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3-D FINITE ELEMENT MODELING OF LUMBAR SPINE (L2/L3) USING DIGITIZER

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ABSTRACT

In the present study, a three-dimensional geometrical and mechanical accurate finite element model of human lumbar spine (L2/L3) was developed from 3D geometrical data of embalmed lumbar spine (L2/L3) obtained using a highly accurate touch-probe digitizer. The methodology developed for the 3D digitizing process provides an alternative method in capturing the highly irregular bony structure of spine as compared to commonly used CT scan image by other investigators. With these direct digitizing approach and advanced modeling techniques, the quality of mesh formed has improved as compared to other models developed from CT images. All complex anatomical features of the spine such as lamina, superior/inferior facet, pedicle, pars interarticularis, spinous process and transverse process were explicitly represented in the unprecedented finite element model, which consist of 8,281 solid 8-noded elements and 817 cable elements with 32,641 degrees of freedoms. Having a realistic and validated mathematical model of the spine would further establish itself a useful adjunct to the experimental approaches for investigating clinical problems of the spine and may be used to predict biomechanical responses of the spine under physiological and trauma loadings.

INTRODUCTION

The human spine is a biomechanical structure that allows complex motions while providing stability and protection for the spinal cord during a variety of loading conditions. The mechanical response of a motion segment (e.g. L2/L3) plays an important role in the overall structural behavior of the spine. Over the years, mathematical modeling (such as finite element method) has established as a complementary to experimental approach in investigating clinical problems of the spine as well as predicting the biomechanical behavior [1,3].

In mathematical modeling of spine, investigators could not emphasize enough the importance of modeling the actual geometry of vertebrae as accurately as possible to obtain reasonable results applicable to clinical and *in vivo* situations as the anatomic structure and surface geometry of the vertebrae greatly define the motion of the spine and its related biomechanical response. Common method used for mesh geometry by investigators is by stacking coronal and sagittal computed tomography (CT) images sequentially to develop and discretize the 3D solid model [2]. With this method, the finite element model could not well represent the geometry of the highly irregular vertebra, especially its posterior element.

We have adopted a direct digitizing approach that provides an alternative method in capturing the highly irregular bony structure of spine. A flexible touch-probe digitizer was being utilized for the geometrical definition and a methodology was developed for this process. Accordingly, this approach has allowed a better mesh representation of the geometry, of which is of the essence in the study of stress distribution patterns in the spine.

MATERIALS & METHODS

In this study, an embalmed lumbar spine from L1 to L5 acquired from the Singapore General Hospital was used to obtain 3D digitized point data of the lumbar spine. The age, sex, height, weight and cause of death are tabulated in Table 1.

Specimen	Age	Sex	Race	Body Mass (kg)	Height (m)	Cause of Death
1	59	M	Chinese	64	1.68	Liver Cancer

Table 1: Specimen Data

The cadaveric spine was inspected and found to be free from spinal disease, metatasis and trauma. Figure 1 shows the embalmed lumbar spine (L2/L3) used in digitizing 3D point data of geometrical details of the finite element model.

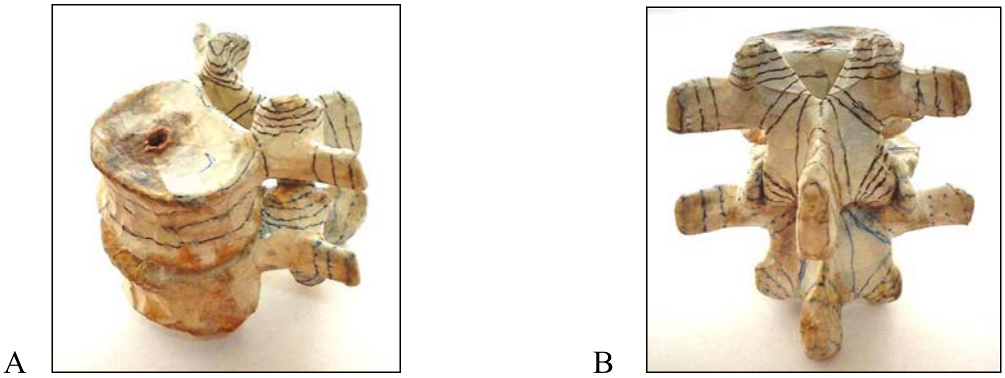

Figure 1: Embalmed Lumbar Spine (L2/L3); A: Iso-View, B: Posterior View

Owning to highly irregular bony structure of the vertebra, a methodology is developed to extract out its crucial geometry to input into downstream process for the development of finite element model. The mesh developed herein has to be well-represented in terms of original geometry as well as achieving a high quality of mesh as poor representation and quality of finite element would lead to inaccurate results. Figure 2 shows the flowchart about the steps involved in digitizing and development of volume mesh.

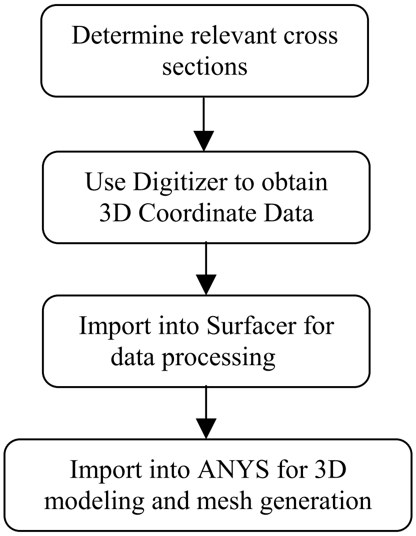

Figure 2: Flowchart for Volume Mesh using Digitizer

Determine Relevant Cross Sections

Prior to the digitizing process, a careful study was conducted to determine the best cross sections to be marked onto the vertebra, the inter-spacing distance as well as dividing prominent features into several modules in order to capture its intricate and highly irregular details. Figure 1 shows the marked cross sections on the vertebra. Also, the marked cross-sections have to consider the viability of forming an acceptable finite element model.

Use Digitizer to obtain 3D Coordinate Data

Before any digitization is carried out, calibration and setting of reference point of touch-probe digitizer were undertaken first in accordance to the instruction stipulated. As shown in Figure 3A, a FaroArm, (Bronze Series, Faro Technologies, Inc), which is a lightweight, multi-axis (six degree of freedom) measurement arm, is used as the touch-probe digitizer to extract the geometrical data of the object. The accuracy of the FaroArm is of a resolution ± 0.012” (0.3mm).

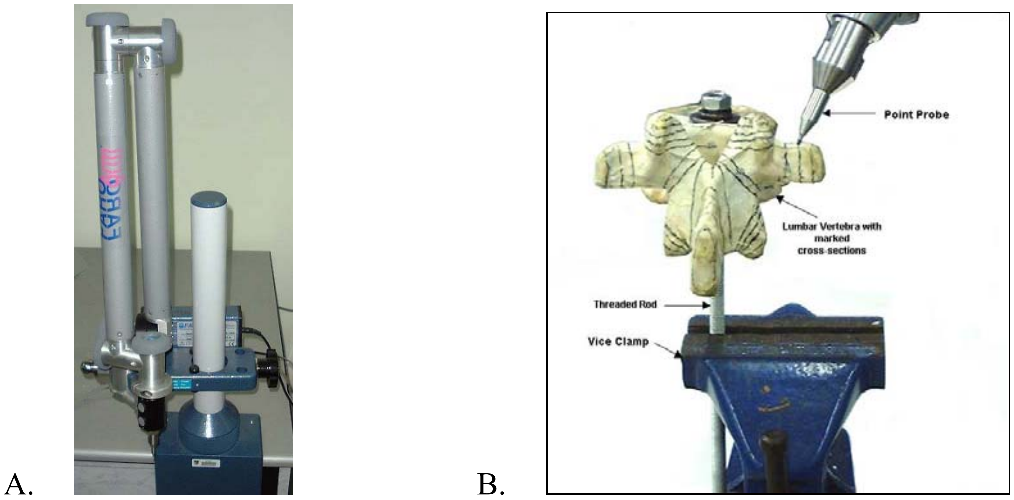

Figure 3: A. FaroArm with point probe. B. Lumbar Vertebra capturing using FaroArm

A small hole was drilled into its body so that threaded rod could be inserted through it, which was then being tightened securely with nuts and washers. The rod was clamped in a vice clamp, which was located within the reach of the digitizer's arm. Figure 3B shows the vertebra being clamped in the vice while the FaroArm was used to extract the geometrical data by moving its point probe across the marked cross-sections of the vertebra. Figure 4 shows the combined coordinate data of the cross sections.

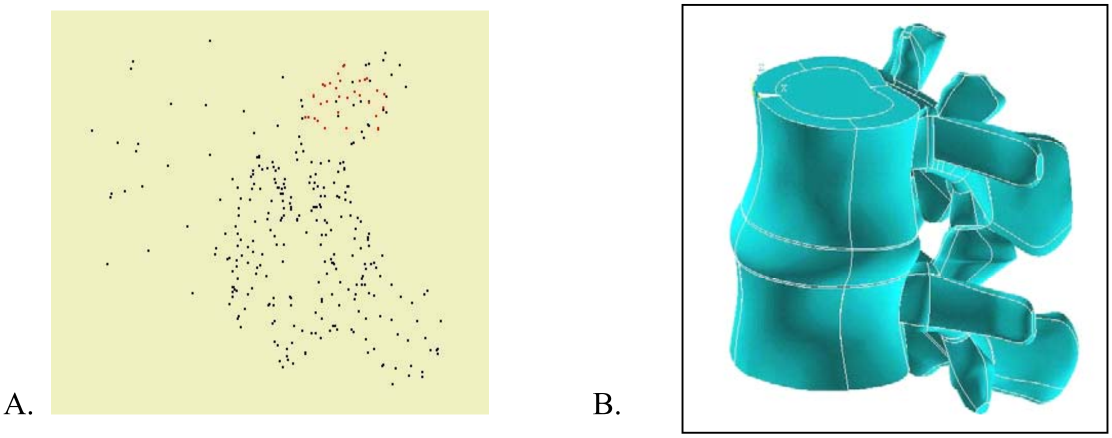

Figure 4: A. Combined Coordinate Data of Cross-sections. B. Volume rendering for L2/L3 lumber spine

Import into Surfacer for data processing

Using computer software, Surfacer 7.0 (Structural Dynamic Research Corporation, Ohio, USA), the three-dimensional coordinate data of each cross section was processed and filtered sequentially to obtain the planar cross sections for the vertebra. The data was then converted into a universal graphics data format (IGES) before importing into a commercially available finite element modeling software, ANSYS (ANSYS Inc, Pennsylvania, USA), for the three-dimensional finite element mesh construction.

Import into ANSYS for 3D Volume Modeling and Mesh Generation

A bottom-up approach was adopted to building the model. The 3D coordinate points were used to define the vertices of each cross section of the model. Keypoints, which are the "lowest-order" solid model entities, are used to define "higher" solid model entities (that is, lines, areas, and volumes). A closed curve was generated from a spline fit to the series of keypoints and subsequently divided into 4 lines for every cross section to meet the requirement of forming a 4-

sided area. With the curves generated for all cross sections, an area was generated by “skinning” surface across adjacent divided lines using the built-in NURBS algorithm in ANSYS. Such skin-modeling function allows editing a NURBS surface model as one continuous “skin”, while maintaining existing continuities between surfaces. At times, Boolean operators, which can be used to work directly with higher solid model entities to create complex shapes in bottom-up approach, were used to "sculpt" the solid model using intersections, subtractions, and other Boolean operations. Furthermore, the surface created was visually compared with the actual vertebra to ensure its geometric integrity. A six-sided volume bounded by continuous areas was thus created to form a solid model. Following this procedure, volume modeling was thus developed for the entire structure. Figure 4B shows the volume rendering for L2/L3 lumber spine.

The finite element mesh was then obtained by discretizing the bony solid domain with eight-noded isoparametric solid elements using an advanced meshing technique. Figure 5 shows the finite element model of L2/L3 structure, which consists of 8,281 solid 8-noded elements and 817 cable element with 32,641 degrees of freedoms.

DISCUSSION

As shown in Figure 5, the finite element model developed from this process has regular mesh as well as good representation of its geometry, which would give a better prediction of its biomechanical response *in vivo* and *in vitro* situations. The use of direct digitizing approach and advanced modeling technique has generally improved the mesh quality as compared to the model created from CT images.

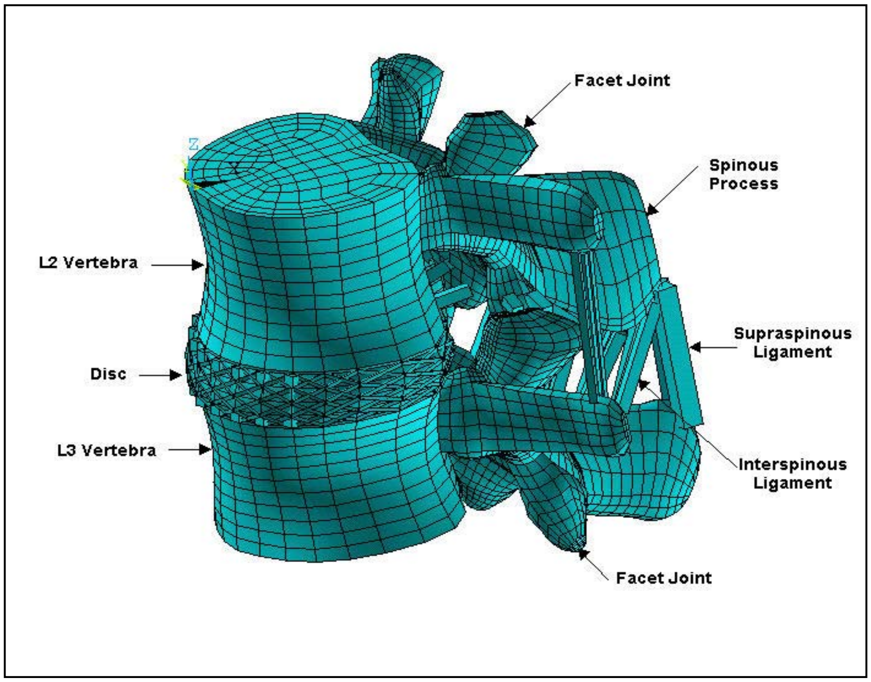

Figure 5: Finite Element Model of L2/L3 Structure.

CONCLUSION

In summary, a well-represented finite element model of lumbar spine (L2/L3) was developed with the adoption of direct digitizing process and advanced modeling technique. The methodology developed has helped in providing necessary geometrical definition for mesh construction. Such model has not only developed a better mesh representation for all spinal components of the vertebra, but it also helps in getting accurate results in predicting biomechanics of human lumbar spine under physiological loadings.

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