Finite Element Mesh Generation of Human Body Segment in 2-D and 3-D Using B-splineMethod

Uday V.Pise[1], Amba D.Bhatt[2] and Ravindra K.Srivastava[3]

[1]Government Polytechnic Mumbai, India, uvp@mnnit.ac.in
[2]Motilal Nehru National Institute of Technology, India, adbhatt@mnnit.ac.in
[3]Motilal Nehru National Institute of Technology, India, rks@mnnit.ac.in

ABSTRACT

In studying subject specific biomechanical behavior of bio-object, finite element method offers number of advantages. Mesh generation and assignment of material property to each element-node is a fundamental and key issue in generation of accurate finite element model of any biological structure. Researchers offered number of methods of mesh generation to subject specific bio-object. In this work, we present B-spline based modeling and mesh generation methodology for bio-object like human body is presented. The distinct advantage of this method is that modeling and meshing is done in a single step along with true representation of material. For demonstration, mesh models of child femur, adult femur and a head from volumetric CT scan data are presented in 2D and 3D. A minimal scaled Jacobian criterion is used to evaluate the quality of quadrilateral and hexahedral elements. The results show that all quadrilateral and hexahedral element meshes are well shaped and able to capture both geometric and material feature accurately.

Keywords:B-spline, mesh generation, human body.
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1 INTRODUCTION

In recent years, studying biomechanics problems with finite element (FE) simulations are getting more popular due to its cost effective alternative to experimental methods. Similarly, with advances in medical imaging modalities like Computed Tomography (CT) and medical resonance imaging (MRI), it has now become possible to extract quantitative information of human anatomical structure in three dimensions.

Mesh generation of a complex anatomical structure is the first step before applying FE method to patient specific biomechanics problems. There have been numerous attempts to develop patient specific three dimensional finite element methods from CT/MRI data set [5],[8],[12],[19],[21]. However, to the best of our knowledge, automatic hexahedral 3D meshing algorithm based on B-spline heterogeneous modeling has not been used in computational biomechanics till date. Geometric modeling, meshing and inhomogeneous material assignment has to be carried out simultaneously in modeling of any biostructure.Although, many commercial meshing softwares are available but they are inadequate for meshing complex anatomical structures and assigning them inhomogeneous properties automatically.

The goal of this work is to automatically generate 3D volumetric FE models based on heterogeneous B-spline methodology for patient specific bio-models like femur, head etc. FE models generated with this methodology mainly consist of hexahedral elements along the boundary as well as on core. Inhomogeneous material is also assigned at each node of every element automatically. The model based on B-spline methodology also provides good geometrical conformity in 2D as well as in 3D physical domain. For better analytical results, the model can be analyzed with graded element approach as discussed in Pise et al.[14].

2. RELATED WORK

Mesh generation process deals with the decomposition of a given domain (geometry) into finite elements in order to facilitate the numerical solution of partial differential equation. There are two methods for automatically generating FE mesh, one is structured meshing and second is unstructured meshing.

Structured meshing is commonly referred as “grid generation”. In which all interior nodes of the mesh have an equal number of adjacent elements. It usually comprises entirely of quadrilateral (2D) or hexahedral (3D) elements. Normally, structured methods and mapped meshes generate the most desirable meshes However, it is always difficult to decompose an arbitrary geometric configuration into mapped meshable regions [27]. In unstructured mesh generation, node valence requirements are relaxed to allow any number of elements to meet at single node. Triangular (2D) and tetrahedral (3D) elements are the most common forms of unstructured elements which can be generated by octree, Delaunay and advancing front algorithms[20]. There are indirect and direct methods for unstructured quad/hex mesh generation. In indirect method triangular/tetrahedral meshes are generated first, and then converted them into quads/hexes. There are about five direct methods for unstructured hex mesh generation namely grid based, medial surface, plastering, whisker weaving and isosurface extraction. Grid base method [16] is robust, but tends to generate poor quality elements at the boundaries. Medial surface methods, plastering and whisker weaving can generates hex meshes for some geometry but are not robust and reliable for an arbitrary geometry domain.

Number of researchers has implemented voxel-based FE method in biomechanical studies of femur [8], Skull [2], Tibia [7], vertebra [19] with partial success. In voxel based method computer images from 3D voxels are directly converted into eight node hexahedral elements and fill the domain with hexahedral elements. However, this method is unable to capture surface boundaries of anatomical surface and tend to produce jagged surfaces. To overcome these difficulties Grossland et al. [6] has proposed a technique to smooth the stair-step geometrical irregularities for the FE contact stress analysis of articular joints. Camecho et al. [2] also proposed a smoothening algorithm to eliminate the sharp edges of voxel models. Wang et al. [22] has extended and implemented this method in three dimensions (3D) for the FE study of a vertebral body. However, the reported performance of this method was not significantly better than conventional voxel based methods. Furthermore, Wang et al.[22] employed marching cube method to extract the smooth surface of anatomical structures and used a tetrahedronization scheme to generate a voxel–based mesh. Being a voxel based method, the resultant number of finite elements are significant. Voxel base methods however are still employed for computational biomechanics investigations due its ability to represent heterogeneity as well as its own ability to automatically assign orthotropic bone mechanical properties based on gray scale intensities [22].

In general, tetrahedral elements are found to be used in number of automatic FE meshing algorithm to fill the anatomical domains as against the hexahedral elements. This may be due to its geometrical versality and its ability to conform geometrical boundaries of anatomical structures. However, linear tetrahedral elements do not perform well because they are constant strain elements and over stiff due their shape [19]. Generally, higher mesh density or higher order tetrahedral elements has to be used to get satisfactory accuracy which may results in higher computational load. Whereas, hexahedral elements are mostly favoured due to its high robustness, better mesh quality and lower elemental count to fill the physical domain. In comparing linear tetrahedral and hexahedral elements, it has been judged that hexahedral elements give better quality results in many structural applications including linear static bending, linear static torsion, and nonlinear elasto-plastic analysis [18]. Therefore,hexahedral elements are preferred by many researchers to the tetrahedral elements. However, there is presumptions that hexahedral elements are unable to represent the contours of bio-structure mathematically and hence automatic mesh generation of hexahedral mesh models are not possible. They require extensive manual meshing effort. Although, few researchers have developed [3-4], [18], [20-21] hexahedral meshes of independent bones with the help of some commercial software.

Teo et al. [19] has developed an algorithm to generate automatically 3D volumetric FE models that are comprised mainly of hexahedral elements within the core, and tetrahedral together with wedge elements at the exterior which are used to provide geometrical conformity with the 3D physical domain boundaries. But these meshes suffer from discontinuities due to different element types used and abrupt jump in material property assignment of cortical or cancellous or soft tissue.

In summary, there is a need to develop automatic hexahedral mesh generation algorithm for heterogeneous bio-object like femur, head and other human body segments. Furthermore, the software must be capable to provide complete solution along with material assignment automatically for constructing volumetric 3D FE models for visualization and as well as for the FE simulations. The proposed B-spline based heterogeneous mesh generation methodology is capable to produce hexahedral FE mesh throughout the domain along with the natural incorporation of inhomogeneous material properties. Thus the modeling and meshing can be done in one step.

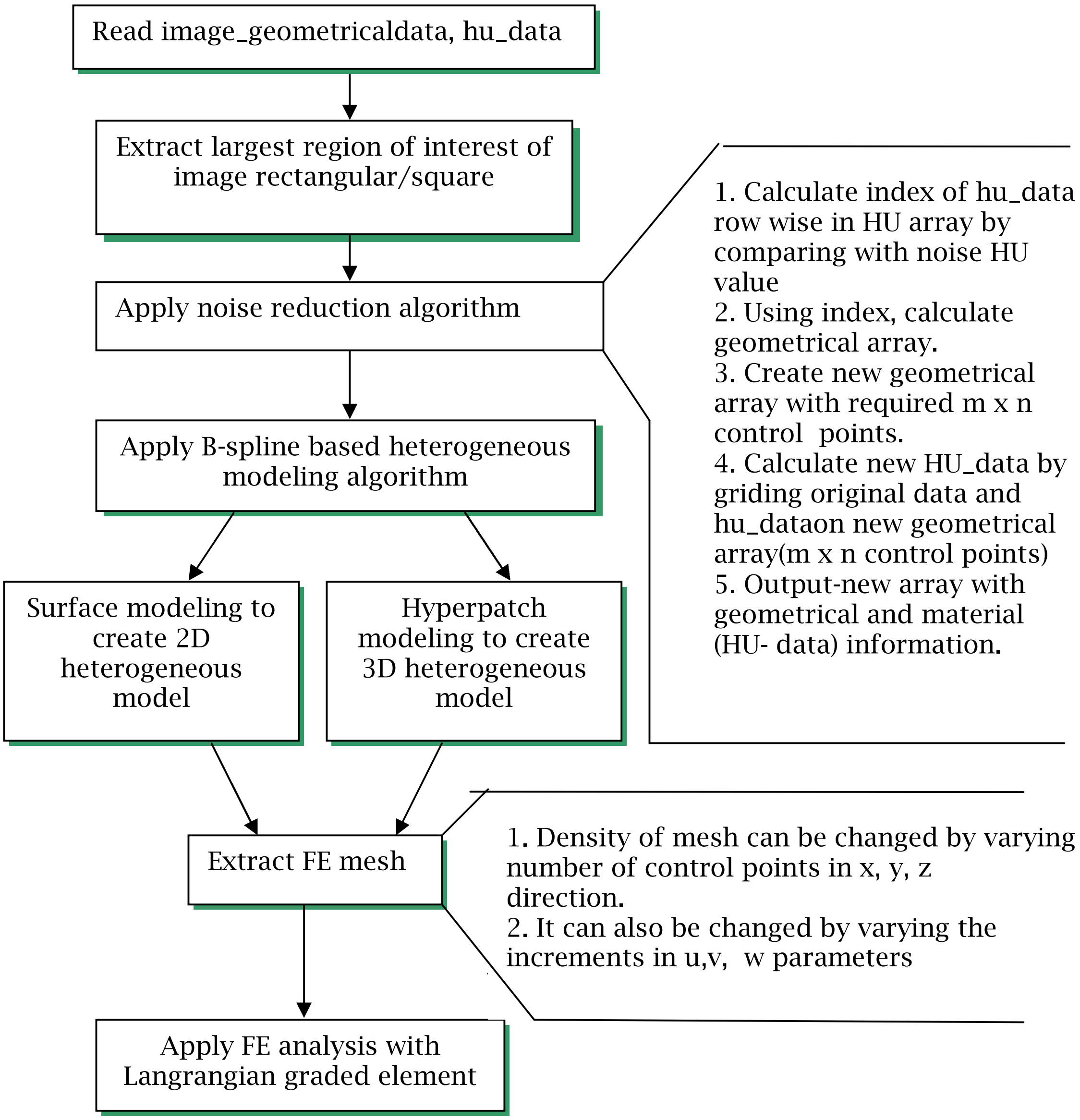
3. B-SPLINE BASED MODELING COUPLED WITH GEOMETRY AND MATERIAL

B-spline based heterogeneous modeling is combination of two processes namely geometrical modeling and material modeling. The CT scan data is the primary source as input to such FE model development. The FE model generation process can be divided into the steps as shown in Fig.1. The segmented slice data of adult femur, child femur and head are used here to generate the B-spline based meshes. The medical based image processing software, MIMICS®is used here for preprocessing of CT images as well as for exporting point cloud data. To develop the FE models the employed CT scan data for child femur and head are takenfrom MIMICS® software database while for adult femur CT scan data has been downloaded from URL: www.bgu.ac.il/~zohari/CT_FF.html[25] .

3.1 2-D Model and Mesh Development

The control point based B-spline modeling methodology is presented in this paper to model both geometry and material variation of human body segments along with mesh generation. In the control point based method, geometry-material values are specified at control points and interpolated by shape functions. The shape functions used are one of the following mathematical functions such as B-spline, Bezier and NURBS. Due to the large number of control points, this method has excellent model coverage. In this work, the B-spline based modeling and meshing method is selected for heterogeneous human body modeling for its following advantages.

Generally, there is smooth variation in material composition within human body. B-splines are capable to represent freeform objects like human body closely (see, [1], [23]). Also the B-spline based method is analytical and intuitive. Qian and Dutta[15] have proposed B-splinehyperpatch product representation of heterogeneous object. A point $\boldsymbol{p}(x, y, z, \boldsymbol{M})$ in a parametric domain is represented by B-spline as follows.



1. Calculate index of hu_data row wise in HU array by comparing with noise HU value
2. Using index, calculate geometrical array.
3. Create new geometrical array with required m x n control points.
4. Calculate new HU_data by griding original data and hu_dataon new geometrical array(m x n control points)
5. Output-new array with geometrical and material (HU- data) information.

1. Density of mesh can be changed by varying number of control points in x, y, z direction.
2. It can also be changed by varying the increments in u,v, w parameters

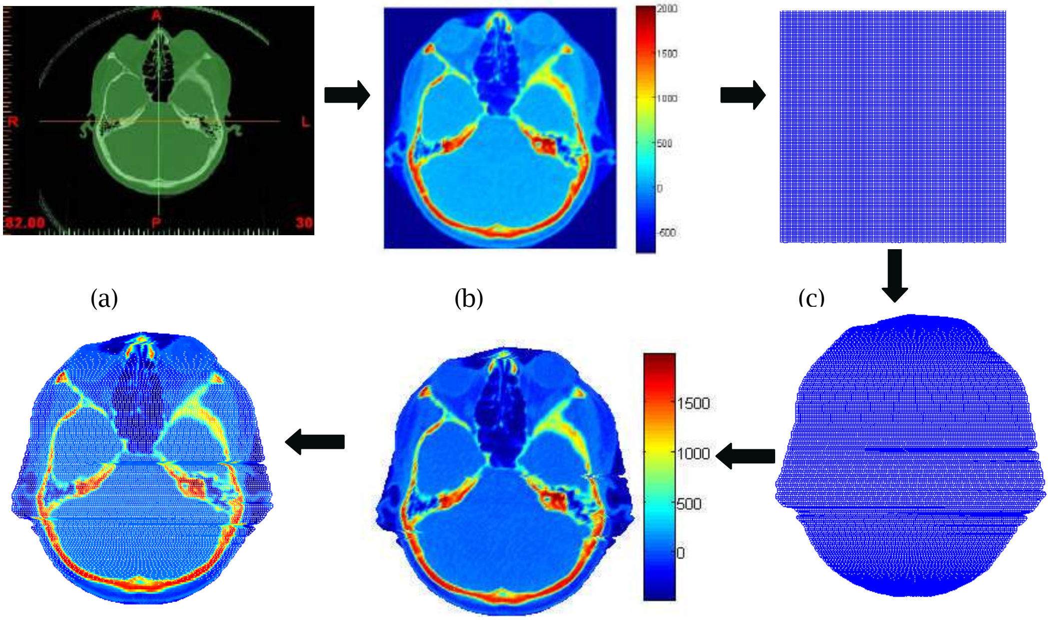
Fig.1: overview of B-spline based biomechanical FE model generation process.

(3.1)
$$\mathbf{p}(u,v,w) = \sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{k=1}^{l} N_{i,p}(u)N_{j,q}(v)N_{k,r}(w)\mathbf{P}_{i,j,k}$$

Where $\mathbf{P}_{i,J,K,} = (x_{i,j,k}, y_{i,j,k}, z_{i,j,k}, \mathbf{M}_{i,j,k})$ are control points for the heterogeneous solid volume,Vector M represents material distribution (elastic modulus in the present case) within geometric volume,p, q, $r$are the order of the B-spline basis functions $N_{i,p}$, $N_{j,q}$, $N_{k,r}$ in the direction of u, v, w respectively. The Eqn. (1) can be simplified to represent a surface model as follows.

$$\boldsymbol{p}(u,v) = \sum_{i=0}^{n} \sum_{j=0}^{m} N_{i,p}(u) N_{j,q}(v) \boldsymbol{P}_{i,j} \tag{3.2}$$

Extending the modeling philosophy to represent human body segment is as follows. An in-house generalized algorithm (see Fig.1) based on MATLAB and C platform is used to clean the images and to find out control polyhedron from the control points by applying B-spline approach. First, the preprocessed (segmented) slice data is read and extracted the largest region of interest of image in rectangular/square shape. Then, calculate the index of HU-data row wise in rectangular/square HU array by comparing with noise HU-value. Using the obtained indices of HU data, evaluate new geometrical array with required *m x n* control points. Therefore, there will be equal number of points in each row. Then, original HU-data is grided on new geometrical array (*m* x*n*). The grids of such input data points form a control polyhedron. These processed grided data of control points ($P_{i,j}$) have four components, three representing geometrics dimensions *x, y* and *z* and fourth specifying material composition m or HU value. By applying Eqn.3.2, B-spline based heterogeneous model of slice is generated along with mesh. The B-spline surface will pass through the end points of the control polyhedron exactly and other parts approximately. With large number of control points, accuracy of surface coverage is large. The steps involved in slice cleaning, model generation and mesh creation are shown in Fig.2.

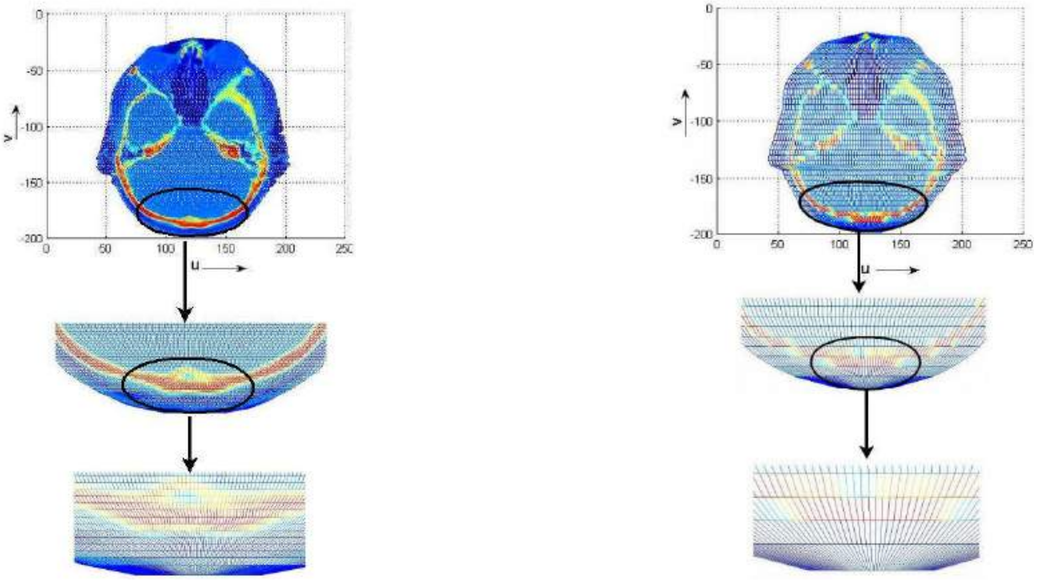


(a) (b) (c)

(f) (e) (d)

Fig.2: The steps for cleaning and generating B-spline based model and mesh; (a) CT image; (b) Extracted region of interest; (c) geometrical array of extracted region;(d) new geometrical array with *'m x n'* control points; (e) B-spline based surface model; (f) Mesh with material assignment at nodes.

In the proposed methodology, mesh is generated either from CT grid data (control point polyhedron) or extracted from the processed points in parametric domain. Thus, once the model has been generated from the required control points, density of mesh can be changed by varying increments in parametric values in *u* and *v* direction as shown in Fig.3. In Fig. 3. (a) surface mesh with 139 x 139 elements is shown while in Fig.3.(b) the same image surface is discretised in 39 x 69 elements. The color bar indicates the Hu value at each node.

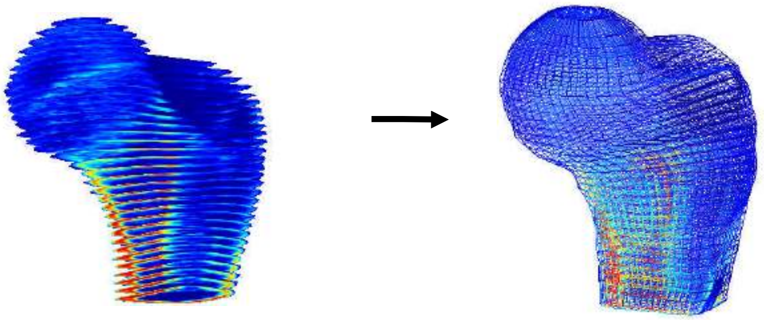


(a) (b)

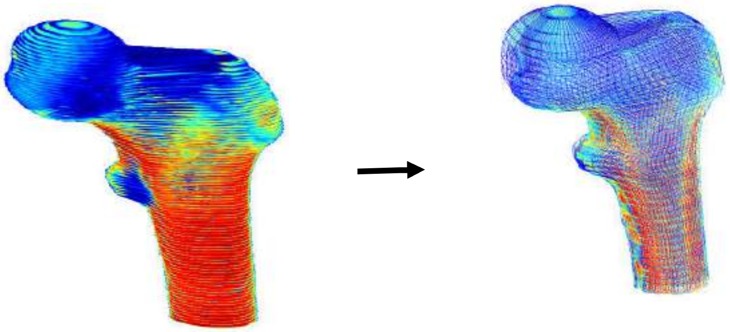
Fig.3: Mesh generation with varying u, v parameters; (a) surface mesh with u=140, v =140; (b)surface mesh with u=40, v=70.

3.2. 3D Model and Mesh Development

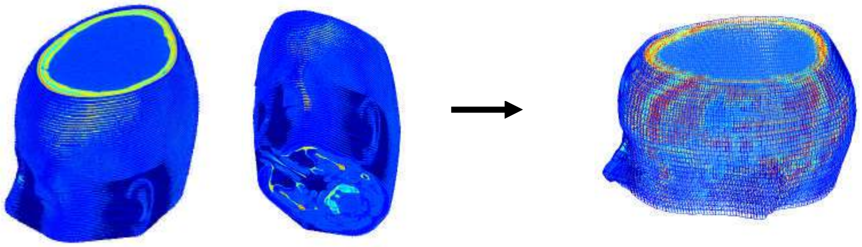
The 2-D methodology used in the previous section can be extended to generate 3D model. The preprocessed (cleaned and segmented) slice data is arranged in a rectangular grid of *n x m* points in *u* and *v* parametric directions respectively. Stack of number of such slices gives a hexahedral grid of *n x m x l* points in *u, v* and *w* parametric directions. This hexahedral grid acts as a control polyhedron. Gridded data points in control polyhedron act as control points $(P_{i,k})$ where geometry is defined by Cartesian components *x,y, z* and material composition by Hounsfield unit HU. By applying tri-parametric tensor product given in Eq. (3.1), solid heterogeneous B-spline based model is generated along with mesh. Fig.4. shows slice models and 3D meshes developed from volumetric CT scan data of child femur, adult femur and head.



(a) Child femur-slice and FE model



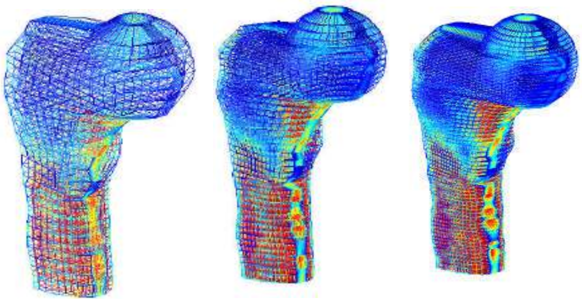
(b) Adult femur-slice and FE model



(c) Head-slice and FE model

Fig.4: 3D slice models and mesh (polyhedrons); (a) slice model and mesh of child femur generated from 34 slices with u=11, v=18, w=34 ; (b)slice model and mesh of adult femur generated from 97 slices with u = 14,v = 24, w = 46; (c) slice model of head and mesh generated from 55 slices with u = 20 ,v = 80, w = 27.

All the 3D FE models generated by this methodology have uniform hexahedral elements in the interior as well as on the exterior. They also conform the geometry very well. Similar to 2D, density of mesh in 3D can be changed by varying increments in u, v and w parametric directions which is shown in Fig.5. for adult femur model.



(a) (b) (c)

Fig.5:Density of mesh variation in adult proximal femur model; (a) model with u=10,v=10,w=30 and nem = 2349;(b) model with u=14,v =26,w = 46 and nem=14625; (c) model with u=20, v=20, w=50 and nem=17689, where nem = number of elements in mesh.

3.3. Quality Measures

To carryout FE analysis, a valid mesh is required. A valid mesh means that all elements are embedded inside the domain and all are noninverted. Therefore, in the present study, to judge the quality of the B-spline based generated mesh, scaled Jacobian is chosen as a quality metric. Scaled Jacobian is the fundamental quantity of any finite element mesh that describes all the first order mesh quantities [9-11]. Let $X_i \epsilon R^3$be the ith position vector in a quad or hex, $X_i = [\ x_i,\ y_i]^T$ in quad and $X_i = [\ x_i,\ y_i, z_i]^T$ in hex. In quad, $i = 1,\ldots,4$ and in hex I = 1,2,……,8. every vertex has 'm' neighboring vertices where $m = 2$ for quad and $m = 3$ for hex. Edge vectors are defined as $e_k = X_k - X_i$ with $k=1,\ldots,m$ and Jacobian matrix with some fixed order at the i$_{th}$ vertex is $J_i = [\ e_1,\ \ldots, e_m]$. The determinant of the Jacobian matrix is called Jacobian as given in Eq. (3.4)

$$\boldsymbol{j}_i = \det(\boldsymbol{J}), \qquad \boldsymbol{i} = 1,\ldots\ldots,8. \quad (3.4)$$

If the edge vectors are scaled to unit length, the derterminant is called scaled Jacobian of the ith vertex. The minimal value of the scaled Jacobian of all the vertices of each element is the final scaled Jacobian (SJ) of that element which can be written as

$$\boldsymbol{SJ} = \min(\boldsymbol{j}), \qquad \boldsymbol{i} = 1,\ldots\ldots,8. \quad (3.5)$$

A scaled Jacobian value varies in the rage of -1 to 1. An element in a mesh is said to be inverted if scaled Jacobian of that element is less than 1and the mesh is considered invalid. Generally, an element with all positive J$_i$ is considered as the minimum quality criteria for a valid mesh.

In the present work, scaled Jacobian metric has been used to measure the qualities of the B-spline based generated meshes of human body segments.

Fig.6 shows a histogram of scaled Jacobian for quad mesh of head slice (Fig.3(a)). The mesh contains 19321 quad elements. All the elements have positive scaled Jacobian value. And about 95% elements of the mesh have the scaled Jacobian value from 0.5 to 1 and which is considered as acceptable range of scaled Jacobians for FE analysis [13].

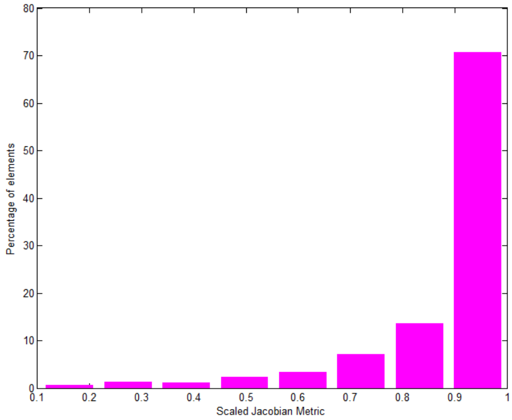
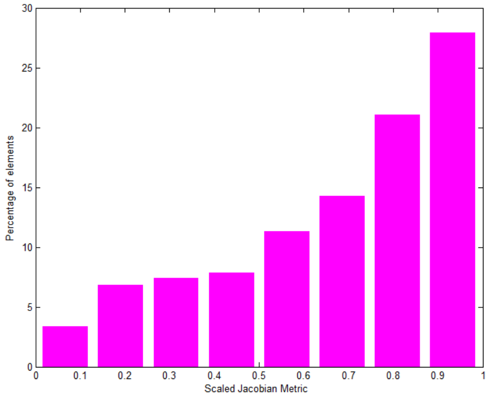


Fig.6:Quality of mesh of head slice model (Fig.3(a)) by Scaled Jacobian metric.

The histograms of the scaled Jacobian values in Figs. 7-9 shows the overall quality of hex meshes for child femur, adult femur and head model respectively. It is observed that all the three models have 100% positive scaled Jacobian elements. The child femur model consists of 5,610 hex elements. Out of this 76 % elements have acceptable or excellent shapes with scaled Jacobian value above 0.5. There are 10.5 % elements with scaled value below 0.1 which can be considered as poor quality elements.



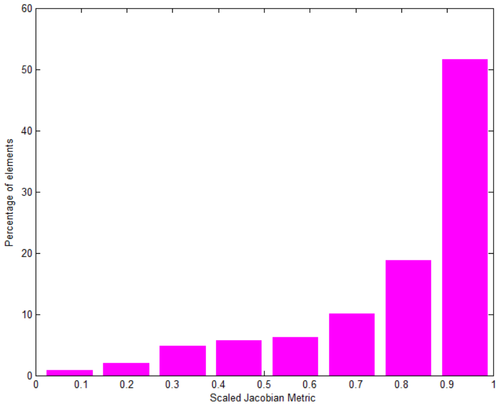


Fig.7:Quality of mesh of 3D child femur model Fig.8:Quality of mesh of 3D adult femur model (Fig.4(a)) by Scaled Jacobian metric.Fig.4(b)) by Scaled Jacobian metric.

In histograms (Fig.8 and Fig.9) of scaled Jacobian for adult femur (Fig.4(b)) and head model (Fig.4(c)) show 88% and 91% elements of excellent shapes(with scaled Jacobian above 0.5 value). The Adult femur model consist of 13,455 hex elements while the head model consist of 40,527 hex elements. In both the models, percentage of poor quality elements is almost 1-2 %.

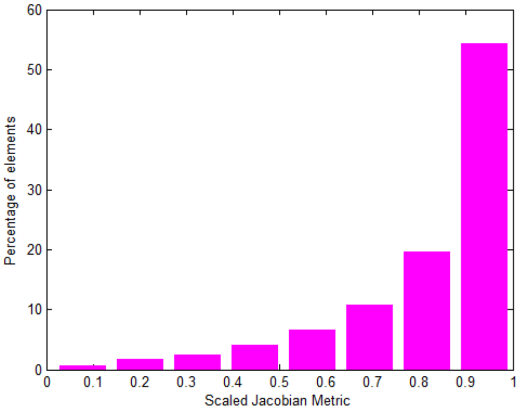


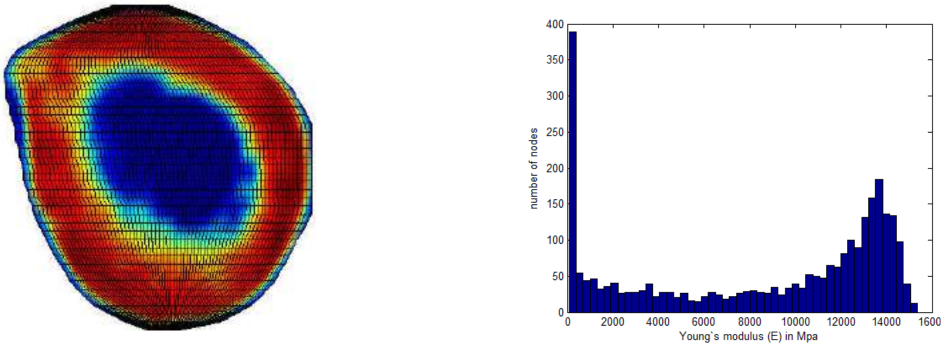
Fig.9:Quality of mesh of 3D head model (Fig.4(c)) by Scaled Jacobian metric.

In subject specific biomechanical FE analysis, mesh algorithm must able to produce good quality of mesh as well as assign inhomogeneous material property in the bio-model automatically. In the present approach it is possible to assign inhomogeneous material properties at each node which is being discussed as follows.

3.5. Material Property Assignment

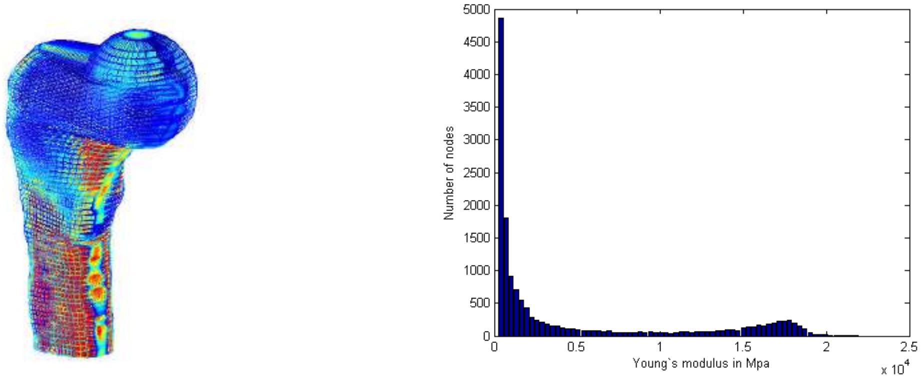
In the present paper proximal femur of child, skull and proximal femur of adult are chosen as the representative candidates of human body for modeling and meshing for various reasons. The skull models are being increasingly used for diagnostic purposes as well as for analysis in vehicle driving safety. In skull both the soft tissues and hard tissues co-exist in the form of cortical bones, cancellous bone, muscles and fat. In proximal femurs the distinction between cortical bone and cancellous bone is very important for biomechanical FE analysis. Assignment of inhomogeneous material property to each element strongly influences biomechanical behavior in subject specific FE models. In the present modeling and meshing methodology material is assigned at each control points. Therefore, each node of generated hexahedral element by B-spline approach is represented by three geometrical parameters x, y, z and one material parameter m. Generally, in biomechanical FE analysis material parameter m is represented by Young's modulus (E) and Poisson's ratio (ν). The input data for model generation is CT scan data where material m is represented in Huvalue which is subsequently converted into apparent density (ρ) with available linear relations in literature. Furthermore, power model relations are used to convert apparent density into Young's module's (E).

The typical distribution of inhomogeneous material property (E) assignment which is done automatically in B-spline based approach are shown in Fig.10 for a 2-D distal slice model of adult femur and in Fig.11 for 3-D adult proximal femur model, respectively.



(a)(b)

Fig.10: (a)2-D geometry/material model of distal end slice; (b) distribution of Young'smodulus (E) at each node inmesh of a distal slice of adult femur.



(a)(b)

Fig.11: (a) 3-D geometry/material model of adult femur; (b) distribution of Young's modulus(E) ateach node in mesh of whole adult proximal femur.

3.6 Optimization of Mesh Grid for Child Femur Model

Out of three hex-mesh models child femur model has shown the minimal percentage of acceptable hex elements. Hence child femur model has been chosen here for convergence study to optimize the mesh grid. Child femur has been analyzed for the single legged stance loading condition as shown in Fig.8. In single legged stance load condition, load on femur due to tension 'T' in gluteal abductor and a reaction force 'R' on the femoral head is taken into account and the distal end of the model was constrained.

The loading and boundary conditions are also shown. To observe the behavior of the finite element model of the femur 11 FE models have been generated by varying mesh density. The variation in the FE mesh models have been created by varying increments in *u, v,* and w parametric direction in B-spline based heterogeneous modeling and meshing method. Modulus of elasticity for cortical and cancellous bone are evaluated by using Wirtz et al.(2000) power law relation as given in Eqn. (5).

$$E = \begin{cases} 1904\rho^{1.64} \\ 2065\rho^{3.09} \end{cases} \quad and \quad \nu = \begin{cases} 0.3 & 100 \le HU \le 349 \\ 0.36 & 350 \le HU \le 2000 \end{cases} \quad (3.6)$$

For dense cortical bone, it is assumed that apparent density (ρ) is 1.9 g / cm^3 (as used Yosibash et al., 2007) associated with maximum HU value 1630 and apparent density of water to be 0 g/cm^3 associated with 0 Hu value. Therefore, the linear relationship between apparent density and HU is used as shown in Eqn. (6).

$$\rho = \frac{1.9 * HU}{1630} \quad (3.7)$$

The maximum Von Mises stress; $\Delta\sigma_v = |(\sigma_i - \sigma_{ref})/\sigma_{ref}$ criteria for the convergence test is adopted Where first parameter $\Delta\sigma_v$ represent, change in Von Mises stress of σ_i with respect to σ_{ref} stress, σ_i is analysis result of the model of ith mesh grid and σ_{ref} is associated with 27,000 mesh grid. The relationship between number of elements and the values $\Delta\sigma_v$ is shown in Fig. 9. A convergence curve is obtained for $\Delta\sigma_v$. Increasing the mesh refinement from 1,350 to 12,000 elements, change in $\Delta\sigma_v$ is significant. Further, increasing mesh refinement from 12,000 to 15,800 elements, change in $\Delta\sigma_v$ is 2.1 percent while further refinement in mesh shows 0.5 percent change in. $\Delta\sigma_v$ It is also observed that FE results also get optimized between 12,000 to 22,000 grid mesh.

R_x	R_y	R_z	T_x	T_y	T_z
-203	-210	-1135	203	210	807

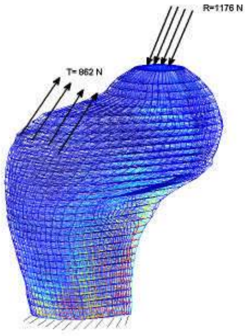


Fig. 12: Loading and boundary condition on proximal child femur model in single- legged stance.

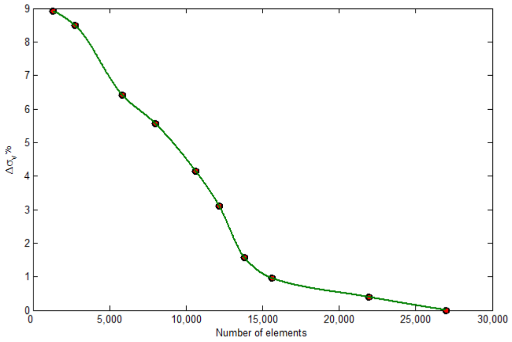


Fig.13: The relationship between values of $\Delta\sigma_V$ and degrees of freedom.

4. DISCUSSION

The B-spline based mesh generation methodology presented in this work offers a novel mesh generation scheme. It accepts cleaned and segmented CT data set as input and outputs 3D volumetric meshes. Present method extracts the inherent hexahedral mesh from B-spline solid model. All the interior and exterior elements are hexahedral and resulting lower number of elements and better computational efficiency. They also confirm the intricate geometry accurately and model the surface very smoothly. In the present method, material property is also assigned automatically at each node of the hexahedral element which incorporates heterogeneity in the model very naturally. Thus, heterogeneous model and meshing can be developed with the present approach in single step along with material information. Because of all hexahedral elements, present method also alleviates problem of mismatch of stiffness due to different types of elements if used and discontinuities due to abrupt jump in material property assignment of cortical or cancellous or soft tissue.

As a demonstration of the presented method, generation of 2-D and 3-D FE models of the proximal femurs and head are carried. A scaled Jacobian quality metric has been used to evaluate the quality of generated quadrilateral and hexahedral mesh. In all the models percentage of acceptable scaled Jacobian is almost 90 percentage and above except for child femur model. None of the model has shown a negative scaled Jacobian value for any element. The locations of the poor quality element (whose Scaled Jacobian value is less than 0.2) are observed at the intersection of the abrupt cross sectional area change and starting points of u,v,w parameters on the model surface. In the present study, no optimization or smoothening technique, available in literature has been adopted to improve the poor quality elements as their percentage was less.

A convergence study has been carried out for child femur model to optimize the mesh size for a given loading and boundary condition. The method showed that the technique is useful in studying biomechanical problems via carrying finite element analysis of child proximal femur. Similar analysis has also been carried out with graded element approach for adult proximal femur and simulated results are validated with the experimental results published in one of the research paper (see Pise et al.2009).

Despite the advantages, the proposed method of generation of meshes also suffers from certain limitations. First, to generate 3-D volumetric meshes from B-spline tensor hyperpatch approach, it is required equal number of control points in each slice. Therefore, the optimized control points say m x n selected for distal end of a proximal femur may not be sufficient for representing larger metaphysealslices in proximal end which results in distorted elements at the connecting boundary of the shaft and proximal end.Experimentally, it is also observed low Jacobean value for these elements. This is unavoidable due to complex geometry of the specimen. Secondly, the algorithm is not able to solve branching modeling problem with the present approach. Because of this reason, geometrically, the femur model is not realistic between the greater trochanter and superior neck region. However, despite of the above limitation, the importance and generality of the results obtained from this study is not reduced.

5. CONCLUSION

A B-spline based heterogeneous modeling and meshing methodology is used to represent complex anatomical structures automatically. The method is capable to generate all hexahedral elements along with inhomogeneous material assignment at each node of the element. Thus, heterogeneous model and meshing can be developed with the present approach in single step along with material estimation for both hard and soft tissues. A minimal scaled Jacobian quality metric criterion is used to evaluate the quality of resulting meshes. The results show that all quadrilateral and hexahedral element meshes are well shaped and able to capture both geometric and material feature accurately. Also, The demonstrated models and FE results shows that the present method is applicable to patient specific biomechanical problems. It is recommended that the method can be extended to simulate vehicle safety problems.

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