Modeling the Rat Cervical Spine

Author:
Colin Russell
5th Year Engineering Physics
Mechanical Option
Student Number 42289025
crussell@interchange.ubc.ca

Supervisor:
Dr. Thomas Oxland, P. Eng.
Professor and Director
Division of Orthopaedic Engineering Research
Canada Research Chair in Biomedical Engineering
toxland@interchange.ubc.ca

September 5, 2007
Preface

The staff at the UBC Division of Orthopaedic Engineering Research (DOER) and at the UBC High Field Animal MRI Centre have been a great resource to me throughout this project, offering friendly advice and ideas on many occasions.

I would specifically like to thank Dr. Thomas Oxland for project inspiration and guidance; Dr. Tae Eun (Tonny) Chung, for leading the work on creating the finite element model; Andrew Yung, for obtaining MRI images of the rat spine; and both Carolyn Greaves and Dr. Anthony Choo for their helpful suggestions and for imparting to me some of their related wisdom.
Abstract

The function of the spinal cord and its surrounding structures in response to injury is not well understood even today. In order to better understand and treat spinal cord injury, especially within the cervical spine where it is most debilitating, further investigation of the properties of the spinal cord is necessary. To aid in this research, a finite element (FE) model of the human cervical spine was previously created by Carolyn Greaves at the UBC Division of Orthopaedic Engineering Research [Greaves 2004]. This model was limited in its application because it was difficult to validate given the lack of human experimental data. Experiments in spinal cord injury research are often carried out on rat subjects, therefore a similar FE model of the rat cervical spine was suggested for more practical model validation. The purpose of this project was to derive surface models of the cervical rat spine geometry from MRI data, for use in the creation of such an FE model.

In vivo high resolution MRI scanning of a single rat cervical spine was performed at the UBC High Field Animal MRI Centre. Images were obtained from the 7 Tesla scanner with in-plane resolution of 156x156 microns, and 1 millimetre through-plane resolution, axial to the spinal cord. Two scans, perpendicular to the upper and lower cervical spinal cord, respectively, were interpolated and registered using Mayo Clinic’s Analyze 7.0 to form the base MRI data. Surface models were extracted structure by structure from the MRI data using the ITK-SNAP volume segmentation software. Polygonal surface data for each of the nine vertebrae (C1–T2), seven intervertebral discs, and the spinal cord’s white and grey matter were output from ITK-SNAP. This surface data was converted to analytical surfaces, and then finite element meshes were created for each object in the rat spine. The 3D model of the cervical rat spine geometry was embedded within this PDF document in Appendix E. An annotated VRML model is additionally available for online viewing at the following address (as is this document in PDF format): [http://www3.telus.net/ColinR/VRML/RatSpine/](http://www3.telus.net/ColinR/VRML/RatSpine/)

This project demonstrates the effectiveness of the UBC High Field MRI Centre combined with ITK-SNAP for high resolution imaging and subsequent volume segmentation of the rat cervical spine. This procedure is currently being used for the creation of a finite element model for spinal cord injury simulations, and could also be useful for imaging and visualizing experimental subjects.
Contents

1 Introduction 1
   1.1 Background and Significance ................................. 1
   1.2 Project Definition and Summary of Results .................. 2
   1.3 Anatomy of the Cervical Spine .............................. 2

2 Discussion 6
   2.1 Surface Model Creation ...................................... 6
      2.1.1 MRI Acquisition ..................................... 6
      2.1.2 Image Selection and Registration ..................... 6
      2.1.3 Image Segmentation .................................. 7
   2.2 Finite Element Modeling .................................... 12
      2.2.1 Mesh Creation ....................................... 12
      2.2.2 Future Goals ...................................... 15

3 Conclusions 16
   3.1 Results .................................................. 16
   3.2 Recommendations .......................................... 16

Appendices 19

A Images of Rat Vertebrae from Literature 19

B Summary of MRI Data 23

C ITK-SNAP Volume Statistics 24

D Image Conversion Scripts 25
   D.1 VTK Tcl script for STL conversion ....................... 25
   D.2 VTK Tcl script for VRML conversion .................... 26

E Embedded 3D Model 29
List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mid-sagittal view of the dorsal-ventral strain for a compression injury [Greaves (2004)]</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Spatial terminology with respect to the rat [Wingerd (1988)]</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>Diagram of a rat skeleton [Muskopf (2007)]</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>Diagrams of generic rat vertebrae [Wingerd (1988)]</td>
<td>4</td>
</tr>
<tr>
<td>4(a)</td>
<td>Cervical vertebra</td>
<td>4</td>
</tr>
<tr>
<td>4(b)</td>
<td>Thoracic vertebra</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>Diagrammatic transverse section of the medulla spinalis [Gray (1918)]</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>MRI acquisition of rat specimen</td>
<td>6</td>
</tr>
<tr>
<td>6(a)</td>
<td>Rat specimen</td>
<td>6</td>
</tr>
<tr>
<td>6(b)</td>
<td>7T animal MRI scanner</td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td>Active contour evolution [Yushkevich et al. (2006)]</td>
<td>9</td>
</tr>
<tr>
<td>8</td>
<td>ITK-SNAP screenshot</td>
<td>9</td>
</tr>
<tr>
<td>9</td>
<td>Surfaces segmented in SNAP</td>
<td>10</td>
</tr>
<tr>
<td>9(a)</td>
<td>Spinal cord</td>
<td>10</td>
</tr>
<tr>
<td>9(b)</td>
<td>Atlas</td>
<td>10</td>
</tr>
<tr>
<td>9(c)</td>
<td>Axis</td>
<td>10</td>
</tr>
<tr>
<td>9(d)</td>
<td>C3</td>
<td>10</td>
</tr>
<tr>
<td>9(e)</td>
<td>C4</td>
<td>10</td>
</tr>
<tr>
<td>9(f)</td>
<td>C5</td>
<td>10</td>
</tr>
<tr>
<td>9(g)</td>
<td>C6</td>
<td>10</td>
</tr>
<tr>
<td>9(h)</td>
<td>C7</td>
<td>10</td>
</tr>
<tr>
<td>9(i)</td>
<td>T1</td>
<td>10</td>
</tr>
<tr>
<td>9(j)</td>
<td>T2</td>
<td>10</td>
</tr>
<tr>
<td>9(k)</td>
<td>IV disc</td>
<td>10</td>
</tr>
<tr>
<td>9(l)</td>
<td>1-cm scalebar</td>
<td>10</td>
</tr>
<tr>
<td>10</td>
<td>C3 vertebra modeling steps</td>
<td>12</td>
</tr>
<tr>
<td>10(a)</td>
<td>Polygonal surfaces</td>
<td>12</td>
</tr>
</tbody>
</table>
List of Tables

| Table B-1 | Summary of MRI imagesets | 23 |
| Table C-1 | Volume statistics          | 24 |
1 Introduction

This report documents the work of co-op student Colin Russell in constructing a computer model of the rat cervical spine. The work was conducted at the UBC Division of Orthopaedic Engineering Research (DOER), under the direction of Dr. Thomas Oxland.

The report first outlines the background and significance of the project, and offers a summary of the project definition and results. A brief primer on relevant spinal anatomy is then given, followed by a detailed discussion of the project methodology. The report concludes with further discussion of the project’s results and recommendations for future work.

1.1 Background and Significance

Spinal cord injury (SCI) is too often a severely debilitating condition, largely because the function of the spinal cord, especially in response to injury, is still not well understood. With over 10,000 annual cases of SCI in the US, the problem cannot be ignored and further research is necessary to better treat such cases (Choo et al., 2007). Due to the invasive nature of SCI research, models of the spine can serve as excellent alternatives to in vivo studies.

The inspiration for this project came from a previous finite element (FE) model of the human cervical spine created by Carolyn Greaves for her Master’s thesis under Dr. Oxland (Greaves, 2004). Figure 1 shows a cross-section of her model, displaying the range of strain resulting from a spinal cord compression injury simulation.

![Figure 1: Mid-sagittal view of the dorsal-ventral strain for a compression injury](image)

Greaves’ model showed promise in allowing simulations to help characterize SCI.
However, validation of the human model was complicated by the fact that little experimental data is available for the human spine.

On the other hand, rats are frequently the subject of SCI research experiments due to the relatively low associated cost and the fact that SCI pathology in the rat closely resembles that in the human (Tator, 2006; Metz et al., 2000). Such experimental data could be used to validate an FE model of the rat spine. In turn, the validated FE model would facilitate further investigation of SCI in the rat.

Validation of the methods and approximations used to construct the rat FE model would also be helpful in appraising those used for Greaves’ model, and provide suggestions for revision of the human model should important differences exist between the two.

1.2 Project Definition and Summary of Results

The following key tasks were outlined in the project definition:

- Coordination with the UBC High Field MRI Centre for acquisition of MRI data
- Creation of a surface model of the rat cervical spine with spinal cord
- Transfer of the surface model to a finite element model (with Dr. Chung)
- Further development of the finite element model (with Dr. Chung)

The first three of these tasks have been completed. Further development of the FE model is currently underway, including modeling spinal ligaments which could not be segmented from the MRI data and assigning material properties. Once the model development is complete and suitable boundary conditions are applied, simulations may then be performed to validate the model against experimental data.

1.3 Anatomy of the Cervical Spine

As vertebrate mammals, the rat cervical spine has much in common with that of the human. Accordingly, much of the scientific literature on the anatomy of the human spine is useful in understanding that of the rat, for which there is less published material. However, the rat spine is not simply a scaled down version of the human spine, and in order to accurately model the former some literature specific to the rat is required (Flynn and Bolton, 2007). In particular, several books and papers on the anatomy of the rat were consulted for assistance in identifying and properly
segmenting parts of the cervical spine (Rowett 1974; Wells 1964; Wingerd 1988; Greene 1935; Howell 1926; Johnson et al. 1999).

A brief summary of the anatomy of the rat cervical spine is now given, to aid the reader in recognizing features of the spine surface model. For clarity of discussion, Figure 2 demonstrates the spatial terminology used when describing various aspects of the rat anatomy.

![Spatial terminology with respect to the rat](image1)

**Figure 2:** Spatial terminology with respect to the rat [Illustration taken from Wingerd 1988]

Figure 3 shows the vertebrae contained in the surface model (coloured) in relation to the rest of the rat skeleton. The seven cervical vertebrae (red) are seen immediately caudal to the skull in the order C1-C7, followed by the first two thoracic vertebrae (blue), T1 and T2.

![Diagram of a rat skeleton](image2)

**Figure 3:** Diagram of a rat skeleton [Illustration adapted from Muskopf 2007]
Each of these vertebrae has the following basic components (see Figure 4): a central body, or centrum; a neural arch which extends from the centrum to create a neural canal axially through the middle of the vertebra; a spinous process which extends dorsally from the neural arch; and articular processes called zygapophyses which form joints between vertebrae (Wingerd, 1988).

![Diagram of generic rat vertebrae](Illustrations taken from Wingerd (1988)]

(a) Cervical vertebra  (b) Thoracic vertebra

Figure 4: Diagrams of generic rat vertebrae [Illustrations taken from Wingerd (1988)]

The first two cervical vertebrae are unlike the others in appearance, and have special names. The first is the Atlas, which articulates with the base of the skull (see Appendix A pp. 19–22). The second is the Axis, with the identifiable odontoid peg about which the Atlas rotates to allow turning of the head, as well as a very pronounced spinous process. Common to all cervical vertebrae are the transverse foramina, or vertebrarterial canals which house local arteries and veins. The sixth cervical vertebra is unique in having two extra ventral processes, the carotid tubercles (see Figure A-2(i), p. 20).

The thoracic vertebrae are characterized by long spinous processes, except for T1. Adjacent vertebrae are connected via a network of ligaments and, more distinctly, via an intervertebral (IV) disc. The discs are a mixture of water and fibrous cartilage, with a central nucleus pulposus having a higher water content than the more rigid annulus fibrosus which composes the remainder. Each disc is located between the centra of adjacent vertebrae, and is fused directly to the vertebral bone.

Within the protective walls of the vertebral canal lies the spinal cord, the main subject of study for the model. The cord itself consists of both gray and white matter, the former making an inner butterfly shape in a cross-section of the cord. Surrounding the cord are the sheathing layers of the meninges—the pia mater, arachnoid, and dura mater (see human diagram in Figure 5). Of these layers, only the dura mater is included in the model as it is the thickest layer and its viscoelastic material properties contribute much more to the overall mechanics of the spinal cord compared to the others. Furthermore, the contribution of the spinal nerves to the mechanics is neglected, and both the cord and dura mater are approximated as tube-like structures.

1The vertebrarterial canal may be small or absent in the seventh cervical vertebra (Wells 1964).
The subarachnoid cavity between the pia mater and arachnoid layers is occupied by the cerebrospinal fluid (CSF). Since the pia mater and arachnoid layers are omitted from the FE model, the CSF is instead bounded by the dura mater and the spinal cord.
2 Discussion

2.1 Surface Model Creation

2.1.1 MRI Acquisition

MRI scans of a normal, freshly euthanized Sprague-Dawley rat (Figure 6(a)) were conducted by research scientist Andrew Yung at the UBC Animal MRI Research Centre. The scans were performed using the Centre’s Bruker Biospec 70/30 7.0 Tesla MRI scanner (see Figure 6(b)), allowing high resolution imaging of the rat spine.

![Rat specimen](image1)

![7T animal MRI scanner](image2)

Figure 6: MRI acquisition of rat specimen

A series of 18 scans were recorded, including several scout scans for testing and orientation (see Table B-1). After calibration, the final images were obtained with a resolution of 156x156 microns in-plane, and 1 millimetre through-plane (axial to the spine). Due to the natural curvature of the spine, separate images were obtained oriented perpendicular to the upper cervical spinal cord (near C1–C3) as well as perpendicular to the lower cervical cord (near C5–T1).

2.1.2 Image Selection and Registration

In order to help expose the complex shapes in the cervical spine, especially in the vertebral bodies, two scans of differing orientation were fused together. Scan 17, perpendicular to the upper cervical spine, and scan 18, perpendicular to the lower cervical spine, were chosen for this task as they were the least noisy and together covered the entire cervical spine and upper thoracic (C1–T2). Each scan covered a field
of view of 40x40x25 mm, with the aforementioned resolution of 0.15625x0.15625x1 mm, constituting 25 axial slices of dimensions 256x256 pixels.

To prepare for image registration, the images were first interpolated to an isotropic resolution of 0.15625 mm using Mayo Clinic’s Analyze 7.0 software. The image intensities were normalized and also zero-padded so that registering one image to the other would not result in cropping of the non-overlapping region. The scan 17 image was then registered to the scan 18 base image using Analyze’s semiautomated 3D registration algorithm. Successful registration was achieved with the following transformation matrix:

\[
\begin{bmatrix}
0.999639554284 & -0.010136422652 & -0.024859896369 & 0.000000000000 \\
0.017058515504 & 0.954847088871 & 0.296607558777 & 0.000000000000 \\
0.020730860100 & -0.296924720781 & 0.954675830651 & 0.000000000000 \\
0.953409311569 & -4.380211523860 & -39.637756039900 & 1.000000000000 \\
\end{bmatrix}
\]

The resultant fused image had pixel dimensions of 256x256x240, isotropic resolution of 0.15625 mm, and covered the full range of the cervical spine.

2.1.3 Image Segmentation

Image segmentation was performed to extract object models of the rat spine components from the MRI data. For this purpose an open source software solution devoted to segmentation, ITK-SNAP (http://www.itksnap.org) was chosen for it’s simple yet powerful interface, despite the availability of the commercial Analyze software which has segmentation capabilities. ITK-SNAP was created using the Insight Toolkit (ITK), an image analysis software kit designed to support the images of the Visible Human Project, and the Visualization Toolkit (VTK), a 3D data visualization package.

SNAP stands for “SNake Automated Partitioning”, referring to the segmentation algorithms employed by the software which make use of active contour and level set methods to partition elements in an image via snake evolution (Yushkevich et al.).

2Load As
- Intensities - Normalized histogram by setting output max=32766, min=0
- Resize - Forced cubic, cubic spline interpolation
- Pad - Zero pad scan 17 with Low 80, scan 18 with high 80 [cropped in z-axis by \( \approx 12 \) slices, \((#\text{cropped slices})\times(#\text{axial slices after interp.})/#\text{slices before}) = 12 \times 160/25 = 77, rounded up to 80]

3The version of SNAP used in this project was 1.5.2.

4The term snake here refers to a closed curve or surface.
The method of active contour evolution involves estimation of a target object’s boundaries with a closed surface contour which gradually conforms to those boundaries. This evolution in time is modeled by the following partial differential equation (PDE) in 2D:

$$\frac{\partial}{\partial t} C(u,v; t) = F\tilde{n}$$  \hspace{1cm} (1)

Where,
- $C = \text{closed surface contour parametrized by spatial variables } u, v \text{ and time, } t$
- $\tilde{n} = \text{unit normal to } C$
- $F = \text{sum of forces acting on } C \text{ in normal direction}$

Of the two active contour methods provided in SNAP, the Region Competition method (called the ‘Intensity regions’ method within SNAP) was found to achieve the desired segmentations relatively quickly and reliably, and was used throughout the semi-automatic segmentation process. This method, pioneered by Zhu and Yuille (1996), uses the following definition of the evolution forces:

$$F = \alpha (P_{\text{obj}} - P_{\text{bg}}) + \beta \kappa$$  \hspace{1cm} (2)

Where,
- $\alpha, \beta = \text{weight parameters}$
- $P_{\text{obj}} = \text{probability of voxel belonging to object}$
- $P_{\text{bg}} = \text{probability of voxel belonging to background}$
- $\kappa = \text{mean curvature of } C$

The respective probabilities are assigned to the image voxels using a fuzzy threshold of image intensity performed in SNAP. As demonstrated in Figure 7, the seed contour gradually conforms to the desired object topology through the region competition method.

The contour evolution problem is solved by means of the level set method of Osher and Sethian (1988); Sethian (1999), in which the contour is prescribed as the zeroth level set of some function $\phi$, defined at every voxel in the image. Using the relation $\tilde{n} = \nabla\phi / \|\nabla\phi\|$, (1) can be transformed to a PDE in $\phi$:

$$\frac{\partial}{\partial t} \phi(x; t) = F\nabla\phi$$  \hspace{1cm} (3)

SNAP then efficiently solves (3) close to the zeroth level set (the level contour corresponding to $\phi = 0$) using the Extreme Narrow Banding Method proposed by Zhu and Yuille (1996).
The propagation force acts outwards over the ‘foreground’ region (red) and inwards over the ‘background’ region (blue), causing the active contour to reach equilibrium at the boundary of the regions. [Figure and caption text taken from Yushkevich et al. (2006)]


The weight parameters in (2) are left up to the user to define for a given situation in order to achieve the desired segmentation result. One of the great strengths of the SNAP Graphical User Interface (GUI) is that it allows the user to respond to the contour evolution process by altering these parameters in real time, enabling intuitive fine-tuning of the object segmentation. Furthermore, the somewhat abstract parameters are displayed alongside the general effect they have on the contour evolution—$\alpha$ is termed the “balloon force” controlling the magnitude of inward or outward force on the contour, and $\beta$ is the “curvature force” affecting the smoothness of the contour.

Figure 8 shows a screenshot of the SNAP GUI. Axial (top left), sagittal (top right), and frontal (bottom right) views of the MRI data are displayed, with a 3D cursor that links all three. In the sagittal slice, the fusion of the two MRI scans is evidenced by two intersecting rectangles.

Figure 8: ITK-SNAP screenshot
The segmentation process for the rat cervical spine began with semi-automated segmentation to achieve rough object boundaries, primarily on the basis of contrast differences. Most objects also required significant “clean-up” work applied manually on a slice-by-slice basis, or via SNAP’s 3D paintbrush or cut-plane tools. This manual work often included removing artifacts located outside an object’s expected boundaries, or creating or enhancing specific attributes of an object such as in the creation of vertebral canals.

Manual intervention was especially necessary for creation of the zygapophyses at the boundaries between adjacent vertebrae, as well as for creation of the intervertebral discs; the subtle boundaries of these parts prevented them from being accurately segmented automatically, and they had to be estimated based on images from literature. In the case of the intervertebral discs, the nucleus pulposi were distinguishable by contrast in the MRI data, and as such provided a landmark for the disc locations.

![Segmented Objects](image)

**Figure 9:** Surfaces segmented in SNAP [not shown to scale]

The resulting objects segmented in SNAP are displayed in Figure 9. The Atlas and T2 vertebrae are slightly incomplete as they were located at the edge of the image.
data. A 1-cm scalebar was manually created in SNAP (Figure 9(l)), with dimensions of 11x11x64 voxels or 1.71875x1.71875x10 mm. SNAP was also used to calculate volumes of the labeled objects in the spine; these could be compared with literature and experimental observations in the future (see Appendix C, p. 24).

With the image segmentation complete, the individual objects in the rat cervical spine model were then ready for the meshing process to integrate them into a finite element model.
2.2 Finite Element Modeling

2.2.1 Mesh Creation

In order to produce a finite element mesh of each object, the object’s surface data had to be converted to Non-Uniform Rational Basis Spline (NURBS) surfaces. To this end, Dr. Chung was able to procure a one month trial license for the INUS Rapidform® rapid prototyping software. Rapidform® does not support importing of surface data in the .vtk format output by SNAP, and so an intermediary conversion script was written for the VTK Tcl binding to convert .vtk files to STL (stereo lithography) format which is supported (see Appendix D, p. 25).

Altair’s HyperMesh FEA pre-processor was used to generate finite element meshes for each object. A typical FE meshing workflow begins with a polygonal surface STL file as shown in Figure 10(a) for the C3 vertebra, which in this case has 18276 vertices and 36560 faces. Rapidform® is then used to generate an IGES (Initial Graphics Exchange Specification) file with a smaller number of analytical NURBS surfaces, in this case 1103 surfaces (Figure 10(b)). This IGES format file is then imported into HyperMesh for mesh generation. The C3 vertebra has an arbitrary shape, so volumetric tetrahedral elements were selected for mesh creation. The tetrahedral elements minimize the risk of introducing instability, which is a problem with rectangular elements used in areas of such arbitrary curvature. Figure 10(c) shows the resulting FE model composed of 4605 tetrahedral elements.

Rapidform® was also used to generate a thin shell surface model for the dura mater which sheathes the spinal cord and CSF (see Figure 11(a)). The dura mater shell was created by specifying an offset thickness of 0.02 mm to the outer surface of a combined model of the cord and CSF segmented in SNAP. Images obtained by Franconi et al. (2000) aided in prescribing the correct boundaries of the rat spinal

---

6DOER has since made plans to purchase Rapidform® for use with a new surface laser scanner, so the software should be available in the near future if necessary.
cord, CSF, and dura mater (see Figure 12). Being a thin membrane, the dura mater was meshed using a mix of quadrilateral and triangular shell elements (Figure 11(b)).

Figure 11: Dura mater modeling steps

Figure 12: In vivo axial T2-weighted MR images of the C3 segment of the rat spinal cord at TE = 10 msec (upper left), TE = 60 msec (upper right), and TE = 120 msec (lower left). The ROIs used for calculation are defined in the lower right frame. ROIs 1-4 correspond to GM, ROIs 5-9 to WM, and ROI 10 to CSF. A 3-mm bar was added on the TE = 10 msec image as a scale reference. [Figure and caption text taken from Franconi et al. (2000)]
The spinal cord was modeled as a solid combination of the white and gray matter, using cubic elements in a semiautomated meshing process appropriate to its quasi-cylindrical shape (see Figure 13). The omission of the white/gray boundary is temporary, and the differences in results compared to separate modeling will be investigated in later work.

![Figure 13: Spinal cord modeling steps](image)

Following meshing of all nine vertebrae, seven IV discs, the spinal cord, and the dura mater, the FE models were then re-assembled together as shown in Figure 14.

![Figure 14: FE mesh of the rat cervical spine](image)
2.2.2 Future Goals

While the geometric framework for the finite element model of the rat cervical spine has been laid, there is still much work to be done to complete the model. The following key tasks remain:

1. Manual modeling of the mechanically significant spinal ligaments
2. Inclusion of the cerebrospinal fluid in the model
3. Assignment of material properties to all structures
4. Creation of appropriate boundary conditions linking objects
5. Performance of vertebral column mechanics validation simulations
6. Modeling of the spinal cord in more detail
7. Implementation of further validation simulations focusing on the spinal cord

The ligaments modeled will borrow from those made by Greaves (2004) for her FE model of the human spine. The CSF may be approximated by several means, such as by specifying a pressure boundary condition, or by using fluid elements in the model; these options will have to be evaluated to decide which is most suitable for the model. Material properties will be taken from literature on the rat spine when available, and otherwise approximated based on human or other animal data. Validation of the vertebral column mechanics and spinal cord properties will be based on comparisons to previous experimental results, and possibly to some in-house custom experiments to be determined.
3 Conclusions

3.1 Results

The use of high field magnetic resonance images to extract geometry of the rat cervical spine proved to be very appropriate, and the models resulting from the project are now being used as the basis for a finite element model of the region.

Custom scans of the rat cervical spine were performed at the UBC High Field Animal MRI Centre, providing high resolution images of the spinal anatomy. The objects segmented from the MRI data include the vertebrae, IV discs, white and gray matter, and the dura mater of the rat cervical spine. These objects were exported as polygonal surface meshes from the ITK-SNAP segmentation program, and converted to STL and VRML formats. The STL format was used to import the objects to Rapidform® for conversion to NURBS analytical surfaces, which were in turn imported into HyperMesh for FE mesh creation. The VRML format was used to create an online 3D model of the spine, available at http://www3.telus.net/ColinR/VRML/RatSpine/ as well as the embedded 3D model in Appendix E.

3.2 Recommendations

Firstly, the ITK-SNAP software is highly recommended for consideration in future image segmentation projects. The workflow encouraged in SNAP proved to be very efficient, and easy to learn for someone new to the process of volumetric image segmentation.

The high field animal MRI modality is also recommended for similar projects, though some refinements to the acquisition step could be useful to further simplify the segmentation process, as outlined below:

- More isotropic, or volumetric, voxel resolution could be used to better capture complex boundaries in the spine, at the cost of slightly noisier data.

- Due to the success in registering the two overlapping angles of image data, additional acquisition angles (perhaps 3–4 in total) may be useful to provide a better description of complicated spinal geometry. Registering the data from these different angles would minimize the impact of noise, and allow details better captured at individual angles (in the case of anisotropic voxel resolution) to be shared with the rest of the data.
References


Johnson, D., T. McAndrew, and Ō. Oguz. Shape differences in the cervical and upper thoracic vertebrae in rats (Rattus norvegicus) and bats (Pteropus poiocephalus): can we see shape patterns derived from position in column and species membership? *Journal of Anatomy*, 194(02):249–253, 1999.


Appendices

A  Images of Rat Vertebrae from Literature

Figure A-1: Cervical vertebrae and nervous system [Illustrations and caption text taken from Greene (1935)]


Figure A-2: Cervical and thoracic vertebrae [Illustrations taken from Wells (1964)]
Figure A-3: Cervical vertebrae [Illustrations taken from Rowett (1974)]
Figure A-4: Cervical and thoracic vertebrae [Illustrations taken from Johnson et al. (1999)]
## B Summary of MRI Data

### Table B-1: Summary of MRI imagesets

<table>
<thead>
<tr>
<th>Scan #</th>
<th>Field of View (mm)</th>
<th>Resolution (mm)</th>
<th>Image Dimensions</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Height Width Depth</td>
<td>Vertical Horizontal Axial</td>
<td>Height (pixels) Width (pixels) Depth (# slices)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>80 80 0</td>
<td>0.625 0.625 -</td>
<td>-</td>
<td>128 128 3</td>
</tr>
<tr>
<td>2</td>
<td>80 80 30</td>
<td>0.3125 0.3125 1.5</td>
<td>256 256 20</td>
<td>Low-res 2D scout images</td>
</tr>
<tr>
<td>3</td>
<td>80 80 30</td>
<td>0.3125 0.3125 1.5</td>
<td>256 256 20</td>
<td>Low quality scout scan</td>
</tr>
<tr>
<td>4</td>
<td>40 40 20</td>
<td>0.15625 0.15625 1</td>
<td>256 256 20</td>
<td>sagittal scout slices showing spine</td>
</tr>
<tr>
<td>5</td>
<td>40 40 20</td>
<td>0.15625 0.15625 1</td>
<td>256 256 20</td>
<td>Noisy axial scan. Tissue light</td>
</tr>
<tr>
<td>6</td>
<td>40 40 20</td>
<td>0.15625 0.15625 1</td>
<td>256 256 20</td>
<td>Noisy axial scan. Tissue light</td>
</tr>
<tr>
<td>7</td>
<td>- - -</td>
<td>- - -</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>40 40 20</td>
<td>0.15625 0.15625 1</td>
<td>256 256 20</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>40 40 20</td>
<td>0.15625 0.15625 1</td>
<td>256 256 20</td>
<td>Noisy axial scan. Tissue dark</td>
</tr>
<tr>
<td>10</td>
<td>40 40 20</td>
<td>0.15625 0.15625 1</td>
<td>256 256 20</td>
<td>-</td>
</tr>
<tr>
<td>11</td>
<td>40 40 20</td>
<td>0.15625 0.15625 1</td>
<td>256 256 20</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>40 40 20</td>
<td>0.15625 0.15625 1</td>
<td>256 256 20</td>
<td>-</td>
</tr>
<tr>
<td>13</td>
<td>80 80 0</td>
<td>0.625 0.625 -</td>
<td>-</td>
<td>128 128 3</td>
</tr>
<tr>
<td>14</td>
<td>80 80 30</td>
<td>0.3125 0.3125 1.5</td>
<td>256 256 20</td>
<td>Good axial scan. Some blurry slices. Vertebrae medium tint, white/grey distinction.</td>
</tr>
<tr>
<td>15</td>
<td>40 40 25</td>
<td>0.15625 0.15625 1</td>
<td>256 256 25</td>
<td>Blurry axial scan.</td>
</tr>
<tr>
<td>16</td>
<td>40 40 25</td>
<td>0.15625 0.15625 1</td>
<td>256 256 25</td>
<td>Very nice set. Easy to distinguish white/grey matter.</td>
</tr>
<tr>
<td>17</td>
<td>40 40 25</td>
<td>0.15625 0.15625 1</td>
<td>256 256 25</td>
<td>Nice axial scan, perpendicular to upper cerv. spine.</td>
</tr>
<tr>
<td>18</td>
<td>40 40 25</td>
<td>0.15625 0.15625 1</td>
<td>256 256 25</td>
<td>Very nice axial scan, perp to lower cerv spine. Easy to distinguish white/grey matter.</td>
</tr>
</tbody>
</table>

**NOTE:**
RAW data filenames are all "2dseq" in folders by Scan Number
16bit signed, little-endian
## C ITK-SNAP Volume Statistics

### Table C-1: Volume statistics

#### SNAP Voxel Count File

Fields:
- **LABEL**: Label description
- **ID**: The numerical id of the label
- **NUMBER**: Number of voxels that have that label
- **VOLUME**: Volume of those voxels in cubic mm
- **MEAN**: Mean intensity of those voxels
- **SD**: Standard deviation of those voxels

<table>
<thead>
<tr>
<th>LABEL</th>
<th>ID</th>
<th>NUMBER</th>
<th>VOLUME</th>
<th>MEAN</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>white matter</td>
<td>1</td>
<td>36308</td>
<td>138.504</td>
<td>117.208</td>
<td>15.3609</td>
</tr>
<tr>
<td>grey matter</td>
<td>2</td>
<td>23273</td>
<td>88.7794</td>
<td>133.903</td>
<td>15.0901</td>
</tr>
<tr>
<td>Atlas</td>
<td>4</td>
<td>34029</td>
<td>129.81</td>
<td>52.4141</td>
<td>25.1725</td>
</tr>
<tr>
<td>Axis</td>
<td>5</td>
<td>30405</td>
<td>115.986</td>
<td>50.4335</td>
<td>21.3069</td>
</tr>
<tr>
<td>C3</td>
<td>6</td>
<td>22754</td>
<td>86.7996</td>
<td>53.3925</td>
<td>23.4129</td>
</tr>
<tr>
<td>C4</td>
<td>7</td>
<td>21048</td>
<td>80.2917</td>
<td>52.7467</td>
<td>22.9321</td>
</tr>
<tr>
<td>C5</td>
<td>8</td>
<td>24336</td>
<td>92.8345</td>
<td>52.6592</td>
<td>23.0501</td>
</tr>
<tr>
<td>C6</td>
<td>9</td>
<td>23729</td>
<td>90.519</td>
<td>51.3612</td>
<td>23.6097</td>
</tr>
<tr>
<td>C7</td>
<td>10</td>
<td>22619</td>
<td>86.2846</td>
<td>52.8819</td>
<td>22.5649</td>
</tr>
<tr>
<td>T1</td>
<td>11</td>
<td>22946</td>
<td>87.532</td>
<td>49.9977</td>
<td>19.3662</td>
</tr>
<tr>
<td>T2</td>
<td>12</td>
<td>16184</td>
<td>61.7371</td>
<td>49.5185</td>
<td>18.4682</td>
</tr>
<tr>
<td>esophagus</td>
<td>13</td>
<td>36789</td>
<td>140.339</td>
<td>25.1725</td>
<td>18.4682</td>
</tr>
<tr>
<td>shoulders</td>
<td>14</td>
<td>206667</td>
<td>788.372</td>
<td>43.6824</td>
<td>17.9445</td>
</tr>
<tr>
<td>Axis-C3 nucleus pulposis</td>
<td>15</td>
<td>93</td>
<td>0.354767</td>
<td>68.3226</td>
<td>7.65728</td>
</tr>
<tr>
<td>Axis-C3 annulus fibrosus</td>
<td>16</td>
<td>2230</td>
<td>8.50677</td>
<td>43.5386</td>
<td>15.1592</td>
</tr>
<tr>
<td>C3-C4 nucleus pulposis</td>
<td>17</td>
<td>296</td>
<td>1.12915</td>
<td>71.5608</td>
<td>11.0117</td>
</tr>
<tr>
<td>C3-C4 annulus fibrosus</td>
<td>18</td>
<td>3266</td>
<td>12.4588</td>
<td>48.7045</td>
<td>19.5512</td>
</tr>
<tr>
<td>C4-C5 nucleus pulposis</td>
<td>19</td>
<td>341</td>
<td>1.30081</td>
<td>76.2287</td>
<td>12.5927</td>
</tr>
<tr>
<td>C4-C5 annulus fibrosus</td>
<td>20</td>
<td>2841</td>
<td>10.8376</td>
<td>46.5576</td>
<td>15.9172</td>
</tr>
<tr>
<td>C5-C6 nucleus pulposis</td>
<td>21</td>
<td>472</td>
<td>1.80054</td>
<td>76.7097</td>
<td>16.3738</td>
</tr>
<tr>
<td>C5-C6 annulus fibrosus</td>
<td>22</td>
<td>2377</td>
<td>9.06754</td>
<td>45.8292</td>
<td>17.8159</td>
</tr>
<tr>
<td>C6-C7 nucleus pulposis</td>
<td>23</td>
<td>341</td>
<td>1.30081</td>
<td>65.5161</td>
<td>12.0608</td>
</tr>
<tr>
<td>C6-C7 annulus fibrosus</td>
<td>24</td>
<td>3134</td>
<td>11.9553</td>
<td>52.0782</td>
<td>18.7846</td>
</tr>
<tr>
<td>C7-T1 nucleus pulposis</td>
<td>25</td>
<td>251</td>
<td>0.957489</td>
<td>59.7331</td>
<td>8.9615</td>
</tr>
<tr>
<td>C7-T1 annulus fibrosus</td>
<td>26</td>
<td>3871</td>
<td>14.7667</td>
<td>49.6339</td>
<td>17.6617</td>
</tr>
<tr>
<td>T1-T2 nucleus pulposis</td>
<td>27</td>
<td>476</td>
<td>1.8158</td>
<td>78.166</td>
<td>12.9787</td>
</tr>
<tr>
<td>T1-T2 annulus fibrosus</td>
<td>28</td>
<td>3854</td>
<td>14.7018</td>
<td>64.5913</td>
<td>23.7927</td>
</tr>
<tr>
<td>1mm scale bar</td>
<td>29</td>
<td>7744</td>
<td>29.541</td>
<td>127.622</td>
<td>17.2739</td>
</tr>
</tbody>
</table>
D Image Conversion Scripts

The following scripts were made to convert the segmented surface mesh files saved from ITK-SNAP (in .vtk format) to other formats (STL and VRML) using VTK’s Tcl binding.

D.1 VTK Tcl script for STL conversion

```tcl
### ColinVTK2STL.tcl.txt
### This script is to be run in the Tcl/Tk VTK framework, and allows a .vtk format surface mesh (output from ITK-SNAP) to be smoothed and converted to .stl format (may be imported to RapidForm).
### Change FileName value in quotations to source surface mesh file (must be .vtk format).
### Then copy and paste this script into the vtk.exe tcl command prompt window (right click mouse to paste).
### Output file will be FileName.stl (in source directory).
###
### Colin Russell July 5th, 2007
#
Enter full input filename here (include directory, but exclude .vtk suffix)
set FileName "C:/Documents and Settings/crussell/Desktop/Mesh Files/RatSpineJuly25/vertC2"

package require vtk
package require vtkinteraction

# read data
#
vtkPolyDataReader input
  input SetFileName "$FileName.vtk"

# generate vectors
vtkCleanPolyData clean
  clean SetInputConnection [input GetOutputPort]
vtkWindowedSincPolyDataFilter smooth
  smooth SetInputConnection [clean GetOutputPort]
  smooth GenerateErrorVectorsOn
  smooth GenerateErrorScalarsOn
  smooth Update

vtkPolyDataMapper mapper
  mapper SetInputConnection [smooth GetOutputPort]
  eval mapper SetScalarRange [smooth GetOutput] GetScalarRange]

# prevent the tk window from showing up then start the event loop
wm withdraw .

# If the current directory is writable, then test the writers
```
if –[catch –set channel [open ”test.tmp” ”w”]] == 0 –
close $channel
file delete -force ”test.tmp”

# test the writers

# the next writers only handle triangles
vtkTriangleFilter triangles
triangles SetInputConnection [smooth GetOutputPort]

### ASCII stl writer
# vtkSTLWriter stl
# stl SetInputConnection [triangles GetOutputPort]
# stl SetFileName ”$FileName.stl”
# stl Write

vtkSTLWriter stlBinary
stlBinary SetInputConnection [triangles GetOutputPort]
stlBinary SetFileName ”$FileName.stl”
stlBinary SetFileType 2
stlBinary Write

D.2 VTK Tcl script for VRML conversion

### ColinVTK2VRML.tcl.txt
### This script is to be run in the Tcl/Tk VTK framework, and allows a .vtk format sur-
### face mesh (output from ITK-SNAP)
### to be smoothed and converted to VRML .wrl format (may be viewed in web browser with plugin).
### Change FileName value in quotations to source surface mesh file (must be .vtk format).
### Then copy and paste this script into the vtk.exe tcl command prompt win-
### dow (right click mouse to paste).
### Output file will be FileName.wrl (in source directory).
### Colin Russell July 19th, 2007

### Enter full input filename here (include directory, but exclude .vtk extension)
set FileName ”C:/Documents and Settings/crussell/Desktop/Mesh Files/VRML/white”

### Enter the target reduction for triangle decimation (higher number -¿ smaller filesize)
### 0¡=decReduce¡=1
set decReduce 0.80

package require vtk
package require vtkinteraction

# Create the RenderWindow, Renderer and both Actors
vtkRenderer ren1
vtkRenderWindow renWin
   renWin AddRenderer ren1
   renWin SetSize 512 512
vtkRenderWindowInteractor iren
   iren SetRenderWindow renWin

# read data
tkPolyDataReader input
    input SetFileName "$FileName.vtk"

# generate vectors
tkCleanPolyData clean
    clean SetInputConnection [input GetOutputPort]

tkWindowedSincPolyDataFilter smooth
    smooth SetInputConnection [input GetOutputPort]
    smooth GenerateErrorVectorsOn
    smooth GenerateErrorScalarsOn
    smooth Update

tkTriangleFilter triangles
    triangles SetInputConnection [smooth GetOutputPort]

# decimate triangles
tkQuadricDecimation decimate
    decimate SetInputConnection [triangles GetOutputPort]
    decimate SetTargetReduction $decReduce

tkPolyDataMapper mapper
    mapper SetInputConnection [decimate GetOutputPort]
    eval mapper SetScalarRange [[decimate GetOutput] GetScalarRange]

tkActor model
    model SetMapper mapper

# Add the actors to the renderer, set the background and size
ren1 AddActor model

iren Initialize
renWin Render

# render the image
iren AddObserver UserEvent –wm deiconify .vtkInteract”

# prevent the tk window from showing up then start the event loop
wm withdraw.

# If the current directory is writable, then test the writer
if –[catch –set channel [open “test.tmp” “w”]] == 0 –
close $channel
file delete -force ”test.tmp”

vtkVRMLExporter vrml
  vrml SetInput renWin
  vrml SetSpeed 16
  vrml SetFileName ”$FileName.wrl”
  vrml Write
 ”
E Embedded 3D Model

This model requires Adobe Acrobat Reader version 7 or higher, available at [www.adobe.com/products/acrobat/readstep2.html](http://www.adobe.com/products/acrobat/readstep2.html). Click on the image below to enter the 3D model interface. Elements of the model may be highlighted by clicking on them, and can be hidden or made transparent by using the model tree in the navigation panel at the left. The model may be rotated by clicking and holding the left mouse button, and then moving the mouse. Click and hold the right mouse button to zoom. For other options, see the 3D toolbar above the model.

[Click here](#) to cycle through a set of predefined views.