MODELLING AND STRESS ANALYSIS OF LUMBAR SPINE

SITI SYAZNI BINTI ZULKIFLI

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by

SITI SYAZNI BINTI ZULKIFLI

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LIST OF ABBREVIATIONS

2D	Two Dimensional
3D	Three Dimensional
CATIA	Computer Aided Three-dimensional Interactive Application
CT	Computer Tomography
DICOM	Digital Imaging and Communication in Medical
DOF	Degree of freedom
FE	Finite Element
FSU	Functional spinal unit
IGES	Initial Graphic Exchange Specification
L1 to L5	Lumbar One to Lumbar Five
MedCAD	Medical Computer Aided Design
MIMICS	Materialise's Interactive Medical Image Control System
MRI	Magnetic Resonance Image
RE	Reverse Engineering
RP	Rapid Prototyping
VR	Volume Rendering

PEMODELAN DAN ANALISIS TEGASAN TERHADAP TULANG BELAKANG LUMBAR

ABSTRAK

Pemodelan dan analisa terhadap tulang belakang lumbar adalah penting untuk meramal kesan beban dan pergerakan badan dalam aktiviti kehidupan harian. Dalam kajian ini, jumlah beban yang berbeza dan momen disiasat. Analisa ini diberi tumpuan kepada penumpuan tegasan yang tinggi kerana kawasan ini lebih cenderung untuk patah. Dalam usaha untuk meramalkan tindak balas biomekanik daripada tulang belakang lumbar, model unsur terhingga tiga dimensi L1 sehingga L5 termasuk cakera diantara tulang telah dibina dengan mengekstrak data imbasan tomografi yang diambil daripada wanita Malaysia. Analisa telah dijalankan di bawah pelbagai beban seperti beban paksi, momen hadapan, belakang, sisi dan kilasan untuk menentukan agihan tegasan dan perubahan bentuk pada model. Hasil kajian menunjukkan bahawa tekanan maksimum Von Mises adalah yang paling rendah di bahagian tulang L5, iaitu 1.37 MPa berbanding bahagian tulang L1 iaitu 4.29 MPa. Sementara itu, bagi anjakan maksimum, tulang L5 juga lebih rendah berbanding dengan L1 iaitu 0.31 x 10-5 mm dan 1.51 x 10-5 mm masing-masing. Bahagian pedikel adalah kawasan yang tertakluk kepada tekanan yang paling besar dan lebih cenderung untuk terdedah kepada penyakit-penyakit degeneratif dan kecederaan dikenalpasti. Analisa ini juga telah dilakukan di lumbar tulang belakang keseluruhan dan hasilnya menunjukkan bahawa tekanan Von Mises adalah paling tinggi di bawah momen sisi dan rendah di bawah momen kilasan. Berdasarkan tahap darjah putaran, ia menunjukkan bahawa tulang belakang lumbar yang paling fleksibel di bawah momen hadapan dan kurang fleksibel di bawah masa kilasan.

MODELLING AND STRESS ANALYSIS OF LUMBAR SPINE

ABSTRACT

The lumbar spine modelling and analysis are crucial for prediction of the load impact and body movement in daily life activities. In this research, different load amount and moment are investigated. The analysis focuses on the high stress concentration since this area tends to get fractures. In order to predict the biomechanical response of lumbar vertebra, the three-dimensional finite element model of L1 to L5 included intervertebral disc was constructed by extracting the computed tomography scan data from Malaysian female. Analysis was performed under various loadings such as axial load, flexion, extension, lateral and torsion to determine the stress distribution and deformation on the model. The result shows that Maximum Von Mises Stress is lowest at vertebra L5, which is 1.37 MPa compared to vertebra L1 which is 4.29 MPa. Meanwhile, for the maximum displacement, vertebra L5 also lower compared to vertebra L1 which is 0.31×10^{-5} mm and 1.51×10^{-5} mm respectively. The pedicle region is the areas that are subjected to the greatest stresses and which are more likely to be susceptible to degenerative diseases and injuries are identified. The analysis also was performed on the whole lumbar vertebra and the result shows that the Von Mises stress was highest under lateral moment and lowest under torsion moment. Based on the degree of rotation, it shows that the lumbar spine most flexible under flexion moment and less flexible under torsion moment.

CHAPTER 1

INTRODUCTION

1.0 Background of the Study

The human spine is a complex biomechanical structure that provides stability to the human body. It protects the spinal cord inside the vertebral segment and allows different motions and movement while encountering a variety of loading conditions. Basically the spine consists of muscles, bones, tendons, cartilage, joints, ligaments, and other soft tissues. Recently, there has been growing concern with the degeneration in the human spine. The lowest part of the spine also known as the lumbar spine bears the highest load of upper body and cause a low back pain when lifting an excessive load or doing wrong movement activities. This back pain limits normal activity or impairs your quality of life. According to (American Association of Neurological Surgeons, 2012), almost all people have been facing low back pain once in their lifetime.

Numerical simulation are used to investigate the properties of biological material, including basic structures and functions in lumbar spine. The finite element analysis (FEA) is a common tool in numerical simulation, which can be applied in various ways to study a complex biological system. By applying finite element analysis on the model, the detailed information regarding the stress distribution, deformation and rotation can be obtained in addition to the experimental technique. In order to investigate the clinical problem regarding the human spine as well as to predict the biomechanical behaviour under different movements, the finite element model is very effective and helpful in addition to the experimental approach (Shenghui et al., 2005)

Various methods and techniques can be applied to predict the biomechanical behaviour of the three dimensional model of the human spine. For example, a three dimensional finite element model can be created by using data from dual-energy X-ray absorptiometry (DXA) scan, magnetic resonance images (MRI), X-ray image and computed tomography (CT) scan image. The developed model also be analyzed for different structures such whole spine, cervical, thoracic, lumbar, thoracolumbar, individual vertebrae, functional spinal unit (FSU) or more stacked vertebrae, intervertebral disc, vertebra and soft tissue. For more accurate results, different material properties of the vertebra, disc and soft tissue are taken into consideration.

The use of finite element model can enhance interpretation, visual evaluation and better understanding of the consequences of each situation which include contact pressure, stress distribution, rotation of the motion and deformation under several parameters. In addition the conversion of 2D image data into 3D models, patients follow-up and screening could be replaced by using the 3D surface topography which can reduce the unnecessary radiation exposure and also surgical treatment could be optimized using simulations before applying the operation. This can minimize problems that potentially can occur after treatment. The used 3D model enables surgeons to visualize the actual surgical process through virtual animation or simulation (Rubelisa CG et al., 2008). The results from these models can be used to identify areas that are subjected to the greatest stresses and which are more likely to be susceptible to degenerative diseases and injuries.

1.1 Problem Statement

The third region of human spine also known as lumbar spine bears the most weight of the body. This region always associated with low back pain due to heavy activities and wrong body posture movement. For example, a degenerative disc disease, herniated disc from a slip and fall or spinal stenosis from aging, bone spur, muscle or joint strain, and other disorders on human spine especially at lumbar spine region can cause low back pain. This spine disorder can cause limited movement and difficulty in having normal life. There is need to identify the relationship between load impact and moment applied on the lumbar spine under normal movement without effect the lumbar spine.

1.2 Objectives

The hypothesis of this study is the degenerative of lumbar spine vertebra under normal activities life will affect peoples' movement. It is the relationship between the load impact while lifting objects and movement of the body during daily life that this study seeks to establish. The objectives of this study are:

- To predict the biomechanical response of lumbar vertebra based on the stress distribution, deformation of the body and degree of motion by performing the stress analysis under various loading conditions such as flexion, extension, lateral and torsion.
- To determine the highest impact area on the interest subject during load and moment applied.

1.3 Scope of Work and Limitations

In this study, a 3D finite element model of the lumbar spine was developed based on the CT scanned images using MIMICS software and reconstructing the surface using CATIA software. Load and boundary conditions were applied to the model using Msc. Patran and Mentat software, to predict the stress distribution of the spine using Msc. Nastran and Marc software processor. The model was limited to the lumbar vertebra spine section (L1 to L5) and intervertebral disc with all soft tissues were removed during the modelling process.

The limitation of this study is the representation of the complex connection of the bone between vertebra itself and other soft tissues nearby. This bone was segmented on every part together with the vertebra and disc because of the different types of structures and materials. However, the most important objective was to prepare an accurate model for simulation in order to assess the effect of structural geometry on the stress distribution under several load conditions.

1.4 Outline of the Thesis

Chapter 1 covers a brief introduction on the research background regarding the biomechanical structure of human spine, especially at the lower part which is known as the lumbar spine. The problems related to the lumbar spine are discussed. The objectives of this research are also explained together with the scope of work and limitations of the research work.

Chapter 2 focuses on the spine anatomy and methods approached by other researchers. Hence, several journals, books and other resources related to this study were used as references and guidance to compare the methods, dimension of vertebra geometry, properties of the material to a get better understanding in order to develop the three dimensional model. In general, it is divided by two common methods which are either by experimentation or simulation. Based on all the information gathered, the most preferable method is discussed and explained.

Chapter 3 explains the procedure which begins with the construction of the three-dimensional model using data of a Malaysian female until the last analysis process of the model of the lumbar spine. Data from Digital Imaging and Communication in Medical (DICOM) taken by a Computer Tomography (CT) scanning machine are further reconstructed and modified using Materialise's Interactive Medical Image Control System (MIMICS) and Computer Aided Three-dimensional Interactive Application (CATIA) software. The load and boundary conditions were applied using software MSC PATRAN and MENTAT. In order to access the results, the final stage was completed by using MSC NASTRAN and MARC as a processor.

Chapter 4 presents the analysis of several cases different parameters and the results obtained from finite element analysis are discussed. Based on the differential pressure acting on the lumbar spine surface, the Von Mises stress, minimum stress, maximum stress and deformation compare with the other researcher work.

Finally, chapter 5 concludes the research work. Recommendations for future work are also suggested.

CHAPTER 2

LITERATURE REVIEW

2.0 Anatomy of the spine

The human spinal column also known as vertebral column is a complex mechanical structure. The spinal column is formed by stacking these vertebrae on top of one another. These columns are important in order to protect the spinal cord and act as the human body main upright support. This column is made up of 24 vertebrae, including the sacrum and it is divided into five main sections as cervical, thoracic (mid region), lumbar (lower back), sacral and coccyx. The lumbar spine or low back bears the highest load among human spine and mostly involves with an incidence of trauma and degeneration (Gregory & Susan, 2005). Table 2. 1 shows the detailed explanation on human spine curvature meanwhile Figure 2. 1 shows anterior, posterior and left lateral views of spinal column and vertebrae parts (Hansen, 2010).

Table 2. 1 : Details of human spine curvatures (Hansen, 2010).

Concave	Curve Types	Details
Anteriorly (Kyphosis)	Thoracic curvature (thoracic kyphosis)	A primary curvature present in the fetus (imagine the spine in the "fetal position"
	Sacral curvature	A primary curvature present in the fetus
Posteriorly (Lordosis)	Cervical curvature (cervical lordosis)	Is acquired secondarily when the infant can support the weight of its own head
	Lumbar curvature (lumbar lordosis)	Is acquired secondarily when the infant assumes an upright posture and supports its weight

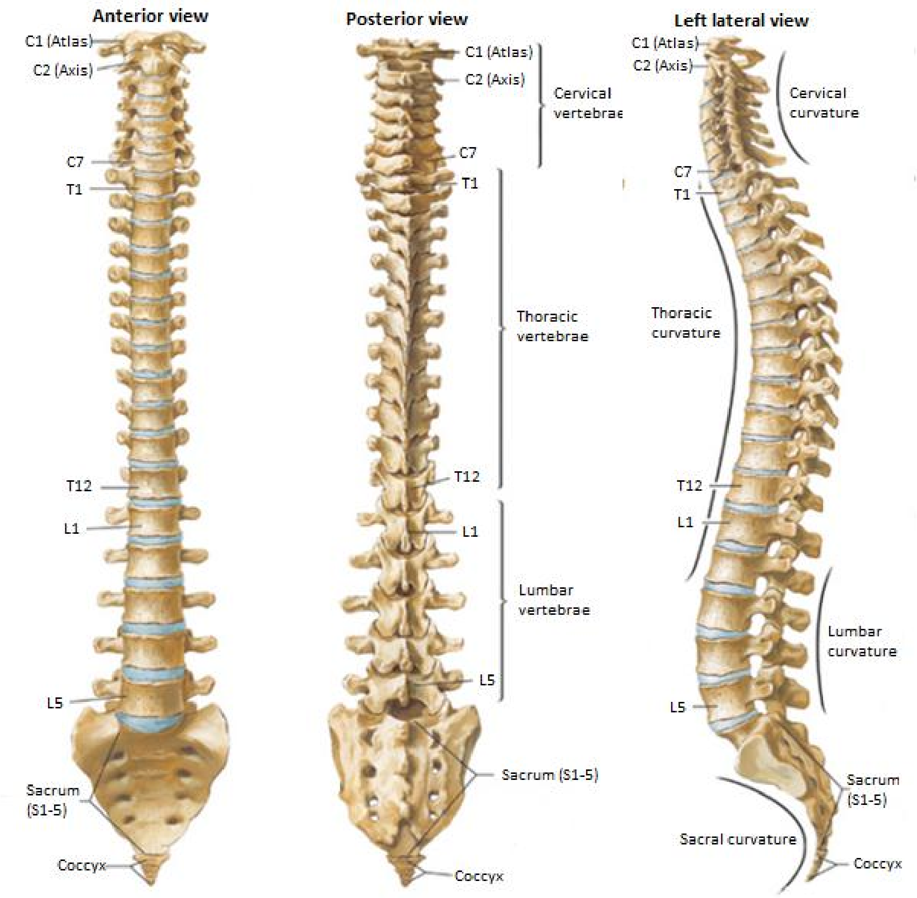


Figure 2. 1: Views of Anterior, Posterior and Left Lateral Spinal Column (Hansen, 2010).

2.0.1 Orientation of human spine

In order to understand and describe the direction of the human anatomy effectively, the body planes and motions are commonly used. The human body has three planes which are coronal (frontal), sagittal (median) and transverse (horizontal) planes and they move in many directions such as superior (cranial - to the top), inferior (caudal - to the bottom), anterior (ventral - to the front), posterior (dorsal - to the back), medial (midline of the body) and lateral (away from the midline of the body). Figure 2. 2 shows planes and the motions of the entire human body.

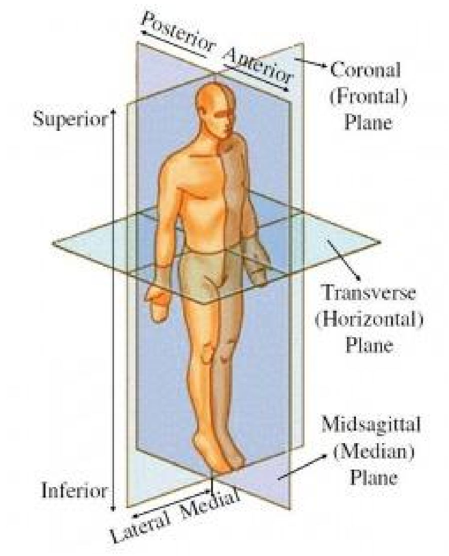


Figure 2. 2 : Body planes and motions (Wilkie et al., 2012).

2.0.2 Functions of the human spine

The human spine has three primary biomechanical functions. First, supporting the body by transferring the weights of the upper body (head and trunk) and any additional weights lifted from the body to the pelvis. Second, providing mobility of the trunk under sufficient physiological motions. Finally, it's protecting the spinal cord and spinal nerve roots from potential damaging forces and motions produced by both physiological movements and properties of the normal spine anatomy (Gregory & Susan, 2005 and Hansen, 2010).

2.0.3 The Vertebral Body

A typical vertebra is divided into vertebral body and vertebral arch. There two bone regions are composed of an outer layer called compact bone (cortical) and a core layer called spongy bone (cancellous) as shown in Figure 2. 3. The density of bone in the vertebrae varies amongst individuals increase significantly and reaches a peak during the mid-twenties (Gilsanz et al., 1988).

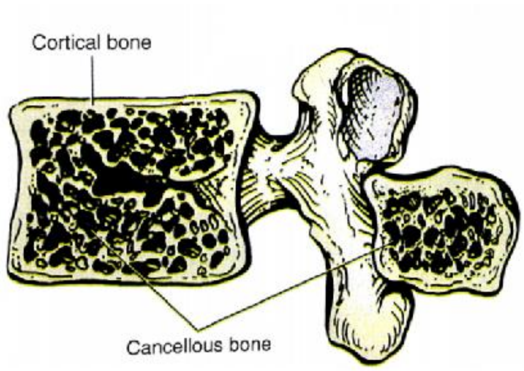


Figure 2. 3 : Typical vertebra regions (Gregory & Susan, 2005).

Figure 2. 4 shows the important parts of the lumbar spine contain bones, joints and several features of the vertebra. The lumbar consists of five total large vertebrae and support the weight of the upper body. Table 2. 2 explained several features of the lumbar vertebra. The lumbar regions are different compared to thoracic or cervical although as we can see them almost similar. Appendix A shows the different features among these vertebrae.

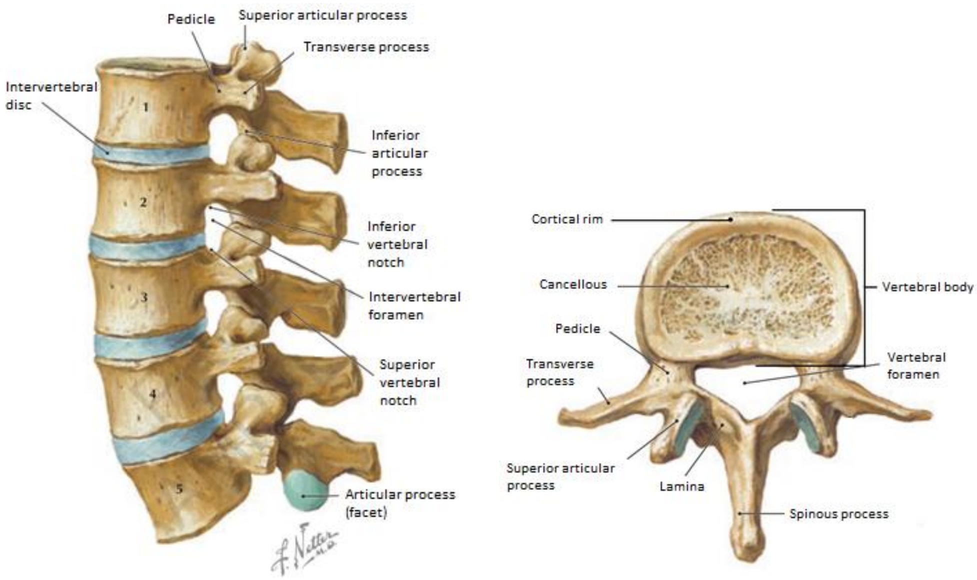


Figure 2. 4 : Features of an Articulated Lumbar Vertebrae and superior view of L2 vertebra (Hansen, 2010).

Table 2. 2 : Features of lumbar vertebra (Hansen, 2010 and Gregory & Susan, 2005).

Features	Details
Body	➢ The weight-bearing portion of a vertebra that tends to increase in size as on descends the spine
Pedicles	➢ The pedicles create the narrow anterior portions of the vertebral arch. ➢ Short, thick, and rounded and attach to the posterior and lateral aspects of the vertebral body. ➢ A groove or vertebral notch id formed above (superior vertebral notches) and below (inferior vertebral notches) the pedicles because the pedicles are smaller than the vertebral bodies.
Lamina	➢ The lamina is continuous with the pedicles. They are flattened from anterior to posterior and from the broad posterior portion of the vertebral arch. They curve posteromedially to unite with the spinous process, completing the vertebral foramen.
Articular process (facets)	➢ Two superior and two inferior facets for articulation with adjacent vertebrae: - • Superior articular process (prezygapophysis) - The articular surfaces are directed more or less backward and project upward from a lower vertebra • Inferior articular process (postzygapophysis) - The articular surfaces are directed more or less forward and outward and project downward from a higher vertebra.

Figure 2. 5 shows the facet orientation of the lumbar spine facilitates more degree of flexion and extension direction than rotation. In the lumbar spine, flexion and extension motions increase in the range of the top to the bottom with exception of the lumbosacral joint (L5-S1). With regards to lateral bending in the lumbar spine, each lumbar segment presents with approximately the same amount of movement. Likewise, axial rotation in the lumbar spine is very limited and nearly equal among each segment (Banton, 2012).

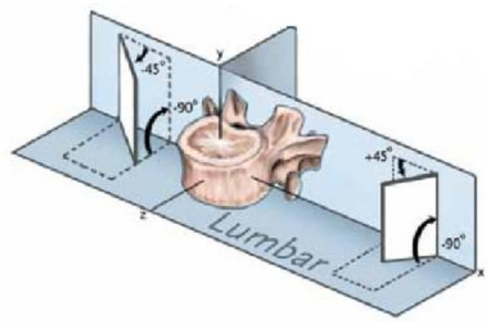
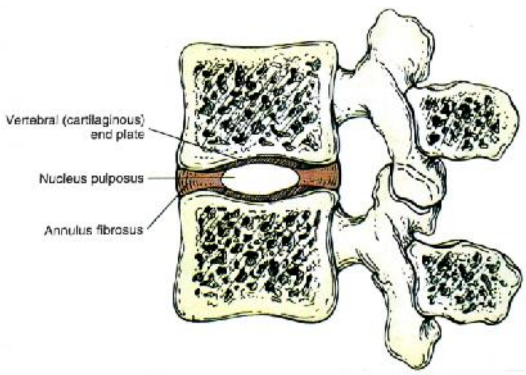


Figure 2. 5 : Facet joint orientation in the lumbar spine (Banton, 2012).

2.0.4 The Intervertebral Disc

Figure 2. 6 shows the intervertebral discs (IVDs) are structures located in between two stacked of vertebrae and contacted by vertebral (cartilaginous) end plate and IVD consists of nucleus pulposus (ability to bind water and swell) and annulus fibrosus (collagen gel or multi-layered cartilage), which also react like a cushion disc. IVD transfers and distributes a loading through the vertebral column and limits motion of the intervertebral joint. The function of the disc is to maintain the changeable space between two adjacent vertebral bodies, the disc aids with the flexibility of the spine while ensuring that too much motion is not occurring between spinal segments. In addition, the IVDs simultaneously help to assimilate compressive loads placed on the spine properly. Table 2. 3 shows the summarized details related to IVD.

(a)



(b)

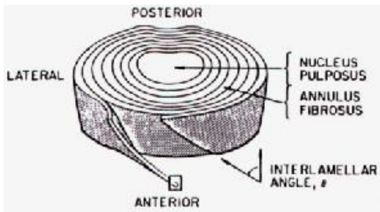


Figure 2. 6 : (a) Midsagittal section of two lumbar vertebrae and the intervertebral disc (Gregory & Susan, 2005) and (b) Intervertebral disc segment (Peter, 2011).

Table 2. 3 : Function of intervertebral disc (Peter, 2011).

Part	Details
Vertebral end plate	• Barrier though, which nutrients must pass to nourish the disc
Nucleus pulposus	• Distributes weight and shock evenly from one vertebral body to the next • Serves as a pivot point for motion
Annulus fibrosus	• Firmly joins one vertebral body to the next while allowing motion • Determines the spine of the openings in the spine for the nerve exits

The discs are usually named by using the two vertebrae that surround the disc, for example, the L4-5 disc is named by referring to the vertebra directly below L5 disc. The shape of the IVD is determined by the shape of the two vertebral bodies to which it is attached. The thickness of the IVDs varies from one part of the spine to the next. The discs are the thickest in the lumbar region and thinnest in the upper thoracic region. The cervical discs are approximately two fifths the heights of the vertebral bodies, the thoracic discs approximately one fifth the heights of their vertebral bodies, and the lumbar discs approximately one third the heights of lumbar vertebral bodies. The discs of the cervical and lumbar regions are thicker anteriorly than posteriorly, helping to create the lordosis found in these regions (Peter et al., 1995).

2.0.5 The Motion Segment

The motion segment or also known as a functional spinal unit (FSU), comprises of two stacked of vertebrae, the intervertebral disc and the soft tissue (Stephen, 2008). The FSU unit is often used to measure biomechanical properties, response and to determine angle deflection by six degrees of freedom of the spine. For example, the FSU in the lumbar motion segment was studied to access the biomechanical response under dynamic load in flexion motion (Osvalder et al., 1993).

Movement between two typical adjacent vertebrae depends on the thickness of the discs and the shape of articular process (facet). The thicker IVD of lumbar regions gives more movements of the angle and the articular process limits the movement of the two stacked vertebrae (Gregory & Susan, 2005). Figure 2. 7, Figure 2. 8 and Figure 2. 9 shows the normal movements also known as six degree of freedom (DOF) that can occur in the spine include flexion, extension, lateral (side bending-left) and rotation.

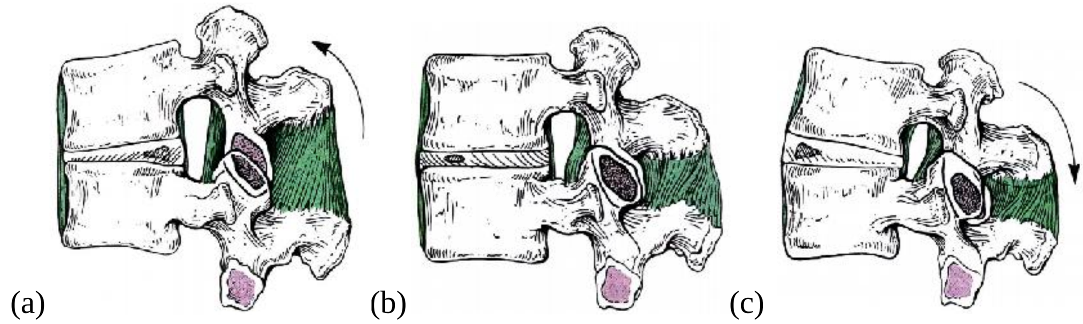


Figure 2. 7 : Motion of two adjacent vertebrae from side view (a) Flexion, (b) Normal and (c) Extension (Gregory & Susan, 2005).

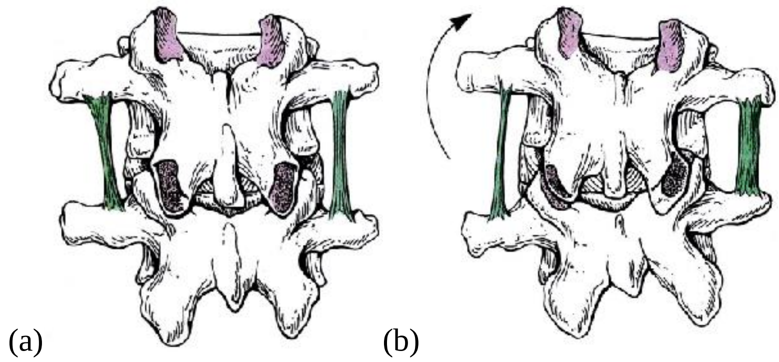


Figure 2. 8 : Motion of two adjacent vertebrae from back view (a) Normal and (b) Lateral (left) (Gregory & Susan, 2005).

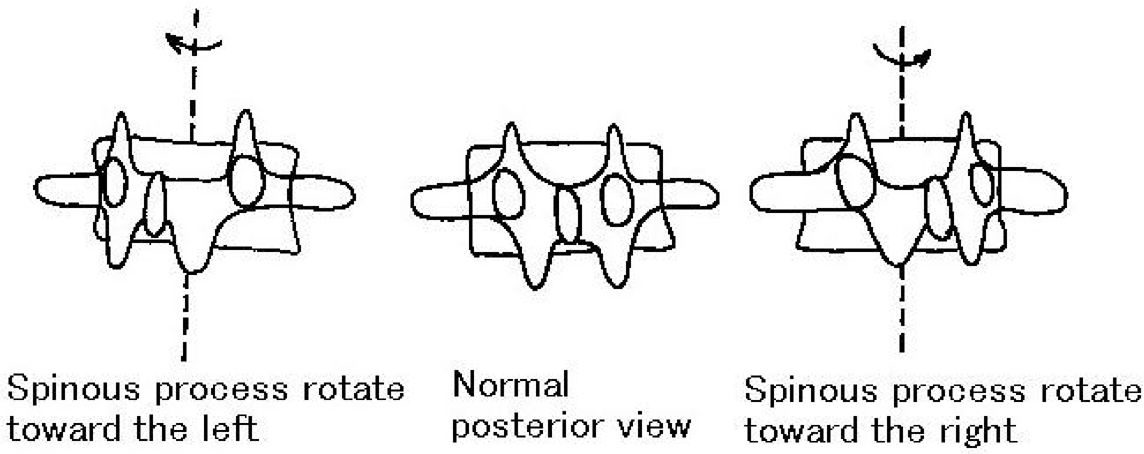


Figure 2. 9 : Motion of two adjacent vertebrae from back view (rotation) (Maeda, 1996).

2.1 Geometry of vertebra

The anthropometric data are referred to measurement gathered on human dimensions which include weight, height and length. It is also used to understand the variation in human physiology and the data obtained is different from one another because of sex, age, race and ethnicity (McDowell et al., 2009). In order to develop three dimensional lumbar spines with a high accuracy, geometrical data from a CT scan is collected in two dimensional planar views and compared with the developed model.

According to Aubin et al. (1997), in their studies was using a 3D coordinate measuring machine (accuracy 0.1mm) to measure geometry dry cadaveric human spine (T1-L5). Meanwhile, a fresh frozen spines of six male human (C3-S1) was scanned with slice thickness of 1mm by the researcher Busscher et al. (2010). Then the data obtained was measured in two dimensional with a multi-planar view system.

Other researchers, Tan et al. (2002) studied on 60 lumbar vertebrae taken from 12 cadavers of lumbar vertebrae L1-L5 of an Asian (Singaporean) in order to measure the quantitative three-dimensional anatomy of the lumbar region. That research was done by varying the different parameters on the interested subject and compared the measured data with the Causian specimens of other studies. The three-dimensional digitizer was used to take the measurement. The reading of means and standard errors for each of the vertebrae body, pedicle, spinal canal, transverse process and spinous process such as linear dimension (mm), surface area (mm^2) and angular dimensions (^{o}) was obtained for each lumbar vertebra.

Meanwhile, the data regarding the coordinating system of the model and geometry of the lumbar spine are taken from Stokes & Gardner-Morse (1999). The study was performed by crossing the musculature in the lumbar spine region. The coordinating centres, mean length, and average of each vertebra were used to reconstruct the spinal segment. Each coordinating point (x, y, z) in existing vertebral was transmitted into the global coordinate system (X, Y, Z). Then, the position of global coordinates obtained for the vertebral body centres.

In addition, the dimensions of six geometrical parameters of the L1-L4 lumbar segment were measured by Robin et al. (1994). However, other researchers Wolf et al. (2001), have shown anatomical parameters which are represented in a cut-away view of the vertebra and mean values of the height of the intervertebral discs Eijkelkamp et al. (2010) and they are slightly different parameters as mentioned before.

2.2 Computational model of the lumbar spine

The spine constructed in the biomechanical study is mainly approached by two main methods either by using computational modelling or experimental analysis. In the computational modelling, for example finite element model which is constructed using a computer also needs to be validated using measurement data taken by experiment. However, computational modelling can provide information which cannot be easily measured by the experimental method such as internal stress inside the lumbar spine. Furthermore, the analysis can be repeated under various parameters loading conditions in finite element model, but not in the experimentation because the original structure of the subject may change due to excessive load or movement.

In recent years, various finite element models of the lumbar spine have been researched and reported. This is because the lumbar spine has become a common medical problem which affects 8 out of 10 people and mostly deals with low back pain during their entire lives (National Institute of Neurological Disorders and Stroke, 2012).

The development of finite element model contributes a great understanding regarding human spine and components nearby. The model is mainly used in medical field to understand biomechanical function of how the spine behaviours under a healthy, diseased or damaged condition. Moreover, it is also useful in applications and designing of spinal instrumentation (Fagan et al., 2002). Other than that, the model is also helpful for creating new spinal implants and also suitable to investigate clinical problems such as comparing with experimental approach in order to predict the biomechanical behaviour (Shenghui et al., 2005).

The model was developed using different techniques either by using experiments or simulation. For example, 3D geometrical data from male lumbar spine cadaver (L2/L3) obtained using a highly accurate flexible touch-probe digitizer (Faroarm-Bronze Series, Faro Technologies, Inc) was used to develop a three-dimensional finite element model (Kim-Kheng et al., 2002). Meanwhile Lavaste et al. (1992) also used digitizer to construct the three dimensional model geometry from two X-rays, which taken from anterior, posterior and lateral view. In order to describe the entire lumbar vertebra's geometry, six main parameters taken from different parts of vertebra were used.

Besides that, Nabhani & Wake (2002) reconstructed the models of L4/5 vertebrae (Asian male) by taking all the co-ordinating data points from slices by using probe and then stored them in a computer. This data was converted into a compatible format before transferring into I-DEA software. Meanwhile, by using CT volume data of the vertebral body (L4-L5), Shenghui et al. (2005) extracted the initial iso-surface from the data. Then, a series of non-parallel in cross section planes based on the surface characteristics of the model was placed accordingly. Coombs et al. (2011) used CT scan data (female) of the lumbar spine and converted it into IGES geometry files. The finite element models also included a disc and a ligament in the lumbar section. Tyndyk et al. (2007) used a series of CT scans cadaver (male) to derive a geometrical thoracolumbar component (Th11-L5). The bone tissue was segmented by using a threshold range to differentiate the pixel gray value of the bone with other soft tissues with MIMICS software. Table 2. 4 shows summarization of all the techniques used by different researchers.

Table 2. 4 : Techniques used to develop the three dimensional model.

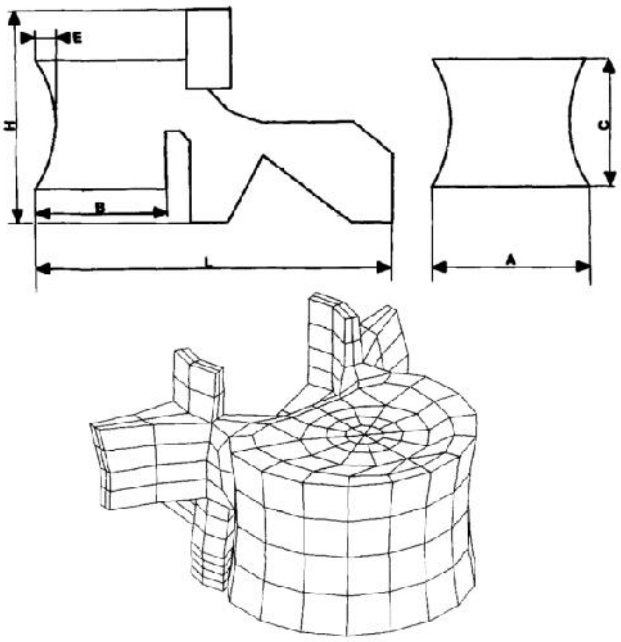
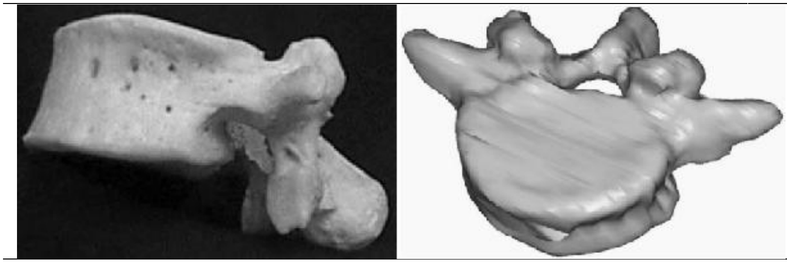
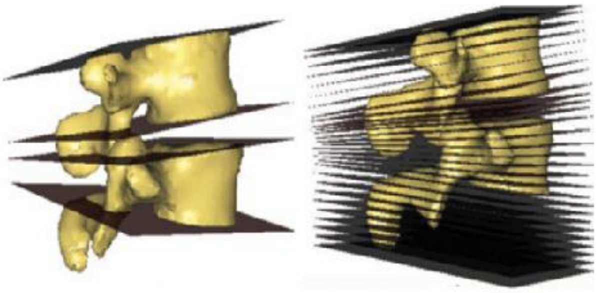
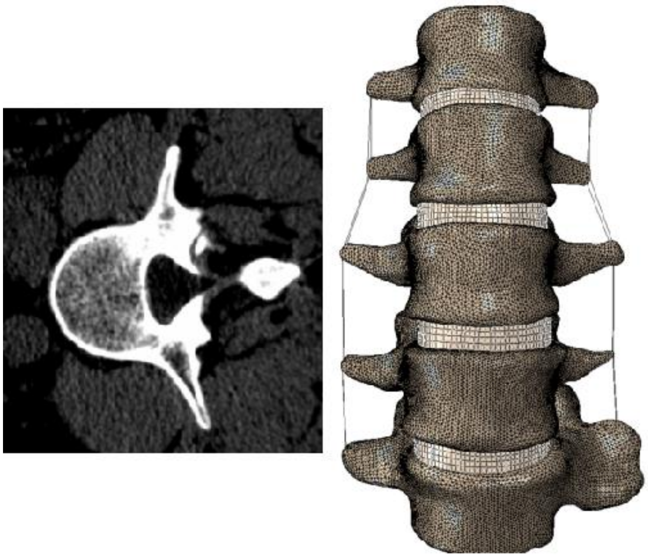
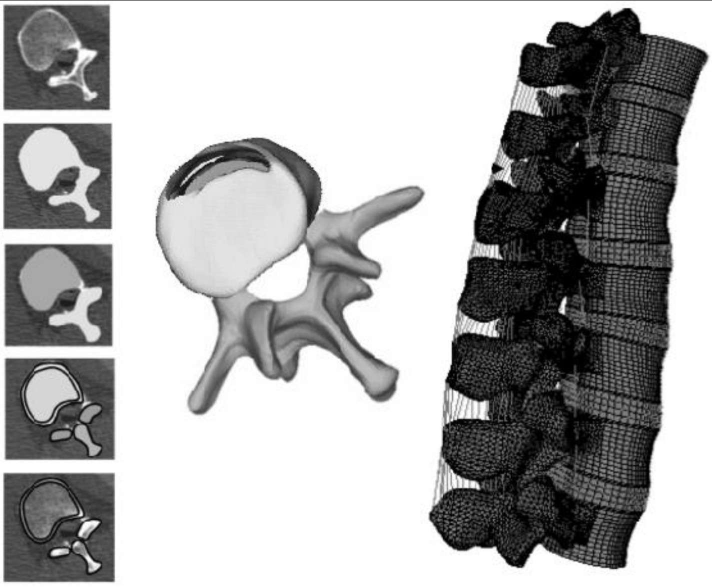
Three dimensional model	Researcher
	Cadaver and volume rendering of lumbar spine L2/L3 (Kim-Kheng et al., 2002)
	The main six parameters digitized on two X-ray and three-dimensional reconstructions of a lumbar spine (Lavaste et al., 1992)

Table 2.4. Continued.

Three dimensional model	Researcher
	Solid model of L5 vertebra (Nabhani & Wake, 2002)
	Model of initial surface model and “the best cross-section planes” in non-parallel series (L4-L5) (Shenghui et al., 2005)
	CT scan of lumbar spine and full model in Abaqus CAE software (Coombs et al., 2011)
	Segmentation of CT scan data, surface model, and finite element model of vertebra (Th11-L5) (Tyndyk et al., 2007)

In order to analyze the three dimensional model, several parameters has been chosen and applied by other researchers to their development model. First, parameter that has been taken into consideration is mesh generation. The meshing types chosen depend on the dimension of the model either two or three dimensions (composed of points and elements) and structure itself either simple or complex. Because of complexity of the lumbar spine structure, usually a tetrahedral or hexahedral type is chosen. Appendix B shows the different types of meshing will result different amounts of elements and the tetrahedral mesh divides more elements compared to hexahedral within the same volume.

According to other findings, the model developed by different methods was analyzed using many ways and various conditions were applied to it. For example, Kim-Kheng et al. (2002) converted the data into IGES before importing into the FE modelling software and ANSYS for the 3D FE mesh construction. The FE model consisted of 817 (noded elements) and 8,281 solids (8-noded elements) with 32,641 DOF. Meanwhile, Pitzen et al. (2002) investigated the biomechanical behaviour of the lumbar spine under the compression load by modelling the nonlinear finite element model (L3/4) by dividing the structure into several parts. It is much easy to characterize and model the lumbar mathematically by developing a simple FE model. The element described in the geometry model is connected with nodes.

Tyndyk et al. (2007) have similar investigations in the extended thoracolumbar region by using a series of medical images (CT data) to generate anatomical 3D FE models. There were two modelling methods as CAD and STL-CAD which were used to create a complex model of the spine. These different methods have resulted in different time consumptions when meshing on the model. The CAD used the conventional mapped mesh meanwhile STL-CAD used the combined 3D tetrahedral element with brick elements which was less time consuming. The finite element models of vertebrae generated by Nabhani & Wake (2002) then were made to use 3D, solid, linear, tetrahedral elements. The volumes of each model were meshed separately with different meshing parameters.

2.3 Properties of materials

The properties of the model must be defined according to the actual human lumbar spine before analyzing the developed model. The material properties shown in Appendix C were taken from the findings of Lavaste et al. (1992); Robin et al. (1994); Ezquerro et al. (2004); Guan et al. (2006) and Kuo et al. (2010) for investigating the biomechanical behaviour of the human lumbar spine.

The studies by Nabhani & Wake (2002) focused on the modelling and analysis of the three dimensional finite element model of lumbar spine L5. The lumbar structures produced were assumed as a solid and hollow cortical bone and were analyzed by using finite element analysis and model. Over the years, finite element method has been recognized as a complementary to the experimental approach in investigating clinical problems and also it is helpful to predict the biomechanical behaviour (Kim-Kheng et al., 2002).

2.4 Loads and boundary conditions

In order to study the different parameters such as effects variation of material property and load cases, different spinal segments, both simple and complex FE models of single vertebrae (Nabhani & Wake, 2002), functional spinal unit (motion segment) (Pitzen et al., 2002; Coombs et al., 2012 and Lodygowski et al., 2005), whole lumbar spine (Shirazi-Adl & Parnianpour, 2000 and Kim et al., 2007), and extended spine (Ezquerro et al., 2004; Tyndyk et al., 2007 and Han et al., 2011) have been proposed.

The 3D model of the developed lumbar spine was further processed in order to evaluate the data. The ways of load and boundary conditions were applied to make each of the study different from another. Figure 2. 10, Figure 2. 11 and Figure 2. 12 shows the type of movement, typical load-displacement and range of motion respectively on the lumbar vertebrae, which is applied when the human body is moved. For example, Nabhani & Wake (2002) developed three types of models which were solid cortical bone, hollow cortical shell, and cortical shell and cancellous centre. The same load was applied to these models to verify the maximum and minimum Von Mises stresses and also maximum displacement that can be occurred. The load used to be about 65% of overall weight body and it is distributed to the upper vertebral body (70%) and superior articular processes (30%). The arranging of both compressive and shears force gave a more accurate mathematical model than just by applying a vertical load on the upper vertebral body only.

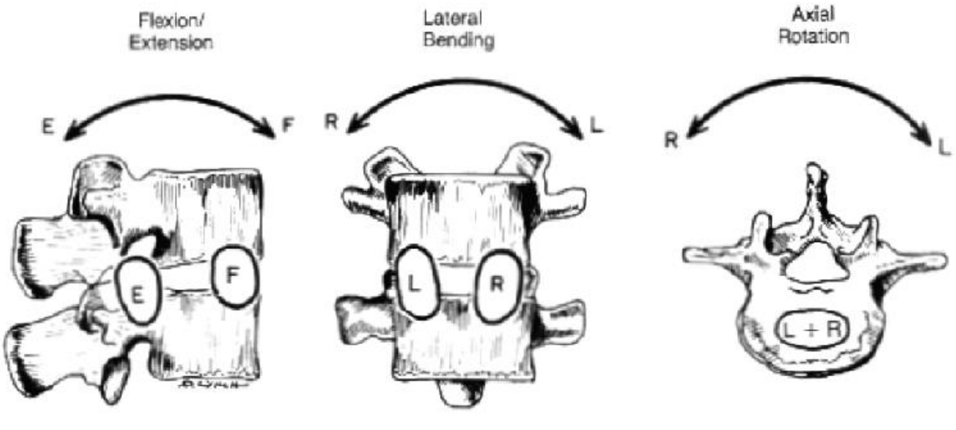


Figure 2. 10 : Instantaneous axes of rotation of the lumbar vertebrae (White & Panjabi, 1990).

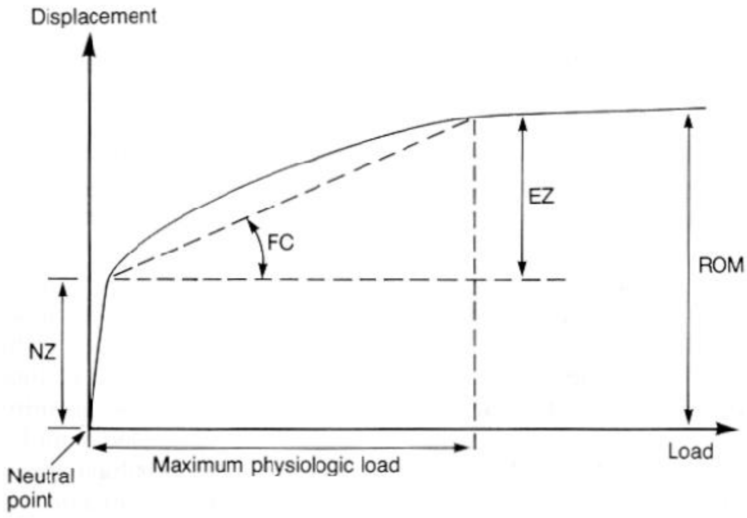


Figure 2. 11 : Typical load-displacement response for a spinal unit (White & Panjabi, 1990).

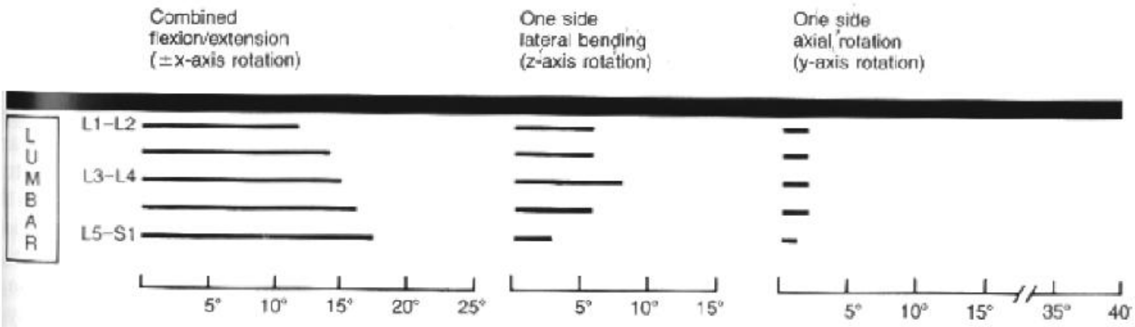


Figure 2. 12 : Ranges of motion throughout the normal spine (White & Panjabi, 1990).

Meanwhile, Tyndyk et al. (2007) used the three specific loading conditions where a load was applied to the first model to a rigid plate located on the first vertebra (Th11). The second model used a compressive force which was divided into upper vertebral body (75%) and to facet joint (25%). Then, the same condition was applied to the third model like in the second model, but the force (Z-axis) acted on facet joint was at an angle of approximately 50^o. The same force in an axial direction was applied to these entire models.

2.5 Finite element analysis

Finite element analysis is a commonly used technique in research activities and industries. It saves a lot of cost since the new designs are allowed to be tested through computer analysis before manufacturing the prototype, examined the components and systems which cannot be readily be experimented and even do the investigation to 'diagnose' the design (Fagan et al., 2002). For example, Rohlmann et al. (2008) used finite element analysis to predict mechanical behaviours such as IVD rotations, pressures and forces in the facet joint of the lumbar spine after a total disc replacement under several factors. Meanwhile, Hsieh et al. (2007) also chose finite element analysis in order to study the injuries of the lumbar spine on collision. The real impact force of a traffic accident was used as a boundary condition parameter in their study in order to examine how many injuries were occurred.

The finite element analysis was also used by Galbusera et al. (2011) to investigate degenerative changes of the intervertebral disc. The changes, especially in disc composition such as disc height loss and water loss were analyzed with a combination of poroelastic non-linear finite element model of L4-L5. Besides that, in implant research, such as comparison to determine which one the best dynamic spinal fixator between Dynesys (DY) and K-ROD (KD), Lin et al. (2013) designed these spinal fixator. These spinal fixator functions are to provide flexibility and to restore spinal stability. The analysis was conducted together with finite element models of the degenerated lumbar spine to examine the biomechanical effects of the spinal fixator in the human body system.

2.6 Summary

The literature review showed the recent research trend in the study of modelling and stress analysis of lumbar spine in particular on types of gender, material properties and load/boundary conditions. It is clear that different parameter applied such as load and moment during analysis can be related to the biomechanical response. Each of lumbar vertebrae has a different maximum degree of rotation since it is located at different level and also has different size of the vertebra. The relationship between load impact while lifting objects and movement of the body of a Malaysian female has never been reported. It is important to determine how these two conditions affect daily life activities.