CHAPTER 6

STRESS ANALYSIS OF FUNCTIONAL SPINAL UNIT DURING LIFTING

6.1 INTRODUCTION

Of all Manual Material Handling (MMH) activities, lifting is considered to be a major cause for low back pain and spinal injuries. Annual costs associated with back pain in US alone ranged from 20 billion US$ to 50 billion US$ (Miller et al 1997). Although epidemiological studies have suggested possible causes, the actual mechanisms by which the lumbar spine is injured during load cycle resulting in low back pain remains unknown. However, the response of the disc to loading conditions that occur during lifting is difficult to measure in vivo and in vitro and has not been investigated using any model so far (Williams et al 2002). In vitro and in vivo studies on real subjects are risky and studies on cadaveric FSU are time consuming. Here, an attempt has been made to analyse FSU using a suitable finite element modelling for sagittal plane lifting activity.

6.2 FINITE ELEMENT ANALYSIS IN ERGONOMICS

Many universities and institutions around the world are producing finite element models of the spine for various analyses. For example, there are FEMs being created to study the effects of automobile accidents on the spine. The geometry, material properties and loading conditions of the lumbar spine are very complex. Though the FEM is a well-established method, various
simplifications have to be used and assumptions are to be made (Jenna Bowling et al 1995). The spine is acted upon by muscle forces. In vitro experiments, almost never consider the muscle forces. It is reported that, experimentation has shown that in lordotic spine during prolonged standing, the impacted joints at each segment level bear an average of 16% of the axial load (Oliver et al 1991).

Hutchinson and Littlefield (Cantu 1991) tried to simplify FEM of vertebral body by modelling it as a cylinder. This study was conducted to determine the stresses induced in a previously injured spine during pilot ejection. Initially Hutchinson and Littlefield started FEM by importing data from the DIGIBOT images of the vertebrae into ALGOR V. After an internal mesh was generated by ALGOR V, a PERL script was written to translate the data for ABAQUS to read. The model was then analysed by ABAQUS-Post. The model, having about 30,000 nodes was too complicated to be processed. As a result of which they have constructed the simplified model. Shirazi-Adl's study (1986) was referenced for the material properties of the lumbar region. The empirical quantities of the spinal components used in shirazi-Adl’s study are shown in Table 6.1.

Literature review shows that a few researchers have applied FEM for analysis of lumbar L2/L3 and cervical spine (Carlos et al 2000 and Lian 2000). However, studies on the combined L1/L2/L3/L4/L5/S1 (FSU), FEM analyses are not found to have been done.
Table 6.1 Empirical quantities of the Spinal components

<table>
<thead>
<tr>
<th>Materials</th>
<th>Young’s modulus (MPa)</th>
<th>Shear modulus (MPa)</th>
<th>Poisson’s ratio</th>
<th>Density (Kg/mm³)</th>
<th>Cross-sectional area (mm²) *</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cortical bone</td>
<td>12.000</td>
<td>4.615</td>
<td>0.30</td>
<td>1.7X 10⁴</td>
<td>-</td>
</tr>
<tr>
<td>Cancellous bone</td>
<td>100</td>
<td>41.7</td>
<td>0.20</td>
<td>1.1 X 10⁴</td>
<td>-</td>
</tr>
<tr>
<td>Bony posterior elements</td>
<td>3.500</td>
<td>1.400</td>
<td>1.25</td>
<td>1.40 X 10⁴</td>
<td>-</td>
</tr>
<tr>
<td>Annulus (ground substance)</td>
<td>4.2</td>
<td>1.6</td>
<td>0.45</td>
<td>1.05X 10⁴</td>
<td>-</td>
</tr>
<tr>
<td>Annulus (Fiber)</td>
<td>175</td>
<td>-</td>
<td>-</td>
<td>1.0 X 10⁴</td>
<td>-</td>
</tr>
<tr>
<td>Nucleus pulposes</td>
<td>1.686.7 **</td>
<td>-</td>
<td>-</td>
<td>1.02X 10⁴</td>
<td>-</td>
</tr>
<tr>
<td>Ligaments</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AL 7.8 (&lt;12.0%) 20.0 (&gt;12.0%)</td>
<td>-</td>
<td>-</td>
<td>1.0X 10⁴</td>
<td>63.7</td>
<td></td>
</tr>
<tr>
<td>PL 10.0 (&lt;11.0%) 20.0 (&gt;11.0%)</td>
<td>-</td>
<td>-</td>
<td>1.0X 10⁴</td>
<td>20.0</td>
<td></td>
</tr>
<tr>
<td>LF 15.0 (&lt;6.2%) 19.5 (&gt;6.2%)</td>
<td>-</td>
<td>-</td>
<td>1.0X 10⁴</td>
<td>40.0</td>
<td></td>
</tr>
<tr>
<td>TL 10.0 (&lt;18.0%) 58.7 (&gt;18.0%)</td>
<td>-</td>
<td>-</td>
<td>1.0X 10⁴</td>
<td>3.6</td>
<td></td>
</tr>
<tr>
<td>CL 7.5 (&lt;25.0%) 32.9 (&gt;25.0%)</td>
<td>-</td>
<td>-</td>
<td>1.0X 10⁴</td>
<td>60.0</td>
<td></td>
</tr>
<tr>
<td>IS 10.0 (&lt;14.0%) 11.6 (&gt;14.0%)</td>
<td>-</td>
<td>-</td>
<td>1.0X 10⁴</td>
<td>40.0</td>
<td></td>
</tr>
<tr>
<td>SS 8 (&lt;20.0%) 15.0 (&gt;20.0%)</td>
<td>-</td>
<td>-</td>
<td>1.0X 10⁴</td>
<td>30.0</td>
<td></td>
</tr>
<tr>
<td>IL 10.0 (&lt;18.0%) 58.7 (&gt;18.0%)</td>
<td>-</td>
<td>-</td>
<td>1.0X 10⁴</td>
<td>26.4</td>
<td></td>
</tr>
</tbody>
</table>

* = Cross-sectional area corresponding to a full model; ** = Bulk Modulus; AL = anterior longitudinal; PL = Posterior longitudinal; LF = Ligamentum flavum; TL = transverse; CL = capsular; IS = interspinus; SS = supraspinus; IL = iliolumbar
6.3 FEM ANALYSIS OF FUNCTIONAL SPINAL UNIT (FSU)

6.3.1 Functional Spinal Unit (FSU)

Spinal unit otherwise known as vertebral column consists of 24 separate bony vertebrae together with 5 fused vertebrae, which form the sacrum and usually 4 fused vertebrae, which form the coccyx, 24 separate vertebrae are interlaced with inter-vertebral discs. Normally the column appears symmetrical in the frontal plane and has characteristic curvatures in the sagittal plane. Curvatures provide natural shock absorbency and flexibility (Fig. 6.1). Three principal functions of vertebral column are to

1. Support the human in the upright posture
2. Allow moment and locomotion
3. Protect the spinal cord.

Knowledge of the load-displacement behaviour of spine and its components is required for biomechanical analysis of spine function.

6.3.1.1 Description of spine

The following two sections detail the general configuration of the spine and specifics of the spine according to region.

6.3.1.2 General description of spine

The spine consists of 33 vertebrae (Fig. 6.1), in all, including those of the sacrum and the coccyx.
CERVICAL VERTEBRAE

THORACIC VERTEBRAE

LUMBAR VERTEBRAE

SACRUM

COCCYX

Fig. 6.1 The spine
The upper portion of the spine is called the cervical region, is made up of 7 vertebrae (C1-C7), while the middle portion of the spine consists of 12 vertebrae (T1-T12) and is termed as Thoracic region. The next 5 vertebrae (L1-L5) make up the Lumbar region. The Sacral region and coccygeal region are made up of 5 fused Vertebrae (S1-S5) and 4 fused vertebrae (Co1-Co4), respectively. The configuration of the regions of the spine is illustrated in Fig. 6.1.

The individual vertebrae of the five regions are labelled by the particular region and location within that region, e.g., the second vertebra of the cervical region is C2 (Fig. 6.2).

Most of the load carried by the spine is supported by the vertebral body, which also serves as a resting-place for the intervertebral discs. Muscles and ligaments used in rotation and lateral flexion are attached to the spine by the transverse processes (2 per vertebra) that extend laterally from the point at which the pedicles and laminae are joined. The pedicles and laminae, shown in Fig. 6.2, connect the vertebral body and processes, forming the vertebral arch. This arch, together with the vertebrae body, forms the vertebral foramen, which is the center hole in each of the vertebrae. The alignment of the vertebral foramina in the spine makes up the vertebral canal through which the central nerve runs.

Including the two transverse processes, there are seven processes on a typical vertebra (Fig. 6.3). These processes are either lever-like to enable the attachment of muscles and ligaments (e.g. the transverse processes) or articular (meaning joining) to help create bony joints. There are four articular processes
Fig. 6.2 Typical vertebra

Fig. 6.3 Location of the processes
on each vertebra that form joints that limit movement of the vertebrae thereby providing stability to the spine.

The remaining vertebral process is the spinous process. The spinous processes vary in size, shape, and direction from one region of the spine to the next. Like the transverse processes, the spinous processes act as levers to which muscles are attached. However, these muscles control posture and flexion/extension, lateral flexion and rotation movements of the spine. The spinous processes are also the bones that can be felt as protrusions down the center of the back.

Each vertebra has a thin outer layer of compact (cortical) bone, which encases a soft, trabecular (cancellous) bone containing red bone marrow as seen in Fig. 6.4. The compact outer shell is thin on the discal surfaces but becomes thicker in the arch and its processes. In between each of the vertebra are intervertebral discs, which act as shock absorbers for the spine. Each disc is surrounded by a hard outer layer called the annulus fibrosus. Cartilage end plates positioned on the top and bottom of the disc act as a barrier between the disc and the vertebral body as seen in Fig. 6.5.

The interior of the disc consists of a moist, jelly-like substance called the nucleus pulposus as seen in Fig. 6.6. The nucleus pulposus is cartilaginous and highly elastic with high water content. It gets nutrients from diffusion of the blood vessels in the annulus fibrosis and the surface of the vertebral body. In general, the intervertebral discs allow free movement of the back by adding flexibility to the spine.

Table 6.1 provides empirical quantities for the different material properties of each component of the spine. This table was extracted from a
Fig. 6.4 View of the vertebral interior/exterior

Fig. 6.5 Vertebra/disc assembly
study of the lumbar region of the spine using a finite-element approach. The vertebral bodies in the lumbar region of the spine are characterised by their massive, kidney-shaped vertebral bodies. Their vertebral foramina vary from oval-shaped vertebral bodies, to triangular-shaped vertebral bodies.

6.3.1.3 Common spinal problems

The spine can become injured in a variety of ways. Spinal injuries can be the result of a sports-related occurrence, the lifting of a heavy object, an auto accident, or ejection from an aircraft. Ultimately, the spine sustains an injury due to the stresses imposed upon it becoming greater than the material strength of the spinal components.

6.3.1.4 Disc herniation or herniated nucleus pulposus

A disc is made of two parts, a hard outer layer and a soft central core. A tear in the outer layer can allow the soft center portion of the disc to leak. This ruptures (herniated) disc may press up against a spinal nerve causing pain, numbness and tingling or weakness in the arms or legs. Herniated discs (Fig. 6.7) may occur at any level of the spine, but are more common in the lumbar or cervical areas followed by the thoracic.

6.3.1.5 Spinal stenosis

This is a form of arthritis in the spine. The hole or canal where the spinal cord runs becomes narrow. Bony growths on the vertebra narrow this opening and cause pressure on the spinal cord and/or nerves. Patients may have pain, with numbness and tingling or weakness to the arms or legs. Spinal stenosis may occur at any level of the spine, but is more common in the lumbar and cervical spine.
Fig. 6.6 Disc and spine details

Fig. 6.7 Disc herniation
6.3.1.6 Degenerative disc disease

This is another form of arthritis to the spine. The discs between vertebrae shrink. Degenerative disc disease is often described as a “wear and tear” condition. It is a normal part of aging, but can also be caused by injury to the disc. Symptoms include pain in the involved areas of the spine and, in some instances, pain or numbness to the arms or legs. Loss of flexibility is also typical.

6.3.1.7 Spondylolisthesis

This is an abnormal spinal condition in which one vertebrae slips or is improperly aligned over another vertebrae. If abnormal motion allows this vertebrae to slip back and forth spinal nerves may be affected causing pain, numbness and tingling or weakness in the legs. Many individuals do not have symptoms with this condition while others experience long standing back pain. Spondylolisthesis is most common in the lumbar area.

6.3.1.8 Scoliosis

It is a condition where the natural curves of the spine are affected. A normal spine has three natural curves that keep the body balanced, but in scoliosis there is an abnormal side-to-side curve. As a result one may have back pain, an uneven waist, uneven shoulders, prominent shoulder blades or elevated hips. One may even lean to one side. In some individuals scoliosis does not cause pain, but in others symptoms are chronic.
6.3.1.9 **Kyphosis**

This involves the backwards bending of the spine. Normally kyphosis is seen in the thoracic region. When this natural curve is increased and structural changes in the vertebrae occur, this kyphosis occur and this disease is also known as Scheuermann's disease. This describes the wedging and irregular edges of the vertebrae as seen on x-rays. This spinal disorder is more commonly known as a “round back” deformity of the spine.

6.3.1.10 **Spinal instability**

It is a condition where vertebrae of the spine become unstable. This can come from an injury or a degenerative disorder.

The normal structure and function of the spine is interrupted and deformity results. In some cases the spinal cord and/or spinal nerves are at risk for injury. Symptoms include pain, numbness, weakening and, in some cases, nerve damage.

6.3.1.11 **Injuries caused by lifting**

Lifting has the potential to contribute to injury. Large extensor moments about the joints of the lumbar vertebral column are produced during lifting by the paravertebral musculature to overcome the flexor moment caused by the weight of the upper body and load. Injury to musculo-ligamentous structures occurs as a direct consequence of the high forces involved. These high forces also result in large compressive and shear forces acting between each pair of vertebrae, which in turn lead to endplates failure and disc prolapse.
6.4 ANTHROPOMETRY OF FSU

Functional Spinal Unit (FSU) consists of Lumbar and sacrum region. Lumbar vertebral column comprises of five vertebrae and the intervertebral discs. It has a characteristic curvature called lumbar Lordosis. In the standing position, the sacrum is tilted forward so that its upper surface is inclined forwards and downwards forming an angle between the top of the sacrum and the horizontal which varies between 50 – 53°.

6.4.1 Factors contributing to the normal shape of the lumbar lordosis

The common factors that maintain the normal shape of the lumbar lordosis are listed below:

1. L5 vertebral body is wedge shaped, the anterior body wall is 3 mm higher than the posterior body wall. This brings the upper surface of the L5 body closer to the horizontal plane than the upper surface of the sacrum.

2. In addition, the L5/S1 disc is also wedge shaped, the anterior vertical height is 6~7 mm greater than its posterior height. As a result of the wedge shape of the disc, the lower surface of the vertebral body is not parallel to the upper surface of the sacrum, so that the angle formed between the two surfaces may vary between 6~29° and has an average size of 16°.

3. Each vertebra above is inclined slightly backwards in relation to the vertebrae below.
4. In 75% of the adults the center of gravity lies anterior to the vertebral column. In these individuals there is constant slight activity in the erector spine muscles, which work to prevent the trunk from falling forwards and assist in maintaining the lumbar lordosis.

5. In a normal spine, in the upright posture, the body of L5 lies directly vertically above the sacrum. Various attempts have been made to measure the lordosis, but as investigators have used different parameters the result differ substantially.

In the standing position measurement for radiographs of the angle between the top of L1 and the sacrum have been recorded as 67°(±3° SD) in Children and 74°(±7° SD) in young males. Development of lumbar lordosis begins as an infant starts to stand, usually between 12-18 months of age and it continues to develop until the completion of spinal growth normally between 13-18 years. In old age, the lumbar column usually becomes flattened.

6.5 MODELLING AND ANALYSIS OF FSU

Finite Element modelling is the modelling of a continuous system, which has an infinite number of degrees of freedom, using a representative geometry of that system made up of a finite number of smaller elements and node points. The more elements in the model, the more accurate it is. The material properties, displacements and other system characteristics are represented by mathematical functions between nodes. This finite element model can then be used to determine the stress, strain, and displacement of the structure resulting form external loading (Cantu 1997).
Once the Finite Element Model has been created and the system characteristics have been established in the model, a global stiffness matrix can then be formed for the whole structure. Given the forces and boundary conditions, the unknown displacements at each of the node points can then be used to determine the stresses and strains acting on each element (Cantu 1997). Initially, the Finite Element Models have been applied to aircraft structures and then FEM rapidly spread to Civil Engineering and Mechanical Engineering. FEM is gaining acceptance as a valuable tool to study static, dynamic as well as cyclic problems. Only recently FEM has been seriously applied to Biomechanical problems.

The following assumptions are made while modelling FSU:

1. Vertebrae is considered as having elliptical cross section. Actually this is an improvement over Hutchinson-Littlefield model (Antonious Rohlmann et al 1999). Ellipse gives a closer approximation.

2. Upright standing posture is assumed for modelling.

With the advent of Magnetic resonance imaging (MRI), one can measure internal organs and bones with high resolution and accuracy. MRI is a non-invasive imaging approach. Cross sectional size of L1 lumbar vertebra are measured from an adult subject using MRI scan. It is found to be 40mm Major and 32 mm minor.

Based on the anthropometric proportions, other dimensions are arrived at.
There are host of software for 3D modelling and here Pro/Engineer is preferred because of its simplicity and seamless integration with analysis package Pro/ Mechanica. Whole FSU is modelled in parts and assembled according to the configuration as shown in fig 6.8. Assembled model is transferred to Pro/Mechanica environment.

The boundary conditions are

1. Lower vertebral disc (L5/S1) of the L5 body was fixed.

2. All other vertebral bodies and discs are allowed all degrees of freedom.

3. Lumbar vertebrae L1 share only 11% of axial load, leaving the rest of the load to muscles (Miller J.A et al, 1997). This is taken in to consideration while loading the FE model. The axial force due to body weight is calculated (at L5/S1) as follows:

From the fig 6.9 forces along spine direction are

\[ F - ES - B \cos \theta - W \cos \theta = 0 \]

\[ \text{Moment:} \quad ES \times l = Bb + Ww \]

Where,

- \( ES \) = Erector spinae muscle force
- \( F \) = Disc compressive force
- \( B \) = Force from upper body weight
- \( W \) = Force from lifted weight
- \( l \) = Length of moment arm from ES
- \( b \) = Length of moment arm from centre of gravity of the body weight
Fig. 6.8 3D Model FSU Assembly
w = Length of moment arm from lifted weight
\[ 0 = \text{Angle made by the force of body weight with erector spinae muscle force (Fig. 6.9)} \]

\[ B = 0.65 \times M \times g \]

Where,

M = The body mass of the individual
\[ g = \text{Acceleration due to gravity} \]

From literature, for a grown up normal adult
\[ l = 6 \text{ cm} \]
\[ b = 25 \text{ cm} \]
\[ \theta = 52^\circ \quad (\text{Helander et al 1984}) \]

Let,
\[ w = 40 \text{ cm} \]
\[ W = 0 \text{ (No load)} \]
\[ M = 63 \text{ Kg} \]

Solving the above equations, the axial force is 1573 N

Axial force on L1 is 173 N @ 11 % (Helander et al 1984)

Load is applied on L1 top surface, as shown in fig 6.10. Pro/Mechanica’s AutoGEM software has been used to create elements and meshes. Solver is run to get the results.
Fig. 6.9 Forces acting along L5/S1
Fig. 6.10 FE Model with load and constraints
6.6 RESULTS AND DISCUSSION

The model is analysed using PRO/E. The FSU assembly model developed is shown in Fig. 6.8. The model has been first generated for upright position with only body weight condition. The normal posture of the FSU has been emulated by implementing the factors listed in section 6.4.1. It can be seen that all the factors are implemented and the shape of the FSU is closely emulated to the reality. The segments from L1 through L5 are modelled for a normal adult.

Fig. 6.10 shows the Finite Element Model of the FSU under loaded condition and the constraints. The deformation of the model, under the load and boundary condition, is depicted in Fig. 6.11. Maximum Von Mises stress is found at L5/S1 and at L4/L5 and its magnitude is found to be 2.343 MPa.

The experimental study made by Antonious Rohlmann (1999) on cadaveric spines under similar condition has been used for comparison. Fig. 6.12 shows the comparative study results of the study with that of Antonious Rohlmann (1999). The results from this study are very close to that of Rohlmann who obtained the stress value as 2.477 MPa.

Fig. 6.13 shows the deformation of the model for lifting a load of 10Kg. Calculations are as shown below:

\[ F - ES - B\cos\theta - W\cos\theta = 0 \] ---- 4.1

Moment:

\[ ES \times 1 = Bb + Ww \] ---- 4.2
ES x 0.06 = (400 x 0.18) + (98 x 0.35) 

\[
\frac{72 + 34.3}{0.06} = \frac{ES}{ES} = 1771.5 = 1772
\]

Substituting the ES value in equation 4.1.

\[F - 1772 - 400 \cos 52^\circ - 98 \cos 52^\circ = 0\]
\[F - 1772 - 306.6 = 0\]
\[F = 2079 \text{ N}\]

Where
\[\theta = 52^\circ\]
Axial force on L1 is 228 N @ 11%

Maximum vonmises stresses are found at L5/S1 and L4/L5 and it's magnitude found to be 3.05 Mpa.

Fig. 6.14 shows the deformation of the model for lifting a load of 20Kg. Calculations are as shown below:

\[F - ES - B\cos \theta - W \cos \theta = 0 \quad ----- 4.1\]

Moment:
\[ES \times 1 = Bb + Ww \quad ----- 4.2\]
\[ES \times 0.06 = (400 \times 0.18) + (196 \times 0.35)\]

\[
\frac{72 + 68.6}{0.06} = \frac{ES}{ES} = 2343.3 = 2343
\]
Fig. 6.11 Deformation of the FSU for zero load

Fig. 6.12 Comparative study of results between experimental (Cadaveric) study and FE study
Fig. 6.13 Deformation of the FSU for 10 Kg load
Fig. 6.14 Deformation of the FSU for 20 Kg load
Substituting the ES value in equation 4.1.
\[ F - 2343 - 400 \cos 52^\circ - 98 \cos 52^\circ = 0 \]
\[ F - 1772 - 306.6 = 0 \]
\[ F = 2710 \text{ N} \]

Where
\[ \theta = 52^\circ \]

Axial force on L1 is 298 N @ 11%

Maximum vonmises stresses are found at L5/S1 and L4/L5 and it’s magnitude found to be 4.083 Mpa.

6.7 CONCLUSION

Although epidemiological studies have suggested possible causes, the actual mechanism by which the lumbar spine is injured during load cycle resulting in low back pain, remains unknown. However, the response of the disc to loading conditions that occur during lifting is difficult to measure in vivo and in vitro methods and has not been investigated so far. Therefore, a finite element model that can predict the loading behaviour of Functional Spinal Unit (FSU) has been developed.

The following conclusion are made from this study.

1. The finite element model of the FSU is found to confirm with the earlier works using cadaveric method (Antonious Rohlmann 1999), thus proving the usefulness of this methodology for biomechanical modelling.
2. The effort to be taken for the in vivo and in vitro data collection and analysis are reduced multi fold in the finite element modelling.

3. The study can be extended to include the loading of the muscles. Same FE model can be extended to all Sagittal plane lifting activity.

Thus, the study established the viability of FEM methodology for analysing FSU.