An investigation into Parametric Modelling and FDM based Rapid Prototyping of Lumbar Spine

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Abstract. Low back pain is the acute problem faced by workforce in the world today. Four out of five adults experience significant low back pain sometimes during their life. Mostly, low back pain problem can only be solved by operations. Each time doctors carrying out operations need to study the patient spine. The objective of the present work is to generate parametric model of lumbar spine using event driven programming approach of Visual Basic 6.0 and CATIA V5 R10. In parametric modelling, the features are parameterized by giving them meaningful labels and relationships between parameters in the entire model rather than giving only fixed numeric values. The output of the developed model is compared with the specimen samples of lumbar spine. Additive manufacturing using FDM (Fused Deposition Modelling) is used for 3D printing the spine model. Thus, the present work will give an insight into additive manufacturing of patient specific model and analyze the outcome before the clinical procedures.

Keywords: Lumbar spine, parametric modelling, Rapid prototyping, FDM.

1. Introduction

The adult spine typically consists of 33 vertebrae most of which are united by a series of intervertebral articulations to form a firm but flexible shaft. The spinal column is divided into five sections. In cephalad-caudal direction (transverse direction), these are cervical (C1-C7), thoracic (T1-T12), lumbar (L1-L5), five sacral vertebrae forming the sacrum and the four coccygeal vertebrae that fuse together as coccyx in adults. In the sagittal plane the spine has four physiological curves. These curves are convex anteriorly in the cervical and lumbar regions. In the thoracic and sacral regions these curves are convex posteriorly. Curvatures of the cervical and lumbar regions are largely due to the wedge-shaped intervertebral discs. These curves increase the flexibility of the spinal column and augment its shock absorbing capacity. The vertebrae in each region of the spinal column have distinguishing characteristics that reflect the differences in the physiological and biomechanical properties of each region. Intervertebral disc degeneration is widely believed to be a main cause of low back pain. It involves gross structural disruption as well as cell-mediated changes in matrix composition of the disc. Treatment of back pain due to disc degeneration is done either by non-surgical or by surgical means. Lumbar fusion or arthrodesis is one of the most commonly performed operative procedures to get relief from back pain. It is often performed when there is significant degeneration or instability which causes significant low back pain or discomfort. Various methods like a simple fusion with a bone graft, fusion using a bone graft along with instruments like pedicle screws and plating systems, or fusion using interbody cages are being employed to fuse the diseased lumbar segments. Lumbar Interbody Fusion is a common treatment alternative for low back pain. To assist clinical assessment of these procedures and devices, and to study their biomechanical effects on the spinal column, various research techniques are employed. Traditionally, research on spine biomechanics has involved two types of approaches viz.
experimental and analytical. It is difficult to conduct experimental studies to determine the effect of pathological conditions like disc degeneration, osteoporosis and surgical interventions like interbody fusion. The experimental difficulties include collecting the specimens and the question of control with regard to the repeated testing of the same spine under various loads. Moreover experimentations are unwieldy and expensive. The analytical approach, on the other hand, bypasses many of these problems. It also permits to simulate the spine behavior under different physiological situations (sound, pathological, instrumented) using sets of mathematical equations. Finite element method is one such approach and is most suitable for complex structures like spine. According to Shih-Hao Chena et al [2], used FEA to study spine discs and explored bio-mechanical aspects. KuSurgical [3] suggested treatments for lower back pain based on fusion (arthrodesis) and disc replacement (arthroplasty). A 3D model of a lumbar segment was created and simulated through static analyses using FEA software. Dong Suk Shin et al. [4] in their study, developed a finite element model of the human lumbar spine for the parametric study and thereby range of motion was investigated for a set of spine discs. Peter J. Evans et al. [5] found out that the degeneration of spine discs serves as a source of pain in elderly patients and in their study, developed a disc model possessing scaffold like geometry to study disc degeneration. According to Horak Z et al [6], degenerative disc disease constitutes one significant reason for low lumbar back pain. In their work, range of motion was studied for the model developed based on the input data received from a class of patients having the disease. Ayturk, U. M., & Puttlitz, C. M[7], in their work generated a FE model of human lumbar spine and performed an extensive validation using kinematic and stress-strain data.

2. Methodology
The present work has undergone the following stages of which the data collection forms the very tedious stage, as it involves various stakeholders from the common man till the medical professionals. The stages that are followed are as follows:

1. Anatomy of Lumbar spine has been studied and specimen (original lumbar spine) models were collected for understanding of lumbar spine morphology.
2. Based on the study and understanding of morphology, parameters governing bone structure were decided and measured using vernier caliper.
3. Model of vertebra is then created using CATIA and Visual Basic.
4. After creating the model, STL file of the model is imported to prototyping machine and a prototype has been created.

The lumbar spine surfaces are not a regular geometry surfaces, it contains lot of curves and projections and sizes of parts of lumbar spine differs from body to body. There are medical imaging software available in the market to develop a model, but each and every time doctor needs a healthy bone to create patient specific model. To overcome the problem, the present study can be very beneficial as models can be generated quite easily only by assigning parameters value. Patient specific model can be easily generated

2.1. Modelling approach
To create the parametric model of this part it is necessary to know the parameters on which it is depended. For this, bones of different human beings had been collected and studied, on the basis of the study parameters were collected. Each bone is then measured with the vernier caliper to get the parameters value. The modeling of lumbar vertebra is then carried out in CATIA. The solid model of lumbar vertebra including all the and parts is modeled in CATIA based on the lumbar anatomical studies. The process and parts were defined based on the parameters considered in the present work and are listed in following Table 1.
Table 1. Parameters defining lumbar vertebra.

| Part     | Body                          |
|----------|-------------------------------|
|          | Major and Minor axis length at superior plane |
|          | Major and Minor axis length at mid plane |
|          | Major and Minor axis length at inferior plane |
|          | Vertebral height               |
|          | Pedicle width                  |
|          | Pedicle height                 |
|          | Pedicle length                 |
|          | Distance between outer layer of pedicles |
|          | Spinous process length         |
|          | Width at the top of spinous process |
|          | Distance between transverse process |
|          | Facet height                   |
|          | Facet width                    |

In vertebra, the body forms the predominant part possessing the shape of a cylinder like. It is shaped like an hourglass, thinner in the center with thicker ends. So, for the ease of the modelling it is assumed that the body contains three major planes namely superior plane, mid plane and inferior plane as shown in Figure 1a. The major and minor axis length at each of the above mentioned plane is measured with the vernier caliper. The pedicles change in the morphology from upper lumbar to the lower lumbar. The parameters considered are pedicle width, height, length from the center of body and the distance between outer layers of the pedicles. All the parameters are measured by vernier caliper. The pedicles are shown in figure 1b. The spinous process of a vertebra is directed backward and downward from the junction of the laminae (in humans) and serves for the attachment of muscles and ligaments. The parameters are length of spinous process and width at the top of spinous process, each parameter are measured with vernier caliper. The spinous processes are shown in figure 2.

The transverse or costal processes of a vertebra is as shown in figure 3a which serves as a medium for the attachment of muscles and ligaments. The only parameter considered is distance between the transverse process. An articular facet (or articular surface) is a surface where two anatomical structures (usually bones) meet. The parameter are facet height and facet width. Again the parameters are measured with the help of vernier caliper. The articulate facet are shown in figure 3b.
The user interface had been developed using the above-mentioned parameters and the different views of model (L1 vertebra). The parameter values have been mentioned in Table 2. The fifth vertebra L5 has not been modeled because of complicated structure due to its relation with sacrum. The table 2 consists of parameters of L1 vertebra.

**Table 2.** L1 Vertebra - Parameters and values

| Parameter                        | Value (in mm) |
|----------------------------------|---------------|
| Height of vertebra               | 24.68         |
| Superior plane major axis length | 19.84         |
| Superior plane minor axis length | 16.25         |
| Mid plane major axis length      | 16.95         |
| Mid plane minor axis length      | 15.65         |
| Inferior plane major axis length | 20.24         |
| Inferior plane minor axis length | 16.05         |
| Pedicle length                   | 19.34         |
Pedicle height 17.86
Pedicle width 6.65
Distance between outer layer of pedicle 36.29
Width of spinous process at top 3.04
Length of spinous process 21.56
Height of facet (Inferior) 5.05
Width of articulate facet (Inferior) 3.00
Articulate facet (Inferior) Major Axis 7.05
Articulate facet (Inferior) Minor Axis 6.25
Distance between tips of transverse process 66.64

3. Rapid prototyping of spline

The prototype of lumbar spine has been developed to compare the model with the original human lumbar spine specimen. The machine used was STRATASYS-FORTUS 360 mc. In the preprocessing stage the 3D CAD model data in the form of STL file is feed into the software. Software automatically slices the model and calculates support structures, creates toolpaths and calculates the time required. In the second stage parts are build layer by layer in an additive process and extrusion heads lay down thermoplastics to create each layer. After completion of second stage support structures are dissolved in a water-based solution or snapped off by hand.

4. Results and discussion

Each lumbar vertebra model was compared with the specimen (original human bone). The deviation of the 3D printed model is compared with the original specimen bone and the deviations are listed in tables 3 and 4 respectively. The deviation is found to be very minimal or negligible as evident from the tables.

| Parameter | Dry vertebra | Modeled vertebra | Deviation |
|-----------|--------------|-----------------|-----------|
| Height of vertebra | 24.68 | 24.68 | 0 |
| Superior plane major axis length | 19.84 | 19.573 | -0.267 |
| Superior plane minor axis length | 16.25 | 13.202 | -3.048 |
| Mid plane major axis length | 16.95 | 16.79 | -0.16 |
| Mid plane minor axis length | 15.65 | 14.23 | -1.42 |
| Inferior plane major axis length | 20.24 | 20.03 | -0.21 |
| Inferior plane minor axis length | 16.05 | 15.95 | -0.1 |
| Pedicle length | 19.34 | 19.34 | 0 |
| Pedicle height | 17.86 | 17.86 | 0 |
| Pedicle width | 6.65 | 6.63 | -0.02 |

Table 3 Comparison between modelled bone and dry vertebra
The spine model that has obtained after the present study can be more useful for the doctors and the spine surgeons in carrying out their studies on the spine. The present study will reduce the dependency on the animals and the dead bodies. The study can be also be used as computer based tutorial for the students. Patient specific model can be generated with giving the parameters values that can be obtained through scan. Patient specific model of spine can be used to determine the type and size of implants required for a particular patient for operations, before hand. The modelled spine can be useful for generation of the finite element model which is useful for different kind of analysis. The present study can help in better case information to reduce operating time, enhance patient and physician communication and improve patient outcomes.

**TABLE 4** Comparison between modelled bone and dry vertebra

| Parameter                              | ORIGINAL BONE (in mm) | PROTOTYPE   | DEVIATION (in mm) |
|----------------------------------------|-----------------------|-------------|-------------------|
| Height of vertebra                     | 24.68                 | 24.88       | 0.2               |
| Superior plane major axis length       | 19.84                 | 19.46       | -0.38             |
| Superior plane minor axis length       | 16                    | 15.21       | -0.79             |
| Mid plane major axis length            | 16.95                 | 17.04       | 0.09              |
| Mid plane minor axis length            | 15.65                 | 14.92       | -0.73             |
| Inferior plane major axis length       | 20.24                 | 19.91       | -0.33             |
| Inferior plane minor axis length       | 16.02                 | 15.23       | -0.79             |
| Pedicle length                         | 19                    | 19          | 0                 |
| Pedicle height                         | 17.86                 | 16.17       | -1.69             |
| Pedicle width                          | 6.65                  | 5.88        | -0.77             |
Distance between outer layer of pedicle 36.29 34.08 -2.21
Width of spinous process at top 3.04 3.02 -0.02
Length of spinous process 21.56 22.28 0.72
HEIGHT OF FACET (inferior) 5.05 5.96 0.91
Width of articulate facet (inferior) 3.20 3.1 0.1
Articulate facet (inferior) Major axis 7.03 7.33 0.3
Articulate facet (inferior) Minor axis 6.25 6.04 -0.21
Distance between tips of transverse process 66.64 66.31 -0.33

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