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Biomechanics Of Human Lumbar Spine (L3 To L5) With Degenerative Disc Disease Using Finite Element Model

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Abstract— ***Human spine is one of the complex structure of the human body. It provides the link between upper and lower extremities of the human body. It is estimated that at least 30% of people in the middle age group from thirty to fifty years have some degree of disc degeneration. Disc degeneration disease can affect the quality of life and in certain individual it can cause severe chronic pain if left untreated. The low back pain associated with lumbar disc degeneration is usually generated from two causes which are abnormal motion instability and inflammation. Abnormal motion instability occurs when the annulus fibrosus are worn down and cannot absorb stress on the human spine effectively resulting in changes in movements along the vertebral segment. To understand lumbar disc problem, a thorough knowledge of the biomechanics of the normal human lumbar spine and a disc degenerated lumbar spine is of great importance. In this study, Computed tomography image of a 33 year old male is used. A three dimensional (3D) human lumbar spine (L3 to L5) is created and validated with literature. The finite element model was modified to degenerated disc and studied the biomechanics of the lumbar spine. Comparison of the biomechanics of normal human lumbar spine is done with the human lumbar spine with disc degeneration for different range of motion and different loads. The result shows that the pressure generated on degenerated disc is greater than normal disc. This work can be implemented and used for designing implants and also for intervertebral disc related analysis.***

Keywords— ***Disc Degeneration, Biomechanics, Finite element analysis***

I. INTRODUCTION

Having a clear understanding of the human lumbar spine is essential in assessing the biomechanics associated with normal spine function, spinal loading, degenerative disc disease (DDD), simulations of surgery, impact of fusion, and total disc replacement. Functional Spinal Unit (FSU) consists of bones and complex soft tissues, such as intervertebral discs (IVD), Tendons, muscles and ligaments. Severe damage or degeneration of structures of the Functional Spinal Unit (FSU) is a common phenomenon resulting in instability of the human spine [1]. In the past years, several Finite Element (FE) models of the human lumbar spine have been created to simulate the behavior of a normal human spine mechanics [2].

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The instrumented spine mechanics and the actual behavior of the degenerated spinal structures are studied [3, 4].

Many FE models have been created and validated with in vitro data from literature to quantify the overall biomechanics of the lumbar segment [5]. FE methods is progressively gaining its popularity in today's biomechanics studies and research. This method is also currently used to bring a clear understanding of the

behavior of a healthy human spine, injured human spine or a diseased human spine, therefore helping in conducting proper prosthesis and surgical inventions. There are various diseases that affect the human lumbar spine which in turn will cause severe chronic back pain to a subject or patient. Some of these diseases are caused by changes in vertebral structures due to osteoporosis while others are due to change in structure of the intervertebral disc. Disc degeneration occurs in different stages that is from grade 0 to grade 3 [6]. Various factors are responsible for rapid worsening of intervertebral disc. The disease is caused mainly due to day to day stresses and minor injuries of the spine that accumulate over time. The annulus fibrosus can progressively loose water leading to the reduction in height of the whole intervertebral disc and changes in structure of endplates causing more pressure to be exerted on the spinal nerves [7, 8]. In most cases, Disc degeneration can cause low back pain or neck pain. The amount of pain experienced by patients differs from individuals and this implies that, the degree of disk degeneration doesn't mean it exactly correlate with the amount of pain. The same amount of disc degeneration may result in severe chronic pain in some patients while in some patients there is less pain being experienced because other people have got nerve endings which deeply penetrate into the outer layer of the disc, thereby causing discs to generate more pain. The amount of pain experienced by the patient affected by disc degeneration can also depends on position in which the affected disc is located and the amount of pressure that is exerted on the surrounding nerves and spinal segment. A degenerated disc in the lumbar region of the human spine can cause lower back pain which sometimes radiate to hips, thighs and legs. Sporadic tingling or weakness can occur to the knees and legs if the pressure is being exerted on the nerves by nucleus pulposus. Disc degeneration disease can cause a weakening condition which can cause a serious negative impact on the lifestyle of a patient. There are many factors that can worsen pain and this include sitting, bending, lifting objects and twisting.

Osteophytes formation and endplate sclerosis are likely to be formed due to the height reduction of intervertebral disc [9, 10]. To undergo an intervertebral disc implant, a close and a thorough study of the biomechanics of spine is to be done. Previous studies were mainly focusing on studying the effects of different loads on a disc degenerated spine. Some of the studies done were mainly focusing on the disc between two adjacent vertebrae, L4 and L5 [11]. Previous studies shows that, the range of motion in flexion + extension continually decreases in intervertebral disc degenerated spine but increased for axial rotation [12]. In this study, the analysis of the degenerated disc is done focusing on L3 to L5 region of the human lumbar spine. The range of motion in flexion + extension direction is done and it is seen that the range of motion decreases. After the range of motion in flexion + extension is completed, the results of the compressive force acting on normal intervertebral disc and degenerated intervertebral disc are also carried out. The relationship between the stress produced between these disc are then compared to see the effect of different loads on intervertebral disc (both normal and degenerated one). The aim of the present study is to develop a finite element model of a human lumbar motion segment (L3 to L5) which allows the simulation of a normal lumbar spine (L3 to L5) and that of a degenerated disc lumbar spine (L3 to L5) and to find-out the effects of disc degeneration on the biomechanical behavior of a motion segment in flexion + extension.

II. MATERIAL AND METHODOLOGY

A 3D human lumbar spine is created from Materialise Interactive Medical Image Control System (MIMICS) software from computed tomography image of a 33 year old male which is in Digital Imaging and Communications in Medicine (DICOM) format.

The Study flow is as follows:

Step 1: Acquisition of computed tomography image

Step 2: Segmentation of lumbar region (L4-L5) using Mimics software

Step 3: Surface creation of the image using computer-aided three-dimensional interactive application (CATIA) software.

Step 4: Meshing of the 3D model

Step 5: Validation of the model

Step 6: Analysis of the model for normal and degenerated Disc in different range of motion and loads using ANSYS software

A proper segmentation of the human lumbar region is performed. Surface creation of a three dimensional human lumbar spine is done using CATIA software just before meshing is performed. Meshing is done using hyper mesh software. The finite element simulation of the disc degeneration is done based on a healthy lumbar spine from vertebrae L3 to vertebrae L5. In this model, there are two intervertebral disc which are L3 to L4 intervertebral disc and L4 to L5 intervertebral disc. These two intervertebral disc consists of the annulus fibrosis and the nucleus fibrosis as shown in fig 1 and fig 2.

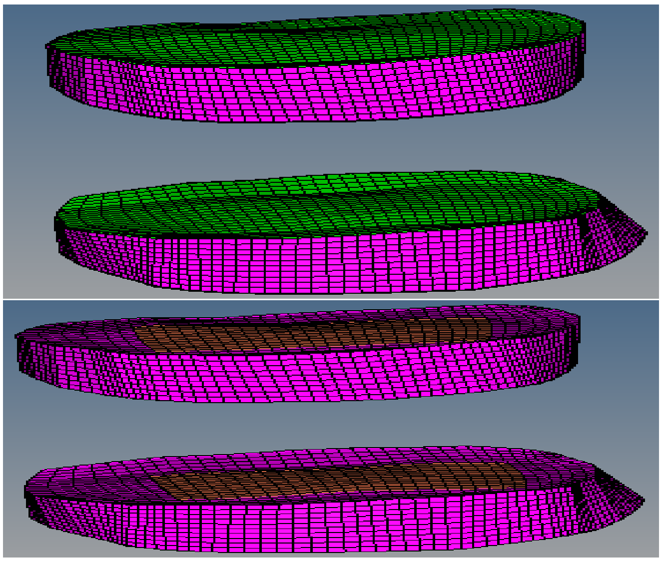

Figure 1: Normal L3 to L5 intervertebral disc with endplates and Normal L3 to L5 intervertebral disc without endplates

For normal intervertebral discs, the number of nodes and elements are 19425 and 16416 respectively. From L3 to L5 of a normal human lumbar spine model, tetra mesh is used in the posterior region with 1mm element size. Hexa mesh is used in the anterior region with 1mm element size. The number of nodes and elements for the human lumbar model L3 to L5 are 170220 and 363649 respectively. From figure 1, the two intervertebral discs shows the endplates which are coloured in green, the annulus fibrosus coloured in purple and the nucleus fibrosus coloured in brown. The height of the normal disc is 11mm while that of the degenerated disc is 3mm smaller than the normal disc to make it 8mm. Figure 2 shows the degenerated intervertebral disc. It can be seen that the height is smaller when compared with that of the normal intervertebral disc.

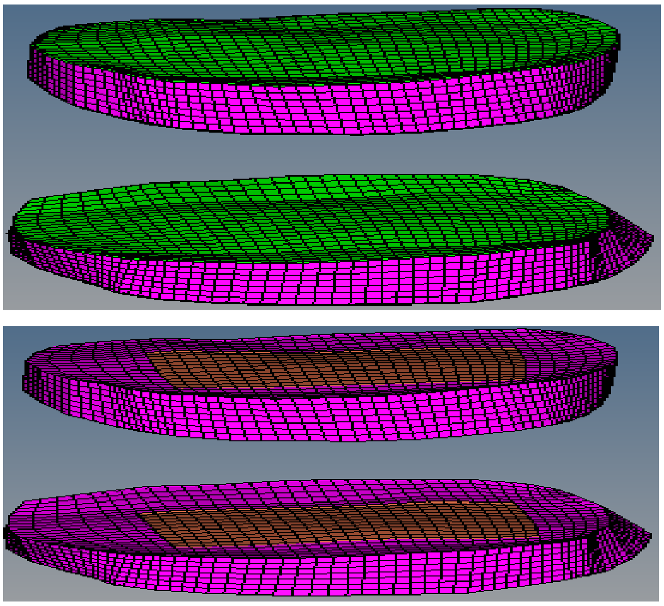

Figure 2: Degenerated intervertebral disc of L3 to L5 of spine

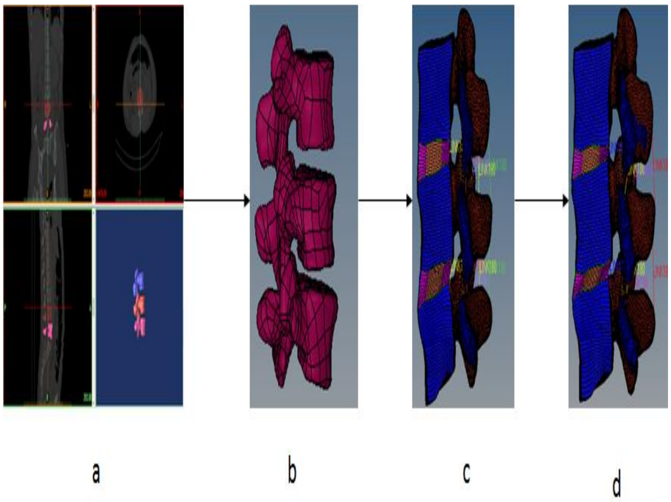

Figure 3 Summary of the methodology from mimics to hyper mesh software.

For degenerated discs, the number of nodes and elements are 18500 and 15552 respectively. From L3 to L5 of the degenerated human lumbar spine model, tetra mesh is used in the posterior region with 1mm element size and hexa mesh is used in the anterior region with 1mm element size. The number of nodes and elements used for the human lumbar model from L3 to L5 are 165595 and 359330 respectively. The three dimensional lumbar spine surface model is created and developed in order to study the biomechanical behavior of a normal disc and degenerated disc conditions. Figure 3 shows the summary of the methodology from mimics to hyper mesh software. The Human lumbar spine model from L3 to L5 is created with a greater consideration of the human lumbar spine anatomy. The cortical bone, trabecular bone, ligaments, endplates, nucleus fibrosus and annulus fibrosus are taken into consideration. Different material properties are assigned to different components of the normal lumbar spine and these specific material properties are shown in table 1 [13]. Assigning material properties of the normal lumbar spine is done in hyper mesh and in ansys software. When assigning material properties of ligaments, ansys software is used while the rest are done in hyper mesh software. The analysis is performed in ansys software. A number of solutions are performed in flexion direction and in extension direction.

After the normal human lumbar spine is analyzed in ansys software, the material properties of a degenerated disc are assigned to the human lumbar spine model with reduced height intervertebral disc. The material properties of the degenerated disc are shown in Table 2 [14]. The difference between a normal human lumbar spine and that of the degenerated human lumbar spine is the height of the intervertebral disc and the material properties of annulus fibrosus and nucleus fibrosus which are assigned to them. The values of the cortical bone, trabecular bone, ligaments, endplates are all the same for the two human lumbar spine models.

Table 1. Material properties of Lumbar spine [13].

Material	Type of Element	Young's modulus (MPa)	Poisson's ratio	Cross section mm^2
Vertebrae				
Cortical bone	Solid 45	12000	0.3	
Cancellous bone	Solid 45	100	0.2	
Intervertebral Disc				
Nucleus		1	0.499	
Annulus		8.4	0.45	
Endplate		24	0.4	
Facet joint	Target and Contact			
Ligament				
ALL	Link 180	7.8		63.7
PLL	Link 180	1.0		20
LF	Link 180	1.5		40
TL	Link 180	10		1.8
CL	Link 180	7.5		30
IL	Link 180	1.0		40
SL	Link 180	3.0		30

Table 2. Material properties of degenerated disc [14].

Component	Young Modulus	Poisson Ratio
Nucleus Fibrosus	1.30	0.40
Annulus Fibrosus	6.00	0.35

This study is not focused on local degenerated disc only but on the behavior of the lumbar spine from L3 to L5 vertebrae. Moreover, simulations of von mises stress produced by the degenerated discs are performed and comparison is also made with the stresses that are produced by normal discs when the load is acting on these discs.

III. RESULTS

A. Validation of the lumbar spine model from L3 to L5

The normal human lumbar spine model from L3 to L5 is used for validation. The bottom part of the human lumbar spine is fixed in all degrees of freedom and the load is applied at the top part of the human lumbar spine model. The forces that are applied to the model are 720N compressive load in the negative Z direction, 1125N flexion load in the negative Y direction and 500N extension load in the positive Y direction. From literature, Lee et al 2007 [13] and Yamamoto et al 1989 [15] comparison is made with the results of the normal human lumbar spine from present study. When the extension load is applied to the normal lumbar spine model, the results are observed and it is discovered that the range of motion for L3/L4 is $6^0$and for L4/L5 is 9^0. After the extension results, 1125N flexion load is applied to the normal lumbar model. The range of motion of flexion for L3/L4 is 7^0 and 9^0 for L4/L5 vertebrae. Adding the values of extension and flexion, the final value for flexion + extension is found. The value for flexion + extension for L3/L4 is 13^0 and that for L4/L5 vertebrae is 18^0. The value of flexion + extension for L3/L4 and L4/L5 vertebrae provided by Lee et al 2007 are $11.2^0$and 14.5^0 respectively [13]. The values for L3/L4 and L4/L5 vertebrae provided by Yamamoto et al 1989 are 11.2^0 and 14.7^0 [15]. From these results, it is seen that the range of motion of present study is greater than that provided by Lee et al 2007 by 1.8^0 for L3/L4 and by $3.5^0$for L4/L5 vertebrae.

Comparing with results from Yamamoto et al 1989 [15], it is seen that the range of motion of present study is slightly greater by 1.8^0 for L3/L4 vertebrae and greater by 3.3^0 for L4/L5 vertebrae. The validation of the human lumbar spine produces correct results because the value of the range of motion in flexion + extension produced by the model from L3 to L5 all fall within the limits provided by the literature [16].

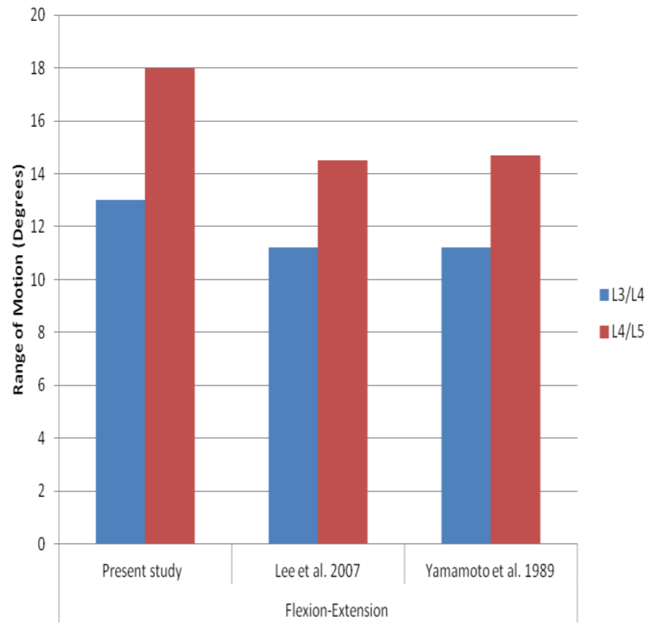

Figure 4: Comparing range of motion between present study and those in literature.

B. Comparison of the range of motion between normal lumbar spine and that with disc degeneration.

After validation was correctly done, the height of the intervertebral disc was reduced by 3mm and the correct material properties for the annulus fibrosus and nucleus fibrosus are correctly assigned. The bottom vertebrae of the disc degenerated lumbar model is fixed in all degrees of freedom. The range of motion in flexion for L3/L4 vertebrae is 30 and for extension for L3/L4 is 20. From these results, it is seen that the range of motion in flexion + extension of the disc degenerated lumbar spine is 50 which deviate from normal range of motion by 10.This might be the reason why disc degeneration can cause diseaes such as osteophytes and endplate sclerosis of the lumbar spine.

From figure 5, the range of motion decreases by 80 from that of normal lumbar spine. From the range provided by Yamamoto in literature, the normal range is from 60 to 150 for flexion and extension. For disc degenerated lumbar spine the value is out of provided normal range of motion provided by literature [15]. Figure 6 shows the comparison of disc degenerated lumbar spine and that of a normal lumbar spine for L4/L5 vertebrae. From this graph, it is seen that the range of motion in flexion + extension for the disc degenerated lumbar spine has decreased from 180 to 80. Comparing these values with the results from Yamamoto et al 1989, it is discovered that the flexion + extension has deviated from the normal range by 10. The normal range of motion provided by Yamamoto is 90 to 200 [15]. Since the range of motion of the degenerated disc is out of normal range of motion, this clearly explains why a degenerated lumbar spine causes pain on the subject when the patient tries to move in flexion and extension direction.

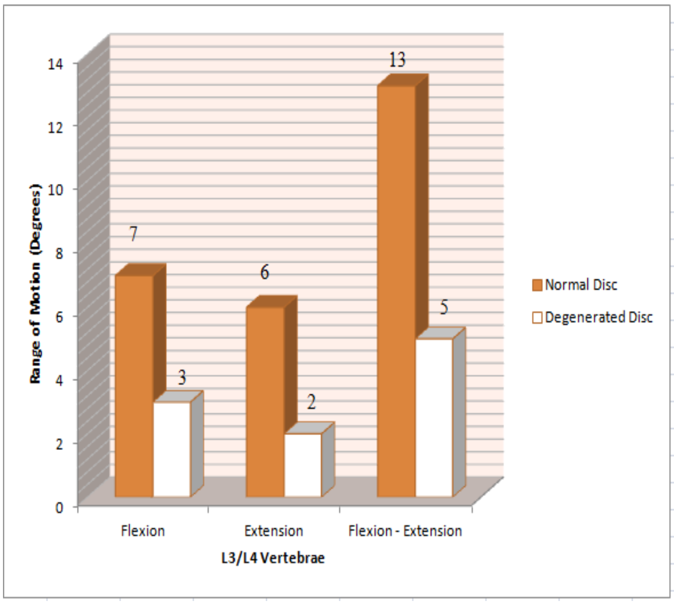

Figure 5. Comparison between normal and degenerated disc in L3/L4 vertebrae

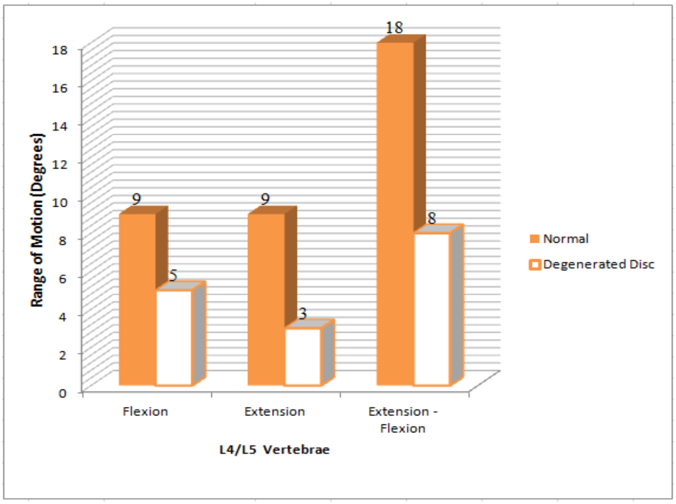

Figure.6 Comparison between normal and degenerated disc in L4/L5 Vertebrae.

Table 3. Comparison between normal and degenerated disc in L3/L4 and L4/L5 vertebrae in different movements.

S.No	Movements	Range of Motion (Degrees)	
		Normal Disc	Degenerated Disc
1	Flexion (L3/L4)	7	3
2	Extension (L3/L4)	6	2
3	Flexion+ Extension (L3/L4)	13	5
4	Flexion (L4/L5)	9	5
5	Extension (L4/L5)	9	3
6	Flexion+ Extension (L4/L5)	18	8

From figure 5 and figure 6, it is clearly seen that from L3 to L5 the range of motion of the disc degenerated lumbar spine model decreases. From this study, the range of motion of the degenerated disc lumbar spine is out of the provided range of motion by literature by 1^0. Table 3 shows the comparison between normal and degeneratde disc in l3 to l5 in different movements.

C. Comparison of the von mises stress produced between normal lumbar spine and that with disc degeneration for different loads.

From information provided in figure 7, it is cleary shown that the von mises stress produced by the disc degenerated lumbar spine is greater when compared with that of the normal human lumbar spine. This difference is slightly little when load is small. Table 4 shows the comparison of von mises stress between normal and degeneratde disc in different loads.

For 100N load, the difference between the von mises stress is only 0.15987 MPa which is just 46.21%. The greatest difference is cleary shown when the load applied is much more, for example 700N load where the difference is 1.415879MPa which is 106% difference.

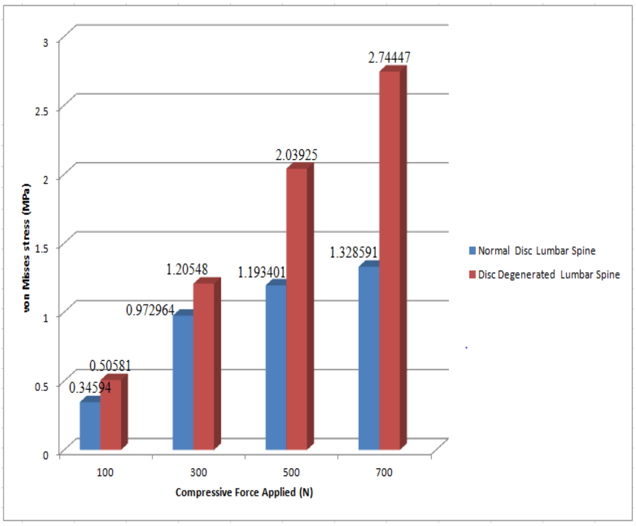

Figure 7. Von Mises stress in normal and degenerated disc.

Table 4. Comparison of Von mises stress between normal and degenerated disc in different loads.

S.No	Compressive Force (N)	Von Mises Stress (Mpa)	
		Normal Disc	Degenerated Disc
1	100N	0.35	0.50
2	300N	0.97	1.20
3	500N	1.19	2.03
4	700N	1.32	2.74

When 300N compressive load is applied on a normal intervertebral disc and the degenerated intervertebral disc, the difference is 0.232516 which is 23.9% difference. For a 500N load, the difference in von mises stress between the normal lumbar intervertebral disc and the degenerated lumbar intervertebral disc is 0.845849MPa which is just 70.9% difference. The difference between normal lumbar spine and disc degenerated lumbar spine progressively increases as the load is increasing. The von mises stress is larger on disc degenerated spine because the strength of the intervertebral disc is low compared to the normal intervertebral disc.

IV. DISCUSSION

The use of Finite Element method for analyzing the study of intervertebral disc would provide a wealth of information that experimentations cannot clearly provide, examples of information that is provided by Finite Element are strain and stress distribution of spinal components. From the Finite Element human lumbar spine model, the results produced gives some general suggestions, which clearly clarifies the effects of diseases found on intervertebral disc of human lumbar spine. After developing a disc degenerated human lumbar spine model, the effects of degenerated disc on the behavior of L3 to L5 functional spinal unit were studied successfully. Apart from simplifying the geometry of the model and assigning different material properties to different tissues, forces in the muscles are completely neglected and pure moments are then applied. While loading, it is assumed that fluid transfer in the intervertebral disc is not present although in real life situation on patients, this is not the case. Validation of the healthy human lumbar spine model was correctly done in previous studies on Range of Motion in terms of flexion + extension [13]. Range of Motion is reduced for degenerated discs in flexion + extension and lateral bending, while it is increased for axial rotation [12]. In this study, it is found that the Range Of Motion in flexion + extension decreases when the intervertebral disc is degenerated. Our Finite Element model predicts the same trend as that of Mimura et al. in flexion and extension however the actual values of these results are different [12]. Hendrick et al. predicted that there is increase in Range of motion for flexion and extension for disc degeneration [6]. The mobility increases in all vertebrae, when there is a progression in disc degeneration [17]. Intervertebral degenerated disc generally cause a progressive rigidity or stiffening of the spinal segment in all load directions which are compression, flexion and extension. Generally, the range of motion of a degenerated disc spine will decrease in its range of motion when considering flexion and extension load directions.

V. CONCLUSION

In this study, it was found that the range of motion of a degenerated lumbar spine is smaller when compared with the range of motion on a normal lumbar spine. When a disc is degenerated, the stress produced is much higher than that produced on the normal disc. The mechanical loads will have a major effect on the vertebrae were the pressure exerted on the disc is much have a higher impact on the degenerated disc than on the normal disc defects. It also found that there was greater impact in loading conditions and the major movement related to intervertebral disc is restricted. The information in the present work can be used for the purpose of designing the implant and studies related to intervertebral disc.

REFERENCES

1. Oxland, T.R., Panjabi, M.M., Southern, E.P., Duranceau, J.S., "An anatomic basis for spinal instability: a porcine trauma model" J Orthop Res 9, 452-462, 1991.
2. Moramarco, V., Perez del Palomar, A., Pappalettere, C., Doblare, M., "An accurate validation of a computational model of a human lumbosacral segment", J Biomech 43, 334-342.
3. Rohlmann, A., Neller, S., Bergmann, G., Graichen, F., Claes, L., Wilke, H.J., "Effect of an internal fixator and a bone graft on intersegmental spinal motion and intradiscal pressure in the adjacent regions", Eur Spine J 10, 301-308, 2001.
4. Zander, T., Rohlmann, A., Bergmann, G., "Influence of ligament stiffness on the mechanical behavior of a functional spinal unit", J Biomech 37, 1107-1111, 2004.
5. Augustus A White III, Manohor M Panjabi. Clinical biomechanics of the spine second edition.
6. Hendrik Schmidt, Frank Heuer, Hans-Joachim Wilke. Dependency of disc degeneration on shear and tensile strains between annular fiber layers for complex loads. Medical Engineering & Physics 31 (2009) 642–649
7. AdamsM, Bogduk N, BurtonK, Dolan P. The biomechanics of back pain. Churchill Livingston; 2002.
8. [8]. AdamsMA, Freeman BJ, Morrison HP, Nelson IW, Dolan P. Mechanical initiation of intervertebral disc degeneration. Spine 2000;25(13):1625–36.
9. Vernon-Roberts B, Pirie CJ. Degenerative changes in the intervertebral discs of the lumbar spine and their sequelae. Rheumatol Rehabil 1977;16(1):13–21.
10. Wilke HJ, Rohlmann F, Neidlinger-Wilke C,Werner K, Claes L, Kettler A. Validity and inter observer agreement of a new radiographic grading system for intervertebral disc degeneration: Part I. Lumbar spine. Eur Spine J 2006;15(6):720–30.
11. Hendrik Schmidt , Annette Kettler a, Antonius Rohlmann , Lutz Claes , Hans-Joachim Wilke. The risk of disc prolapses with complex loading in different degrees of disc degeneration – A finite element analysis.science direct july 2007.
12. Mimura, M., Panjabi, M.M., Oxland, T.R., Crisco, J.J., Yamamoto, I., Vasavada, A., 1994. Disc degeneration affects the multidirectional flexibility of the lumbar spine. Spine 19, 1371–1380.
13. [13]. Dong Suk Shin, Kunwoo Lee,Daniel Kim. Biomechanical study of lumbar spine with dynamic stabilization device using finite element method. Computer-Aided Design 39 (2007) 559–567
14. Ibarz E, Más Y, Mateo J, Lobo-Escolar A, Herrera A, Gracia L. Instability of the lumbar spine due to disc degeneration. A finite element simulation. Advances in Bioscience and Biotechnology. 2013 Apr 1;4(4):548.
15. Yamamoto I, Panjabi MM, Crisco T, Oxland T. Three-dimensional movements of the whole lumbar spine and lumbosacral joint. Spine 1989;14(11):1256–60.
16. Augustus A White III, Manohor M Panjabi. Clinical biomechanics of the spine second edition.
17. Elena Ibarz, Yolanda Más, Jesús Mateo, Antonio Lobo-Escolar, Antonio Herrera, Luis Gracia. Instability of the lumbar spine due to disc degeneration. A finite element simulation. Advances in Bioscience and Biotechnology, 2013, 4, 548-556.

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