Finite Element Meshing Of Human Bones From MRI/CT Raw Data

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ABSTRACT

Finite element modeling of human bones is quite useful in biomechanical simulations. In the present work a technique is developed to make FE model of bones from MRI/CT scan data. Developed technique is a modification over conventionally used techniques. In conventional technique solid modeling processes intermediate solid / surface generation is essential before getting finite element model from the scan data. In the present work this necessity is eliminated and process time and steps are shortened. Conventional process for finite element meshing from MRI scan data requires two intermediate steps first interior and exterior contour point extraction of bones and second solid modeling from contour data extracted. In the present work an algorithm is developed and implemented to obtain meshed model of bones directly from the contours

Key Words: FE model, Solid elements, Contour data, Bones, Image processing, Mapping

1. INTRODUCTION

Finite element analysis is the most appropriate technique for analyzing mechanical properties of complex human bone structure. Due to the availability of low cost computing power, three-dimensional analysis and investigation of any complex structure can be done in virtually no time. However, the generation of a suitable finite element model of human body parts with accurate anatomically specific geometry is still a formidable task, especially if hexahedral solid elements are preferred. Conventional methods adopted in existing FE modeling packages are very time consuming and not suitable for modeling of human bones. So compared to the computational time, the effort needed to generate the finite element model generally dominates the overall process time.In the present work a technique is developed and implemented to obtain FE meshes from Magnetic Resonance Imaging (MRI) / Computed Tomography (CT) scan data. Human bone FE models are generated from image data obtained from medical scanning systems like MRI or CT. Medical scanning system gives accurate measurement of anatomical geometry. The accurate representation of the anatomically specific geometry in the finite element model enhances its function especially when motion of a joint is of major concern. Conventional process for finite element meshing from scan data requires two intermediate steps. First interior and exterior contour point extraction of bones is done. This is followed by solid modeling from contour data extracted.

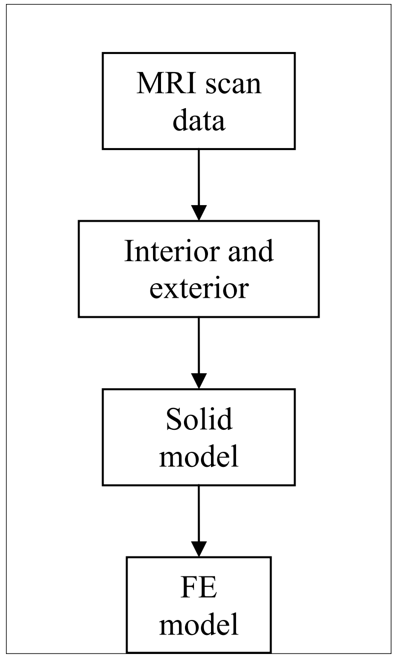

Figure 1 : Steps of finite element modeling from MRI data

By skipping the solid modeling process a lot of time can be saved in FE modeling process. Solid modeling is not an essential task, meshes can be generated directly from the contour data but all existing meshing packages require solid modeling task to get FE model from the contour points. So it becomes necessary to develop a method to obtain FE model directly from contourCouteau et.al. [4] and, Zhang et.al [14] generated solid model of femur and human knee joint bones respectively. From solid model they developed meshed model. This process of meshing from scan data is very time consuming. So it is better that solid modeling part is eliminated and finite element meshes are generated directly from the contour data obtained from the scan data. Work in this direction is reported in the literature. Chae S W, Lee G M [3] and Bajaj C L, Coyle E J, Lin K N [2] proposed methods for generating tetrahedral meshes from planner contours. All work on finite element meshing is reported on tetrahedral meshing only. Hexahedral meshes give better results as compared to tetrahedral meshes and are hence preferred. So some technique must be developed to generate hexahedral meshes directly from contour data. This paper describes generation of femur end meshed model with solid modeling, development of a method allowing generation of meshed model of human bones directly from contour data without solid modeling, generation of femur end meshed model from developed method and finally comparison of the two developed meshed models.

2. ACQUIRING THE DATA AND PRE PROCESSING

MRI scan data were taken from a GE MR scanner. A 26 year old male volunteer was approached to have MRI scans of his right leg knee. Raw data (GE specific format) from MRI Scanner were transferred to a computer and later processed.

Slice Plane	**No. of Slices**	**Sequence**	**Scan Area mm^2**	**Pixel area**	**Slice Spacing mm**	**Format**
Transverse	80	T1	200x200	256x256	0.0	GE specific
	80	T2				

Table 1 : MRI Scan data parameters

Various parameters pertaining to MRI scans are as given in Table 1. Transverse plane divides human body along body height. Scanner converted a scan area, at knee, of 200x200 mm^2 into 256x256 pixel area. It means a scan has 65536 intensity values. All intensity values are written in a binary file format of that binary file in 'ieee-be' (IEEE floating point with big-endian byte ordering) machine format and precision of 'int16' i.e. an image intensity value is written as 16 bit Integer .Binary file contains two sections in first section format information is written and in the last section all intensity values are written with a precision of. 'int16'.

2.1 Reading and Visualization of Data

Scan data extracted from MRI scanners as mentioned in above section were in some specific format. To retrieve intensity values from scan data file a Matlab routine was developed. To obtain gray scale image from intensity values Matlab provides inbuilt routine which takes intensity values as input and returns gray scale image. One of the images of the femur condyle is shown in Figure 2.

3. SEGMENTATION AND CONTOUR EXTRACTION

In order to have three-dimensional geometry from scanned images segmentation process carried out on images. Segmentation is basically dividing the image in parts having similar characteristics i.e. separating bone from other parts in scan image. For segmentation of bones from scanned images a Matlab routine was written using region based algorithm. Algorithm is based on the fact that a region consisted of points with nearly same intensity values can be assigned an entirely different identity from rest of the image points. Detected region points are assigned a value of 1 and rest 0. So, detected region appears white and rest of the portion black as shown in Figure 3.By processing all the scans of femur end, bone parts from the scans were segmented.After having segmented bones from images contour points data were generated. That is to say edges were extracted from the segmented bone region. For this task Image Processing Tool Box of Matlab provides routine based on edge detection. Contour extracted from the segmented femur condyle part is shown in Figure 4.Contour points were extracted from all the axial scans. To define three dimensional structure of femur end all contours were stacked one over another and stacked contours were transferred to ANSYS.

Figure 2 : An axial image of femur end (Condyle)

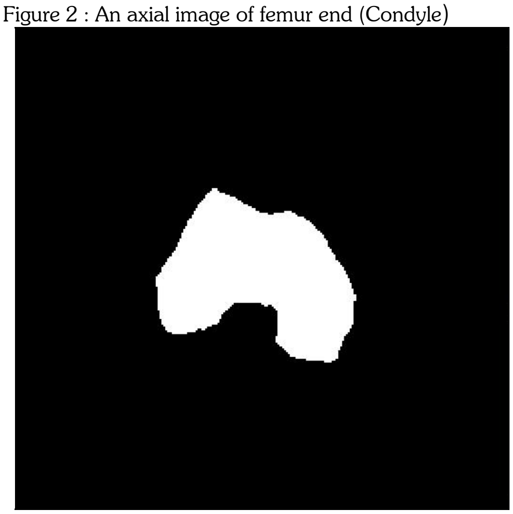

Figure 3: Segmented femur condyle

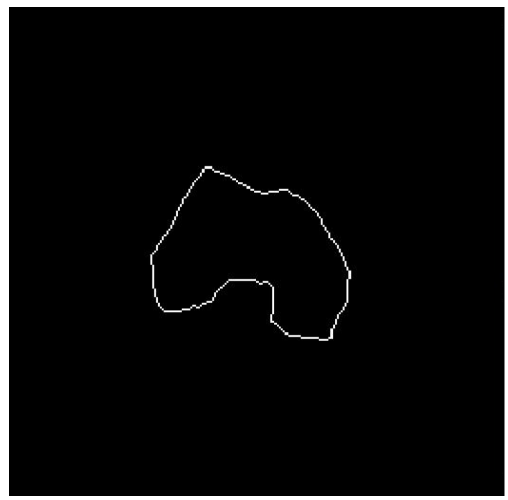

Figure 4 : Contour from segmented femur condyle

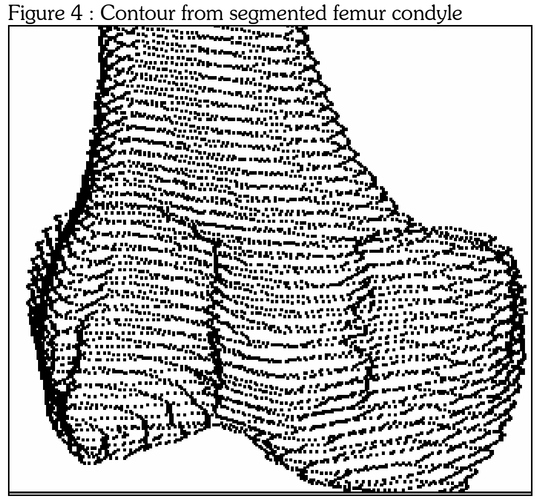

Figure 5 : Lofted contour points of the femur

4. SOLID MODELING AND MANUAL MESHING

On ANSYS complete solid model of femur end was constructed from the contour points extracted from MRI scans. Solid modeling required spline curve fitting on contour points and outer surface generation of femur.
Solid model created in ANSYS was meshed by meshing tool available in ANSYS. The solid model was meshed by sweep method. Solid model consisted many volume slices, each between two consecutive contours. Each volume slice meshed using sweep algorithm. Elements were created in each consecutive volume slice one by one. By using this approach number of elements remains same in each volume slice. This causes relatively dense meshes in slices made by small contours. Use of this approach was necessary as no other alternative was available.Complete meshing on ANSYS from solid model depends upon the way solid modeling is done. As in the case of femur bone, in which at the condyle bifurcation needs to be treated specially. To mesh femur by sweep algorithm whole bone was split in two parts so that bifurcation problem could be avoided. That caused lot of time to be spent in solid modeling only.

5. MESH GENERATION FROM CONTOUR DATA

One another model of femur end was generated without solid modeling i.e. directly from contour points. For FE mesh generation from contour data an algorithm was developed. Algorithm for FE mesh generation from contour points is shown in the flow chart Figure 6. Algorithm for FE mesh generation from contour data consists of two major steps. First, making quadrilateral meshes inside each contour secondly, defining connectivity between consecutive contours such that solid hexahedral or wedge elements get fitted between contours. Quadrilateral Elements are fitted inside contours by using conformal mapping algorithm. Prior to the mesh generation inside any contour some preprocessing on contours was required as contour data points could not be used directly for conformal mapping algorithm. Pre processing consist two processes, sequencing and splitting of contour (if required). This algorithm is implemented using Matlab programming language and user interactive interface MESHCON is developed based on the algorithm.

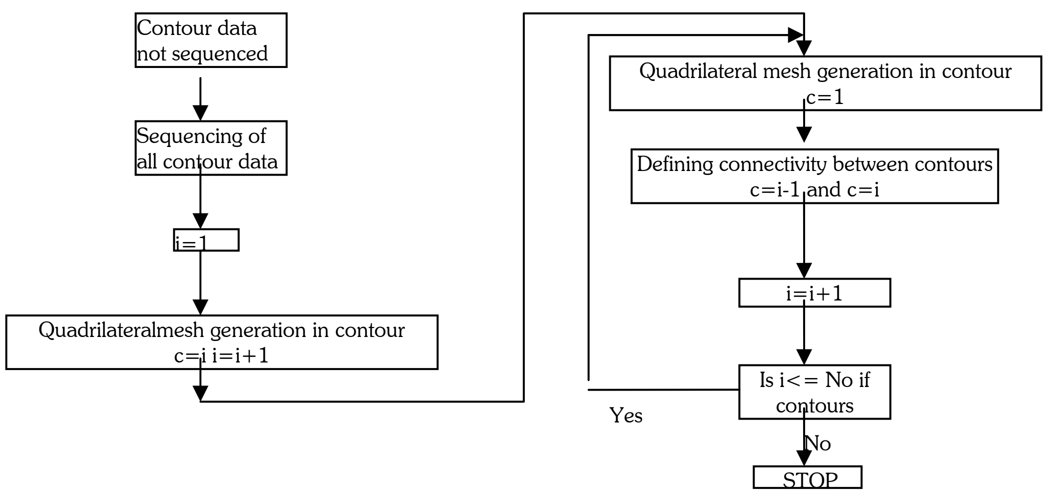

Figure 6 : Flow chart for meshing from contour data

5.1 Sequencing of contour data

Contour data obtained from MRI Scans can not be directly used for mesh generation. Some preprocessing on contour data is needed. Points of a contour obtained from the Scan were arranged in such a way that if moved along data a closed contour does not form. Instead a zigzag pattern appears as shown in Figure 7. So, contour points were made in a sequence such that if moved along points a closed contour forms as shown in Figure 8.

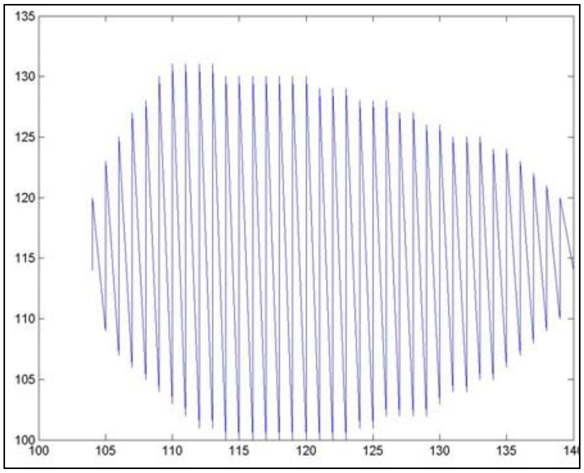

Figure 7 : Contour data points without sequencing

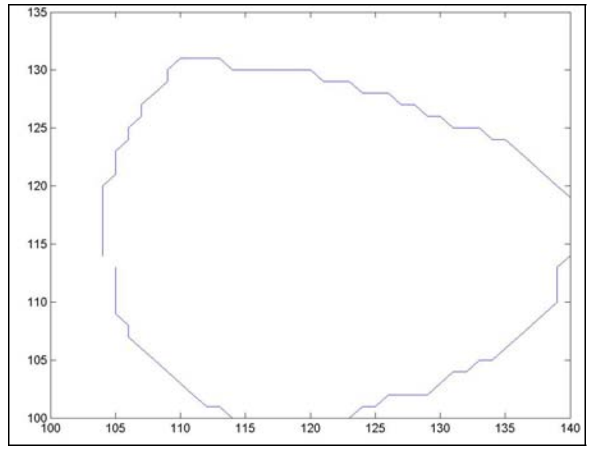

Figure 8 : Contour data points after sequencing

5.2 Splitting of Contour

Another kind of preprocessing required on some of the contours is splitting of contour. Splitting of some contours was necessary before mapping operation because some contours are ill shaped and cause a distorted mesh to be created while mapping This is shown in Figure 9 and **Figure 10**, which respectively show a contour with a bad shape and a mesh generated from this contour. The generated mesh has many distorted elements (shown in the encircled area). The same contour when split and meshed, obtained a reasonable mesh, as shown in Figure 11. To split a contour into two contours two points are selected which form a splitting line between newly formed contours. Splitting line is treated as a set of discretized points between two selected points.

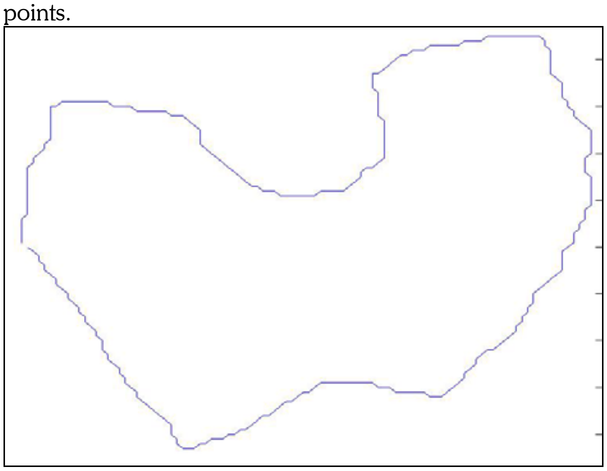

Figure 9 : Badly shaped contour

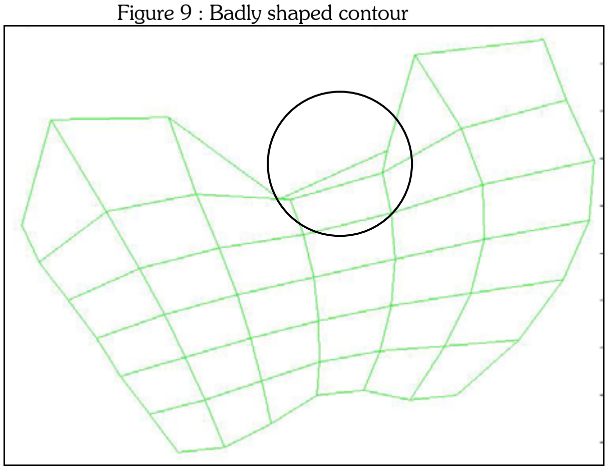

Figure 10 : Distorted elements in badly shaped elements

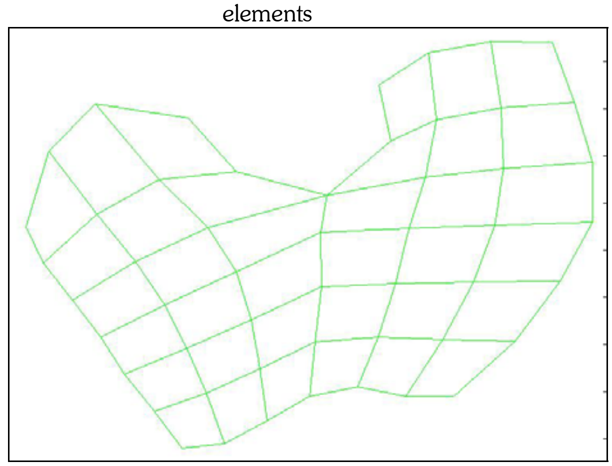

Figure 11 : Meshed contour after splitting

5.3 Quadrilateral mesh generation inside a contour

For defining solid elements (Hexahedral, wedge and tetrahedral) between any set of two consecutive contours, quadrilateral mesh is produced inside both the contours. To generate solid elements connectivity of each quadrilateral element in one contour is set to quadrilateral elements of another contour.

Quadrilateral mesh inside a contour is produced by using a conformal mapping algorithm. Conformal mapping is a one to one angle preserving mapping. A mapping $w = f(z)$ is said to be angle preserving, or conformal at z_0, if it preserves angles between oriented curves in magnitude as well as in orientation. If $f(z)$ is analytic and $f'(z) != 0$ then the mapping is conformal and orthogonal curves are mapped onto orthogonal curves. In the present work conformal mapping is used to map contour points on to a unit rectangle. For this four points are selected on the contour (Figure 12). These points represent the four corner points of a unit rectangle. Grid points are then generated inside a unit rectangle are generated. These generated grid points are then mapped back to inside of the contour. Mapped grid points are shown in Figure 13.

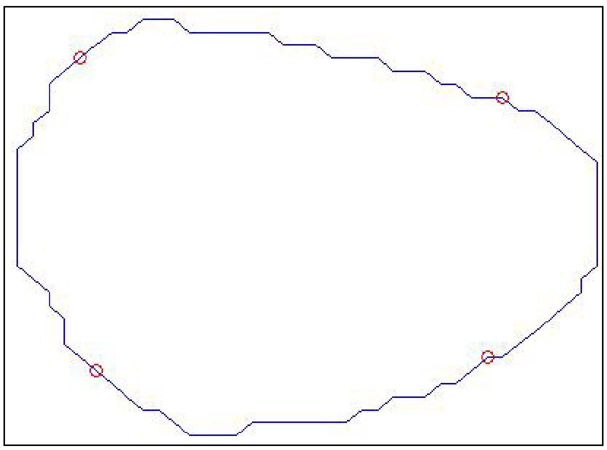

Figure 12 : Contour with four encircled points (to be mapped on unit rectangle corners)

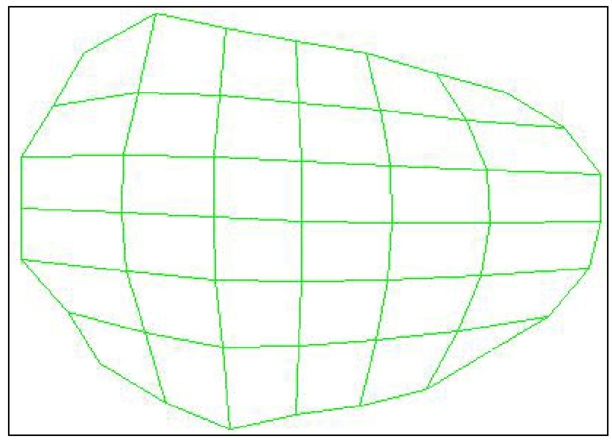

Figure 13 : Meshed contour

5.4 Generation of solid elements

After defining meshes or nodes in all contour planes, nodes in one contour plane were connected by solid elements to the nodes of next consecutive contour plane. Solid elements hexahedral, wedge and pyramid are used for the mesh generation. By connecting four nodes of one contour to the four nodes of another contour Figure 14, hexahedral elements were fitted. Wedge elements were fitted between four nodes of one contour and two of another Figure 15. Some pyramids had to be generated using four nodes of one contour and one node of another contour Figure 16 which can be converted into two tetrahedral elements.

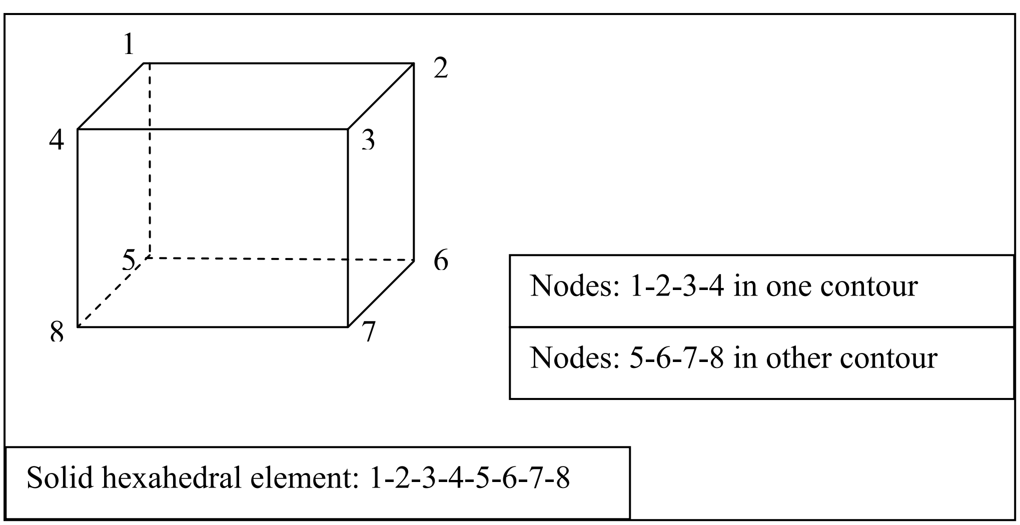

Figure 14 : solid hexahedral element with eight connected nodes

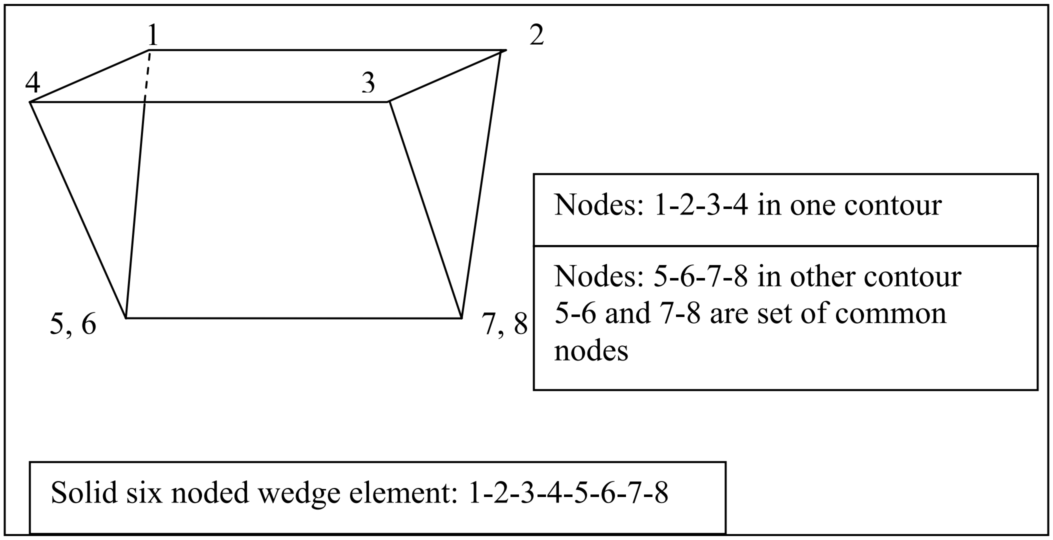

Figure 15 : Six noded wedge element

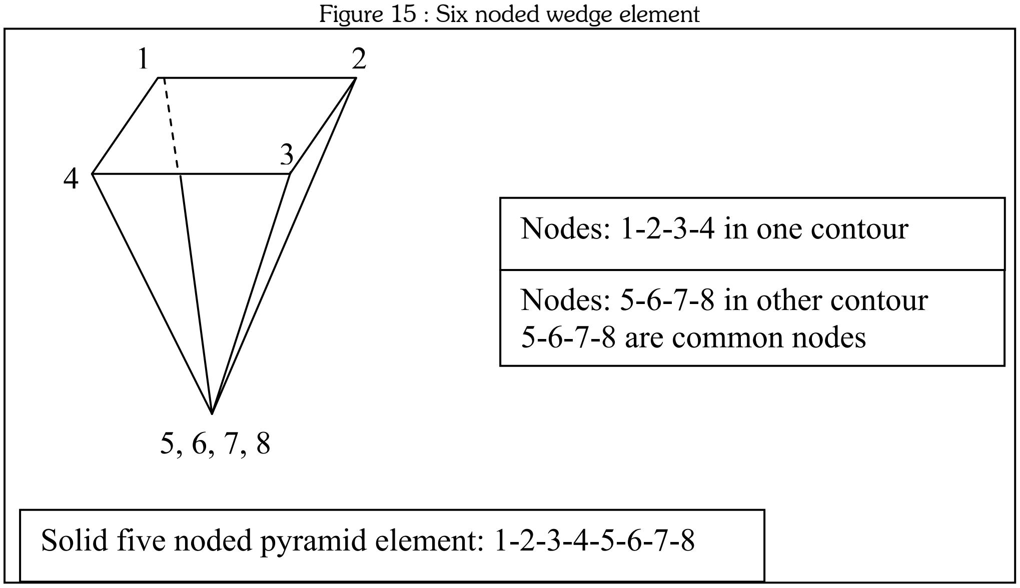

Figure 16 : Five noded pyramid element

6. RESULTS AND DISCUSSION

Two different model of femur end developed from manual meshing (with solid modeling) and from MESHCON (without solid modeling) respectively. The two models are shown in Figure 17 and **Error! Reference source not found.** respectively.

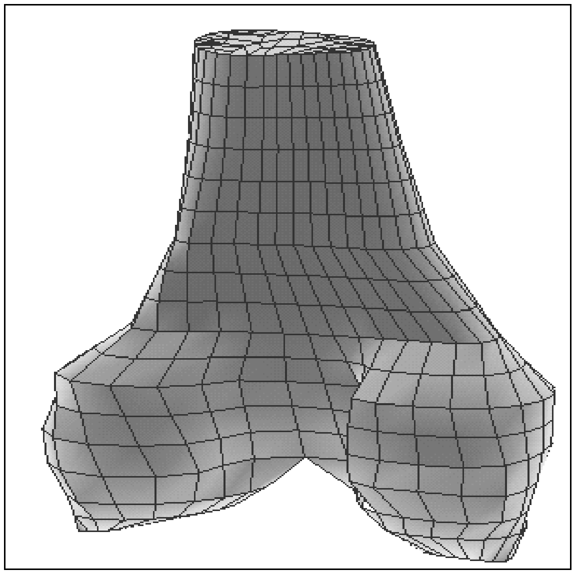

Figure 17 : Meshed model of femur end from manual meshing

6.1 Comparison of manual meshing and meshing from meshcon

In the manual meshing process smaller contours got fine meshing than bigger contours and bigger contours got coarse meshing than smaller ones. It was because of the generation of same number of nodes in all contours. In all contours number of nodes remains same irrespective of the size of contour. So there is no control over mesh size after mesh size is defined in one contour. After defining mesh size in first contour mesh size in all other contours depends upon size of contour it self. Whereas in MESHCON package mesh size can be specified in each contour irrespective of the size of contour. So fine meshing can be avoided in smaller contours and similarly coarse meshing in bigger contours. In case of different number of nodes in two consecutive contour planes MESHCON fits some wedge / tetrahedral elements instead of hexahedral elements. So element edge length in each contour can be maintained within certain tolerance limit.In manual meshing process getting meshed model from contour data becomes very tedious when all contour data are to be used for solid modeling and subsequently for meshing. Solid modeling requires contours data points to be replaced by b-spline curves which is done by picking all contour points. In the presence of all contour data visualization and picking of points becomes too difficult this increases modeling time. So in the presence of thousands of contour points solid modeling not only becomes very time consuming but also very difficult. Whereas meshing on MESHCON does not require any solid modeling so mesh generation from contour data becomes very simple. No matter how many contours are there at a time only one contour is processed so meshing process is very simple on MESHCON.

6.2 Comparison of quality of mesh

Two models of femur end developed, one from the manual meshing process and another from the MESHCON package, are compared with the femur end model of THUMS [12] results of which are shown in [Table 2].

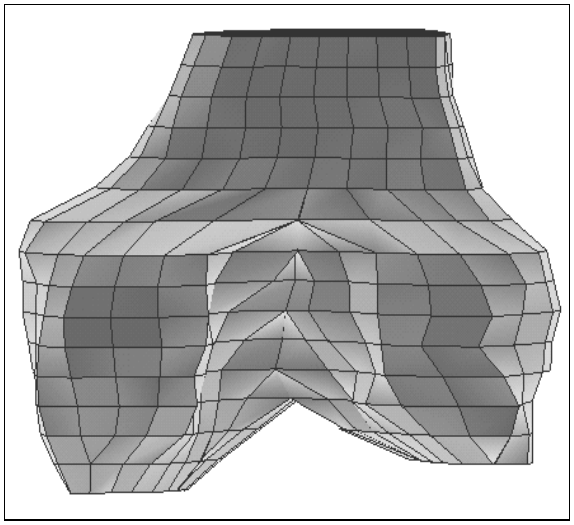

Figure 18 : Meshed model of femur end from MESHCON

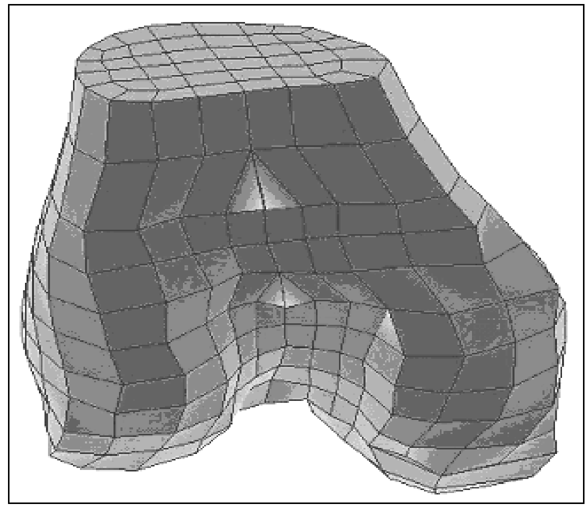

Figure 19 : Femur end of THUMS

Model → Parameter (limit)↓	Manually meshed	MESHCON model	THUMS model
Total number of elements in model	833	802	683
	% of elements out of limit		
Aspect Ratio (max 20)	0.00 %	0.50 %	0.15 %
Parallel Deviation (max 70 degrees)	6.84 %	0.37 %	0.15 %
Maximum Angle (max 155 degrees)	14.29 %	7.73 %	0.29 %
Jacobian Ratio(max 30)	2.04 %	1.50 %	0.00 %
Warping Factor (max 0.2)	3.60 %	5.99 %	6.59 %
Any	21.61 %	13.97 %	7.03 %

Table 2 : Comparison of quality of mesh

7. CONCLUSIONS

A new method has been developed and implemented in MESHCON for getting meshed model of human bones directly from the contour points obtained from MRI scans. MESHCON package uses very simple and less time consuming technique for obtaining meshed model from contour data. As, this package does not require solid modeling to get finite element meshed model from contour data obtained from MRI scans. Generation of finite element meshed model from contour points without solid modeling is the biggest advantage of the package. Mesh quality of meshed model of femur end obtained from MESHCON is not as good as femur end model of THUMS but they are not as poor as obtained from the manual meshing. At the same time process of solid generation is not required on the MESHCON. Efforts are needed to improve the mesh quality obtained from the MESHCON software. This package is not fully automated but in future, work can be done to fully automate it. MESHCON code can be extended with adaptive mesh refinement methods to reduce element distortion.

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