheological model proposed by the authors is as shown in figure 1:

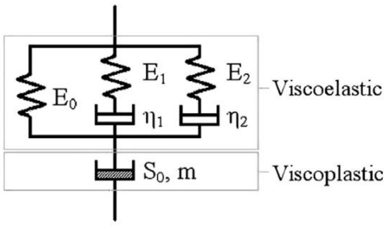

Figure 1: Schematic representation for the mechanical analog of the viscoelastic, viscoplastic constitutive model proposed for cortical bone. (Johnson, Socrate and Boyce, 2010)

(Shirazi *et al.*, 2017) have performed nanomechanical testing to obtain accurate mechanical properties of an orthopaedic PMMA Bone. Due to viscoelastic characteristics, the mechanical properties cannot be identified using conventional indentation methods. A complete analogical study between the finite element simulation results and the experimental data was made to reach the best-optimized parameters for the selected model. The proposed model in this research can be used to obtain the constitutive material relationship for polymeric materials.

The authors employed an ISO-compliant Nano indentation test apparatus with a Berkovich indenter. The Oliver-Pharr approach was used to calibrate the instrument and analyze the experimental results. During the indentation process, load of 400µN was applied. Accordingly, the elasticity modulus and the normal hardness were calculated based on the formula proposed by Sneddon and Briscoe et al.

$$\frac{1}{E_r} = \frac{1-\vartheta^2}{E} + \frac{1-\vartheta_i^2}{E_i}$$

Where E_r is the reduced modulus of the indentation contact, E and ϑ are elastic modulus and poissons ratio.

(Soltanihafshejani *et al.*, 2021) have conducted Compression tests under uniaxial and confined loading conditions on fifty-nine human trabecular bone specimens. Three main material parameters were obtained as a function of BMD to develop the isotropic material model. The results are evaluated with the experimental data. Based on the three main material parameters a relative constitutive law was implemented in finite element models.

Experimental setup and process parameters: The samples were subjected to preload of max 10N to ensure uniform contact with the supports. For compression test a load at constant velocity of 5mm/min up to 58% of strain was applied.

The von Mises equivalent stress (q) and the hydrostatic pressure regulate the Crushable Foam model with an isotropic hardening rule (ICF) (p). In the p–q stress plane, the yield surface is an ellipse centred at the origin.
A computer model of a cylinder with a diameter of 11.5 mm and a height of 12 mm was developed to give BMD values to the specimens. To assign the local Hounsfield units, the cylinder was virtually positioned in the QCT images at the site of the drilled specimens (HU). A calibration phantom was used to convert the collected readings to BMD. To avoid alignment mistake, the cylinder's diameter was set slightly smaller (0.1 mm) than the real size.

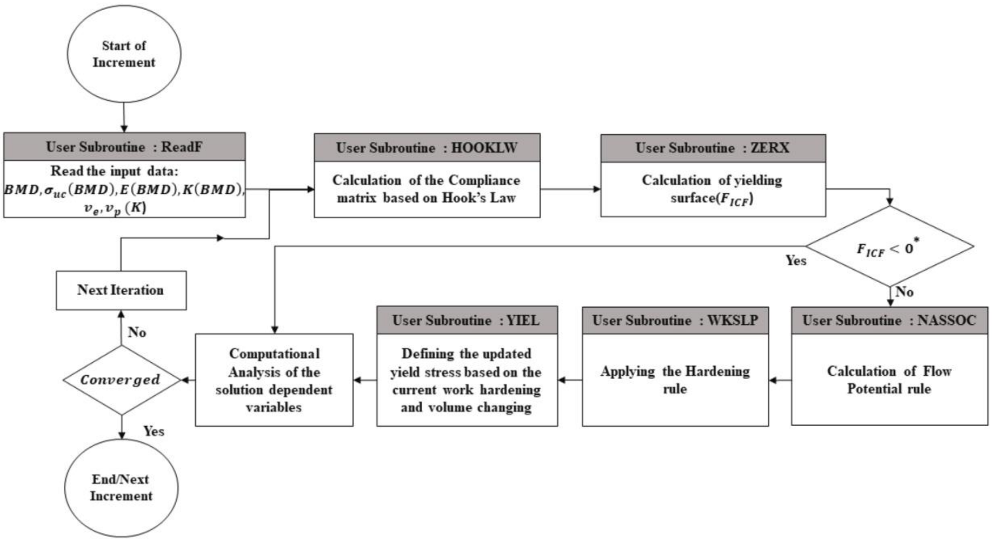

Figure 2. Computational algorithm of numerical simulation, including all the necessary subroutines to be called from available Marc-Mentat routines. Referred to research by (Soltanihafshejani *et al.*, 2021)

(Weed *et al.*, 2010) The focus of this research was to study the mechanics of the human knee using a method that considers multibody system & large deformation FE algorithms. The major bones in the knee joint are femur, tibia, and fibula are modeled as rigid bodies in this study. The ligaments are modeled using the large displacement absolute nodal coordinate formulation (ANCF) with usage of a Neo-Hookean constitutive model that accounts for large change in the configuration as experienced in knee flexion, extension, & rotation.

The main objective of this research was to propose a new method that integrates multibody system and large displacement finite element algorithms for finite element analysis of the knee joint.

Ligament kinematics: The existing beam, plate, shell finite elements do not allow straight forward implementation of general nonlinear constitutive models such as neo-Hookean and Mooney Rivlin material models. Solid components that use linear or bilinear interpolation do not accurately capture major curvature changes, necessitating the use of a large number of elements to construct a satisfactory ligament model.

Authors have used ANCF finite beam element in this investigation. This approach is implemented considering nearly incompressible hyperelastic behavior. The global position vector r_{ij} of an arbitrary point on the finite element j of body i can be defined using the element shape functions and the nodal coordinate vector as follows:

$$r^{ij} = S^{ij}(x,y,z)e^{ij}(t)$$

Where S^{ij} is the element shape function represented in local coordinates, e^{ij} is the vector of nodal co-ordinates and t is the time.

M^{iJ} is the constant symmetric mass matrix given by the equation:

$$M^{ij} = \int_{V^{ij}} (\rho^{ij} S^{ijT} S^{ij})\, dV^{iJ}$$

Where ρ^{ij} is the density and V is the volume of the finite element.

(Abdel-Wahab, Alam and Silberschmidt, 2011)To numerically model the fracture of a cortical bone tissue caused by an impact, authors have considered the parameters characterizing its Visco elastoplastic behaviour. Due to the high non-linearity of the elastic-plastic behavior, cyclic loading-unloading uniaxial tension tests were conducted to obtain the elastic moduli from the initial loading part of the cycle and its unloading part.

Since visco-elasto-plasticity of cortical bone affects its damping properties due to energy dissipation, the advanced characterization technical like Dynamic Mechanical Analysis (DMA) technique was used to obtain magnitudes of storage and loss moduli for various frequencies. Based on analysis of elastic-plastic behaviour of the bovine cortical bone tissue, it was observed that the magnitudes of the longitudinal Young's modulus (E) for four cortical positions were in the range of 15-24 GPa. Refer figure 3 for bone sample preparation and location selection strategy.

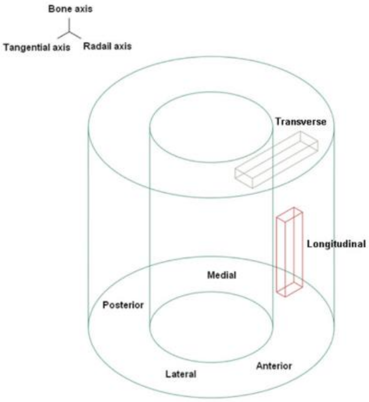

Figure 3: Cortical bone axes (longitudinal, transverse and radial) and anatomical positions (anterior, posterior, medial and lateral). Specimens were cut along longitudinal and transverse axes and from four anatomical positions.(Abdel-Wahab, Alam and Silberschmidt, 2011)

(Taddei *et al.*, 2007) have evaluated the average element Young's modulus in subject-specific finite element models of bones based on computed tomography data. The average of the Young's moduli is directly produced from each voxel Hounsfield Unit and the standard technique of deriving the Young's modulus from an average element density were both considered. The finite element model of a genuine human femur was used to test these strategies. The accuracy of the data is validated with experimental validation, using strain gauges in the instrumented bone samples (13 locations). Refer figure 4 for the instrumented bone samples. The models have predicted stresses, with regression coefficients more than 0.9.

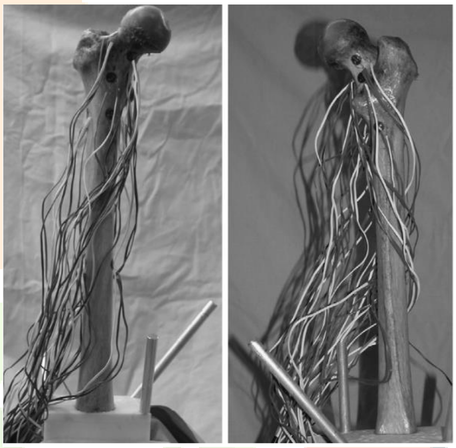

Figure 4: Figure A frontal (left) and posterior (right) view of the instrumented specimen. (Taddei *et al.*, 2007)

III Conclusion:

In the current systematic review of Finite element material models for nonlinear analysis of cortical bone, Ten important well citied international papers were selected and reviewed. As per the review it is evident that the human cortical bone is a very complex material, and its properties are directly related with the cellular structures that characterize this living tissue. The advantage of the computational or the numerical method is that a wide range of loading and impact conditions can be easily reconstructed and analyzed. Therefore, this phenomenon has been gaining increasing interest in the last century. Especially in the last twenty years, many numerical algorithms have been developed to simulate this process.

The finite element models prescribed by have shown very good correlation with the experimental results. The experimental validation tests include compression test – Considering the standard stance loading conditions, Nano indentation test – This test gives very precise material properties at particular location of the bone, later this can be used to calculate multiple other material parameters.

For formulation of finite element models authors have either proposed a Rheological model or a damage evolution law. The geometry input for these cases were from a very accurate Micro computational tomography scanning methods. The data form Micro computational tomography scanning were processed and using a computer program a three-dimensional finite element model was created.

REFERENCES

1. Abdel-Wahab, A.A., Alam, K. and Silberschmidt, V. v. (2011) “Analysis of anisotropic viscoelastoplastic properties of cortical bone tissues,” *Journal of the Mechanical Behavior of Biomedical Materials*, 4(5), pp. 807–820. doi:10.1016/j.jmbbm.2010.10.001.

2. Du, J., Li, S. and Silberschmidt, V. v. (2020) “Trabecular bone remodelling: Finite-element simulation,” in *Procedia Structural Integrity*. Elsevier B.V., pp. 577–583. doi:10.1016/j.prostr.2020.10.067.

3. Johnson, T.P.M., Socrate, S. and Boyce, M.C. (2010) “A viscoelastic, viscoplastic model of cortical bone valid at low and high strain rates,” *Acta Biomaterialia*, 6(10), pp. 4073–4080. doi:10.1016/j.actbio.2010.04.017.

4. Shirazi, H.A. *et al.* (2017) “A constitutive material model for a commercial PMMA bone cement using a combination of nano-indentation test and finite element analysis,” *Polymer Testing*, 59, pp. 328–335. doi:10.1016/j.polymertesting.2017.01.031.

5. Soltanihafshejani, N. *et al.* (2021) “Development of a crushable foam model for human trabecular bone,” *Medical Engineering and Physics*, 96, pp. 53–63. doi:10.1016/j.medengphy.2021.08.009.

6. Taddei, F. *et al.* (2007) “The material mapping strategy influences the accuracy of CT-based finite element models of bones: An evaluation against experimental measurements,” *Medical Engineering and Physics*, 29(9), pp. 973–979. doi:10.1016/j.medengphy.2006.10.014.

7. Weed, D. *et al.* (2010) “A new nonlinear multibody/finite element formulation for knee joint ligaments,” *Nonlinear Dynamics*, 60(3), pp. 357–367. doi:10.1007/s11071-009-9600-2.

8. F. Goehre et al., “Micro-computed tomography, scanning electron microscopy and energy X- ray spectroscopy studies of facet joint degeneration: A comparison to clinical imaging,” 2017, doi: 10.1016/j.micron.2017.04.011.

9. A. Syahrom, M. Al-Fatihhi, M. Szali, J. Muhamad, N. Harun, and A. Öchsner, “Advanced Structured Materials Cancellous Bone Mechanical Characterization and Finite Element Simulation”.

10. M. Mashiatulla, R. D. Ross, and D. R. Sumner, “Validation of cortical bone mineral density distribution using micro-computed tomography,” *Bone*, 2017, doi: 10.1016/j.bone.2017.03.049.