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COMPUTER AIDED PARAMETRIC SOLID MODELLING OF THE SPINE

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Summary

The advances in computer modelling provide a safe mechanism for conducting research on the human spine. By simulating the geometry and form of the spine, true results of the ergonomic nature of designs and practices can be attained.

The objectives of this study are to look at the development of a parameter driven feature based model of the human spine. The parameters have been defined and developed after a morphometric study of a spinal model. The form and dimensions of these parameters were incorporated into a computer program capable of developing this model on the Unigraphics solid modelling tool.

By developing a program to generate the model, the parameters can be edited to see how different geometric properties react within a mechanical and ergonomic analysis. By changing the geometric properties of the spine it is possible to encompass a greater percentile of the human population in the research.

Currently the model generated by the program reflects the nature of the spinal model used in the morphometric study. To change any of the parameters the 'C' code must be accessed and the parameters edited within. This code also calculates the positions of the features relative to other features using the parameter dimensions.

The position of each vertebral segment in 3-D space is calculated in the computer code. The segments can be assembled to show a complete section of the spine, including the intervertebral disks.
1 Introduction

The spinal column is one of the most important structures within the human skeletal system. It provides movement to the trunk and head, transmits loads from the upper to the lower limbs and protects the spinal cord. The spine, though is susceptible to many disorders, from scoliosis and osteoporosis, to fractures, disk prolapse, and more commonly low back pain. Many individuals suffer from back trouble caused by a gradual weakening of the tissues. The cause for this weakening is not known but it is thought that modern working practices and seat designs are involved. This large number of sufferers provide a hidden cost to industry, from the increasingly high levels of absenteeism and sick leave. In 1992/93 the NBPA (National Back Pain Association) calculated the costs to be over £5 billion, through loss of production and compensation.

In order to understand the mechanics of the spine, we need to measure the forces and strains acting upon it in different situations. One method may be to conduct experiments directly on humans in the confines of a laboratory. This can pose risks for human life under certain conditions, the limits for spinal forces may not be known and experiments may pass through the upper limits boundary. The environments also may not be adequately simulated within the laboratory, or sometimes the length of the experiments may be unrealistic for research projects. Another method may be to develop a computerised model of the human spine. This model would need to be dynamic and suited to the needs of designers. It would also need to represent the subtleties and geometric complexities inherent in each individual spinal vertebra.

Such a model of the human spine could potentially be useful to improve existing research in the following areas. Seat and workplace design, the lifting of weights (both dynamic and static), forces on the human caused by ejector seats, the G-Forces on the neck caused by aircraft and spacecraft takeoff, fairground rides, aircraft manoeuvres, and car crashes. A model may also be able to look at how the spine behaves in specific situations, such as impacts (e.g. car crashes) and pregnancy. A computer generated model would be able to provide more information than by testing on humans because it would be able to be tested and analysed thoroughly without concerns about safety.

Models of the human spine do exist, Monheit and Badler (1991) created a model of the spine to study movement in humans. However, this spine model appears to have been simplified and thus would not provide the complete data required for a full mechanical and FE analysis. Geometric models have also been created by others for use in finite element analysis. The information for these models has been retrieved from CT (computed tomography) scans, radiographs or dried spinal specimens and the models constructed in a finite element mesh. Lavaste et al (1992), Skalli et al (1993) and Robin et al (1994) discuss the use and development of six primary parameters in the construction of a finite element model. Shirazi-Adl et al (1984), Ueno and Liu (1987) and Goel et al (1988) have concentrated on the just the lumbar area in the development of their 3-D non-linear finite element models. Lee et al (1995) developed a model of the spine, ribcage and pelvis to examine lumbar forces. Even though these mesh models do provide a realistic representation of the vertebrae, they tend to be very individualised and new digitised data would be required to develop a new model. An extensive review of all existing mathematical models of the human spine can be found in Grilli (1995).

The model generated in this research project needed to be developed as a solid so that material properties can be assigned and analysis, either finite element or mechanical, be carried out. This geometric model, through the use of standards, such as IGES and STEP, can be imported into other packages for such analysis to be carried out.
This paper shows the development of a human spine model through the development of geometric properties to the construction of a program which is able to create individualised models.

2 Materials and Methodology

2.1 Features and Parameters

In order to generate a computer model of the human spine it is first necessary to carry out a study to determine the form and structure of the individual vertebra and disks. From this study, features could be identified and their structure analysed to determine areas of possible parameterisation. Parameters have been researched and developed over the last twenty years and have been used to aid in the development of spinal fixation devices. The parameters which have been defined and measured either tend to be related to the main structure of the spine, such as the width, height and depth of the vertebral body and pedicles, or they tend to concentrate on a specific part of the vertebra, such as the articulating facets.

![Figure 1: The Structure Of The Vertebra And The Origin Of The Axes](image)

The most comprehensive study into the dimensions of vertebral parameters has been carried out by Panjabi et al. Where, in a three part study, the cervical (1991), thoracic (1991) and lumbar (1992) vertebrae were analysed and parameter measurements taken. The morphometric studies carried out by Berry et al (1987) and Scoles et al (1988) provide information on selected lumbar and thoracic vertebral parameters. The anthropometric studies by Gilad and Nissan (1984 & 1986) looked at the geometric relations of the vertebrae and disks.
in the cervical and lumbar spines. The study by Postacchini et al (1983) looked at the difference in vertebral dimensions between two different ethnic groups. Krag et al (1988) and Zindrick et al (1987) studied the morphometric characteristics of the lumbar and thoracic pedicles with respect to the development of transpedicular spinal fixation devices. The study by Van Schaik et al (1985) concentrated on the orientation of the laminae and facet joints of the lower lumbar spine. Even though some of this information is useful for this project, a more comprehensive study relating to the complete nature of the processes and articulating facets is also needed.

In order to find the parameters and information for this new computerised model. A physical spine model was analysed to understand its structure and shape. From this study the ten main structures of the vertebra were viewed to see how they fit together and 60 parameters were measured. The measurements were taken by using a caliper and compass, providing a linear accuracy to 0.1mm and an angular accuracy to 10°. The structures within the vertebra are the vertebral body, spinous process, left and right pedicles, left and right transverse processes, left and right inferior facets, and left and right superior facets (these structures can be seen in Figure 1). The intervertebral disks were also studied for form and contain only 6 parameters, having a far simpler geometric structure. The reason for the large number of parameters is the complex non-linear nature of each vertebra.

2.2 Development of the Geometric CAD Model

The vertebrae are constructed from complex shapes which cannot be easily modelled. Each vertebra is individual to each person and thus a mathematical surface equation describing one person's vertebrae will not be the same as the equation describing another. Due to both this individuality and its complicated mathematical nature it is necessary to simplify the features into regular shaped sections in order to create the model. The parameters, developed above are used to control the geometry of these simplified features.

All the CAD modelling was carried out using Unigraphics V10.5 on Sun Spare Stations. The features were created by sweeping closed B-spline section curves along guide curves to generate an enclosed solid.

For the vertebral body, the closed sections were created by fitting a cubic B-spline curve through ten points in 2-D space incorporating the parameters of length and width. The lower section was created by the same method, but with different dimensions for length and width, and using the Z co-ordinate to define the height. The end result is two parallel kidney shaped curves. The guide curves were created by utilising two existing points and defining a third point half way between the curves. This third point incorporates the two parameters describing the central cross-section of the vertebral body. These parameters give us the concavity of the vertebral body. The height of the vertebral body is assumed to be constant throughout each individual vertebra. The difference between the front and the back heights of the vertebral bodies have been added onto the height of the intervertebral disk. This allows us to maintain the correct vertebral inclination in the transverse plane.

The pedicles are simplified as two elliptical cylinders with the height, width and length parameters providing all the necessary information. The position of the pedicles is related to the width of the spinal canal. The pedicles were then rotated in both the transverse and sagittal planes to provide their inclinations.

Three parallel rectangles make up the section curves for each transverse process. The distance between the nearest and furthest rectangles define the length of the transverse process. The second rectangle is positioned mid-way between the other two. The height and width of each rectangle relate to the dimensions of these parameters. The guide curves are created by
fitting a quadratic B-spline curve to the corresponding corner points. The two outer rectangles have translations in both the X and Z axes to provide inclinations in both the sagittal and longitudinal planes.

The spinous process is also defined by three parallel rectangles created in the same way as those for the transverse processes. These two furthest rectangles have a translation in the Z axis to provide the transverse inclination.

For the lumbar vertebrae, the superior facets are created from four rectangles, two of which are positioned at right angles to the other two. These rectangles are then swept to provide an internal curve. This geometry was then rotated about the Y-axis to provide an inclination. The thoracic and cervical vertebrae have far simpler facets and are constructed from two parallel six-pointed sections with linear guide curves between them.

The inferior facets are constructed in the same way as the superior facets for the cervical and thoracic vertebrae. For the lumbar vertebrae, these facets are created by sweeping from one rectangle to another with an internal angle of 45°. This creates an external curve which is compatible with the internal curve of the superior facet.

Once all these features have been created they were all merged to create a single solid body.

2.3 Development of the Generation Program

The Unigraphics solid modelling system incorporates a programming tool which can be used to simplify repetitive tasks. This programming function utilises all the creation and editing mechanisms within Unigraphics. The advantage of generating a program is that it allows individual parameters to be picked up and edited automatically. The programming tool uses the ‘C’ computer language to call up functions within Unigraphics and uses the information stored within strings and arrays to create the points, curves, sections and swept solids. The spinal vertebrae have been created using this mechanism. By entering all the parameters, the program uses these dimensions to create the co-ordinates and structures of curves and sections. The co-ordinates are calculated from the parameters and inserted automatically into arrays. By inserting the data automatically, the direction of the curves can be kept constant which then in turn aids the sweeping algorithms. Trigonometry is used to calculate the X, Y and Z displacements caused by rotating features to create their planar inclinations. The trigonometry functions are accessed through the program and the displacements calculated automatically. When created, each curve and section is given an identity which is then called upon to create the swept free form feature.

Using the library of functions within the Unigraphics environment, a menu-driven system has been created. The menus were then programmed to access the parameters and create a vertebra or intervertebral disk through the methods outlined above.

Each vertebra is constructed with a work co-ordinate system independent of the absolute co-ordinate system. This allows the construction of the vertebra in its actual position in 3-D space with its correct inclination. By using the lumbar vertebra L5 as the base of the spine, the positions of the other vertebra and disks can be calculated by adding the heights of the vertebral body and the intervertebral disk. The inclinations of the vertebrae and disks are calculated from the angle caused by the difference in height from the front to the back of the intervertebral disk. The position of the body in 3-D space includes the displacements caused by the inclinations and curvature of the spine.
2.1 Assemblies

To create the lumbar spine, as seen in figure 3, assemblies were used. Assemblies provide the ability to link up many different parts to create a complex structure. Each part within an assembly is modified individually and these modifications are automatically displayed within the assembly structure. To develop the assembly each individual vertebra and disk was created and positioned in 3-D space. This process was carried out manually using the assemblies functions within Unigraphics.

3 Results

The model, as seen in figure 2, is representative of a typical vertebra (excluding the atlas and axis) created using the program. The model seen in figure 3 is constructed by combining five consecutive lumbar vertebra to form a model of the lumbar spine. Once the model has been generated it can be edited manually through the functions available within Unigraphics. However, it would be unwise to edit the parameters this way, as the positions of the features are created relative to each other in the 'C' program. To change the parameters, the method to use would be to access the 'C' code and edit the parameters within this. This means that each feature will be created and positioned using information gained from these new parameters.

![Figure 2: The L3 Lumbar Vertebra](image)

The user interface for the program is very simple and allows the choice of any individual vertebra or disk from the menus. Once a choice is made a part name will need to be entered and the chosen vertebra will then be constructed. Once the part has been created it is possible to
export the geometry through the IGES translator into another package for mechanical or finite element analysis.

The models created have a functional rather than aesthetic appearance. The vertebra are created as individual solids and values for their density can be assigned to them. When the models are placed within an assembly the articulating facets meet each other to provide the points of contact required for rotation.

Figure 3: The Lumbar Spine

4 Discussion and Conclusions

The purpose of this research was to generate a solid model of the human spine. The model which has been created is a representation of one spine rather than one which is representative of the total population. However, the geometry can be amended by changing the dimensions listed in the 'C' code to create either a more representative or an individualised model. The model which is created here can be used as a template for many different spinal segments, through the editing of the parameters.

This solid model can be used in many situations, and imported into different analysis packages. The geometry from this model could potentially be used in ergonomics packages to analyse the spine curvature and stresses caused by different seat and workplace designs. The model can also be used as a visualisation tool within a mechanics package to show how the spine moves with certain actions. This may be useful to sport scientists, medical and biology students. Loads within a mechanics package can be applied to the spine to analyse the forces, stresses and strains on certain areas of the vertebra. This may allow us to see how and when the spine degenerates under certain conditions.
If the nature of spinal degeneration is known then this information could be used in the development of techniques for preventative medicine. The model created in this study is based on a healthy spine, but it can be eroded manually for use in the analysis and study of spinal disorders.

The solid model can behave dynamically to view collisions between vertebral elements. The generation of a single solid does have disadvantages, as only one density can be attributed to the model, whereas both the vertebra and intervertebral disk have material non-linearities. Another disadvantage is that it is not able to provide an accurate surface representation of a vertebra. This is because vertebrae are too individualised and complicated to model using parameters. To get a precise representation of a vertebra CT scans and radiographs are required from living specimens. A high quality computer driven co-ordinate measuring machine could provide a complete geometric study and surface representation of a cadaver specimen. If the model is only required for visualisation purposes, a graphics package would be better suited as the model is generated from facets and not parametric features.

The Unigraphics modelling system provides feature development from both primitives and free forms. The use of free forms allows the user to control the shape and nature of the solid. The modelling mechanisms within Unigraphics are well documented and simple to use. The information on User Functions programming is the opposite, and trial and error methods were used extensively to understand how the models could be created. The programming function within Unigraphics is useful as it provides the ability to control and understand the model geometry before the solid model is created. The parameters can also be easily edited at the point of entry rather than by post processing. This ensures that the features are all placed in their correct positions relative to each other and not elsewhere as a result of editing the parameters after the model has been created.

5 Future Work

To aid in the development of future models, a more comprehensive study of the dimensions, form and features of many different spines will need to be taken. The dimensions taken from this study can be used to develop a model which is more representative of the total population. These parameter dimensions can also be used to see how the dimensions change from one vertebra to another, this could then potentially be used in the generation of a program which will be able to recreate one vertebra from the dimensions of another. The results from this comprehensive study could also be used to find relationships between the many different parameters. If relationships are found it may be possible to reduce the number of parameters required for input, as some of the parameters may be used in the creation of others.

Currently the parameter dimensions have been entered into the program. Future programming will allow the user to enter their own dimensions, within a given range, to develop an individual vertebra. Another area of future programming will be to incorporate the assembly functions into the program. This will allow the user to choose the first and last vertebra for their model and the program will then develop all the vertebra between and display them all in an assembly in their correct positions in the absolute co-ordinate system.

References