ABSTRACT

GONZALEZ, ANTONIO JOSE. An Analysis of the Effect of Artificial Disc Replacement on the Mechanical Response of the Human Lumbar Spine. (Under the direction of Dr. Andre Mazzoleni.)

The objective of this project is to develop a simplified, two-dimensional mathematical model of the lumbar spine for the purpose of studying the behavior the lumbar spine when affected by degenerative disc disease. Several hypothetical treatment options, including fusion and different types of artificial disc replacements (ADR) were examined. The cases presented consisted of three one-degree of freedom artificial discs, three two-degrees of freedom artificial discs, one ideal three-degrees of freedom artificial disc, a degenerated disc, a fused disc and a healthy spine. The equations of motion were generated for a healthy lumbar spine using Lagrange's equations and numerically integrated using Matlab®. Results were obtained for all cases at two different levels, L4-L5 and L5-S1 in response to an impulsive force of 100N applied at L3 in the posterior anterior direction. In the 1-DOF ADR cases at the L4-L5 level, the shear ADR performed better than the other two ADR, while at the L5-S1 level, the rotational ADR performed better than the other two ADR, and significantly better than the fused vertebrae case since it matched the behavior of the healthy spine much more closely. All the other 1-DOF ADR provided little or no improvement when compared to the fused case. In the 2-DOF ADR cases, the shear rotational ADR behaved very similarly to the healthy spine when implanted at both levels, L4-L5 and L5-S1, showing a behavior that varied by less than 1% in the posterior anterior direction and flexion extension rotation and less than 10% in the axial displacement when compared to the behavior of a healthy spine. Overall, the results of this thesis indicate that implanting an artificial disc to replace a damaged disc offers more benefits for the spine than fusion since this allows the spine to behave closer to the natural healthy spine, and hence most likely cause less damage to adjacent discs.

An Analysis of the Effect of Artificial Disc Replacement on the Mechanical Response of the Human Lumbar Spine

by
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Dedication

I want to dedicate this thesis to *my parents*, for being the source of my inspiration and pride. Thank you very much.

Biography

Antonio J. González was born and raised in Caracas, Venezuela were he began his studies in Mechanical Engineering in Universidad Simon Bolivar. He transferred to North Carolina State University where he finished his undergraduate degree, graduating Summa Cum Laude. He continued to pursue his Master's degree at North Carolina State University where he plans to graduate in December of 2007. Antonio has performed several different jobs in industry related to manufacturing, civil engineering, and most recently in the biomedical field. He plans to continue studying human spine mechanics as a PhD student at North Carolina State University.

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I would like to thank Dr. Andre Mazzoleni for all his help and support through out thesis project and my time at North Carolina State University. You have been a great professor in academics and life. Thank you very much.

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1 Introduction

Approximately 80% of Americans suffer significant back pain at least once in their life time [Haid, Artificial], and about 70% of all spinal injuries are associated with the lumbar spine [McLean, The Spine]. Degenerative disc disease is one of the main causes of back pain [Haid, Artificial], a very difficult and unpredictable condition to treat [McLean, The Spine]. Treatment and healing of intervertebral discs is unpredictable and unreliable because the discs have no vascular or neural components [McLean, The Spine].

To solve this problem, the first approach is a non-surgical treatment "including rest, heat, pain medication, therapy, and chiropractic manipulation" [Haid, Artificial]. When the pain persists, surgical methods are used to help the patient. Currently the most widely used and approved method is spinal fusion [Lumbar Artificial], which consists of removing the degenerated disc and fusing the two adjacent vertebrae together by implanting bone in between, restoring disc height. Even though spinal fusion is a widely accepted and used technique to replace a degenerated disc, it has many problems associated to the procedure [Haid, Artificial], so a new technology and procedure is gaining ground and acceptance that consists of replacing the damaged disc with a mechanical artificial disc [Blumenthal, Artificial].

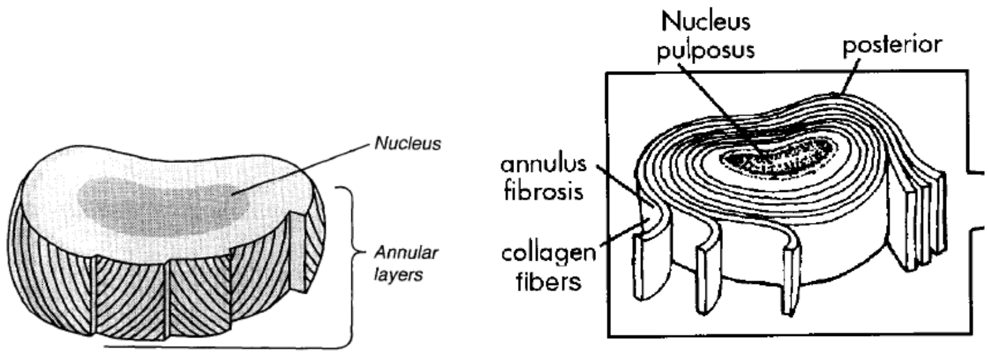
The idea of an artificial disc is not something new, but it is an evolving technology that has not been fully mastered yet. The first artificial disc replacement (ADR) attempt happened more than forty years ago when a surgeon implanted stainless steel balls on one hundred patients [Haid, Artificial]. "There are many artificial disc designs classified into two general types: total disc replacement and disc nucleus replacement" [Artificial Discs]. Total disc replacements, as its name implies, replaces the entire natural intervertebral disc with a new mechanical disc, while the nucleus replacement, substitutes the nucleus pulposus section of the natural disc with a hydrophilic substance keeping the original annulus fibrosis in place. The most common design for total disc replacement consists of two metallic plates that are attached to the bottom and top vertebrae and some have a plastic-like device in between the metallic plates to serve as cushioning [Artificial Discs].

Some of the advantages that artificial disc replacement offers over spinal fusion are a quicker recovery, shorter operating time, lower rate of disc degeneration at adjacent levels, and greater mobility [Haid, Artificial]. It is clear that artificial disc replacement will eventually substitute spinal fusion entirely, and currently many artificial discs are undergoing clinical trails and modifications to improve their design, but are only implanted in a very limited pool of patients. Exclusion criteria are very strict and require a very healthy spinal column to be eligible for an ADR, leaving a large portion of the population outside of the benefits that this new technology offers.

2 Intervertebral Discs

The intervertebral disc plays a very important role in the behavior of the spinal column. The spinal disc has three main functions, first to maintain a proper intervertebral spacing, second to bear and distribute loads in the vertebral column, and third to restrain excessive motion in the vertebral segment [McLean, The Spine].

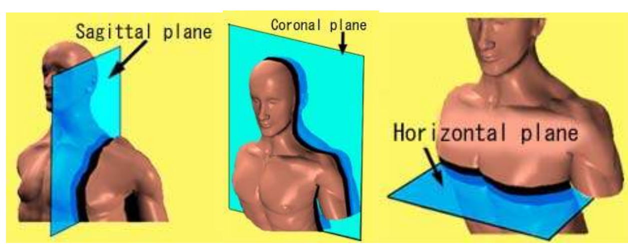
Intervertebral discs are composed of two main sections, an outer shell called annulus fibrosis (AF) and an inner soft center called the nucleus pulposus (NP) [Bao, Review], [McLean, The Spine][Lee, Artificial]Frelinghuysen, Lumbar]. Concentric, parallel layers of fibro-cartilaginous material form the AF, these layers are arranged at a 65 degree angle to the long axis of the spine in alternating opposite directions [Frelinghuysen, Lumbar]. (Figure 2-1) The AF is made up of about 50-60% collagen with the rest mostly being water and proteoglycans, giving it a harder and stronger characteristic. Proteoglycans are large molecules formed by protein core attached to one or more chains of glucosaminoglycans, which in intervertebral discs, bind to water and regulate the flow through the disc [Mow]. The NP's collagen levels vary between 15%-20% with the rest mostly water and proteoglycans, giving it a soft-spongy characteristic. Additionally, the NP holds its hydrophilic proteoglycan gel-like mass under pressure, preloading the disc to maintain its shape and properties under high loads [McLean, The Spine]. The disc structure allows the disc to tolerate very high compressive loads, generally withstanding higher loads than the vertebrae before failure [McLean, The Spine]. Another important property of the discs is that they are highly avascular and aneural components, so healing of discs is unpredictable and unreliable [McLean, The Spine]. Figure 2-1 (a-b) shows the different layers of a typical spinal disc and its orientation.



(a) (b)

Figure 2-1: Intervertebral disc layers (a) Collagen fibers orientation in the Annulus fibrosis [Bao, et. al., Review] (b) layers [McLean, The Spine]

To describe the 3-D structure of the body, three orthogonal planes have been defined. The sagittal plane separates the body into left and right, the coronal or frontal plane in front and back, and the horizontal plane separates the top and bottom. Figure 2-2 (a-c) shows the different planes of the body.



(a) (b) (c)

Figure 2-2: Body planes (a) Sagittal Plane, (b) Coronal Plane, (c) Horizontal Plane [Basic Matters]

As the vertebral spine moves, the center of rotation (COR) between each vertebra migrates along the sagittal plane, typically forward in extension and backwards in flexion [Lee, Artificial], [Bono, History]. This translation of the COR allows the body to minimize the loads on each disc and vertebrae and use more muscles to support the load [McLean, The Spine].

The lumbar region of the spine supports the highest loads of all the spinal column, and also suffers the most amounts of injuries in the spine. Lumbar spinal injuries add up to about 70% of all spinal injuries [McLean, The Spine]. When discs become damaged they follow a degenerative progression that may be observed in Figure 2-3. Disc damage generally occurs through repetitive overloading of the spine, immobility of the spine and age [Stokes].

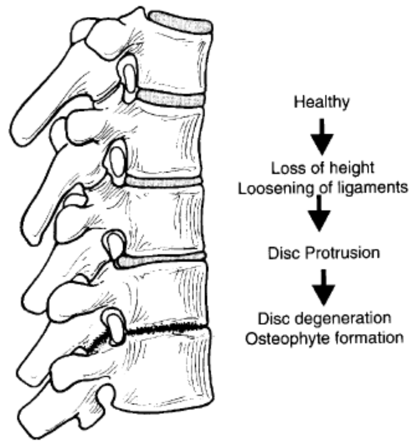
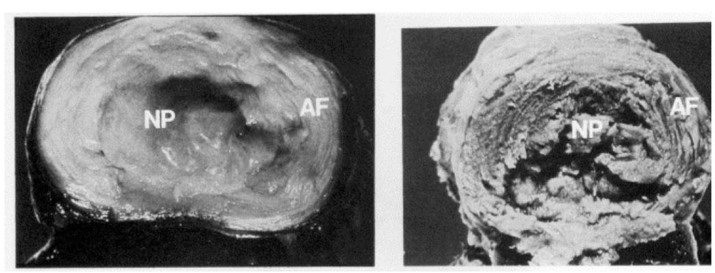


Figure 2-3: Progression of disc degeneration [McLean, The Spine]

A degenerated disc becomes stiffer and loses the capability of retaining water, additionally the dried disc becomes smaller and the ability to distribute loads across the disc changes [McLean, The Spine]. Figure 2-4 (a) and (b) shows a healthy disc and a degenerated disc, where the differences between both discs are obvious.



(a) (b)

Figure 2-4: Intervertebral disc (a) Healthy disc, (b) degenerated disc [McLean, The Spine]

A fully degenerated disc can become twice as stiff in the sagittal plane rotation and becomes less stiff under axial compression [Mow][Rohlmann][Nachemson]. It is believed that the two most common factors that cause degeneration of the spine are repetitive overloading, wear and tear, and lack of motion, underuse and hypomobility, of the spine [Stokes].

3 Artificial Discs

Even though artificial vertebral discs are still evolving and being modified significantly, the idea of using an artificial disc is not as recent as most people may think. The first intervertebral artificial disc was implanted more than forty years ago when a surgeon implanted stainless steel balls (Fernström ball) between the vertebrae of one hundred patients [Haid, Artificial],[Bono, History]. The stainless steel balls restored inter-vertebral spacing and allowed full range of motion [Bono, History]. Figure 3-1 shows an x-ray of a patient with stainless steel balls implanted on his back.

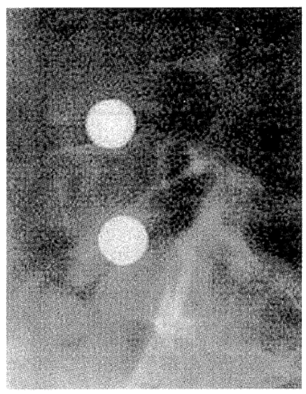


Figure 3-1: X-Ray of stainless steel ball ADR [Bono, History]

Good results were obtained from this concept, but the device failed in the long term because the ball's contact point caused excessive compressive stresses [Bono, History]. This was attributed to the fact that the material did not match the bone's biomechanical modulus and the contact point was too small, concentrating the load; so another ball type implant was designed [Back and Neck]. The new design was made out of silastic, an elastic material that promised to reduce compressive stresses and match the biomechanical modulus of the vertebrae much better and also included a non-compressive horseshoe shape plateau to prevent subsidence [Bono, History].

For over ten years, similar pioneering efforts occurred in the research of spinal disorders [Haid, Artificial], but only in recent years, with advances in modern materials and technology, has the new era of artificial discs been created. As a result of these trials, a solution to the three main failure sources were found: maximize the area of contact between bone and prosthesis, use synthetic on synthetic articulating surfaces instead of synthetic on bone, and finally the material in contact with the bone should have an elastic modulus very similar to the bone [Bono, History].

The next major step in artificial disc replacement (ADR) was the design of an articulated device, with the introduction of the first generation of SB Charitè [Bono, History] in the early 1980’s. Two major types of discs have been developed, metal on plastic and metal on metal prosthesis [Errico, Why]. The most widely used and developed discs for the lumbar spine of the metal on plastic type are the SB Charitè and the ProDisc, and of the metal on metal are the Maverick and the Kineflex. The SB Charitè has the longest history of all, but currently all of these are either approved by the FDA or undergoing clinical trials before approval [FDA][Delamarter, Clinical][Artificial Disc Clinical][Le Huec, Clinical]. Each artificial disc has its own design concept that addresses the design criteria in different ways, each with its own pros and cons. Figure 3-2 (a-d) show a picture of these ADR.

Figure 3-2: Artificial discs (a) SB Charité, (b) ProDisc, (c) Maverick, (d) Kineflex

A summary of the information for these four ADR is listed on Table 3-1 where the manufacturer’s information and design highlights are listed.

Table 3-1: Artificial discs design highlights

	Charité	Kineflex	Maverick	ProDisc
Company	DePuy Spine Johnson & Johnson	Spinal Motion, Inc.	Medtronic Sofamor Danek	Synthes-Stratec (Spine Solutions Inc.)
Design	Metal - Polymer - Metal	Metal - Metal	Metal - Metal	Metal - Polymer - Metal
Rotation	Anterior - Posterior (Limited Migrating COR)	Limited translation of COR	Posterior (Fixed COR)	Posterior (Fixed COR)
Shock Absorption	Yes (UHMWPE)	No	No	Yes (UHMWPE)
Instant Fixation to Vertebrae	Perimeter Teeth	Central Fin	Central Fin	Central Fin
Long Term Attachment to Bone	Yes (Calcium Coating)	Yes (Calcium Coating)	Yes (Calcium Coating)	Yes (Calcium Coating)
FDA Status	Approved for commercial use (Oct. 2004)	Randomized, Controlled Clinical Trials compared to SB Charité	Randomized Clinical Trials compared to spinal fusion	Randomized, Controlled Clinical Trials compared to Spinal Fusion
Trial Locations	None	See Appendix C	See Appendix B	See Appendix A
Number of Levels Implanted	4 levels (L1-S1)	3 levels (L3-S1)	3 levels (L3--S1)	4 Levels (L2 - S1)
Maximum Multiple Levels Implanted	4 consecutive levels (L2-S1)	one	one	4 consecutive levels (L2-L5)
Design Revisions in Progress	n/a	n/a	n/a	Reduction of shear stress on adjacent vertebrae, angle adjustment in the lower endplate

UHMWPE = ultra high molecular weight polyethylene

4 Procedure

The procedure is split into three main sections: the elaboration of the mathematical model, computer simulations using Matlab®, and data manipulation using MS Excel®. The following three sections contain detailed explanations of each section.

4.1 Mathematical Model

This section explains all the important properties, principles, assumptions, and calculations involved in mathematical model of the lumbar spine used in this thesis.

4.1.1 Physical Description

A simplified model of the lumbar spine, thorax through pelvis+sacrum is modelled in two dimensions with three degrees of freedom, X and Y translations and rotation in the XY plane. Each block represents a segment of the model that ranges from the thorax through all lumbar vertebrae L1-L5 and the pelvis+sacrum. In total there are 7 rigid blocks connected by a flexible joint structure as shown in Figure 4-1.

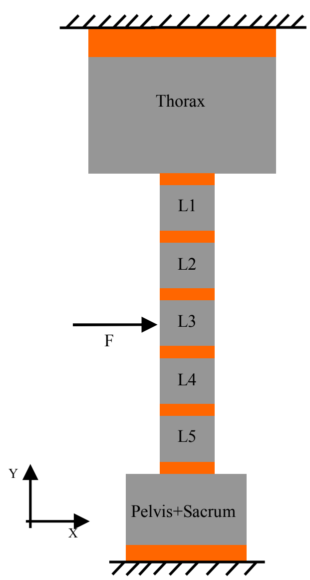


Figure 4-1: Mathematical model physical schematic

Each flexible joint structure consists of three springs and three dampers that lump the material properties of connective tissue, intervertebral discs, ligaments, muscles, etc. with single equivalent values obtained from previous studies [Keller, TS, Colloca, CJ, Beliveau, JG]. Each spring-damper pair acts in one primary direction, X or Y translation or XY plane rotation. Spring constant values are shown in Table 4-1.

Table 4-1: Spring constants

	Thorax	T12-L1	L1-L2	L2-L3	L3-L4	L4-L5	L5-S1	S1-Pelvis
Kx (kN/m)	30	50	40	35	30	30	45	200
Ky (kN/m)	1250	640	620	600	525	450	510	300
Kt (Nm/rad)	400	160	140	120	100	80	75	700

For simplicity, the spring constants were labelled according to the direction they act on, x, y, z, and the flexible joint the spring represents, 1 for the thorax to ground, 2 for the T12 to L1, 3 for L1-L2, 4 for L2-L3, 5 for L3-L4, 6 for L4-L5, 7 for L5-S1, and 8 for S1+pelvis to ground.

The rigid blocks are given only one dimension along the Y-axis that corresponds to the height of the vertebra or the equivalent height of the pelvis and thorax. A coupling constant “a” is incorporated to link the vertical displacement along the Y-axis and the rotational spring and damper. The lengths of each segment are shown in Table 4-2 based on a 170cm body height person and the coupling constant “a” was assumed to be 20mm [Keller, TS, Colloca, CJ, Beliveau, JG].

Table 4-2: Segment dimensions

Segment	Thorax	L1	L2	L3	L4	L5	Pelvis - Sacrum
Length (m)	0.1240	0.0355	0.0375	0.0390	0.0400	0.0390	0.0410

The masses of each rigid segment assumed a person’s body weight of 70kg and are shown in Table 4-3 [Keller, TS, Colloca, CJ, Beliveau, JG].

Table 4-3: Segment masses

Segment	Thorax	L1	L2	L3	L4	L5	Pelvis - Sacrum
mass (kg)	26	0.17	0.17	0.114	0.114	0.114	6

As shown in Figure 4-1, a force is applied at L3 parallel to the x-axis. A positive force is assumed when the force is being applied in the positive x-axis direction. The applied force is a 100N impulsive force.

4.1.2 Assumptions

The following assumptions were made to simplify the actual behaviour of the lumbar spine while still providing useful results.

- A two dimensional model was generated by combining rigid segments and flexible joint sections. The rigid segments or blocks represent the vertebrae, thorax and pelvis+sacrum and the flexible joint sections lump all the connective tissue, intervertebral discs, muscles, ligaments, etc. as shown in Figure 4-1.
- Masses and segment lengths were obtained from psychometric data for a person of 170cm in body height and 70kg of body weight [Keller, TS, Colloca, CJ, Beliveau, JG].
- There is no mass coupling in the system.
- All flexible joint structures can be modelled and lumped into a series of massless springs and dampers that act in one primary direction, x, y or z.
- For all the analyses the damping ratio, ξ, was assumed to be 0.25 or 25% of the critical damping ratio [Keller, TS, Colloca, CJ, Beliveau, JG].
- Full disc degeneration doubles the xy-plane rotation spring constant and reduces by half the y-direction spring constant [Mow][Nachemson]. No change occurs in the x-direction spring constant, since no reference was found that stated a quantitative change.
- A fused disc can be modeled as a disc with very high spring constants, restraining the movement. The fused disc is assumed to have spring constants one thousand times higher than healthy discs.

4.1.3 Equations of Motion

In order to generate the equations of motion for this system Lagrange equations were used. Initially seven reference frames were defined for each mass or rigid segment as shown in Figure 4-2 and the positive rotation was defined as a rotation from the positive x-axis to the positive y-axis or in the positive z-axis direction. The reference frame number is shown in the upper right quadrant and the positive x and y directions are shown by the arrows of each axis. The center of each reference frame is at the center of mass of each rigid segment at its neutral position. The position of each vertebra is defined from this neutral position. This will yield a total of 21 reference variables or degrees of freedom, 7 translations in the x-direction, 7 translations in the y-direction, and 7 rotations in the z-direction.

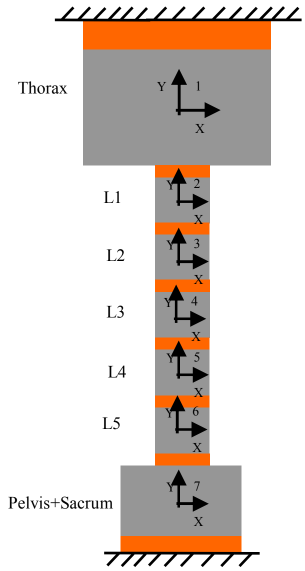


Figure 4-2: Reference frames

In order to generate Lagrange's equations for an undamped system, the potential and kinetic energies for each rigid segment were calculated using the following formulas, where *V* is the potential energy, *K* is the spring coefficient, *X* is the rigid segment displacement or rotation, *m* is the mass or inertia of the rigid segment, *X dot* is the velocity of the rigid segment and subscripts *j* and *i* reference the direction of the motion and spring coefficient number respectively. Values for *j* range between 1 and 7 for each reference frame and values of *i* range between 1 and 8 for each spring, where X_0 and X_8 are zero.

$$V = \sum_{1}^{8} \frac{1}{2} K_i \left(X_i - X_{i-1} \right)^2 \qquad \text{(Potential energy)}$$

$$T = \sum_{1}^{7} \frac{1}{2} m_j \dot{X}_j^2 \qquad \text{(Kinetic energy)}$$

The same formulas were used to calculate the potential and kinetic energies for the *Y* and θ direction. Using these calculated energies the Lagrange equations can be written as shown below, where *L* is the Lagrange equation, *T* is the kinetic energy and *V* is the potential energy.

$$L = T - V$$

From this equation, the equations of motion can be obtained by differentiating the Lagrange equation as follow, where *q sub i* is the generalized coordinate, *q dot sub i* is the velocity of the generalized coordinate and *Q sub i* is the generalized force:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q_i} = Q_i$$

These generated 21 equations that can be expressed in 21x21 coefficient matrices multiplied by column vectors of 21 elements that represent each reference variable as shown bellow, where *M* is the mass matrix, *K* is the spring coefficient matrix, *F* is the force column vector, and *X* is the displacement column vector.

$$\frac{dT}{dt} + V = F \quad \rightarrow \quad M\ddot{X} + KX = F$$

This can be written like this because the kinetic energy of the system only depends in the *q dots* and the potential energy only depends in the *q* generalized coordinate values. In a more general form the equations of motion can be written as

$$M\ddot{X} + C\dot{X} + KX = F$$

Where *M* is the mass matrix, *C* is the damping coefficients matrix, *K* is the spring coefficient matrix, *F* is the force column vector and *X* is the displacement column vector. In order to obtain the *C* coefficients the homogeneous equations of motion are solved in modal space using the eigensolution such that these two conditions are satisfied

$$\phi^{tr} M\phi = I \qquad \text{and} \qquad \phi^{tr} K\phi = \Omega^2$$

Where Φ and Φ^{tr} are the eigenvectors and the transpose of the eigenvectors correspondingly, M is the mass matrix, I is the identity matrix, K is the spring coefficient matrix, and Ω is the natural frequencies matrix. Once these two conditions are met, the 21x21 damping coefficient matrix, C, can be formulated by

$$C = M\phi 2\xi\Omega\phi^{tr} M$$

Where M is the mass matrix, Φ are the modal eigenvectors, ξ is the damping ratio, Ω is the natural frequency matrix, and 2 is just a scalar value. For all the analyses the damping ratio, ξ, was assumed to be 0.25 or 25% of the critical damping ratio [Keller, TS, Colloca, CJ, Beliveau, JG]. With this final calculation all the coefficients of the equations of motion are known and can be written as shown bellow where all the coefficients are 21x21 matrices and the column vectors contain 21 elements.

$$M\ddot{X} + C\dot{X} + KX = F$$

All these calculations can be found in the Appendix.

4.1.4 Impulsive Force Input

Previous researchers have established that typical posterior anterior impulsive forces on the thoracolumbar spine are on the order of 100N in a period of 0.005sec, and the impulse imparted by these forces can be expressed by the following equation as a function of time [Keller, TS, Colloca, CJ, Fuhr, AW][Nathan, M, Keller, TS].

$$F = 466e^{-1000t}\sin(200\pi t)$$

Integrating this function with respect of time and using the impulse momentum theory, an equivalent initial velocity, v_0, can be calculated for the system to act as an impulsive force reaction.

$$v_0 = \frac{1}{m}\int F dt$$

This initial velocity acts in the same direction that the force is acting and can be input into the initial conditions to solve the differential equations obtained from the equations of motion. The value obtained for the initial velocity as a result of an impulsive force acting on the L3 vertebra along the x-axis was $1.8414^{m}/_{s}$.

4.2 Matlab Simulations

In order to numerically solve the equations of motion, the system must be transformed into state space. Rewriting the equations of motion in state space generated coefficient matrices of 42x42 and column vectors of 42 elements that contain 21 velocity elements and 21 displacement elements. The MathWorks® Matlab R2007a software was used to numerically solve the equations of motion.

An m-file was created containing all the variables and equations describing the system. (Appendix). The state space equations were solved using Matlab's ode45 solver and initial conditions of zero except at the velocity in the x-direction of L3, which was set to $1.8414^{m}/_{s}$ as calculated previously to represent the impulsive force input.

The model was validated using the properties of a healthy spine and comparing the results to the published results in the journal article "Force-deformation response of the lumbar spine: a sagittal plane model of posterior anterior manipulation and mobilization" by Tony S. Keller, Christopher J. Colloca and Jean-Guy Beliveau.

A series of 7 different ADR, fused vertebrae, degenerated disc and healthy spine cases were modelled at different intervertebral levels, L4-L5 and L5-S1, by changing the spring constant values.

For the healthy spine cases, the spring constants were kept as original to obtain the response of a healthy spine. For the degenerated disc cases, the torsional spring constants were multiplied by 2 and the compressive spring constant was multiplied by 0.5 at the level of interest to mimic the behaviour of a fully degenerated disc as described in Basic Orthopaedic Biomechanics & Mechano-biology by Van C. Mow and Rik Huiskes. For the fused disc cases, all three spring constants were multiplied by one thousand to increase the stiffness of the joint attempting to represent a fused segment.

The cases were analysed per single implantation level, beginning with L4-L5 and then with L5-S1 as shown in Figure 4-3. These ADR cases contained a combination of possibilities of degrees of freedom, 1-degree of freedom, 2-degrees of freedom and 3-degrees of freedom. For the 1-degree of freedom case, only one translation or rotation was allowed in the ADR by changing the spring constant values. This was done by multiplying two spring constants by one thousand to mimic a very stiff material, and keeping the original spring constant in the direction of interest. The same was done for the 2-degrees of freedom cases and the ideal 3-degrees of freedom cases where the ADR mimics a healthy intervertebral disc.

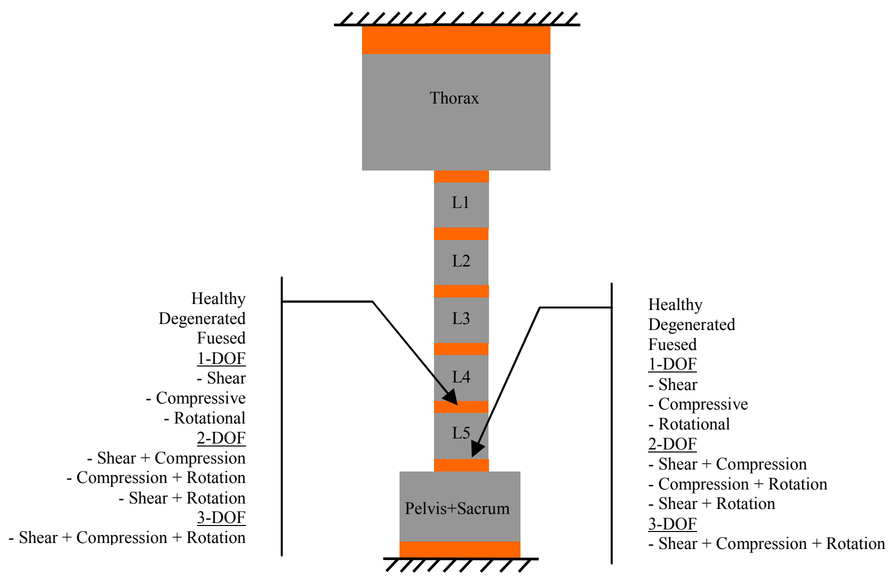


Figure 4-3: Schematic of cases at different levels

For the 1-degree of freedom cases, the original spring constants were multiplied by different values to represent the desired cases as shown in Tables 4-4 and 4-5. All other spring constant values were kept with the original values that represent healthy intervertebral discs.

Table 4-4: Spring constant multiplier for 1-DOF ADR at L4-L5

L4-L5	Multiplier		
	Kx6	**Ky6**	**Kt6**
Degenerated	1	0.5	2
Fused	1000	1000	1000
Shearing	1	1000	1000
Compressive	1000	1	1000
Rotational	1000	1000	1

Table 4-5: Spring constant multiplier for 1-DOF ADR at L5-S1

L5-S1	Multiplier		
	Kx7	**Ky7**	**Kt7**
Degenerated	1	0.5	2
Fused	1000	1000	1000
Shearing	1	1000	1000
Compressive	1000	1	1000
Rotational	1000	1000	1

For the 2-degree of freedom cases, the original spring constants were multiplied by different values to represent the desired cases as shown in Tables 4-6 and 4-7. All other spring constant values were kept with the original values that represent healthy intervertebral discs.

Table 4-6: Spring constant multiplier for 2-DOF ADR at L4-L5

L4-L5	Multiplier		
	Kx6	**Ky6**	**Kt6**
Degenerated	1	0.5	2
Fused	1000	1000	1000
Shearing-Compressive	1	1	1000
Compressive-Rotational	1000	1	1
Shearing-Rotational	1	1000	1

Table 4-7: Spring constant multiplier for 2-DOF ADR at L5-S1

L5-S1	Multiplier		
	Kx7	**Ky7**	**Kt7**
Degenerated	1	0.5	2
Fused	1000	1000	1000
Shearing-Compressive	1	1	1000
Compressive-Rotational	1000	1	1
Shearing-Rotational	1	1000	1

For the 3-degree of freedom case, , the original spring constants were multiplied by different values to represent the desired cases as shown in Tables 4-8 and 4-9. All other spring constant values were kept with the original values that represent healthy intervertebral discs.

Table 4-8: Spring constant multiplier for 3-DOF ADR at L4-L5

L4-L5	Multiplier		
	Kx6	Ky6	Kt6
Degenerated	1	0.5	2
Fused	1000	1000	1000
3-DOF	1	1	1

Table 4-9: Spring constant multiplier for 3-DOF ADR at L5-S1

L5-S1	Multiplier		
	Kx7	Ky7	Kt7
Degenerated	1	0.5	2
Fused	1000	1000	1000
3-DOF	1	1	1

The system's response to the impulsive force was obtained for a 1sec period to allow the system to obtain a steady state value of zero displacement at all levels in all directions. The solver was forced to make 1/10000 sec steps for uniformity and consistency of results.

4.3 Excel Data Manipulation

The results obtained from Matlab® were exported into MS Excel® spreadsheets to perform additional calculations and graphs.

The data obtained from Matlab reflected the displacement of each mass associated with each vertebra, thorax and pelvis+sacrum. All this data was then separated into the different ADR cases. To obtain the intervertebral disc displacements, the relative displacement between each segment was calculated for the full 1 sec period at each time step and summarized in tables where the maximum, minimum, range, and average displacements were calculated. After observing all the data, only the first 0.3sec were used since all the cases reached steady state, zero displacement, in this time interval. The average of the absolute intervertebral disc displacements was used to generate bar charts of each case containing all flexible joint segments to aid in the comparison of the results and be able to visualize the trends. Additionally, the rms value of the displacements was calculated to obtain more information about the response. The rms results are shown in the Appendix.

The percent difference between the intervertebral disc displacements for all the cases and the healthy spine response was used to numerically compare the average of the absolute displacements in tables, as well as the rms values. These tables were used as a summary of results for each case, 1-DOF, 2-DOF, and 3-DOF, where the difference at each segment can be quantified and compared.

5 Results

Figure 5-1 shows the vertebral response of the system to an impulsive shear force (posterior anterior) of 100N at the L3 level, displacements in mm and rotations in degrees for better visualization.

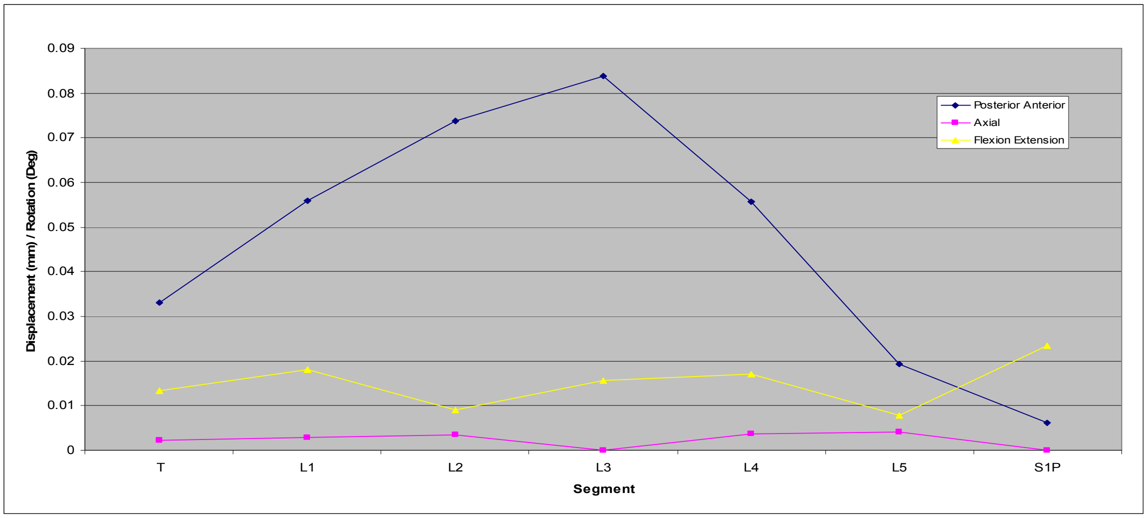


Figure 5-1: Vertebral response of a healthy lumbar spine to a 100N impulsive shear force at L3.

Figure 5-2 shows the relative intervertebral response of the system to an impulsive shear force (posterior anterior) of 100N at the L3 level, displacements in mm and rotations in degrees for better visualization.

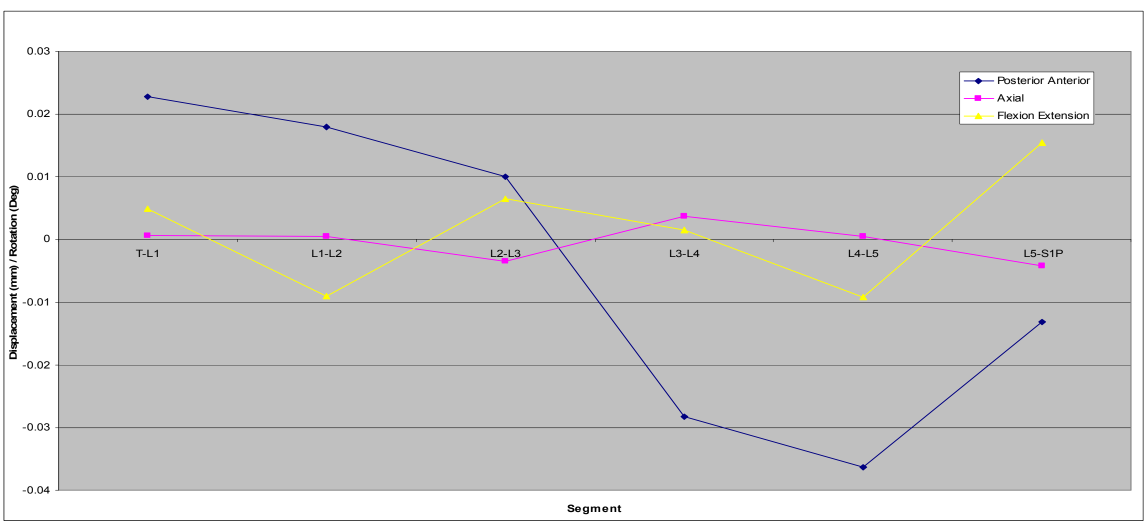


Figure 5-2: Intervertebral response of a healthy lumbar spine to a 100N impulsive shear force at L3.

5.1 *One Degree of Freedom Artificial Discs*

The artificial discs results for the one degree of freedom case have been divided into three separate degrees of freedom x, y, and z or Shear, compressive and rotational respectively. Each disc was implanted at L4 – L5 and L5 – S1 levels. The following results are divided and presented by level and degree of freedom. Bar charts of all segments are presented to aid in the visualization of the overall trends and summary tables are presented at the end of each section where the differences can be compared quantitatively.

5.1.1 L4 – L5 Level Degeneration

The following results reflect the 1 degree of freedom ADR's, fused vertebrae and degenerated disc cases at the L4 – L5 level.

5.1.1.1 Shear ADR

Figures 5-3 – 5-5 show the response of the lumbar spine to an impulsive shearing force acting on L3. The figures include the response of a spine with a degenerated disc, fused disc and a Shear ADR at the L4 – L5 level as well as the response of a healthy spine.

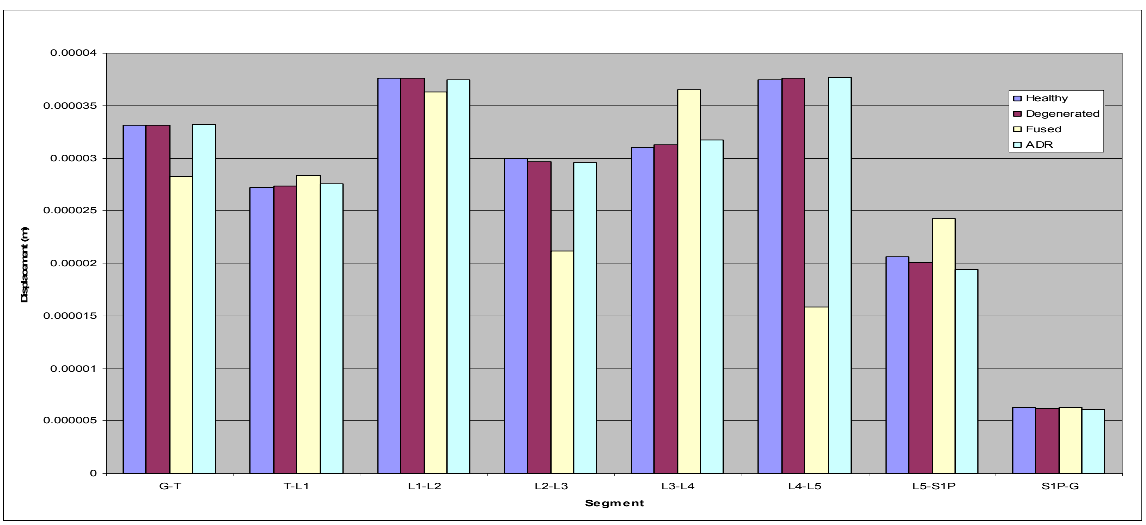


Figure 5-3: Posterior Anterior response of Shear ADR at L4-L5

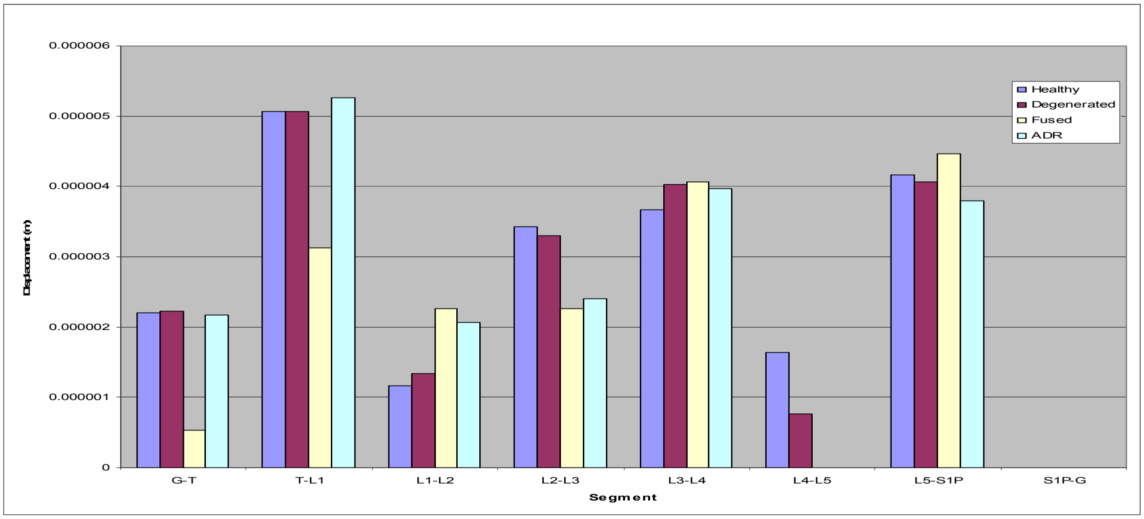


Figure 5-4: Axial response of Shear ADR at L4-L5

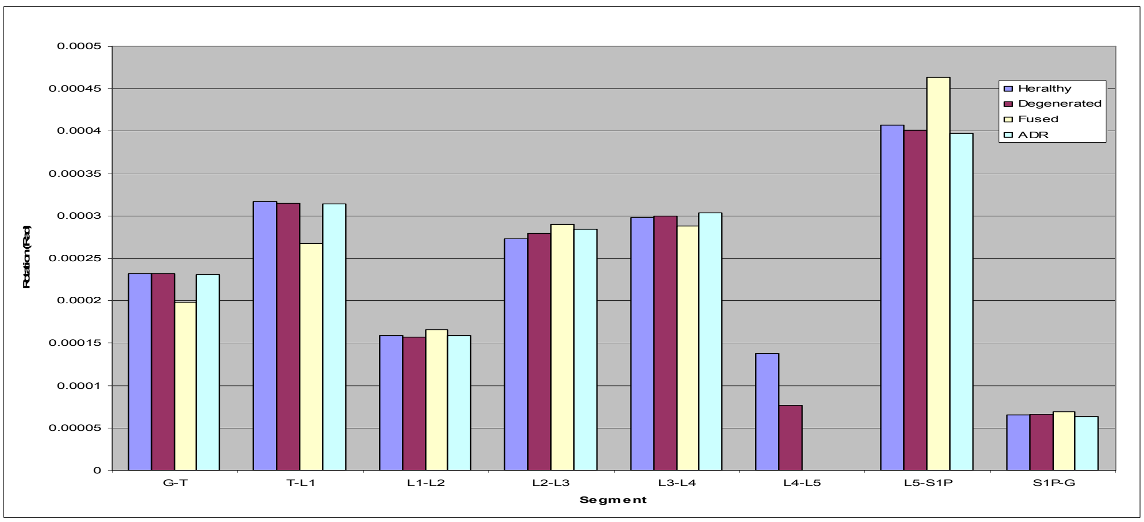


Figure 5-5: Flexion Extension response of Shear ADR at L4-L5

5.1.1.2 Compressive ADR

Figures 5-6 – 5-8 show the response of the lumbar spine to an impulsive Shear force acting on L3. The figures include the response of a spine with a degenerated disc, fused disc and a compressive ADR at the L4 – L5 level as well as the response of a healthy spine.

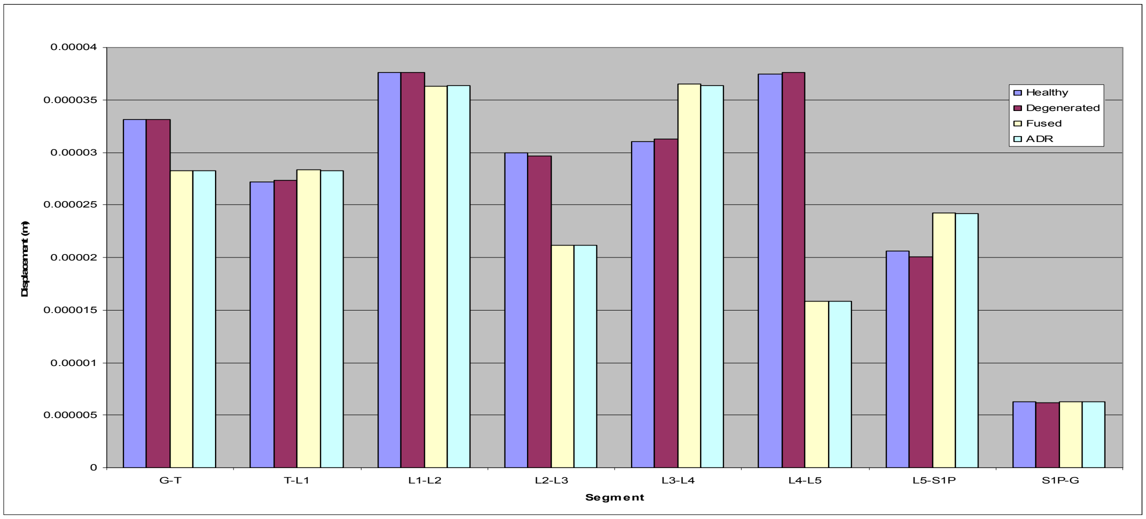


Figure 5-6: Posterior Anterior response of a compressive ADR at L4-L5

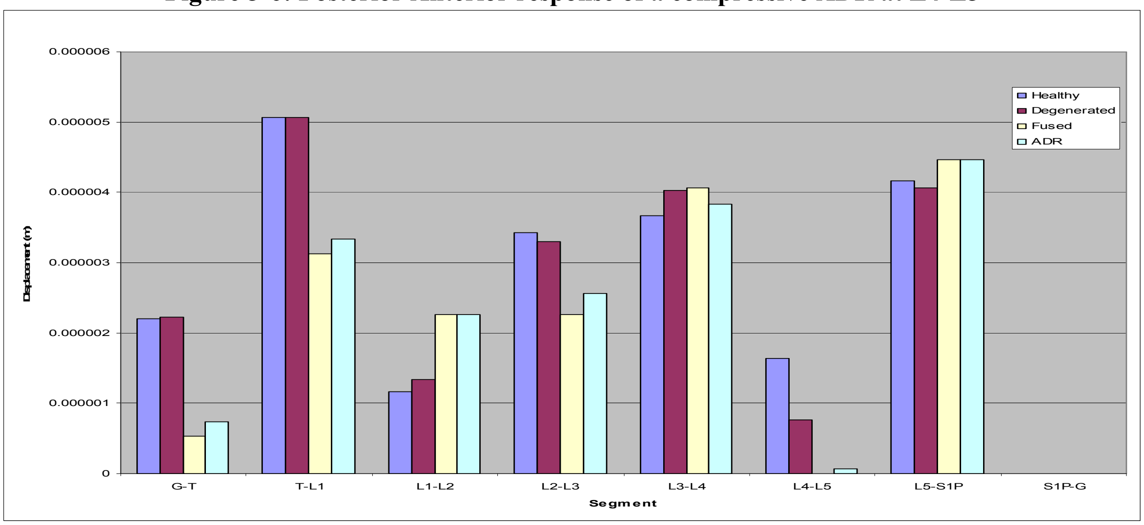


Figure 5-7: Axial response of a compressive ADR at L4-L5

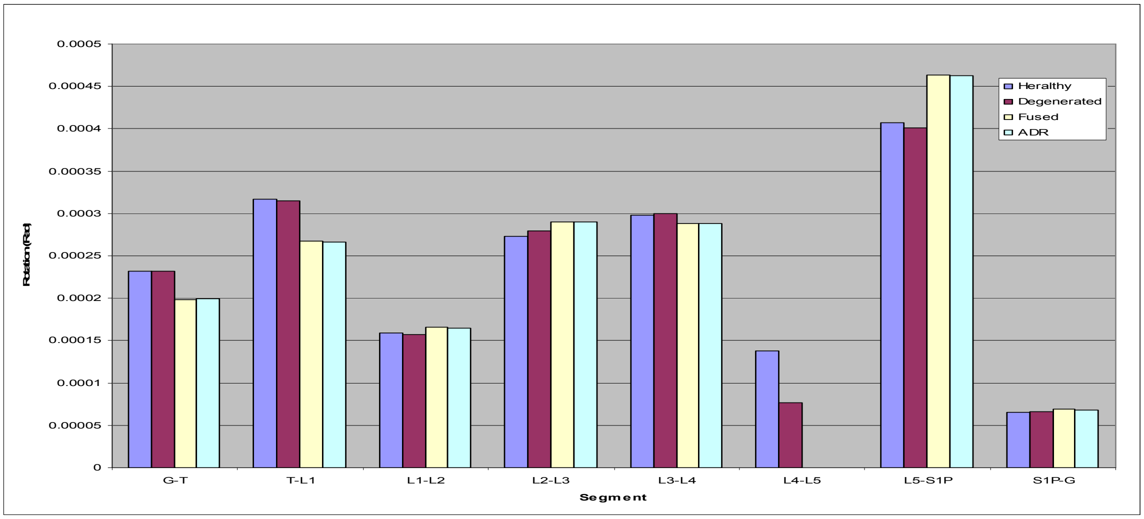


Figure 5-8: Flexion Extension response of a compressive ADR at L4-L5

5.1.1.3 Rotational ADR

Figures 5-9 – 5-11 show the response of the lumbar spine to an impulsive shearing force acting on L3. The figures include the response of a spine with a degenerated disc, fused disc and a rotational ADR at the L4 – L5 level as well as the response of a healthy spine.

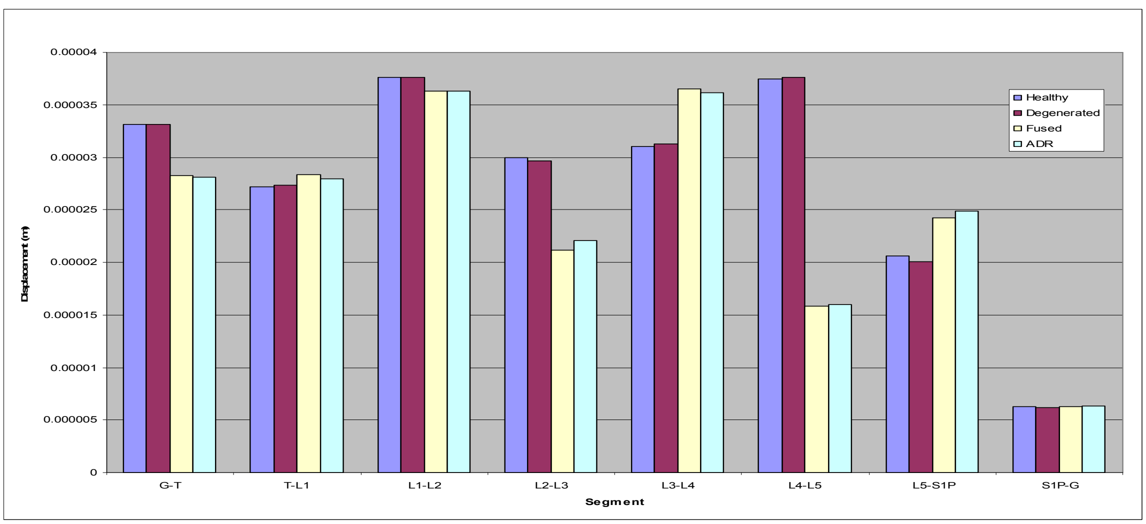


Figure 5-9: Posterior Anterior response of a rotational ADR at L4-L5

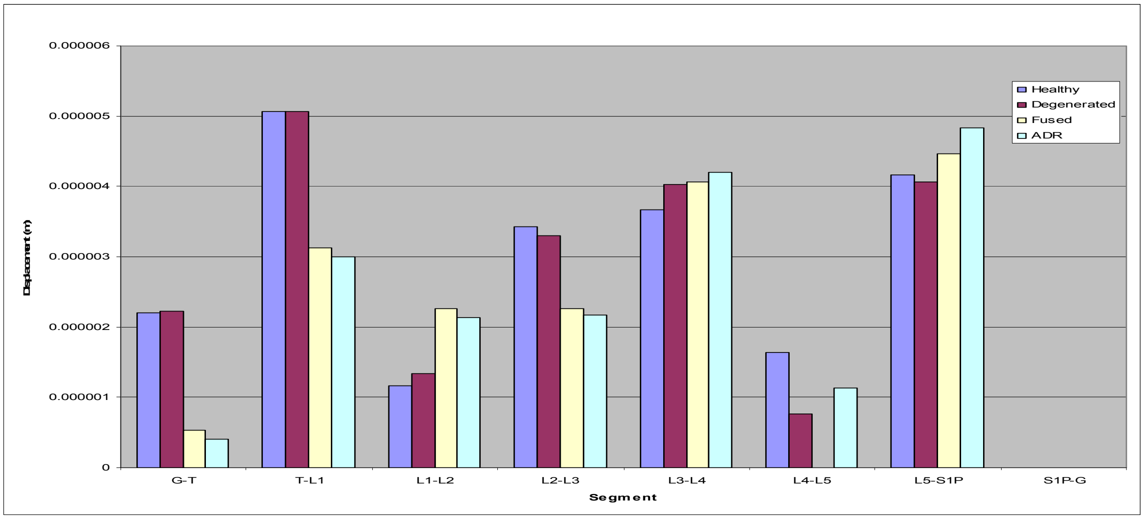


Figure 5-10: Axial response of a rotational ADR at L4-L5

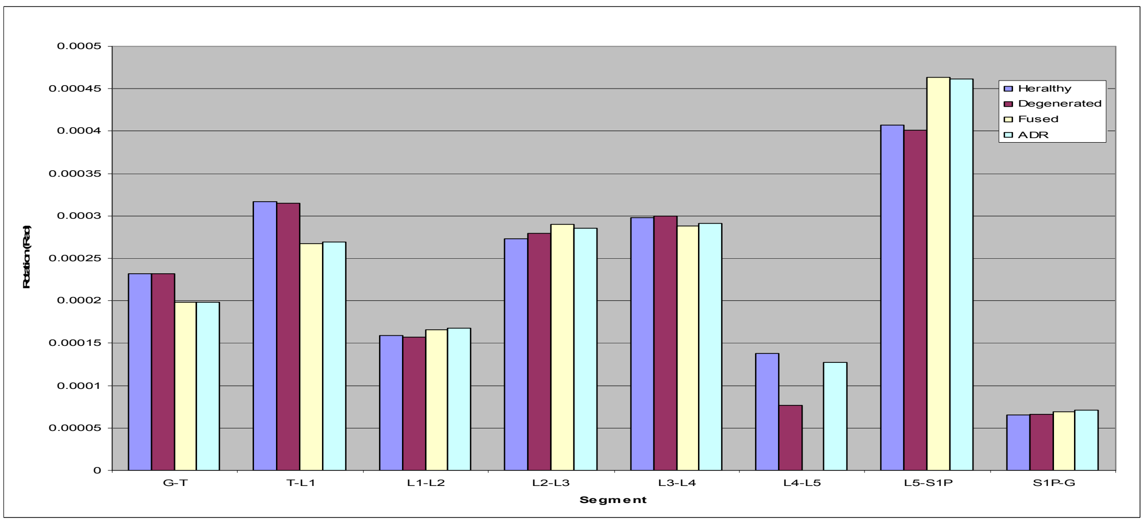


Figure 5-11: Flexion Extension response of a rotational ADR at L4-L5

5.1.1.4 Result Summary of One Degree of Freedom L4 – L5 ADR's

Tables 5-1 through 5-3 show a comparative summary of the results obtained for each 1-degree of freedom ADR case.

Table 5-1: Posterior Anterior intervertebral displacement summary for the 1-DOF L4- L5 ADR cases

	Posterior Anterior Intervertebral Displacement % Difference					
	T-L1	**L1-L2**	**L2-L3**	**L3-L4**	**L4-L5**	**L5-S1P**
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	0.61%	0.09%	-0.89%	0.75%	0.36%	-2.43%
Fused	4.17%	-3.46%	-29.48%	17.49%	-57.74%	17.64%
Shear	1.47%	-0.35%	-1.22%	2.15%	0.62%	-5.99%
Compressive	4.04%	-3.28%	-29.48%	17.17%	-57.65%	17.31%
Rotational	2.70%	-3.37%	-26.36%	16.42%	-57.30%	20.71%

Table 5-2: Axial intervertebral displacement summary for the 1-DOF L4- L5 ADR cases

	Axial Intervertebral Displacement % Difference					
	T-L1	**L1-L2**	**L2-L3**	**L3-L4**	**L4-L5**	**L5-S1P**
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	0.00%	14.29%	-3.88%	10.00%	-53.06%	-2.40%
Fused	-38.16%	94.29%	-33.98%	10.91%	-100.00%	7.20%
Shear	3.95%	77.14%	-30.10%	8.18%	-100.00%	-8.80%
Compressive	-34.21%	94.29%	-25.24%	4.55%	-95.92%	7.20%
Rotational	-40.79%	82.86%	-36.89%	14.55%	-30.61%	16.00%

Table 5-3: Flexion Extension intervertebral rotation summary for the 1-DOF L4- L5 ADR cases

	Flexion Extension Intervertebral Rotation % Difference					
	T-L1	**L1-L2**	**L2-L3**	**L3-L4**	**L4-L5**	**L5-S1P**
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	-0.62%	-0.86%	2.59%	0.47%	-44.77%	-1.60%
Fused	-15.90%	4.22%	6.35%	-3.46%	-99.93%	13.76%
Shear	-1.10%	0.29%	4.20%	1.75%	-99.88%	-2.36%
Compressive	-16.00%	3.94%	6.29%	-3.32%	-99.86%	13.64%
Rotational	-15.08%	5.81%	4.58%	-2.41%	-7.70%	13.41%

5.1.2 L5 – S1 Level Degeneration

The following results reflect the 1 degree of freedom ADR's, fused vertebrae and degenerated disc cases at the L5 – S1 level.

5.1.2.1 Shear ADR

Figures 5-12 – 5-14 show the response of the lumbar spine to an impulsive shearing force acting on L3. The figures include the response of a spine with a degenerated disc, fused disc and a Shear ADR at the L5 – S1 level as well as the response of a healthy spine.

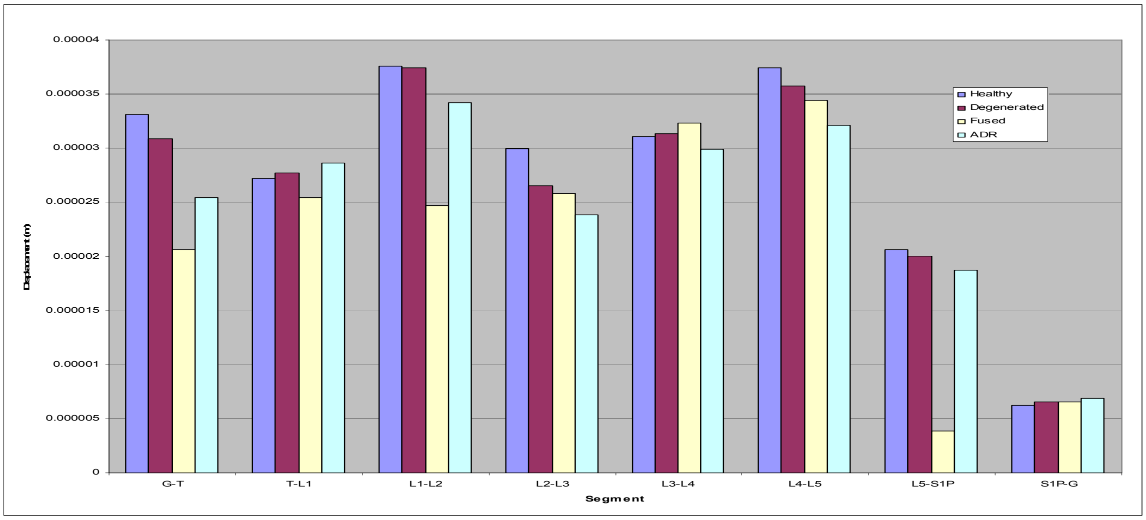


Figure 5-12: Posterior Anterior response of Shear ADR at L5-S1

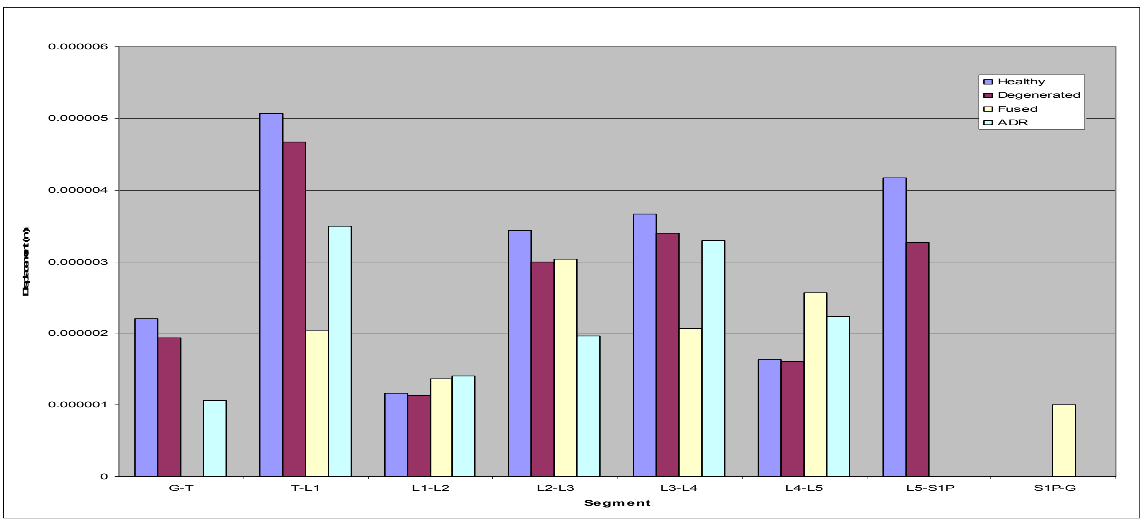


Figure 5-13: Axial response of Shear ADR at L5-S1

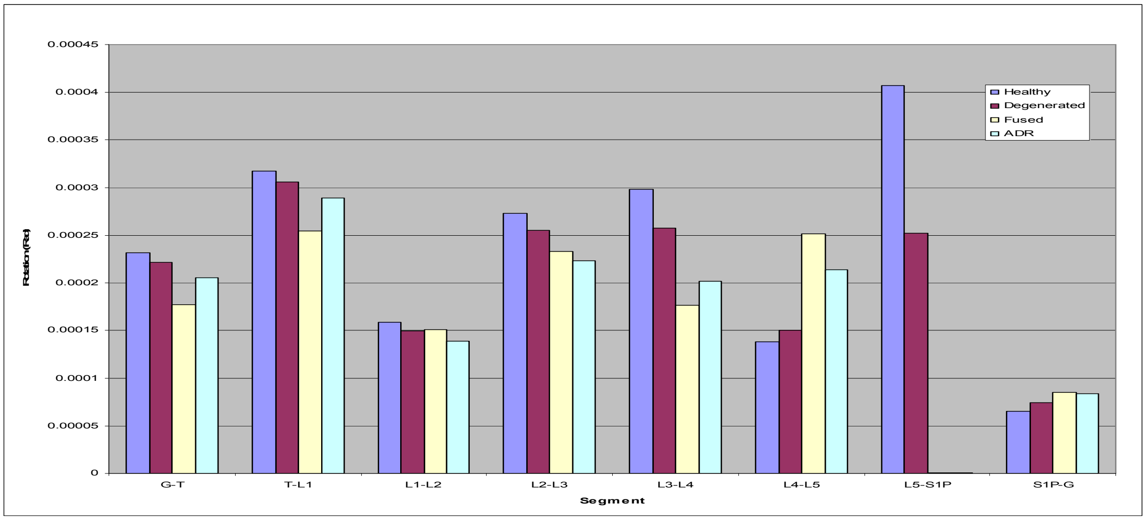


Figure 5-14: Flexion Extension response of Shear ADR at L5-S1

5.1.2.2 Compressive ADR

Figures 5-15 – 5-17 show the response of the lumbar spine to an impulsive shearing force acting on L3. The figures include the response of a spine with a degenerated disc, fused disc and a compressive ADR at the L5 – S1 level as well as the response of a healthy spine.

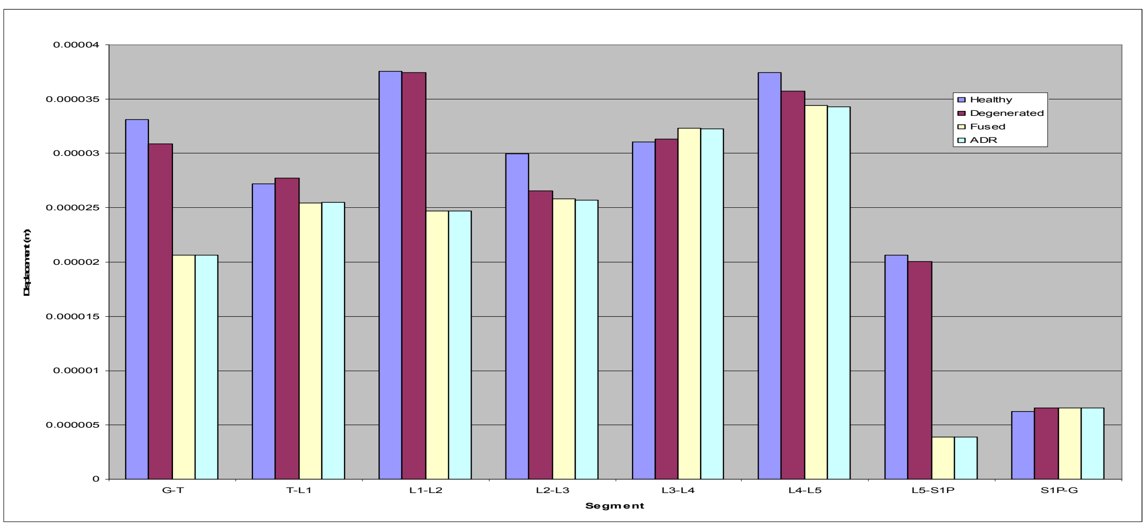


Figure 5-15: Posterior Anterior response of a compressive ADR at L5-S1

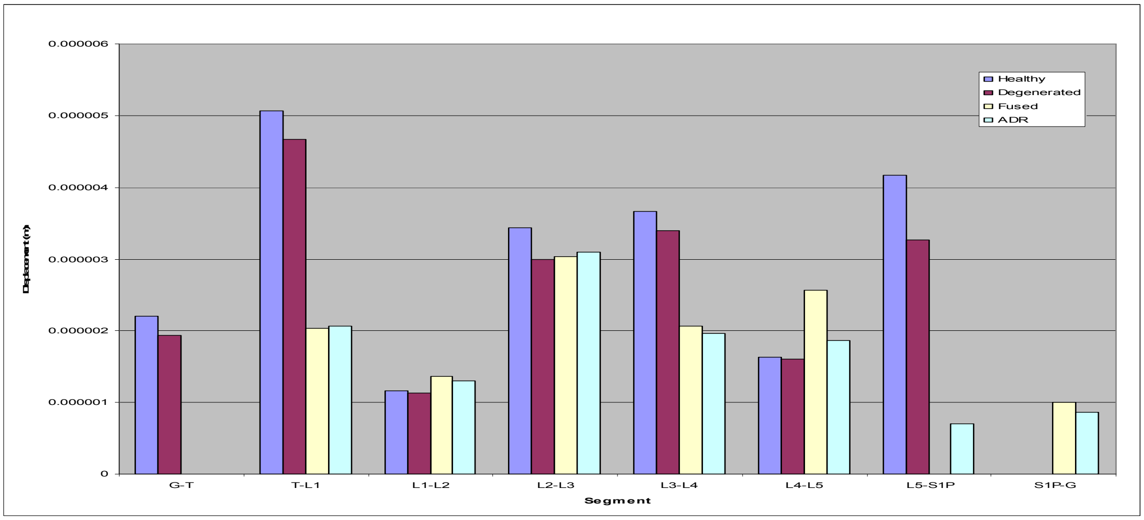


Figure 5-16: Axial response of a compressive ADR at L5-S1

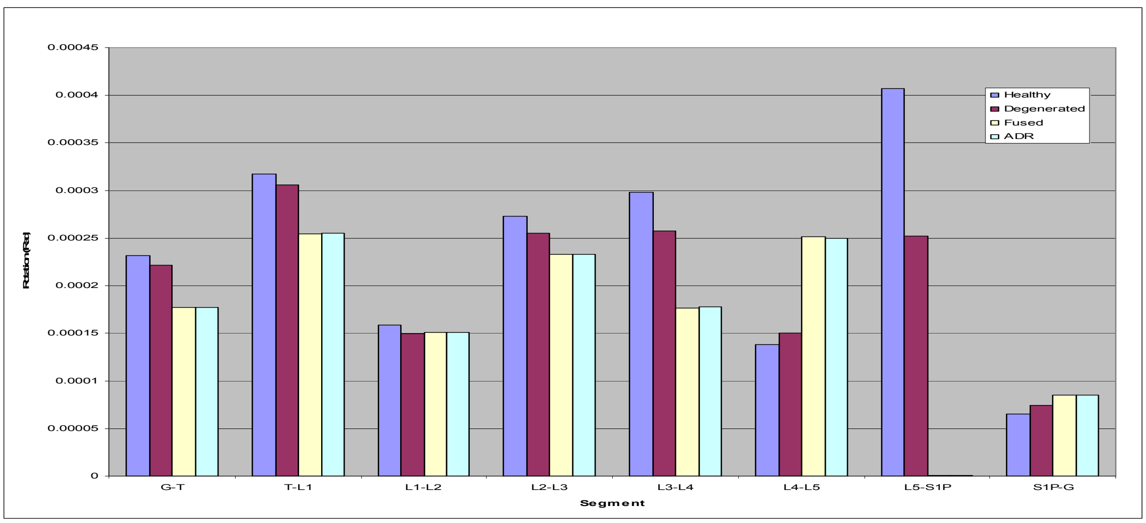


Figure 5-17: Flexion Extension response of a compressive ADR at L5-S1

5.1.2.3 Rotational ADR

Figures 5-18 – 5-20 show the response of the lumbar spine to an impulsive shearing force acting on L3. The figures include the response of a spine with a degenerated disc, fused disc and a rotational ADR at the L5 – S1 level as well as the response of a healthy spine.

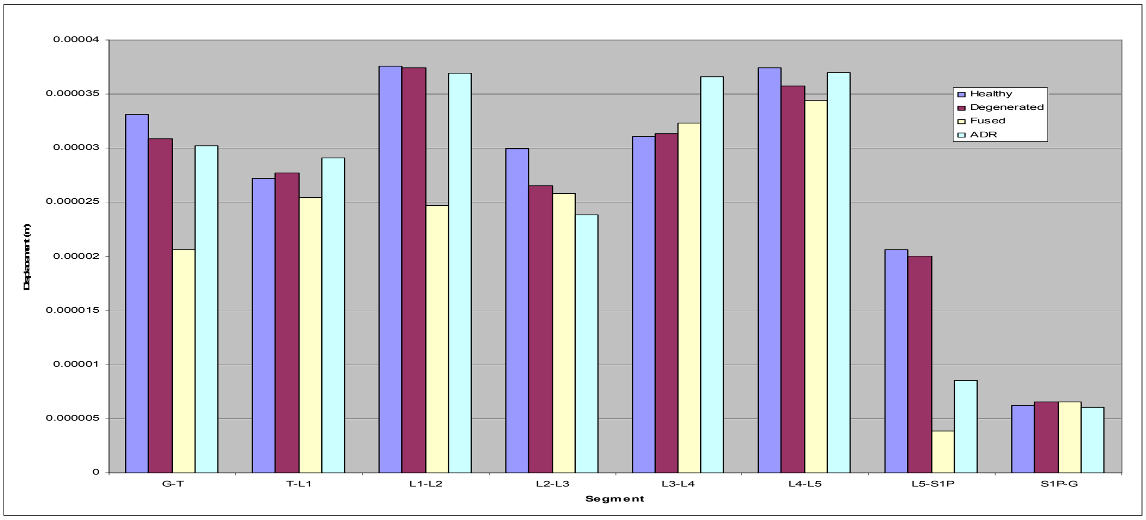


Figure 5-18: Posterior Anterior response of a rotational ADR at L5-S1

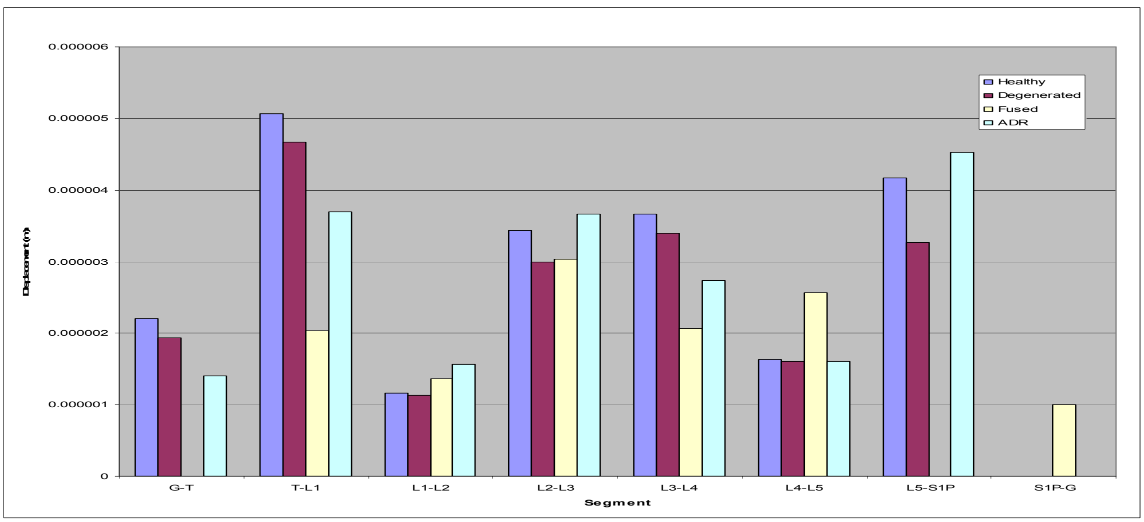


Figure 5-19: Axial response of a rotational ADR at L5-S1

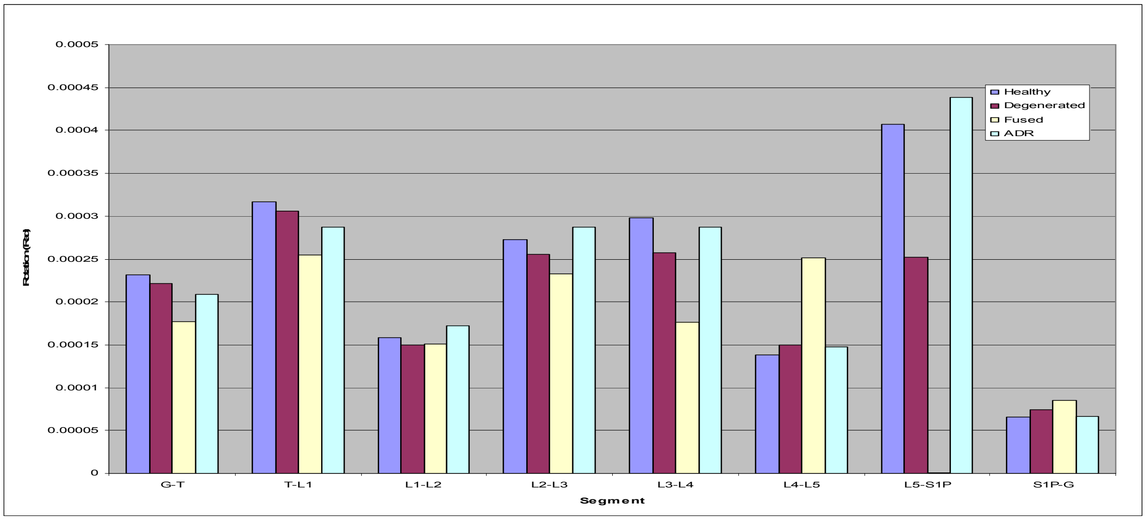


Figure 5-20: Flexion Extension response of a rotational ADR at L5-S1

5.1.2.4 Result Summary of One Degree of Freedom L5 – S1 ADR's

Tables 5-4 through 5-6 show a comparative summary of the results obtained for each 1-degree of freedom ADR case.

Table 5-4: Posterior Anterior intervertebral displacement summary for the 1-DOF L5-S1 ADR cases

	Posterior Anterior Intervertebral Displacement % Difference					
	T-L1	**L1-L2**	**L2-L3**	**L3-L4**	**L4-L5**	**L5-S1P**
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	1.96%	-0.35%	-11.35%	0.97%	-4.63%	-2.59%
Fused	-6.62%	-34.31%	-13.90%	3.97%	-8.19%	-81.23%
Shear	5.27%	-8.95%	-20.36%	-3.76%	-14.23%	-9.06%
Compressive	-6.25%	-34.22%	-14.24%	3.76%	-8.45%	-81.23%
Rotational	7.11%	-1.77%	-20.36%	17.81%	-1.25%	-58.58%

Table 5-5: Axial intervertebral displacement summary for the 1-DOF L5-S1 ADR cases

	Axial Intervertebral Displacement % Difference					
	T-L1	**L1-L2**	**L2-L3**	**L3-L4**	**L4-L5**	**L5-S1P**
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	-7.89%	-2.86%	-12.62%	-7.27%	-2.04%	-21.60%
Fused	-59.87%	17.14%	-11.65%	-43.64%	57.14%	-100.00%
Shear	-30.92%	20.00%	-42.72%	-10.00%	36.73%	-100.00%
Compressive	-59.21%	11.43%	-9.71%	-46.36%	14.29%	-83.20%
Rotational	-26.97%	34.29%	6.80%	-25.45%	-2.04%	8.80%

Table 5-6: Flexion Extension intervertebral rotation summary for the 1-DOF L5-S1 ADR cases

	Flexion Extension Intervertebral Rotation % Difference					
	T-L1	**L1-L2**	**L2-L3**	**L3-L4**	**L4-L5**	**L5-S1P**
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	-3.64%	-5.77%	-6.26%	-13.62%	8.59%	-38.07%
Fused	-19.73%	-5.03%	-14.65%	-40.88%	82.21%	-99.88%
Shear	-8.91%	-12.82%	-18.24%	-32.41%	55.03%	-99.89%
Compressive	-19.49%	-4.72%	-14.60%	-40.42%	81.20%	-99.84%
Rotational	-9.43%	8.35%	5.13%	-3.73%	6.44%	7.78%

5.2 Two Degree of Freedom Artificial Discs

The artificial discs results for the two degree of freedom case have been divided into three separate combinations of degrees of freedom xy, yz, and xz or Shear-compressive, compressive-rotational and Shear-rotational respectively. Each disc was implanted at L4 – L5 and L5 – S1 levels. The following results are divided and presented by level and degree of freedom.

5.2.1 L4 – L5 Level Degeneration

The following results reflect the 2 degree of freedom ADR's, fused vertebrae and degenerated disc cases at the L4 – L5 level.

5.2.1.1 Shear-Compressive ADR

Figures 5-21 – 5-23 show the response of the lumbar spine to an impulsive shearing force acting on L3. The figures include the response of a spine with a degenerated disc, fused disc and a Shear-compressive ADR at the L4 – L5 level as well as the response of a healthy spine.

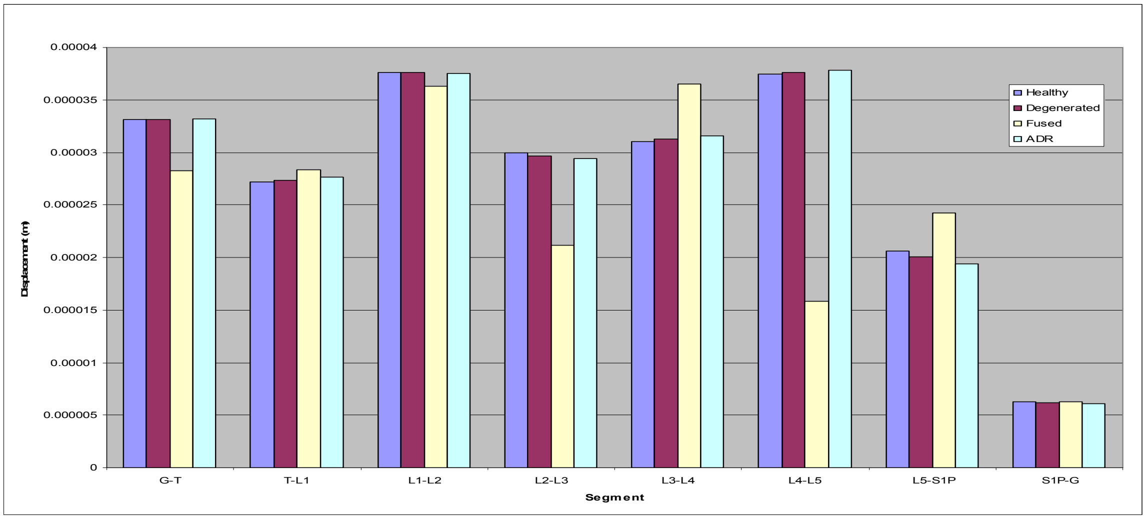


Figure 5-21: Posterior Anterior response of a Shear-compressive ADR at L4-L5

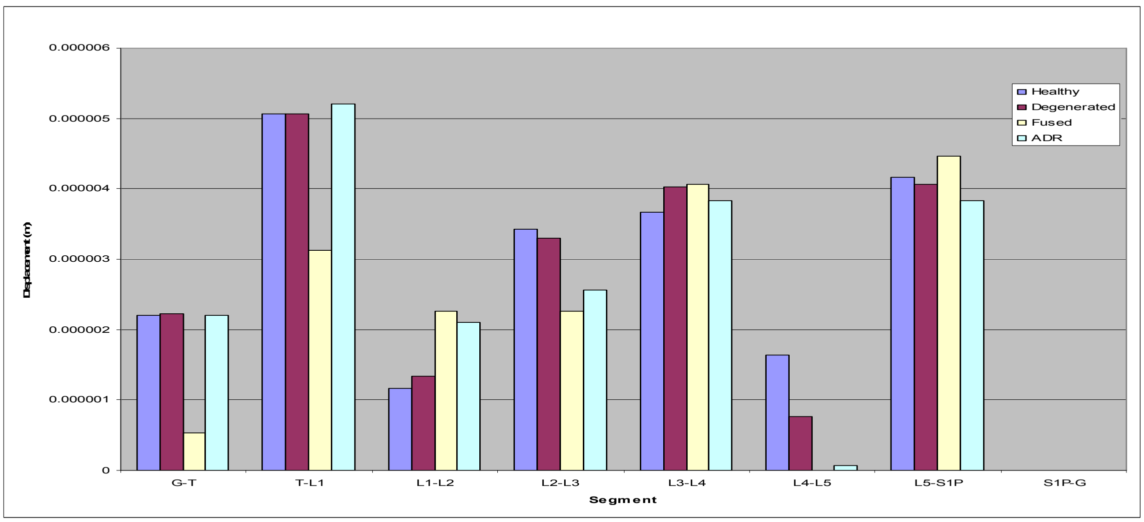


Figure 5-22: Axial response of a Shear-compressive ADR at L4-L5

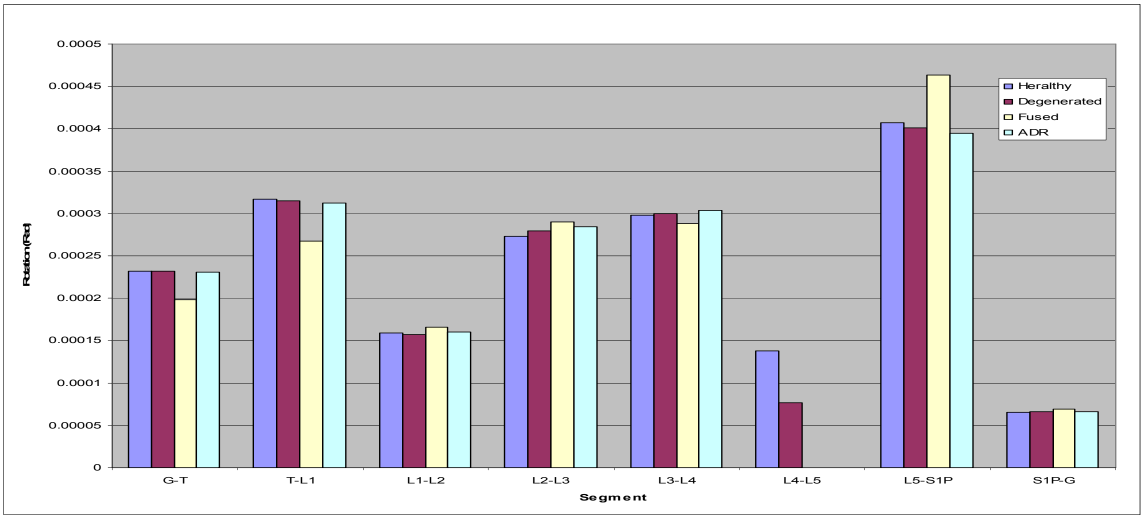


Figure 5-23: Flexion Extension response of a Shear-compressive ADR at L4-L5

5.2.1.2 Compressive-Rotational ADR

Figures 5-24 – 5-26 show the response of the lumbar spine to an impulsive shearing force acting on L3. The figures include the response of a spine with a degenerated disc, fused disc and a compressive-rotational ADR at the L4 – L5 level as well as the response of a healthy spine.

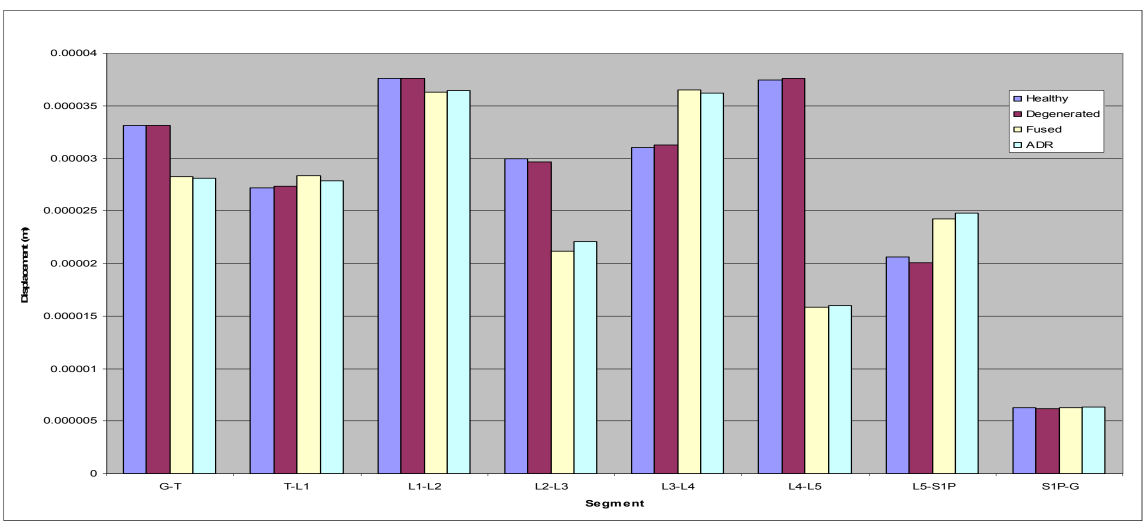


Figure 5-24: Posterior Anterior response of a compressive-rotational ADR al L4-L5

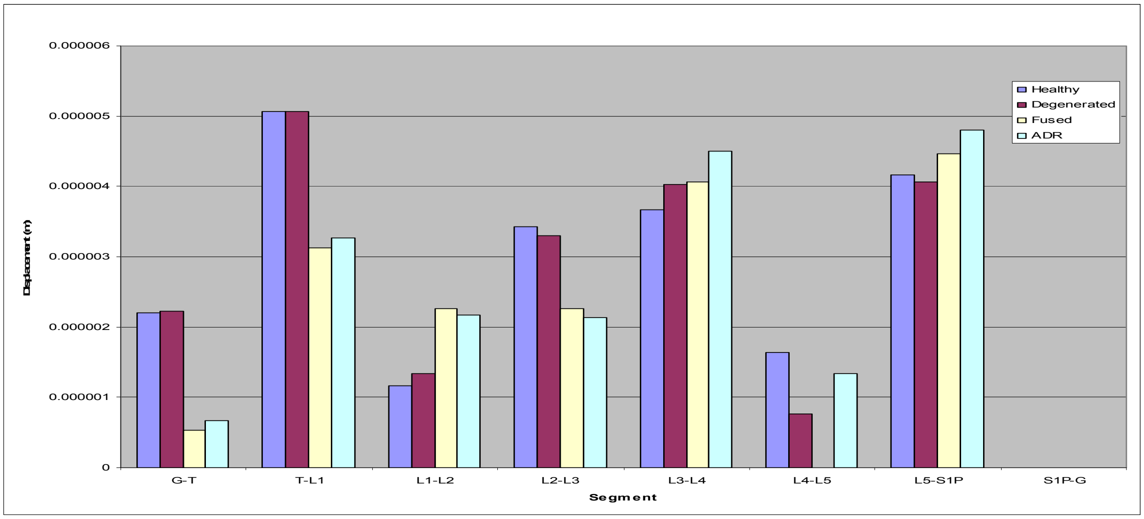


Figure 5-25: Axial response of a compressive-rotational ADR at L4-L5

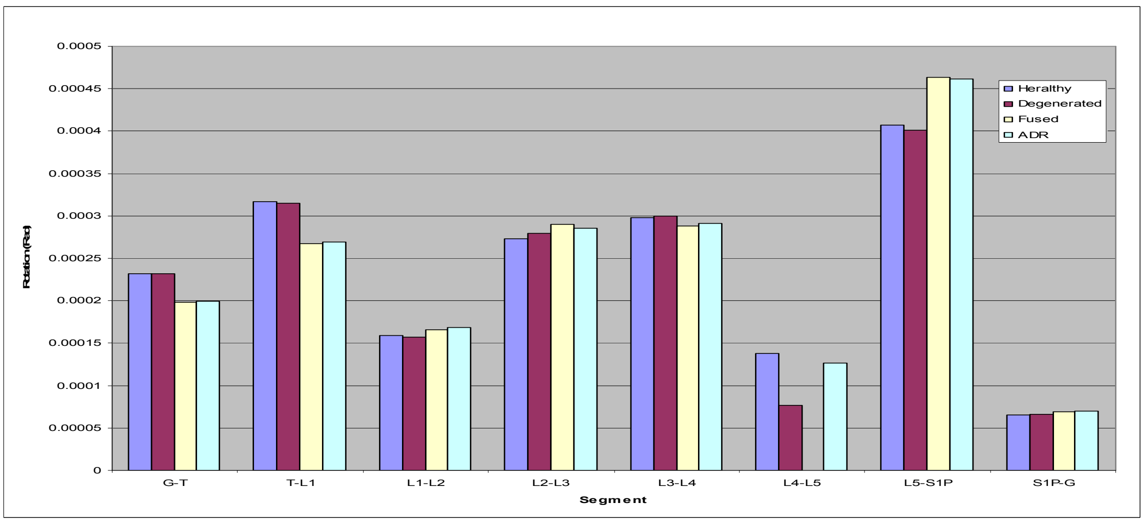


Figure 5-26: Flexion Extension response of a compressive-rotational ADR at L4-L5

5.2.1.3 Shear-Rotational ADR

Figures 5-27 – 5-29 show the response of the lumbar spine to an impulsive shearing force acting on L3. The figures include the response of a spine with a degenerated disc, fused disc and a Shear-rotational ADR at the L4 – L5 level as well as the response of a healthy spine.

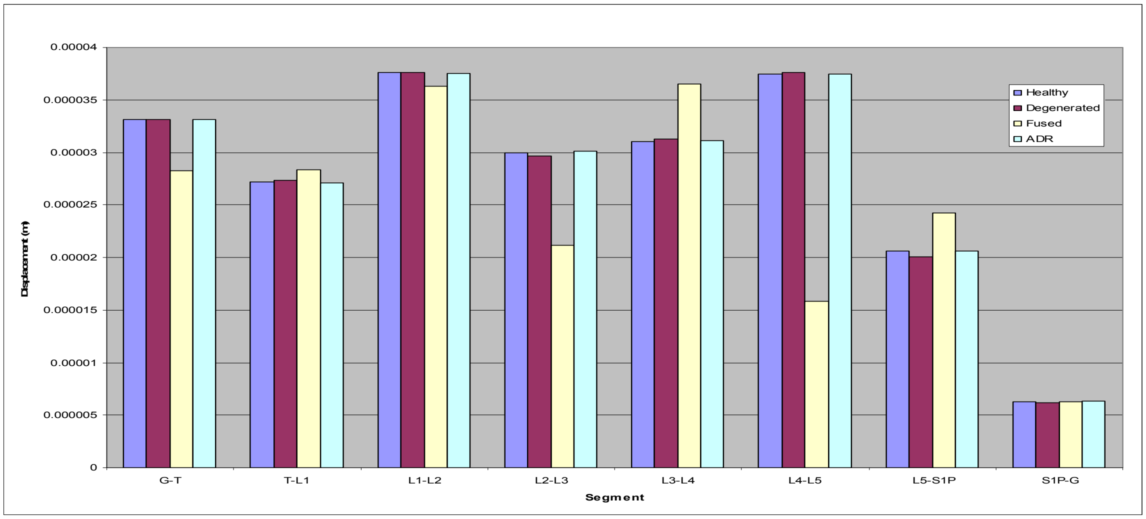


Figure 5-27: Posterior Anterior response of a Shear-rotational ADR at L4-L5

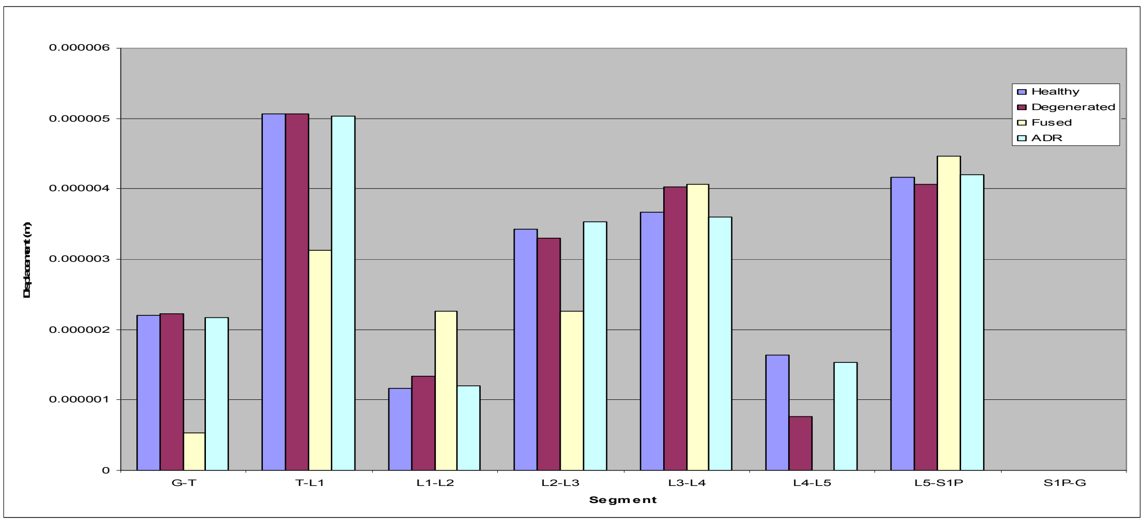


Figure 5-28: Axial response of a Shear-rotational ADR at L4-L5

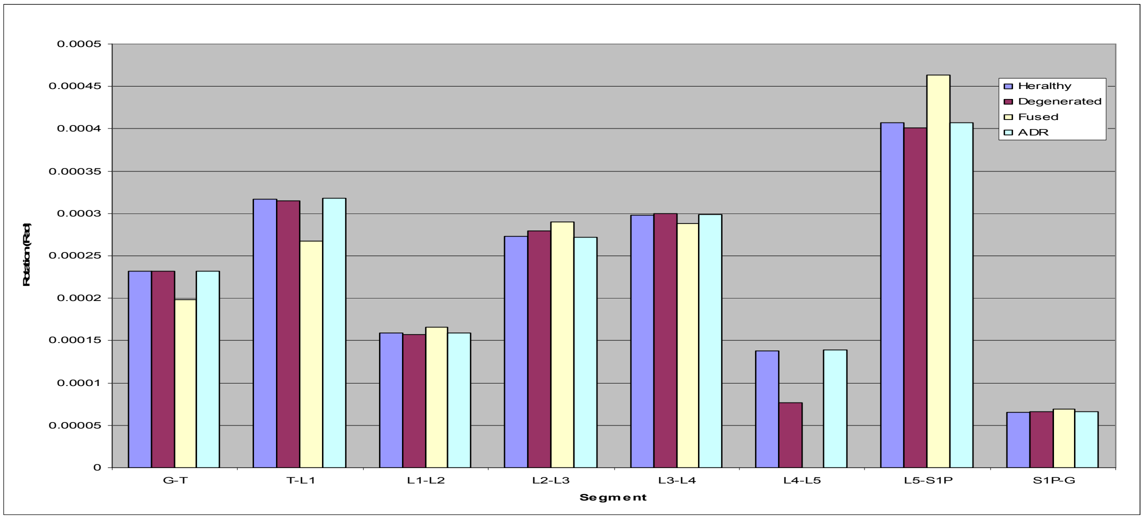


Figure 5-29: Flexion Extension response of a Shear-rotational ADR at L4-L5

5.2.1.4 Result Summary of Two Degree of Freedom L4 – L5 ADR's

Tables 5-7 through 5-9 show a comparative summary of the results obtained for each 2-degree of freedom L4 - L5 ADR case.

Table 5-7: Posterior Anterior intervertebral displacement summary for the 2-DOF L4-L5 ADR cases

	Posterior Anterior Intervertebral Displacement % Difference					
	T-L1	**L1-L2**	**L2-L3**	**L3-L4**	**L4-L5**	**L5-S1P**
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	0.61%	0.09%	-0.89%	0.75%	0.36%	-2.43%
Fused	4.17%	-3.46%	-29.48%	17.49%	-57.74%	17.64%
Shear-Compressive	1.72%	-0.09%	-1.89%	1.61%	0.98%	-5.99%
Compressive-Rotational	2.57%	-3.10%	-26.25%	16.63%	-57.30%	20.39%
Shear-Rotational	-0.37%	-0.09%	0.56%	0.21%	-0.09%	0.16%

Table 5-8: Axial intervertebral displacement summary for the 2-DOF L4-L5 ADR cases

	Axial Intervertebral Displacement % Difference					
	T-L1	**L1-L2**	**L2-L3**	**L3-L4**	**L4-L5**	**L5-S1P**
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	0.00%	14.29%	-3.88%	10.00%	-53.06%	-2.40%
Fused	-38.16%	94.29%	-33.98%	10.91%	-100.00%	7.20%
Shear-Compressive	2.63%	80.00%	-25.24%	4.55%	-95.92%	-8.00%
Compressive-Rotational	-35.53%	85.71%	-37.86%	22.73%	-18.37%	15.20%
Shear-Rotational	-0.66%	2.86%	2.91%	-1.82%	-6.12%	0.80%

Table 5-9: Flexion Extension intervertebral rotation summary for the 2-DOF L4-L5 ADR cases

	Flexion Extension Intervertebral Rotation % Difference					
	T-L1	**L1-L2**	**L2-L3**	**L3-L4**	**L4-L5**	**L5-S1P**
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	-0.62%	-0.86%	2.59%	0.47%	-44.77%	-1.60%
Fused	-15.90%	4.22%	6.35%	-3.46%	-99.93%	13.76%
Shear-Compressive	-1.57%	0.71%	4.41%	1.85%	-99.93%	-3.22%
Compressive-Rotational	-15.27%	5.85%	4.55%	-2.31%	-8.13%	13.36%
Shear-Rotational	0.22%	0.02%	-0.38%	0.22%	0.77%	0.01%

5.2.2 L5 – S1 Level Degeneration

The following results reflect the 2 degree of freedom ADR's, fused vertebrae and degenerated disc cases at the L5 – S1 level.

5.2.2.1 Shear-Compressive ADR

Figures 5-30 – 5-32 show the response of the lumbar spine to an impulsive shearing force acting on L3. The figures include the response of a spine with a degenerated disc, fused disc and a Shear-compressive ADR at the L5 – S1 level as well as the response of a healthy spine.

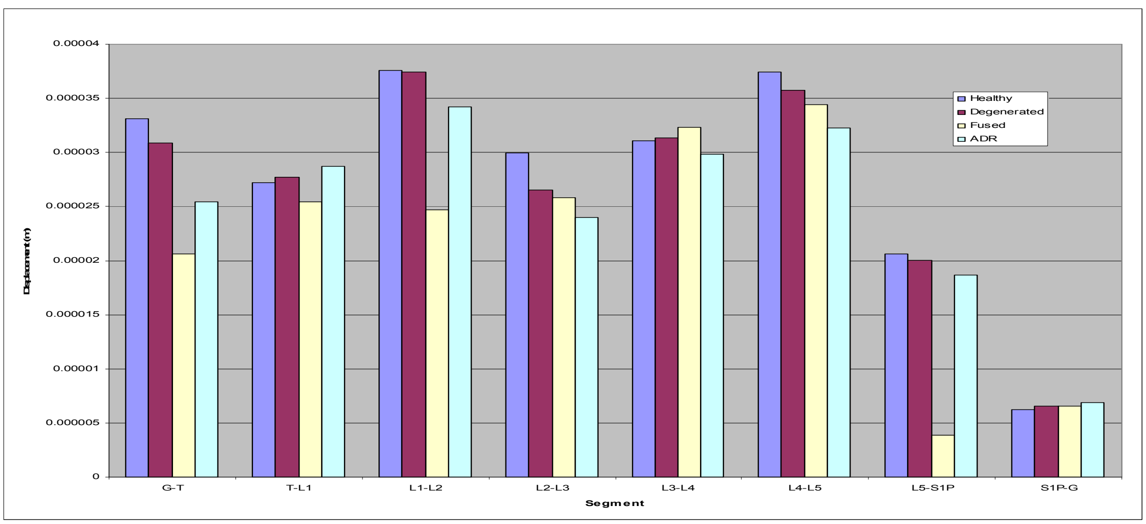


Figure 5-30: Posterior Anterior response of a Shear-compressive ADR at L5-S1

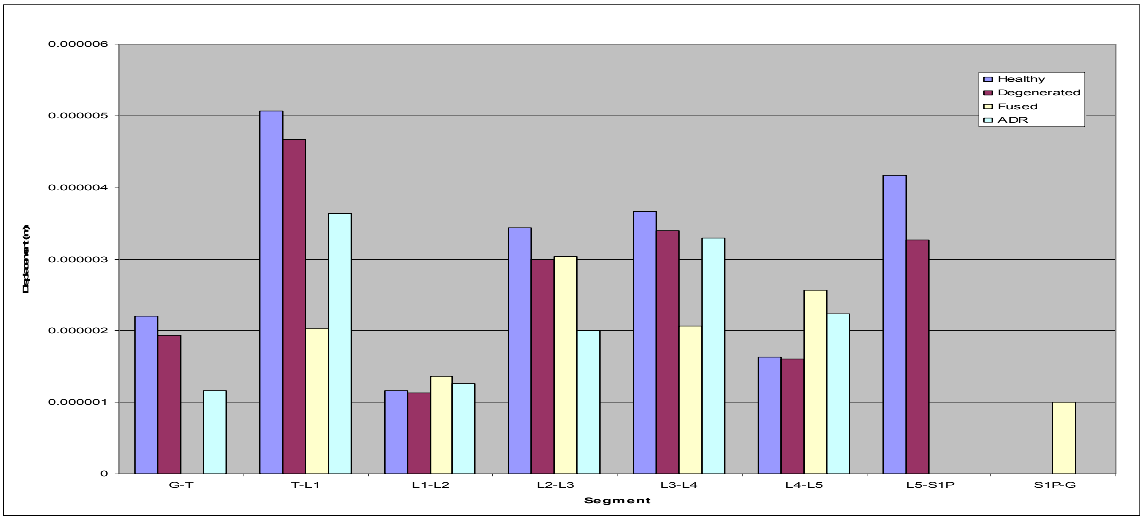


Figure 5-31: Axial response of a Shear-compressive ADR at L5-S1

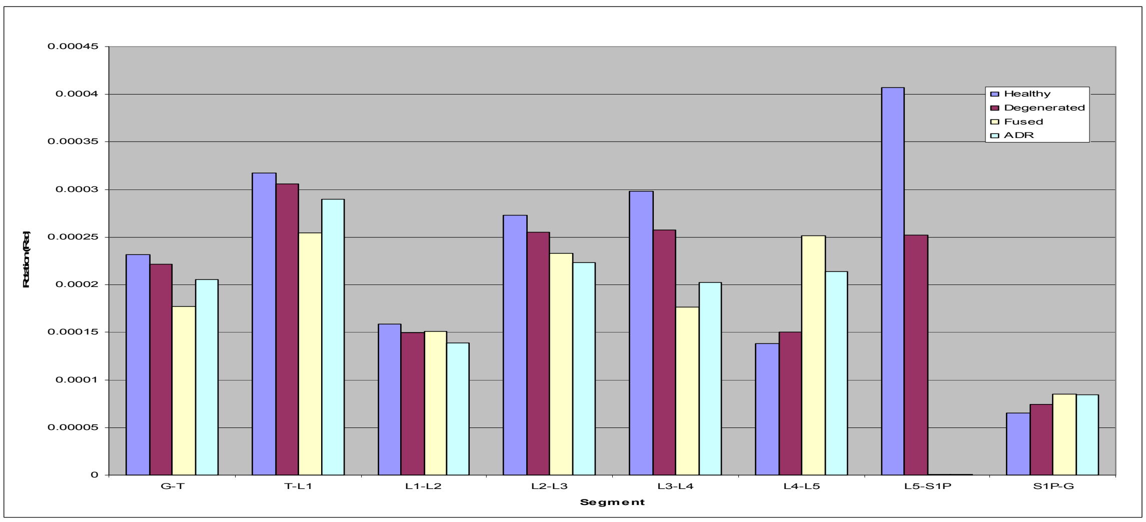


Figure 5-32: Flexion Extension response of a Shear-compressive ADR at L5-S1

5.2.2.2 Compressive-Rotational ADR

Figures 5-33 – 5-35 show the response of the lumbar spine to an impulsive shearing force acting on L3. The figures include the response of a spine with a degenerated disc, fused disc and a compressive-rotational ADR at the L5 – S1 level as well as the response of a healthy spine.

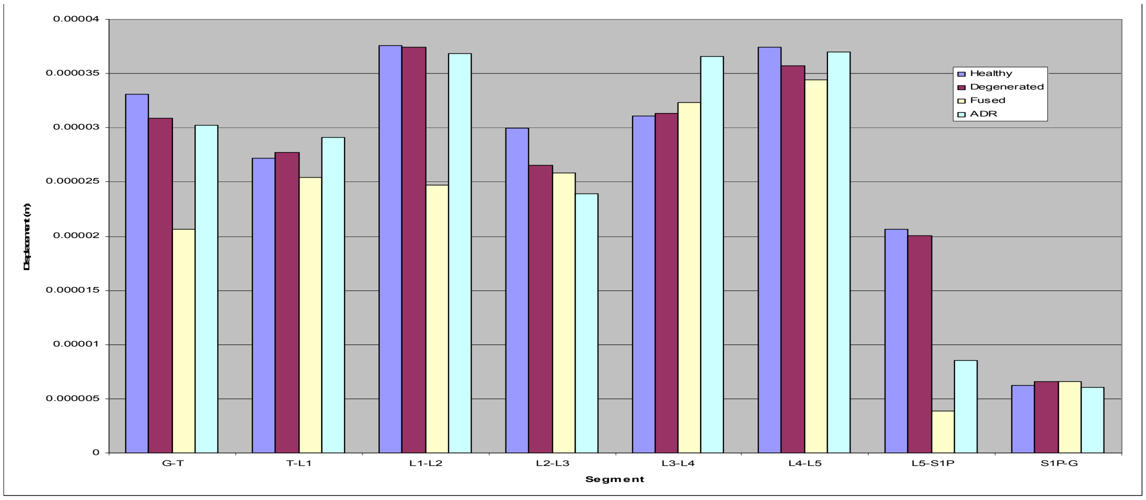


Figure 5-33: Posterior Anterior response of a compressive-rotational ADR at L5-S1

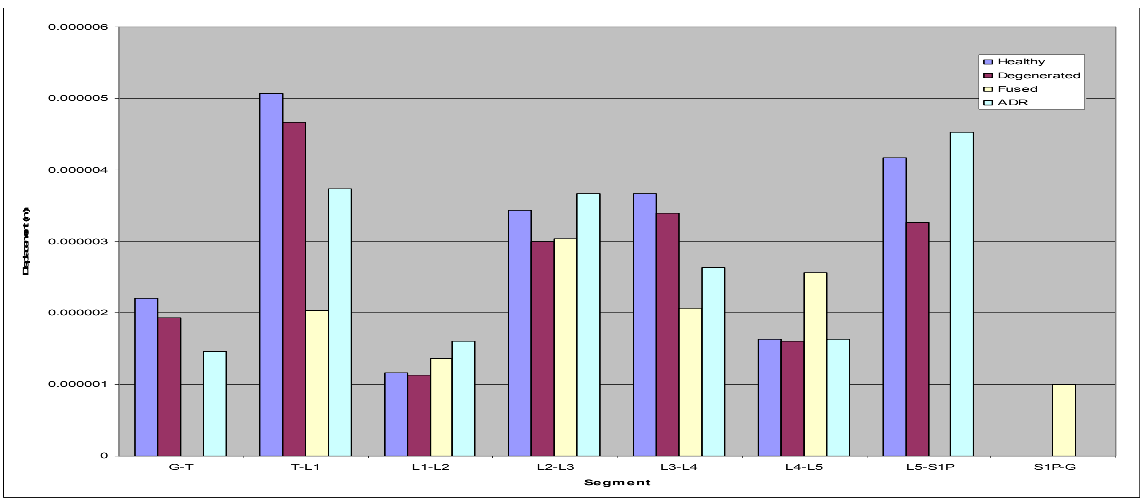


Figure 5-34: Axial response of a compressive-rotational ADR at L5-S1

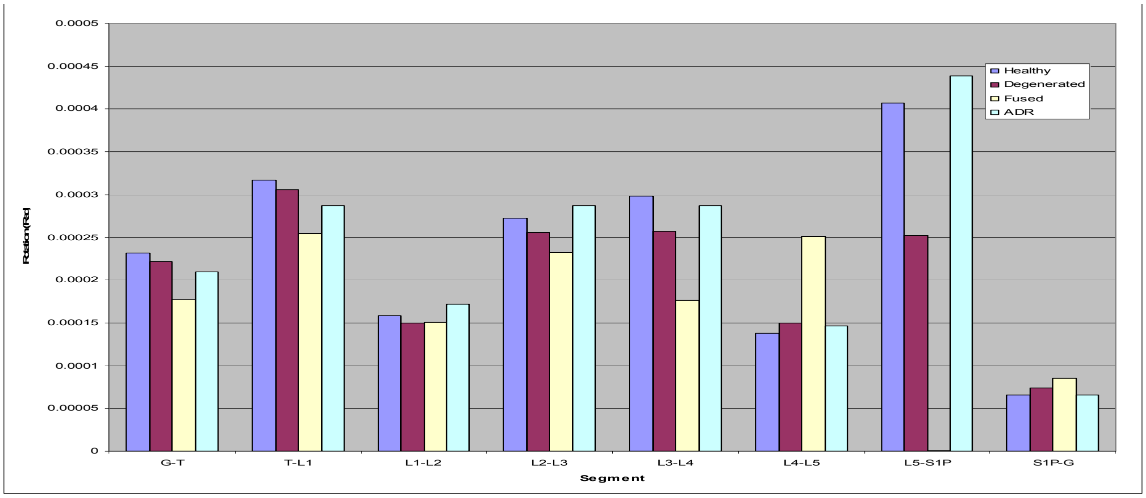


Figure 5-35: Flexion Extension response of a compressive-rotational ADR at L5-S1

5.2.2.3 Shear-Rotational ADR

Figures 5-36 – 5-38 show the response of the lumbar spine to an impulsive shearing force acting on L3. The figures include the response of a spine with a degenerated disc, fused disc and a Shear-rotational ADR at the L5 – S1 level as well as the response of a healthy spine.

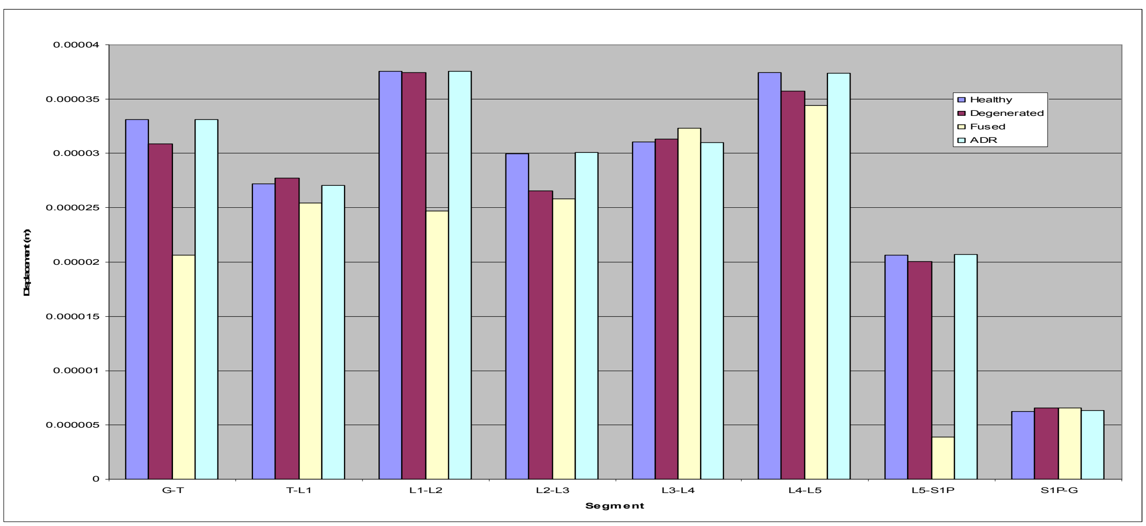


Figure 5-36: Anterior Posterior response of a Shear-rotational ADR at L5-S1

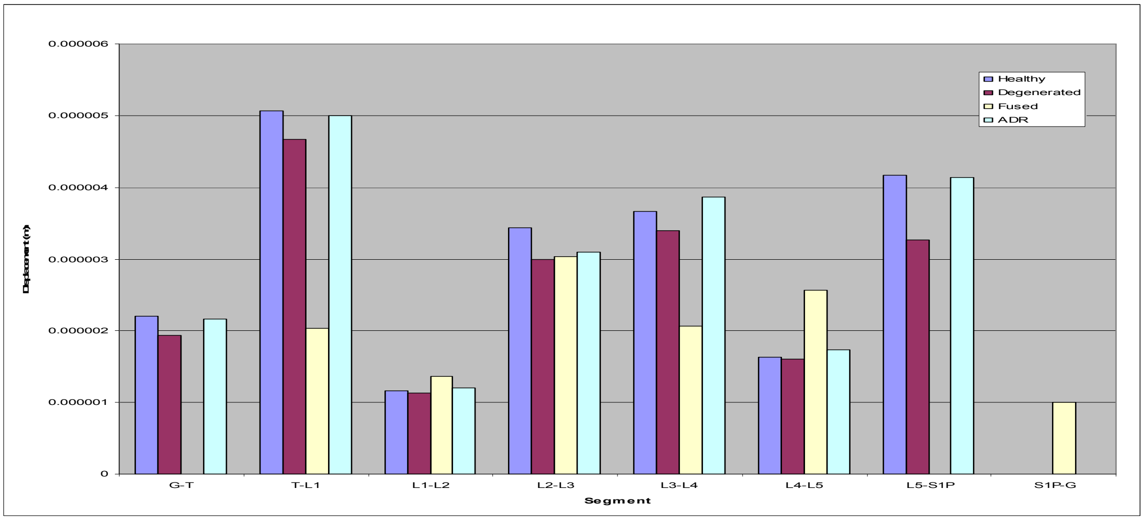


Figure 5-37: Axial response of a Shear-rotational ADR at L5-S1

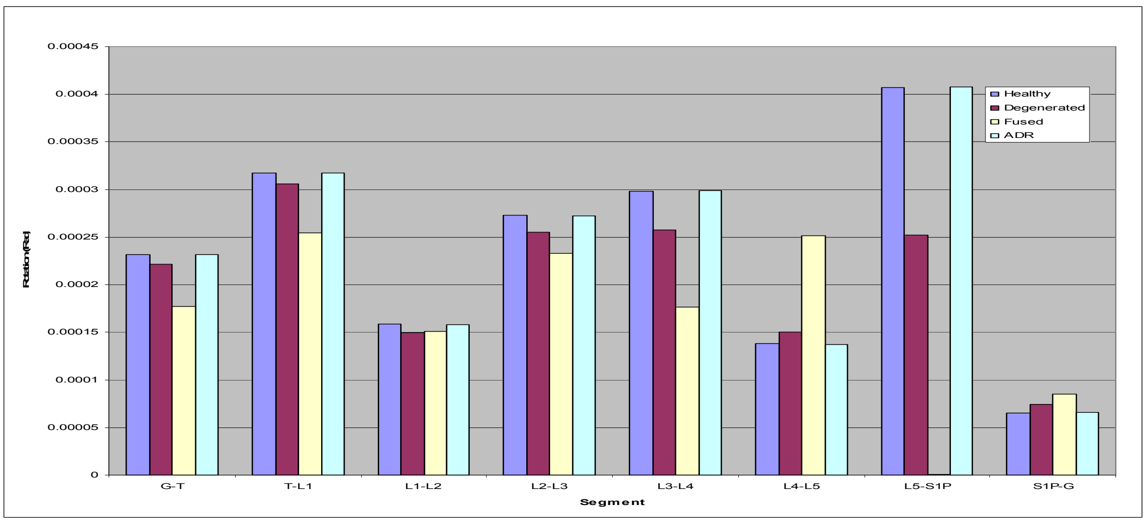


Figure 5-38: Flexion Extension response of a Shear-rotational ADR at L5-S1

5.2.2.4 Result Summary of Two Degree of Freedom L5 – S1 ADR's

Tables 5-10 through 5-12 show a comparative summary of the results obtained for each 2-degree of freedom L5 – S1 ADR case.

Table 5-10: Posterior Anterior intervertebral displacement summary for the 2-DOF L5-S1 ADR cases

	Posterior Anterior Intervertebral Displacement % Difference					
	T-L1	**L1-L2**	**L2-L3**	**L3-L4**	**L4-L5**	**L5-S1P**
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	1.96%	-0.35%	-11.35%	0.97%	-4.63%	-2.59%
Fused	-6.62%	-34.31%	-13.90%	3.97%	-8.19%	-81.23%
Shear-Compressive	5.51%	-8.95%	-20.02%	-4.08%	-13.88%	-9.39%
Compressive-Rotational	6.99%	-1.95%	-20.24%	17.70%	-1.25%	-58.58%
Shear-Rotational	-0.49%	0.00%	0.33%	-0.21%	-0.27%	0.49%

Table 5-11: Axial intervertebral displacement summary for the 2-DOF L5-S1 ADR cases

	Axial Intervertebral Displacement % Difference					
	T-L1	**L1-L2**	**L2-L3**	**L3-L4**	**L4-L5**	**L5-S1P**
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	-7.89%	-2.86%	-12.62%	-7.27%	-2.04%	-21.60%
Fused	-59.87%	17.14%	-11.65%	-43.64%	57.14%	-100.00%
Shear-Compressive	-28.29%	8.57%	-41.75%	-10.00%	36.73%	-100.00%
Compressive-Rotational	-26.32%	37.14%	6.80%	-28.18%	0.00%	8.80%
Shear-Rotational	-1.32%	2.86%	-9.71%	5.45%	6.12%	-0.80%

Table 5-12: Flexion Extension intervertebral rotation summary for the 2-DOF L5-S1 ADR cases

	Flexion Extension Intervertebral Rotation % Difference					
	T-L1	**L1-L2**	**L2-L3**	**L3-L4**	**L4-L5**	**L5-S1P**
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	-3.64%	-5.77%	-6.26%	-13.62%	8.59%	-38.07%
Fused	-19.73%	-5.03%	-14.65%	-40.88%	82.21%	-99.88%
Shear-Compressive	-8.77%	-12.54%	-18.29%	-32.12%	55.18%	-99.86%
Compressive-Rotational	-9.49%	8.50%	5.35%	-3.61%	5.99%	7.63%
Shear-Rotational	0.06%	-0.55%	-0.09%	0.28%	-0.39%	0.02%

5.3 Three Degree of Freedom Artificial Disc

The artificial discs results for the three degree of freedom cases have been divided in two, implanted at L4 – L5 and L5 – S1 levels. The following results show the behavior of the spine with the artificial disc, fused disc and degenerated disc at each level.

5.3.1 L4 – L5 Level Degeneration

Figures 5-39 – 5-41 show the response of the lumbar spine to an impulsive shearing force acting on L3. The figures include the response of a spine with a degenerated disc, fused disc and a full 3-degree of freedom ADR at the L4 – L5 level as well as the response of a healthy spine. It is assumed that the 3-DOF ADR exactly matches the healthy disc, so the results for the ADR and the healthy disc are identical in this section.

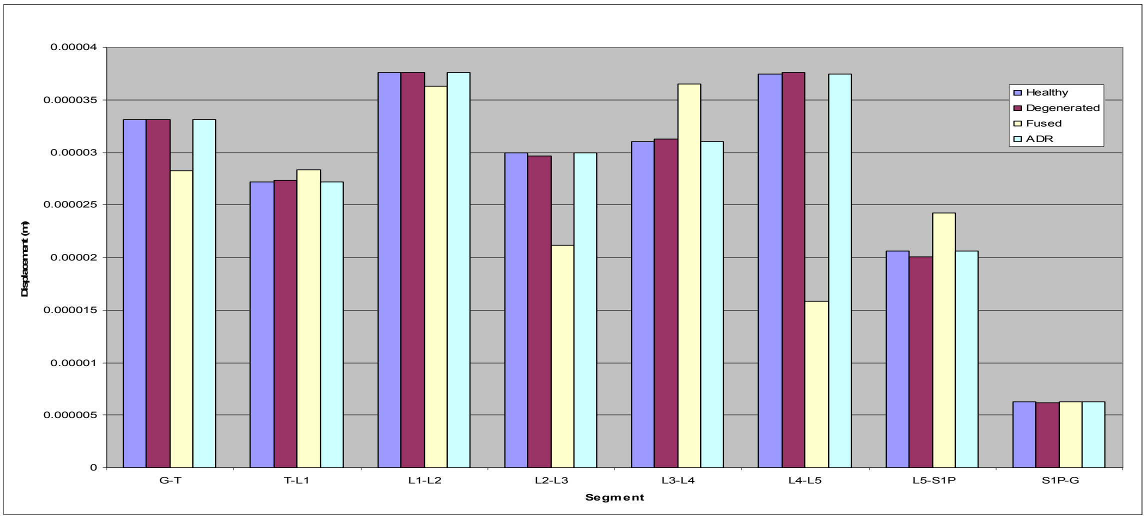


Figure 5-39: Anterior Posterior response of a full 3-degree of freedom ADR at L4-L5

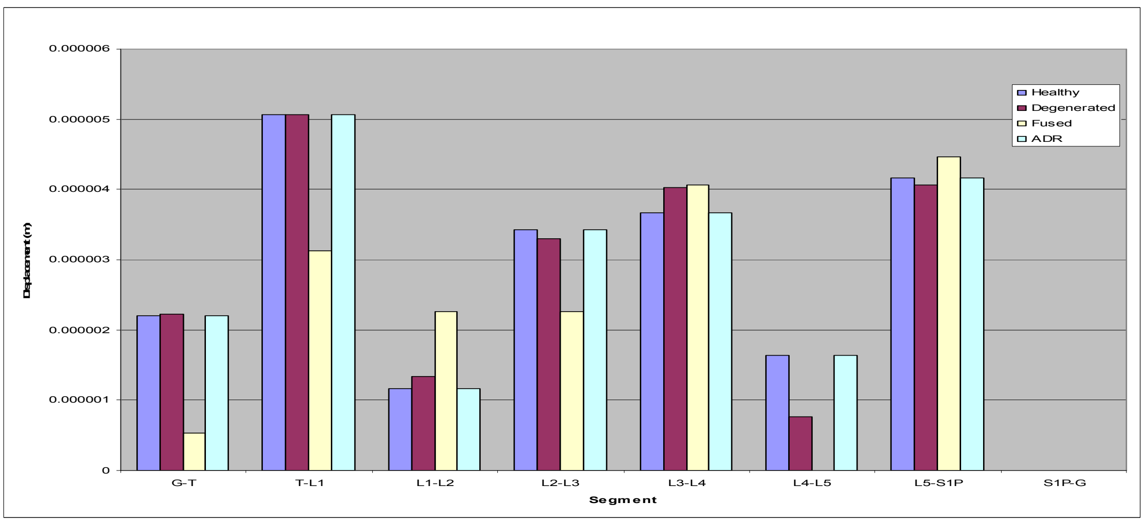


Figure 5-40: Axial response of a full 3-degree of freedom ADR at L4-L5

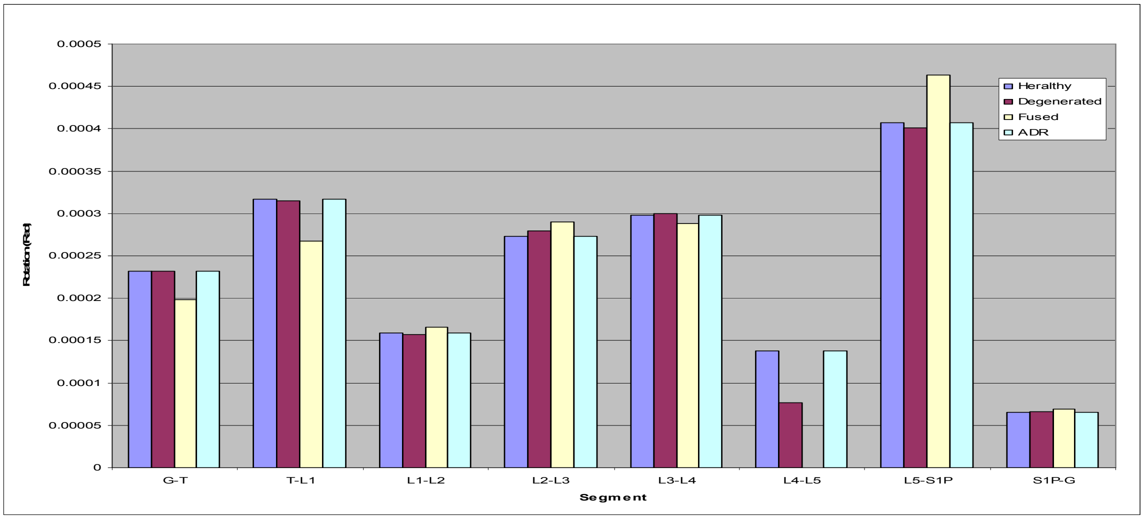


Figure 5-41: Flexion Extension response of a full 3-degree of freedom ADR at L4-L5

5.3.1.1 Result Summary of Three Degree of Freedom L4 – L5 ADR's

Tables 5-13 through 5-15 show a comparative summary of the results obtained for each 3-degree of freedom L4 – L5 ADR case.

Table 5-13: Posterior Anterior intervertebral displacement summary for the 3-DOF L4-L5 ADR case

	Posterior Anterior Intervertebral Displacement % Difference					
	T-L1	**L1-L2**	**L2-L3**	**L3-L4**	**L4-L5**	**L5-S1P**
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	0.61%	0.09%	-0.89%	0.75%	0.36%	-2.43%
Fused	4.17%	-3.46%	-29.48%	17.49%	-57.74%	17.64%
3-DOF	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Table 5-14: Axial intervertebral displacement summary for the 3-DOF L4-L5 ADR case

	Axial Intervertebral Displacement % Difference					
	T-L1	**L1-L2**	**L2-L3**	**L3-L4**	**L4-L5**	**L5-S1P**
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	0.00%	14.29%	-3.88%	10.00%	-53.06%	-2.40%
Fused	-38.16%	94.29%	-33.98%	10.91%	-100.00%	7.20%
3-DOF	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Table 5-15: Flexion Extension intervertebral rotation summary for the 3-DOF L4-L5 ADR case

	Flexion Extension Intervertebral Rotation % Difference					
	T-L1	**L1-L2**	**L2-L3**	**L3-L4**	**L4-L5**	**L5-S1P**
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	-0.62%	-0.86%	2.59%	0.47%	-44.77%	-1.60%
Fused	-15.90%	4.22%	6.35%	-3.46%	-99.93%	13.76%
3-DOF	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

5.3.2 L5 – S1 Level Degeneration

Figures 5-42 – 5-44 show the response of the lumbar spine to an impulsive shearing force acting on L3. The figures include the response of a spine with a degenerated disc, fused disc and a full 3-degree of freedom ADR at the L5 – S1 level as well as the response of a healthy spine. It is assumed that the 3-DOF ADR exactly matches the healthy disc, so the results for the ADR and the healthy disc are identical in this section.

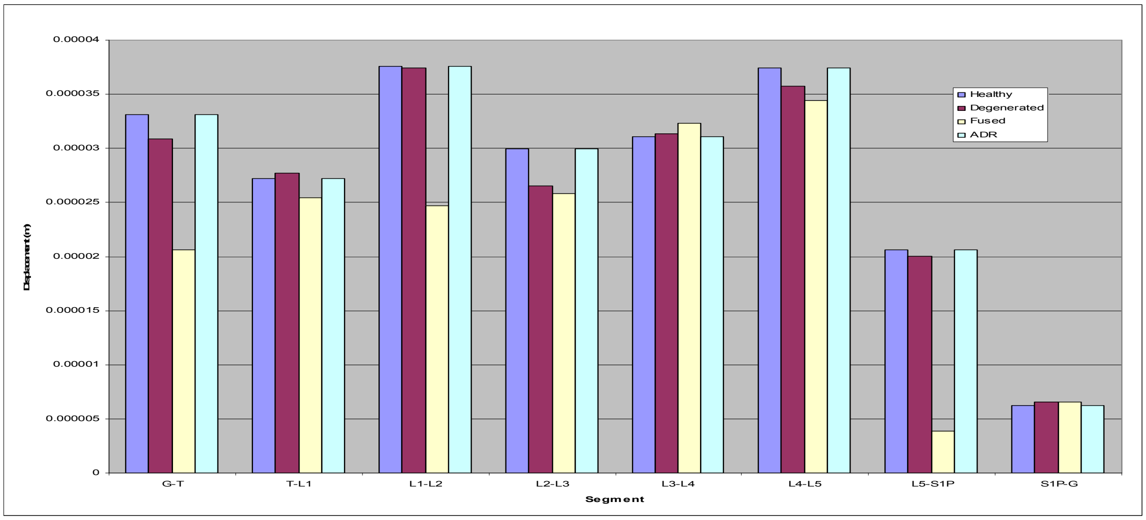


Figure 5-42: Anterior Posterior response of a full 3-degree of freedom ADR at L5-S1

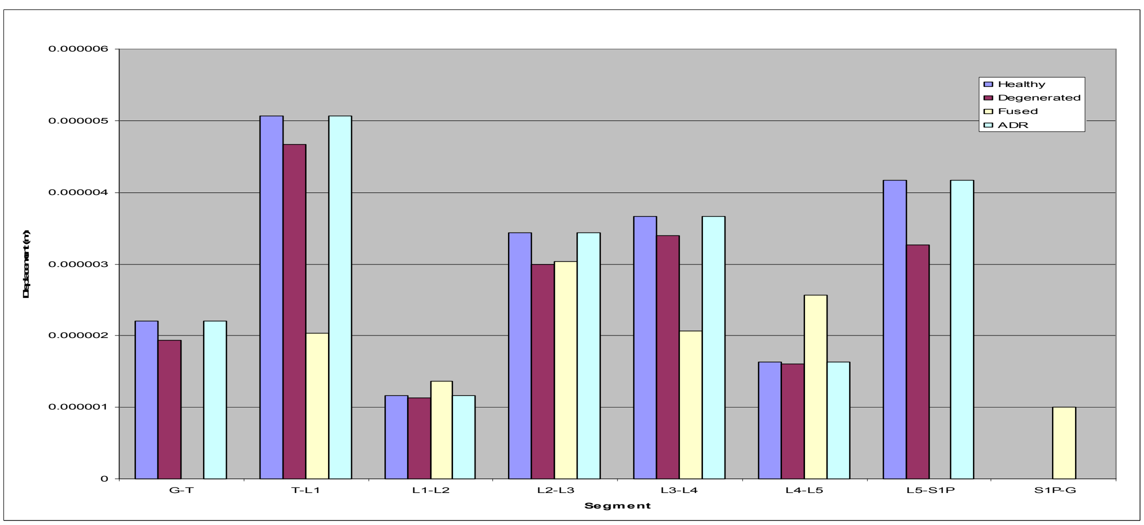


Figure 5-43: Axial response of a full 3-degree of freedom ADR at L5-S1

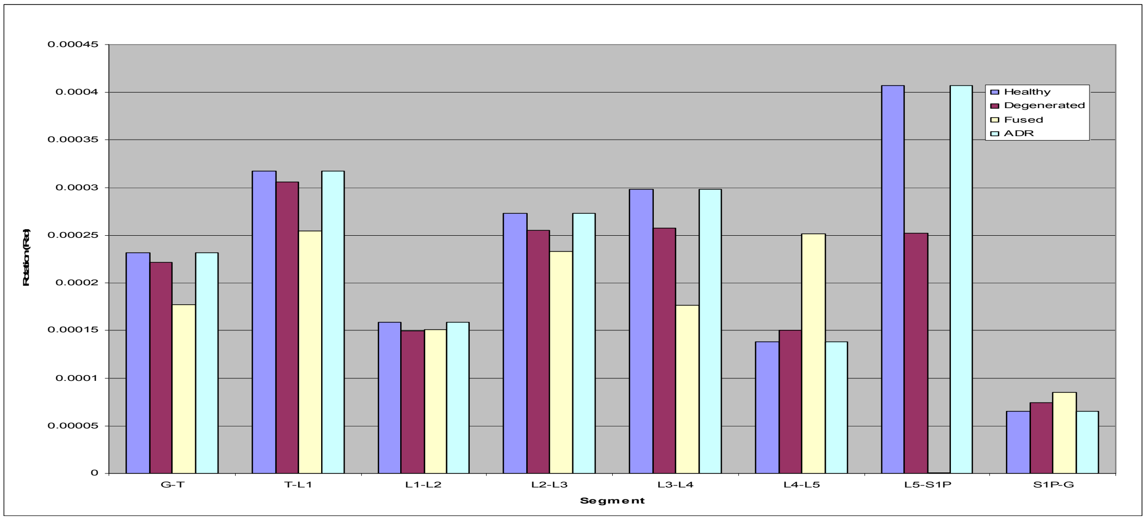


Figure 5-44: Flexion Extension response of a full 3-degree of freedom ADR at L5-S1

5.3.2.1 Result Summary of Three Degree of Freedom L5 – S1 ADR's

Tables 5-16 through 5-18 show a comparative summary of the results obtained for each 3-degree of freedom L5–S1 ADR case.

Table 5-16: Posterior Anterior intervertebral displacement summary for the 3-DOF L5-S1 ADR case

	Posterior Anterior Intervertebral Displacement % Difference					
	T-L1	**L1-L2**	**L2-L3**	**L3-L4**	**L4-L5**	**L5-S1P**
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	-9.80%	13.36%	-22.60%	1.86%	-9.54%	-1.03%
Fused	-20.39%	-38.66%	-84.93%	-6.45%	-20.88%	-79.49%
3-DOF	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Table 5-17: Axial intervertebral displacement summary for the 3-DOF L5-S1 ADR case

	Axial Intervertebral Displacement % Difference					
	T-L1	**L1-L2**	**L2-L3**	**L3-L4**	**L4-L5**	**L5-S1P**
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	-7.89%	-2.86%	-12.62%	-7.27%	-2.04%	-21.60%
Fused	-59.87%	17.14%	-11.65%	-43.64%	57.14%	-100.00%
3-DOF	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Table 5-18: Flexion Extension intervertebral rotation summary for the 3-DOF L5-S1 ADR case

	Flexion Extension Intervertebral Rotation % Difference					
	T-L1	**L1-L2**	**L2-L3**	**L3-L4**	**L4-L5**	**L5-S1P**
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	-3.64%	-5.77%	-6.26%	-13.62%	8.59%	-38.07%
Fused	-19.73%	-5.03%	-14.65%	-40.88%	82.21%	-99.88%
3-DOF	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

5.4 Results Summary

The following tables summarize all the results obtained by level of implantation, L4 – L5 and L5 – S1.

5.4.1 L4 – L5 ADR's

Tables 5-19 through 5-21 show a comparative summary of all the results obtained for each ADR case implanted at the L4 – L5 level.

Table 5-19: Posterior Anterior intervertebral displacement summary for all L4-L5 ADR cases

	Posterior Anterior Intervertebral Displacement % Difference					
	T-L1	L1-L2	L2-L3	L3-L4	L4-L5	L5-S1P
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	0.20%	0.61%	1.13%	1.58%	0.52%	-2.31%
Fused	-23.14%	19.64%	-58.19%	15.90%	-58.63%	26.92%
Shear	0.39%	0.40%	1.32%	2.01%	1.68%	-6.41%
Compressive	-22.94%	19.23%	-58.19%	15.76%	-58.25%	25.90%
Rotational	-23.92%	19.84%	-58.19%	15.04%	-57.99%	28.72%
Shear-Compressive	0.39%	0.61%	2.07%	2.15%	2.19%	-6.41%
Compressive-Rotational	-23.73%	20.04%	-58.38%	15.33%	-57.73%	27.69%
Shear-Rotational	0.20%	-0.20%	-0.19%	0.00%	-0.13%	0.26%
3-DOF	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Table 5-20: Axial intervertebral displacement summary for all L4-L5 ADR cases

	Axial Intervertebral Displacement % Difference					
	T-L1	L1-L2	L2-L3	L3-L4	L4-L5	L5-S1P
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	0.00%	14.29%	-3.88%	10.00%	-53.06%	-2.40%
Fused	-38.16%	94.29%	-33.98%	10.91%	-100.00%	7.20%
Shear	3.95%	77.14%	-30.10%	8.18%	-100.00%	-8.80%
Compressive	-34.21%	94.29%	-25.24%	4.55%	-95.92%	7.20%
Rotational	-40.79%	82.86%	-36.89%	14.55%	-30.61%	16.00%
Shear-Compressive	2.63%	80.00%	-25.24%	4.55%	-95.92%	-8.00%
Compressive-Rotational	-35.53%	85.71%	-37.86%	22.73%	-18.37%	15.20%
Shear-Rotational	-0.66%	2.86%	2.91%	-1.82%	-6.12%	0.80%
3-DOF	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Table 5-21: Flexion Extension intervertebral rotation summary for all L4-L5 ADR cases

	Flexion Extension Intervertebral Rotation % Difference					
	T-L1	L1-L2	L2-L3	L3-L4	L4-L5	L5-S1P
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	-0.62%	-0.86%	2.59%	0.47%	-44.77%	-1.60%
Fused	-15.90%	4.22%	6.35%	-3.46%	-99.93%	13.76%
Shear	-1.10%	0.29%	4.20%	1.75%	-99.88%	-2.36%
Compressive	-16.00%	3.94%	6.29%	-3.32%	-99.86%	13.64%
Rotational	-15.08%	5.81%	4.58%	-2.41%	-7.70%	13.41%
Shear-Compressive	-1.57%	0.71%	4.41%	1.85%	-99.93%	-3.22%
Compressive-Rotational	-15.27%	5.85%	4.55%	-2.31%	-8.13%	13.36%
Shear-Rotational	0.22%	0.02%	-0.38%	0.22%	0.77%	0.01%
3-DOF	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

5.4.2 L5 – S1 ADR's

Tables 5-19 through 5-21 show a comparative summary of all the results obtained for each ADR case implanted at the L5 – S1 level.

Table 5-22: Posterior Anterior intervertebral displacement summary for all L5-S1 ADR cases

	Posterior Anterior Intervertebral Displacement % Difference					
	T-L1	L1-L2	L2-L3	L3-L4	L4-L5	L5-S1P
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	1.96%	-0.35%	-11.35%	0.97%	-4.63%	-2.59%
Fused	-6.62%	-34.31%	-13.90%	3.97%	-8.19%	-81.23%
Shear	5.27%	-8.95%	-20.36%	-3.76%	-14.23%	-9.06%
Compressive	-6.25%	-34.22%	-14.24%	3.76%	-8.45%	-81.23%
Rotational	7.11%	-1.77%	-20.36%	17.81%	-1.25%	-58.58%
Shear-Compressive	5.51%	-8.95%	-20.02%	-4.08%	-13.88%	-9.39%
Compressive-Rotational	6.99%	-1.95%	-20.24%	17.70%	-1.25%	-58.58%
Shear-Rotational	-0.49%	0.00%	0.33%	-0.21%	-0.27%	0.49%
3-DOF	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Table 5-23: Axial intervertebral displacement summary for all L5-S1 ADR cases

	Axial Intervertebral Displacement % Difference					
	T-L1	L1-L2	L2-L3	L3-L4	L4-L5	L5-S1P
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	-7.89%	-2.86%	-12.62%	-7.27%	-2.04%	-21.60%
Fused	-59.87%	17.14%	-11.65%	-43.64%	57.14%	-100.00%
Shear	-30.92%	20.00%	-42.72%	-10.00%	36.73%	-100.00%
Compressive	-59.21%	11.43%	-9.71%	-46.36%	14.29%	-83.20%
Rotational	-26.97%	34.29%	6.80%	-25.45%	-2.04%	8.80%
Shear-Compressive	-28.29%	8.57%	-41.75%	-10.00%	36.73%	-100.00%
Compressive-Rotational	-26.32%	37.14%	6.80%	-28.18%	0.00%	8.80%
Shear-Rotational	-1.32%	2.86%	-9.71%	5.45%	6.12%	-0.80%
3-DOF	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Table 5-24: Flexion Extension intervertebral rotation summary for all L5-S1 ADR cases

	Flexion Extension Intervertebral Rotation % Difference					
	T-L1	L1-L2	L2-L3	L3-L4	L4-L5	L5-S1P
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	-3.64%	-5.77%	-6.26%	-13.62%	8.59%	-38.07%
Fused	-19.73%	-5.03%	-14.65%	-40.88%	82.21%	-99.88%
Shear	-8.91%	-12.82%	-18.24%	-32.41%	55.03%	-99.89%
Compressive	-19.49%	-4.72%	-14.60%	-40.42%	81.20%	-99.84%
Rotational	-9.43%	8.35%	5.13%	-3.73%	6.44%	7.78%
Shear-Compressive	-8.77%	-12.54%	-18.29%	-32.12%	55.18%	-99.86%
Compressive-Rotational	-9.49%	8.50%	5.35%	-3.61%	5.99%	7.63%
Shear-Rotational	0.06%	-0.55%	-0.09%	0.28%	-0.39%	0.02%
3-DOF	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

6 Discussion of Results

Applying a posterior anterior impulsive force at the center of the lumbar spine, L3, served as an instructive disturbance of the system since this impulsive force caused the system to move in all directions of interest, posterior anterior displacement, axial displacement and flexion extension rotation as seen in Figures 5-1 and 5-2. The two methods, average of absolute magnitude of the displacements and rms values provided a good summary of the behavior of the system, but using the average magnitude of the displacements provided a less biased point of comparison than the rms values since the rms values accentuated the spike responses caused by the impulsive force disturbance of the system. Clinical trials will need to be done to determine if the amplitude of the response is of more significance than the length of the response. Since this project assumes that hypomobility is one of the main causes of disc degeneration, the total length of the response was chosen over the amplitude of the response. Nonetheless, it can be seen by studying the rms results presented in the appendix that both methods yield the same basic conclusions.

It can be observed from the vertebral healthy lumbar spine response in Figure 5-1 that the maximum posterior-anterior (PA) displacement was obtained at L3, the maximum axial displacement (AX) was obtained at L5 and the maximum flexion-extension (FE) rotation at L5. Since the force was applied at L3 in the PA direction, it seems logical that the maximum PA displacement was obtained at L3, but that the maximum AX displacement and FE rotation were obtained at L5 is unexpected and very interesting. These results could support why the L4-L5 and L5-S1 discs are the two discs that have the greatest incidence of degeneration. The vertebral healthy spine response results show how an applied force can cause a much greater effect away from the point of application.

By inspecting Figure 5-2, it can be observed that the intervertebral disc that experienced the largest PA displacement was L4-L5 and that the highest AX displacement and FE rotation was experienced by L5-S1, thus showing which two discs experience the greatest deformations caused by the impulsive force at L3. These results provide good evidence to show that the L4-L5 and the L5-S1 discs are the two discs that have the highest chances of degeneration, since they are affected the most by the input force. Additionally, the relationship between Figure 5-1 and Figure 5-2 is very clear, noting that where Figure 5-1 changes slope, Figure 5-2 changes sign.

Examining the behavior of the degenerated discs at both the L4-L5 and L5-S1 levels, the degenerated disc reduces the motion of the next adjacent disc, by more than 2.0% at L5-S1 and by more than 1.5% at L4-L5 respectively. This tendency of reduced mobility may be the cause of future accelerated degeneration of the disc.

Similarly, examining the behavior of the fused vertebrae case at L5-S1, it can be observed that the motion of the L4-L5 disc is increased significantly, more than 50% in the AX direction and in FE rotation, but it decreases by 8.1% in the PA direction. Additionally, when the fusion happens at the L4-L5 level, there is also a tendency of increased mobility at the L5-S1 disc of 17.6% in the PA direction, 7.2% in the AX direction, and 13.8% in the FE rotation. This doesn't prove that either the L4-L5 or the L5-S1 disc degenerated quicker because of hypo mobility, but may be a hint of higher stresses at each level due to larger than normal displacements and rotations that could be studied in a future project.

In the 1-DOF ADR cases at the L4-L5 level, the shear ADR performed better than the other two ADR, and much better than the fused vertebrae case since it matched the behavior of the healthy spine much closer. This is evident in Figures 5-3 through 5-11 and Tables 5-1 through 5-3. Additionally, the effect caused by the shear ADR on the next adjacent level is smaller than the effect caused by disc fusion, possibly improving the degeneration rate. The second best choice for this level would be the rotational ADR since it also resembled the healthy spine better than the compressive ADR. Nonetheless, the behaviors of the compressive and rotational ADR were very similar to the behavior of the fused vertebrae, providing only slight improvements at very few segments as shown in Tables 5-1 through 5-3. When comparing all the 1-DOF ADR at L4-L5 to the fused vertebrae case only significant improvement can be observed from the shear ADR.

Overall, in the 1-DOF ADR at the L5-S1 level, the rotational ADR performed better than the other two ADR, and significantly better than the fused vertebrae case since it matched the behavior of the healthy spine much closer. This is evident in Figures 5-12 through 5-20 and Tables 5-4 through 5-6. Additionally, the effect caused by the rotational ADR on the next adjacent level is smaller than the effect caused by disc fusion, possibly improving the degeneration rate. The second best choice for this level would be the shear ADR since it also resembled the healthy spine better than the compressive ADR. Nonetheless, the behaviors of the compressive and rotational ADR were very similar to the behavior of the fused vertebrae, providing only slight improvements at very few segments as shown in Tables 5-1 through 5-3. When comparing all the 1-DOF ADR cases at L5-S1 to the fused vertebrae case only significant improvement can be observed from the rotational ADR.

From all the 1-DOF cases, it can be observed that only one main degree of freedom affected the behavior of the system, the shear at L4-L5 and the rotation at L5-S1. All the other cases provided little benefit, if any, when compared to the fused case.

In the 2-DOF ADR cases, the shear rotational ADR behaved very similarly to the healthy spine when implanted at both levels, L4-L5 and L5-S1. These results can be observed in Figures 5-21 through 5-38 and Tables 5-7 through 5-12. This ADR differed from the behavior of a healthy spine by less than 1% in the PA direction for both the L4-L5 and L5-S1 case, by less than 10% and 7% in the AX direction for the L5-S1 and L4-L5 cases respectively, and by less than 1% in the FE rotation for both L5-S1 and L4-L5 cases. Additionally, all ADR cases matched the overall behavior of the healthy spine more closely than the fused vertebrae did and had much smaller effects on the next adjacent level, possibly decreasing the rate of degeneration.

Inspecting Tables 5-19 through 5-24 shows that the 2-DOF ADR case that resembles the healthy spine the closest is the shear rotational ADR. The shear rotational 2-DOF ADR combines the best two ADR cases of the 1-DOF ADR, shear at the L4-L5 and rotational at the L5-S1 level. From these results it becomes apparent that the PA and FE motions are the two motions that influence the most the behavior of the spine. Also, the use of an ADR decreases the effect on the adjacent level, hence decreasing the rate of disc degeneration at the next adjacent level caused by hypo mobility.

7 Conclusion

The objective of this project was to develop a simplified, two-dimensional mathematical model of the lumbar spine for the purpose of studying the behavior of the lumbar spine when affected by degenerative disc disease. Several hypothetical treatment options, including disc fusion and different types of artificial disc replacements (ADR) were examined. The cases presented consisted of three one-degree of freedom artificial discs, three two-degrees of freedom artificial discs, one ideal three-degrees of freedom artificial disc, a degenerated disc, a fused disc and a healthy spine. The equations of motion were generated for a healthy lumbar spine using Lagrange's equations and input into an m-file to obtain numerical results of the model and the different cases using Matlab®. Results were obtained for all cases at two different levels, L4-L5 and L5-S1 in response to an impulsive force of 100N applied at L3 in the posterior anterior direction. The degenerated disc consistently decreased the motion of the next adjacent level, hinting accelerated degeneration of the next adjacent level caused by hypo mobility. The fused disc at L5-S1 case decreased the motion of the L4-L5 level, but the fused disc at L4-L5 increased the motion at the L5-S1 level. Studies need to be done to quantitatively examine the relationship between increased adjacent disc degeneration and finite element stress analysis of spinal fusion.

In the 1-DOF ADR cases at the L4-L5 level, the shear ADR performed better than the other two ADR, while at the L5-S1 level, the rotational ADR performed better than the other two ADR, and significantly better than the fused vertebrae case since it matched the behavior of the healthy spine more closely. All the other 1-DOF ADR provided little or no improvement when compared to the fused case. In the 2-DOF ADR cases, the shear rotational ADR behaved very similar to the healthy spine when implanted at both levels, L4-L5 and L5-S1, showing a behavior that varied by less than 1% in the PA direction and FE rotation and less than 10% in the AX displacement when compared to the behavior of a healthy spine. The shear rotational 2-DOF ADR combines the best two ADR cases of the 1-DOF ADR, shear at the L4-L5 and rotational at the L5-S1 level. From these results it can be concluded that the PA displacement and FE rotation are the two most influential motions on the behavior of the spine.

Overall, from the results of this thesis it can be concluded that implanting an artificial disc to replace a damaged disc offers more benefits for the spine than fusion since this allows the spine to behave more closely to natural healthy spine behavior, and hence most likely cause less damage to adjacent discs. Currently, the available technology limits the performance of an artificial disc, so it will never be a perfect match to a healthy disc, but an artificial disc still offers great benefits when compared to the current most popular treatment option, disc fusion, as shown in this thesis.

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9 Appendix

9.1 RMS Results

Figure 9-1 shows the vertebral response of the system to an impulsive shear force (posterior anterior) of 100N at the L3 level, displacements in mm and rotations in degrees for better visualization.

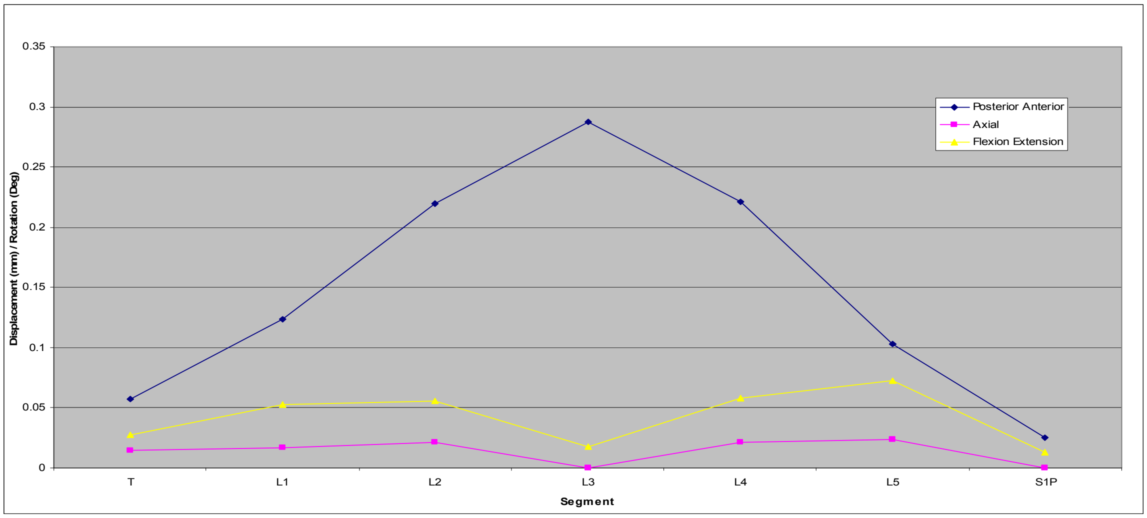

Figure 9-1: Vertebral response of a healthy lumbar spine to a 100N impulsive shear force at L3.

Figure 9-2 shows the relative intervertebral response of the system to an impulsive shear force (posterior anterior) of 100N at the L3 level, displacements in mm and rotations in degrees for better visualization.

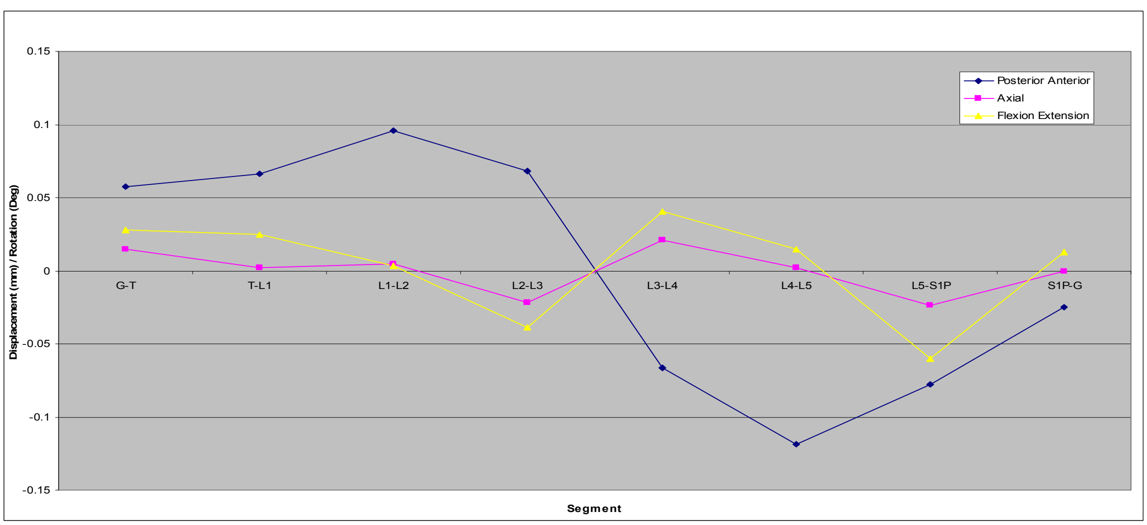

Figure 9-2: Intervertebral response of a healthy lumbar spine to a 100N impulsive shear force at L3.

9.2 One Degree of Freedom Artificial Discs (RMS)

The artificial discs results for the one degree of freedom case have been divided into three separate degrees of freedom x, y, and z or Shear, compressive and rotational respectively. Each disc was implanted at L4 – L5 and L5 – S1 levels. The following results are divided and presented by level and degree of freedom. Bar charts of all segments are presented to aid in the visualization of the overall trends and summary tables are presented at the end of each section where the differences can be compared quantitatively.

9.2.1 L4 – L5 Level Degeneration

The following results reflect the 1 degree of freedom ADR's, fused vertebrae and degenerated disc cases at the L4 – L5 level.

9.2.1.1 Shear ADR

Figures 9-3 – 9-5 show the response of the lumbar spine to an impulsive shearing force acting on L3. The figures include the response of a spine with a degenerated disc, fused disc and a Shear ADR at the L4 – L5 level as well as the response of a healthy spine.

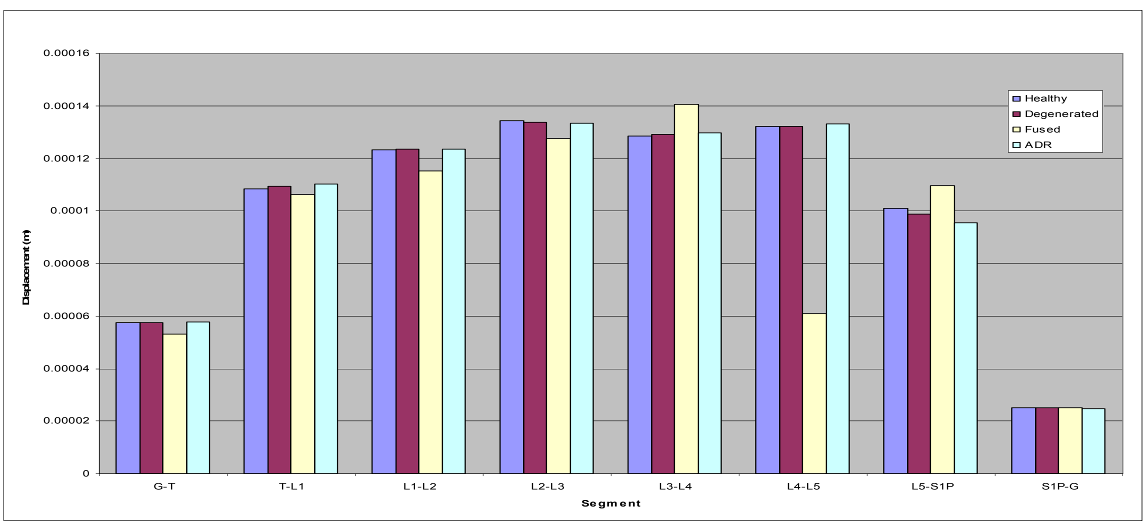

Figure 9-3: Posterior Anterior response of Shear ADR at L4-L5

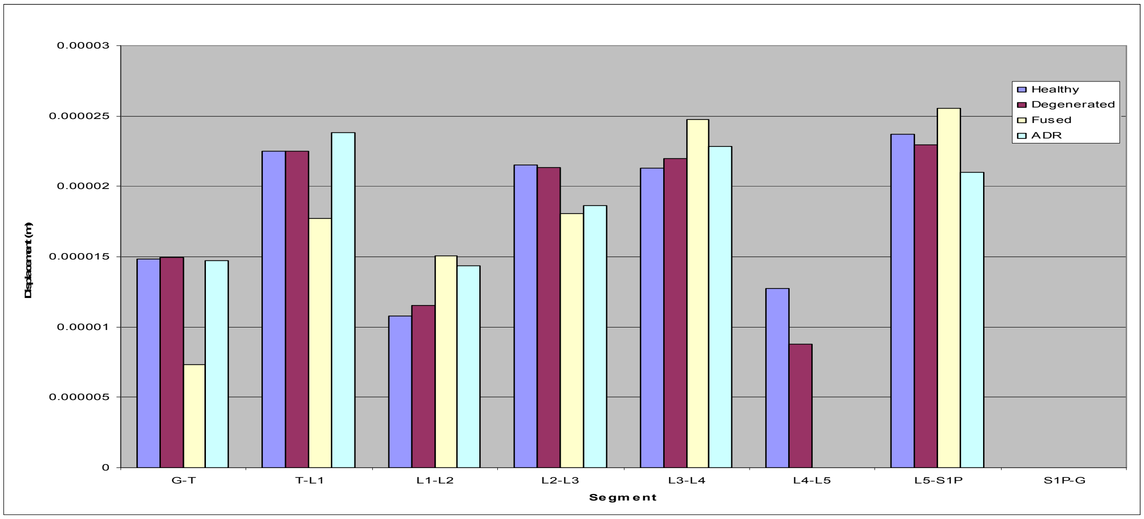

Figure 9-4: Axial response of Shear ADR at L4-L5

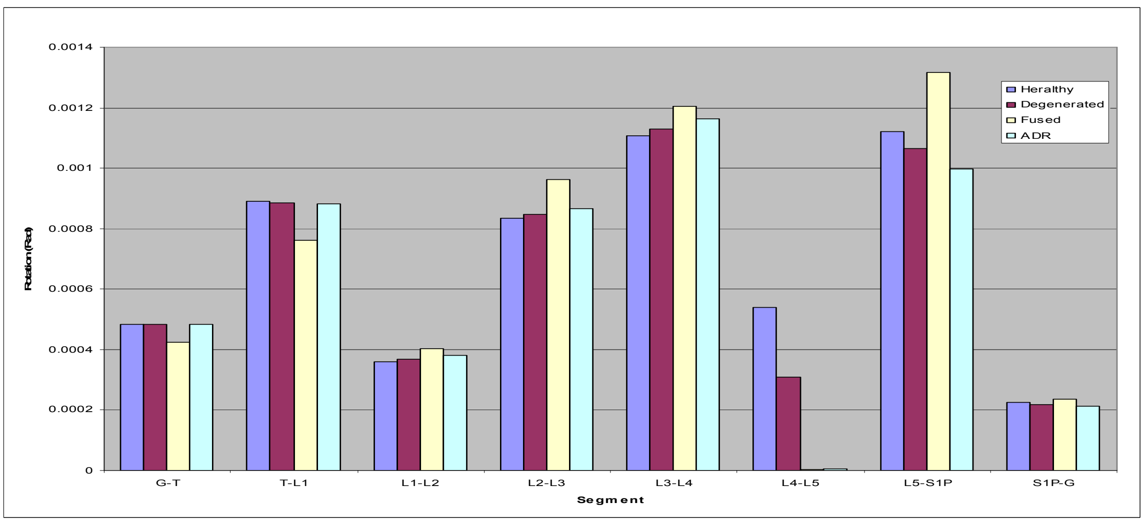

Figure 9-5: Flexion Extension response of Shear ADR at L4-L5

9.2.1.2 Compressive ADR

Figures 9-6 – 9-8 show the response of the lumbar spine to an impulsive shearing force acting on L3. The figures include the response of a spine with a degenerated disc, fused disc and a compressive ADR at the L4 – L5 level as well as the response of a healthy spine.

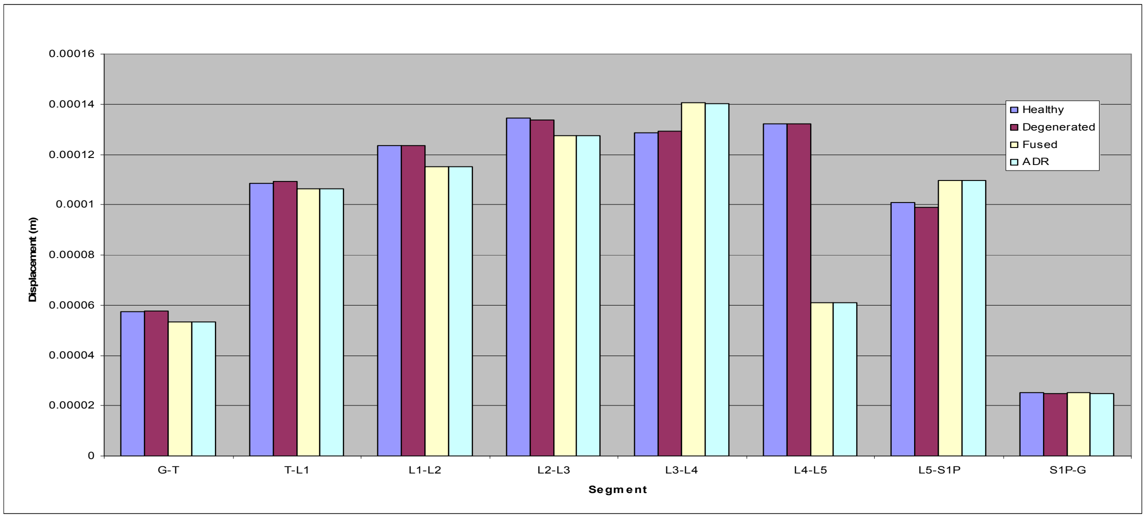

Figure 9-6: Posterior Anterior response of a compressive ADR at L4-L5

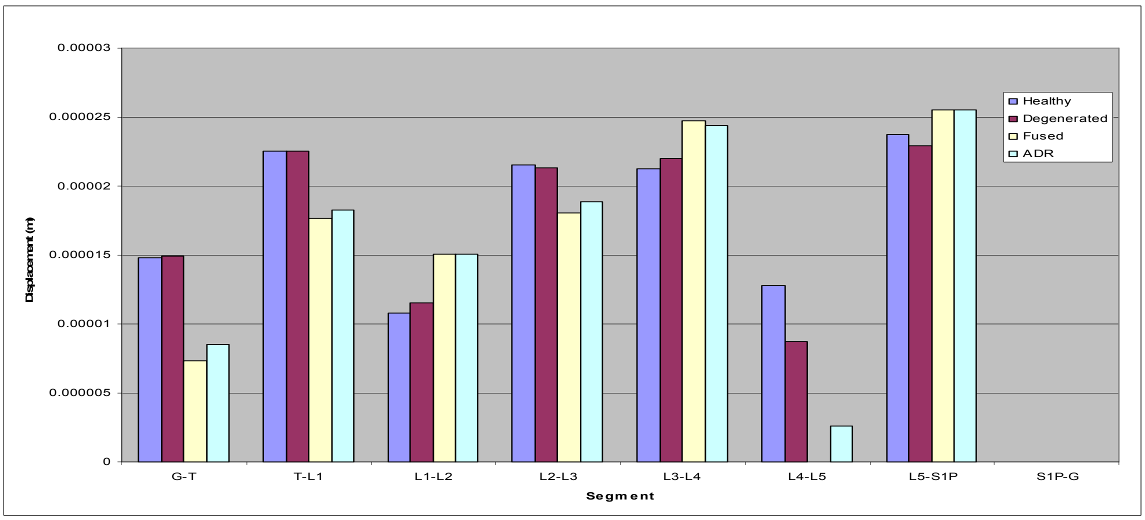

Figure 9-7: Axial response of a compressive ADR AT L4-L5

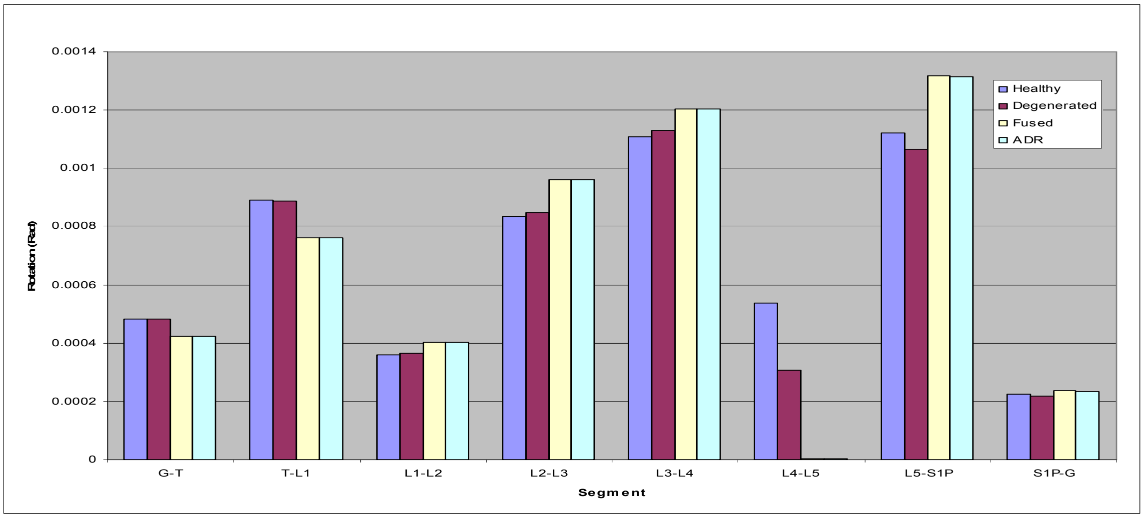

Figure 9-8: Flexion Extension response of a compressive ADR at L4-L5

9.2.1.3 Rotational ADR

Figures 9-9 – 9-11 show the response of the lumbar spine to an impulsive shearing force acting on L3. The figures include the response of a spine with a degenerated disc, fused disc and a rotational ADR at the L4 – L5 level as well as the response of a healthy spine.

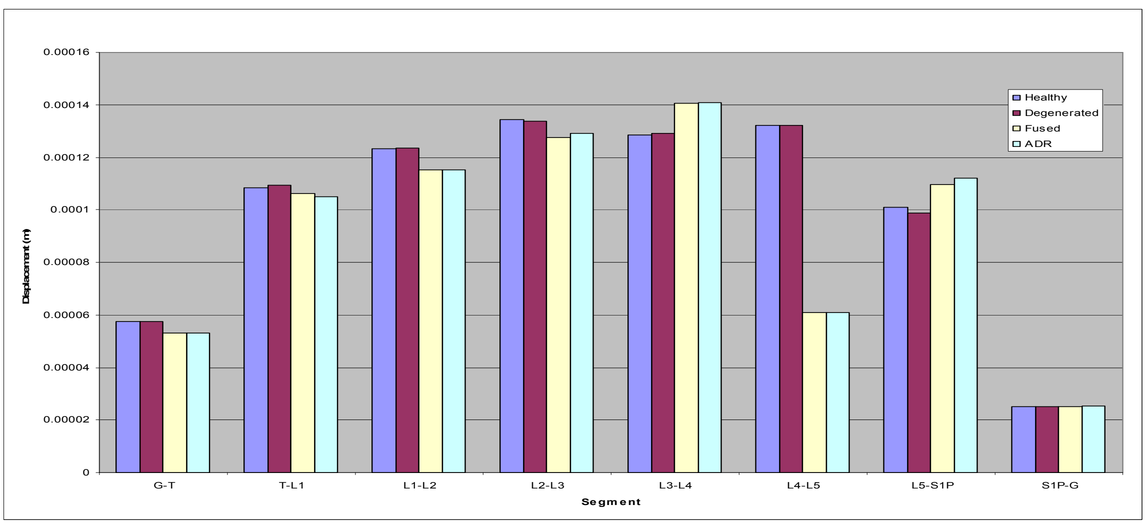

Figure 9-9: Posterior Anterior response of a rotational ADR at L4-L5

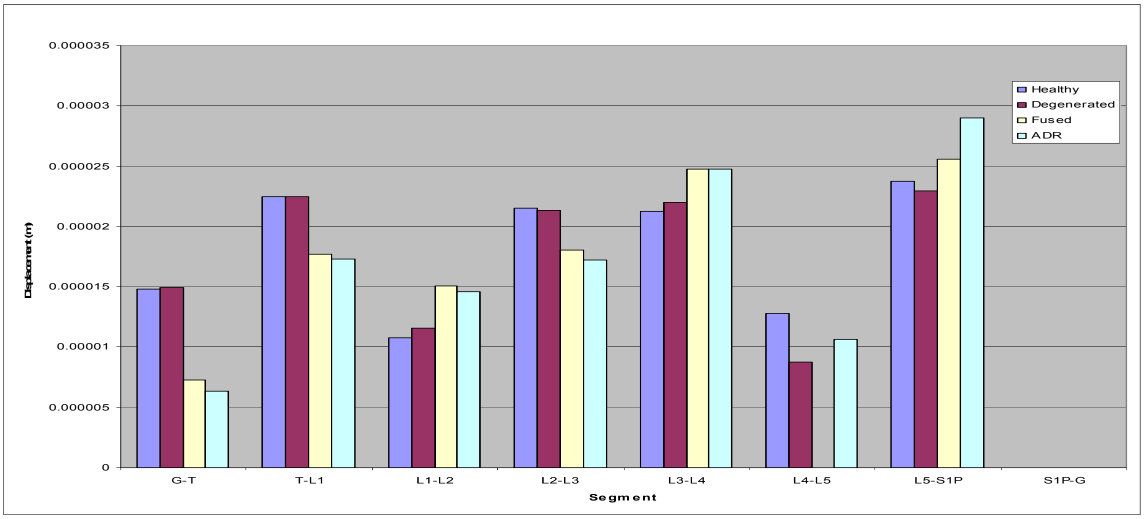

Figure 9-10: Axial response of a rotational ADR at L4-L5

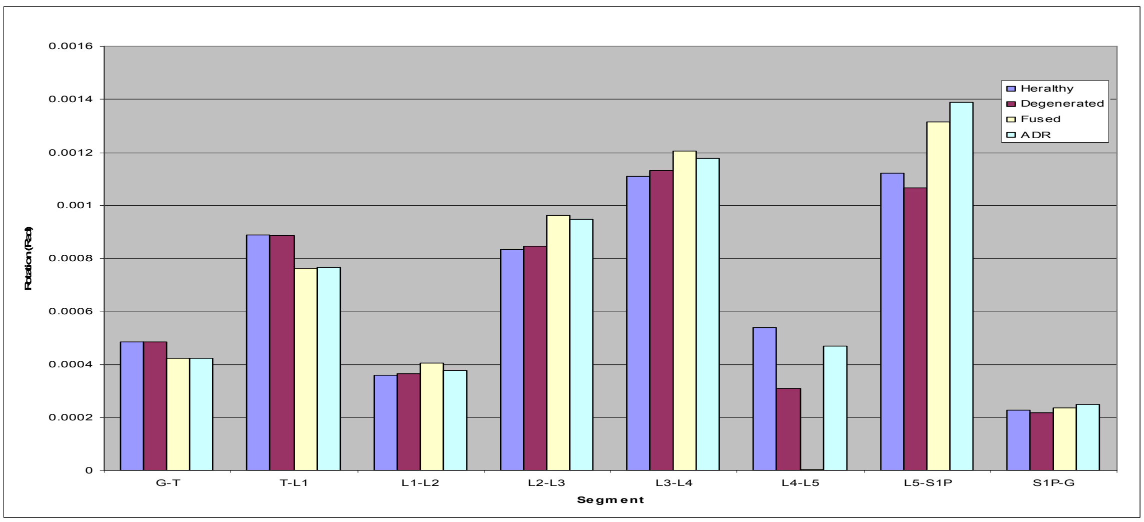

Figure 9-11: Flexion Extension response of a rotational ADR at L4-L5

9.2.1.4 Result Summary of One Degree of Freedom L4 – L5 ADR's

Tables 9-1 through 9-3 show a comparative summary of the results obtained for each 1-degree of freedom ADR case.

Table 9-1: Posterior Anterior intervertebral displacement summary for the 1-DOF L4- L5 ADR cases

	Posterior Anterior Intervertebral Displacement % Difference					
	T-L1	**L1-L2**	**L2-L3**	**L3-L4**	**L4-L5**	**L5-S1P**
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	0.72%	0.21%	-0.46%	0.43%	0.04%	-1.97%
Fused	-1.94%	-6.65%	-5.04%	9.19%	-53.91%	8.80%
Shear	1.71%	0.07%	-0.82%	0.90%	0.71%	-5.26%
Compressive	-1.96%	-6.63%	-5.04%	9.17%	-53.89%	8.77%
Rotational	-3.14%	-6.52%	-4.04%	9.41%	-53.97%	11.28%

Table 9-2: Axial intervertebral displacement summary for the 1-DOF L4- L5 ADR cases

	Axial Intervertebral Displacement % Difference					
	T-L1	**L1-L2**	**L2-L3**	**L3-L4**	**L4-L5**	**L5-S1P**
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	0.00%	6.90%	-0.72%	3.26%	-31.49%	-3.31%
Fused	-21.36%	39.39%	-16.03%	16.32%	-100.00%	7.69%
Shear	5.76%	33.10%	-13.50%	7.44%	-100.00%	-11.62%
Compressive	-18.89%	39.39%	-12.26%	14.72%	-79.80%	7.69%
Rotational	-23.05%	35.22%	-19.98%	16.32%	-16.70%	22.35%

Table 9-3: Flexion Extension intervertebral rotation summary for the 1-DOF L4- L5 ADR cases

	Flexion Extension Intervertebral Rotation % Difference					
	T-L1	**L1-L2**	**L2-L3**	**L3-L4**	**L4-L5**	**L5-S1P**
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	-0.46%	2.24%	1.51%	1.94%	-42.79%	-4.94%
Fused	-14.39%	12.62%	15.30%	8.62%	-99.41%	17.35%
Shear	-0.91%	6.40%	3.85%	5.10%	-99.24%	-10.92%
Compressive	-14.41%	12.47%	15.28%	8.63%	-99.17%	17.29%
Rotational	-13.97%	5.63%	13.53%	6.26%	-12.99%	23.95%

9.2.2 L5 – S1 Level Degeneration

The following results reflect the 1 degree of freedom ADR's, fused vertebrae and degenerated disc cases at the L5 – S1 level.

9.2.2.1 Shear ADR

Figures 9-12 – 9-14 show the response of the lumbar spine to an impulsive Shear force acting on L3. The figures include the response of a spine with a degenerated disc, fused disc and a Shear ADR at the L5 – S1 level as well as the response of a healthy spine.

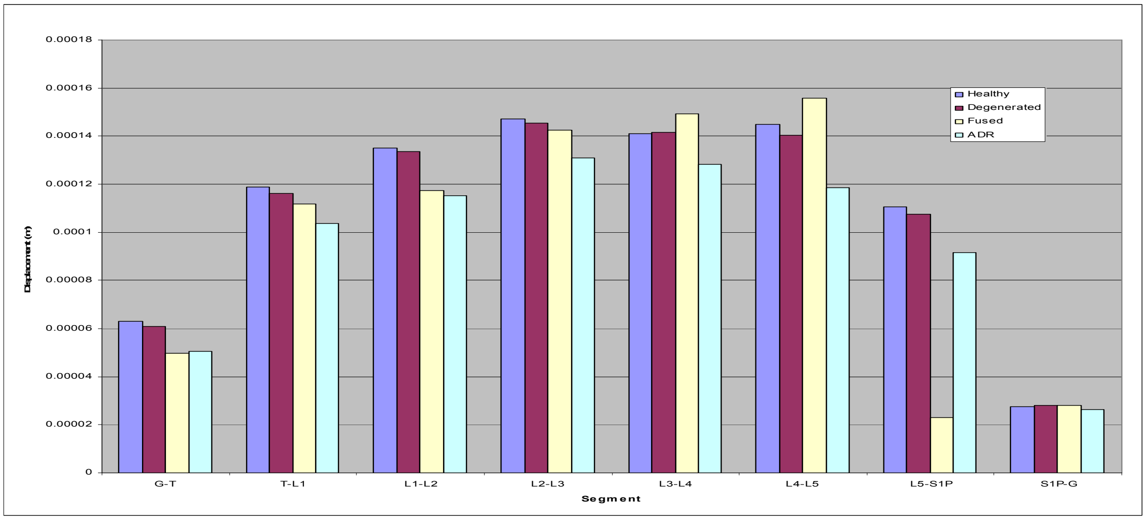

Figure 9-12: Posterior Anterior response of Shear ADR at L5-S1

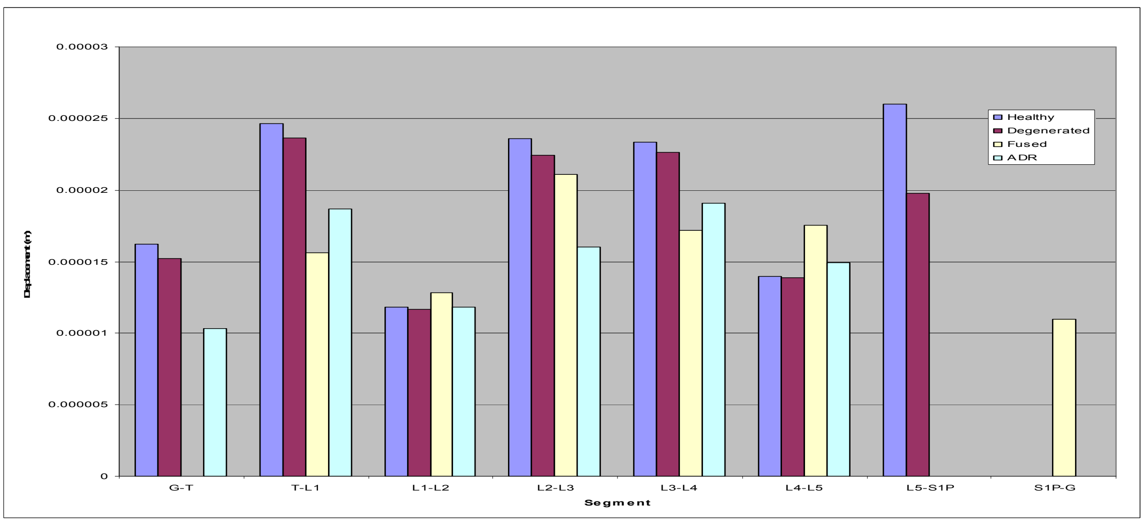

Figure 9-13: Axial response of Shear ADR at L5-S1

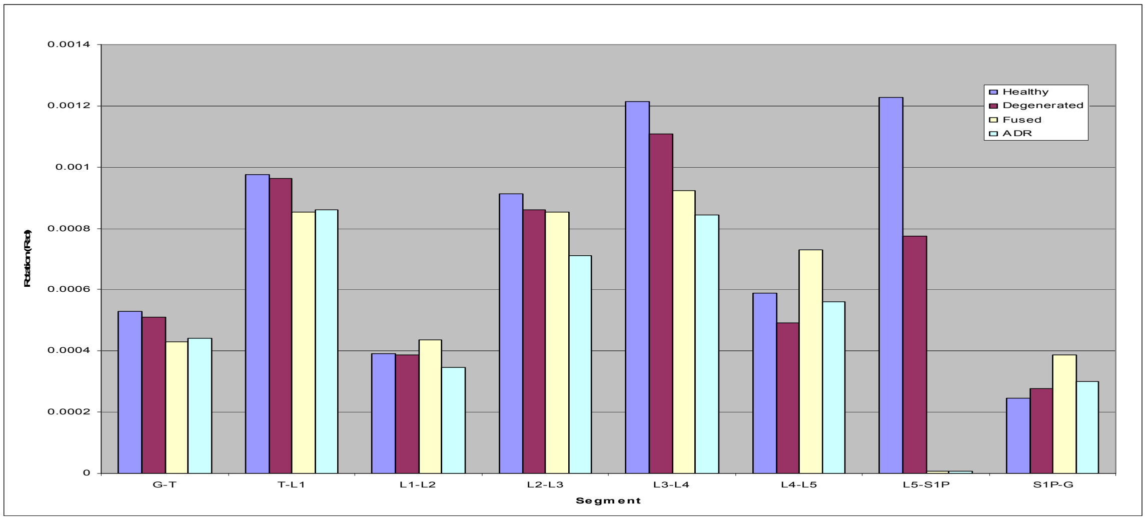

Figure 9-14: Flexion Extension response of Shear ADR at L5-S1

9.2.2.2 Compressive ADR

Figures 9-15 – 9-17 show the response of the lumbar spine to an impulsive Shear force acting on L3. The figures include the response of a spine with a degenerated disc, fused disc and a compressive ADR at the L5 – S1 level as well as the response of a healthy spine.

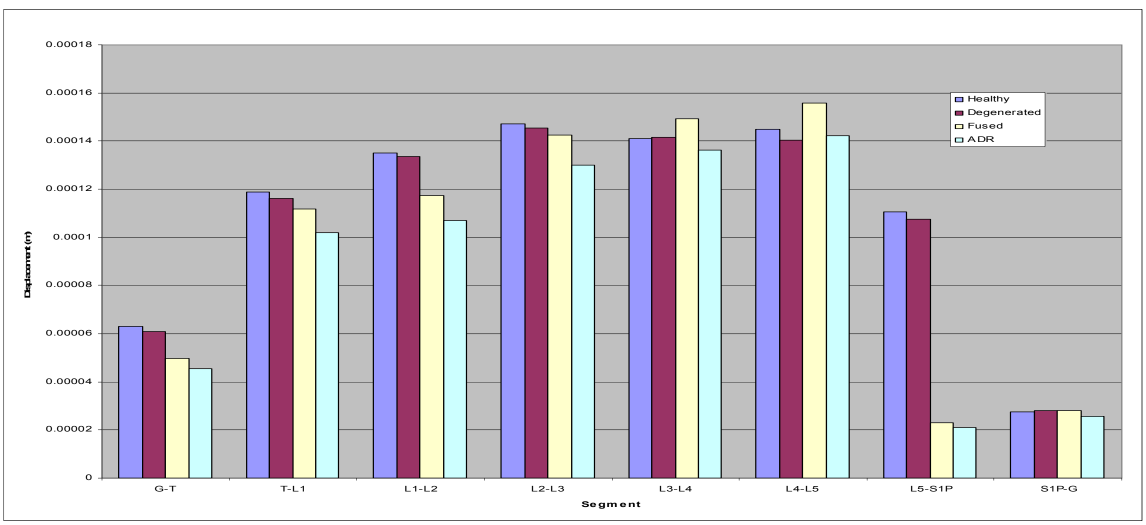

Figure 9-15: Posterior Anterior response of a compressive ADR at L5-S1

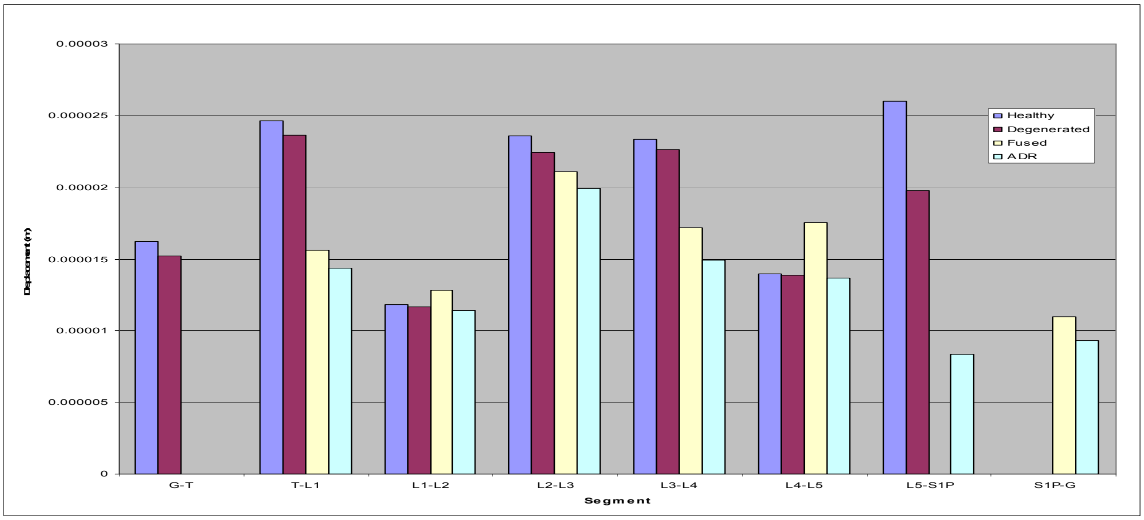

Figure 9-16: Axial response of a compressive ADR at L5-61

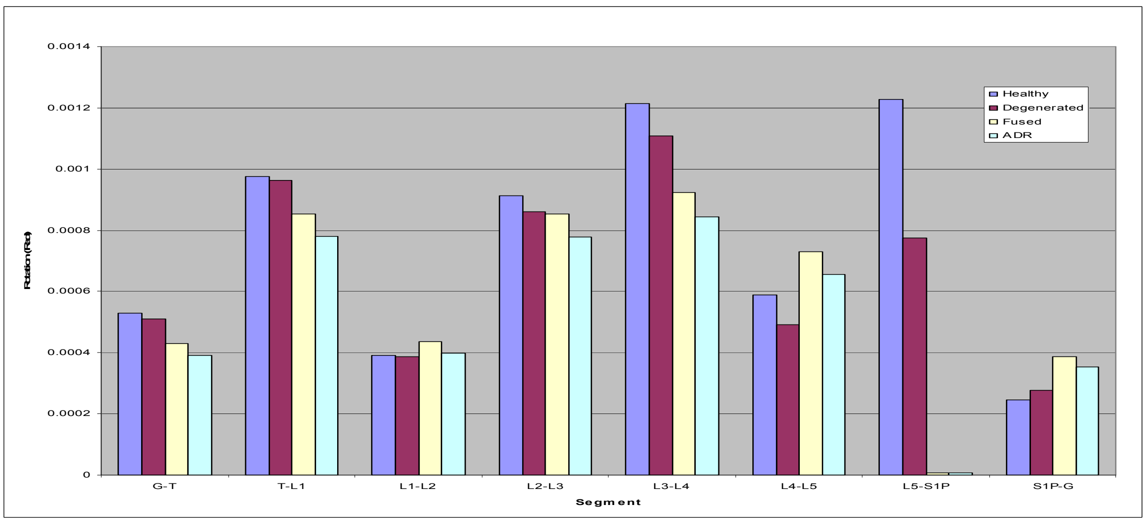

Figure 9-17: Flexion Extension response of a compressive ADR at L5-S1

9.2.2.3 Rotational ADR

Figures 9-18 – 9-20 show the response of the lumbar spine to an impulsive Shear force acting on L3. The figures include the response of a spine with a degenerated disc, fused disc and a rotational ADR at the L5 – S1 level as well as the response of a healthy spine.

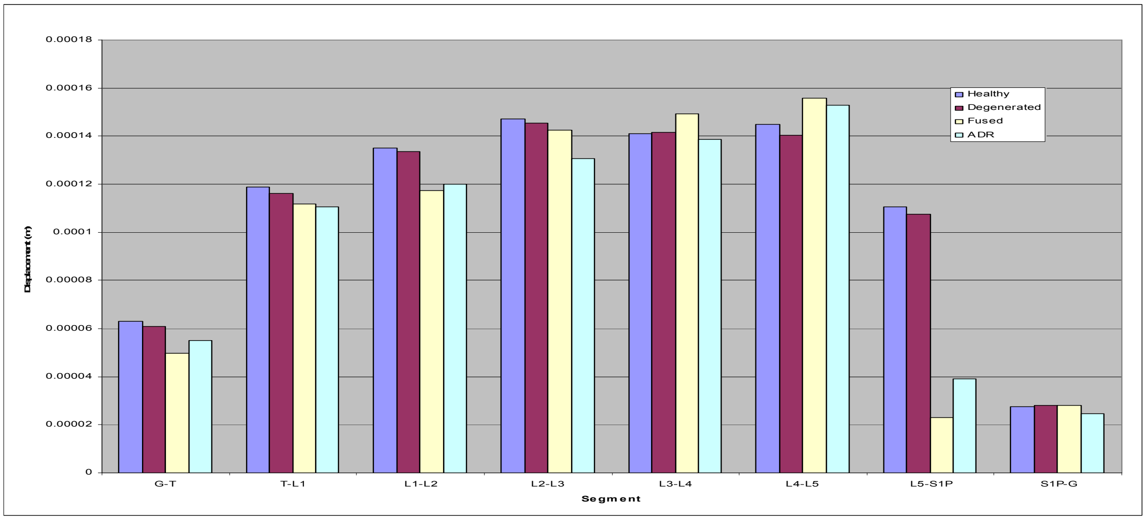

Figure 9-18: Posterior Anterior response of a rotational ADR at L5-S1

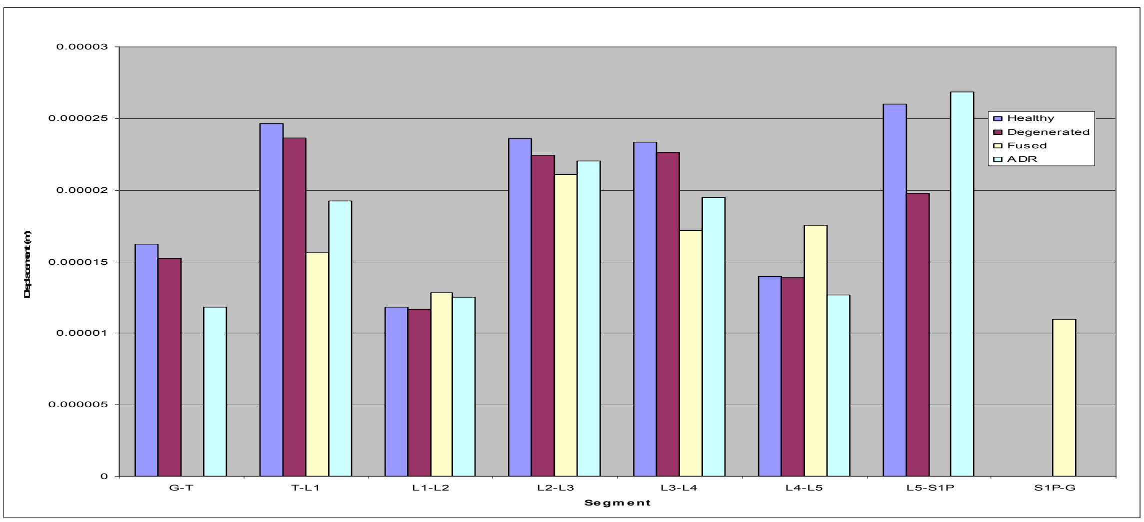

Figure 9-19: Axial response of a rotational ADR at L5-S1

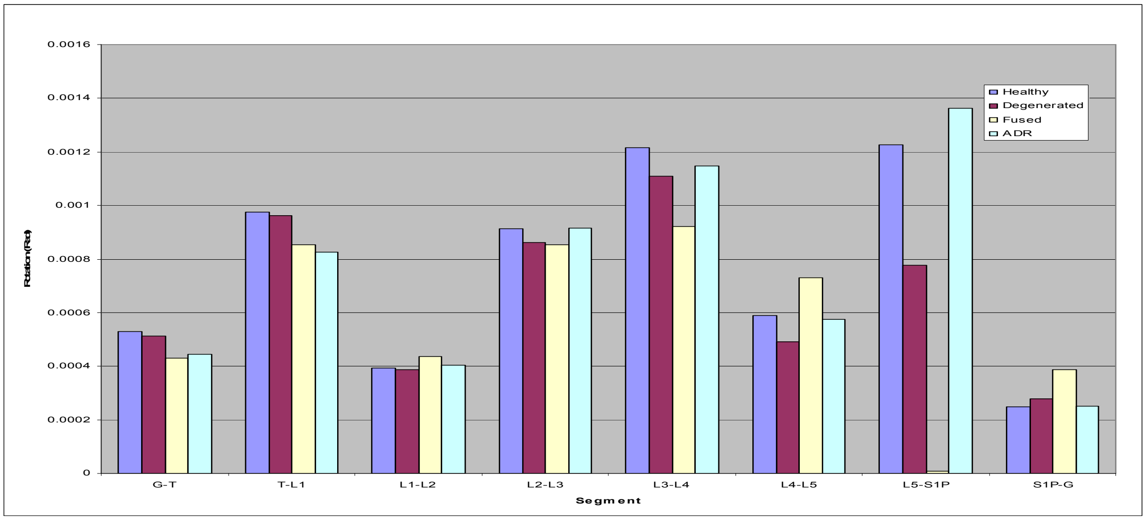

Figure 9-20: Flexion Extension response of a rotational ADR at L5-S1

9.2.2.4 Result Summary of One Degree of Freedom L5 – S1 ADR's

Tables 9-4 through 9-6 show a comparative summary of the results obtained for each 1-degree of freedom ADR case.

Table 9-4: Posterior Anterior intervertebral displacement summary for the 1-DOF L5-S1 ADR cases

	Posterior Anterior Intervertebral Displacement % Difference					
	T-L1	**L1-L2**	**L2-L3**	**L3-L4**	**L4-L5**	**L5-S1P**
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	-2.23%	-1.08%	-1.32%	0.43%	-3.12%	-2.62%
Fused	-5.98%	-13.26%	-3.21%	5.84%	7.53%	-79.05%
Shear	-12.66%	-14.65%	-11.18%	-8.87%	-18.27%	-16.98%
Compressive	-14.10%	-20.81%	-11.69%	-3.36%	-1.89%	-80.88%
Rotational	-7.02%	-11.18%	-11.21%	-1.60%	5.45%	-64.57%

Table 9-5: Axial intervertebral displacement summary for the 1-DOF L5-S1 ADR cases

	Axial Intervertebral Displacement % Difference					
	T-L1	**L1-L2**	**L2-L3**	**L3-L4**	**L4-L5**	**L5-S1P**
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	-4.03%	-1.44%	-4.79%	-2.99%	-1.03%	-23.85%
Fused	-36.65%	8.23%	-10.64%	-26.24%	25.36%	-100.00%
Shear	-24.13%	0.00%	-32.05%	-18.27%	6.75%	-100.00%
Compressive	-41.70%	-3.63%	-15.53%	-35.92%	-2.41%	-67.82%
Rotational	-21.99%	5.79%	-6.44%	-16.42%	-9.65%	3.21%

Table 9-6: Flexion Extension intervertebral rotation summary for the 1-DOF L5-S1 ADR cases

	Flexion Extension Intervertebral Rotation % Difference					
	T-L1	**L1-L2**	**L2-L3**	**L3-L4**	**L4-L5**	**L5-S1P**
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	-1.17%	-1.45%	-5.66%	-8.61%	-16.65%	-36.78%
Fused	-12.34%	11.09%	-6.65%	-24.07%	23.67%	-99.37%
Shear	-11.77%	-11.82%	-22.16%	-30.47%	-5.17%	-99.44%
Compressive	-20.09%	1.79%	-14.80%	-30.55%	11.08%	-99.35%
Rotational	-15.28%	3.21%	0.18%	-5.41%	-2.57%	11.08%

9.3 Two Degree of Freedom Artificial Discs (RMS)

The artificial discs results for the two degree of freedom case have been divided into three separate combinations of degrees of freedom xy, yz, and xz or Shear-compressive, compressive-rotational and Shear-rotational respectively. Each disc was implanted at L4 – L5 and L5 – S1 levels. The following results are divided and presented by level and degree of freedom.

9.3.1 L4 – L5 Level Degeneration

The following results reflect the 2 degree of freedom ADR’s, fused vertebrae and degenerated disc cases at the L4 – L5 level.

9.3.1.1 Shear-Compressive ADR

Figures 9-21 – 9-23 show the response of the lumbar spine to an impulsive Shear force acting on L3. The figures include the response of a spine with a degenerated disc, fused disc and a Shear-compressive ADR at the L4 – L5 level as well as the response of a healthy spine.

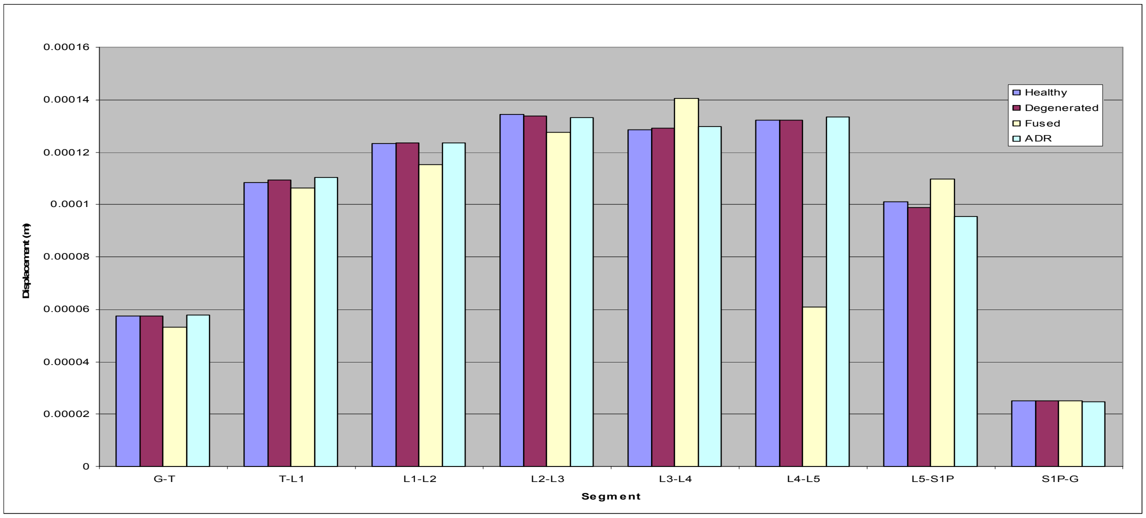

Figure 9-21: Posterior Anterior response of a Shear-compressive ADR at L4-L5

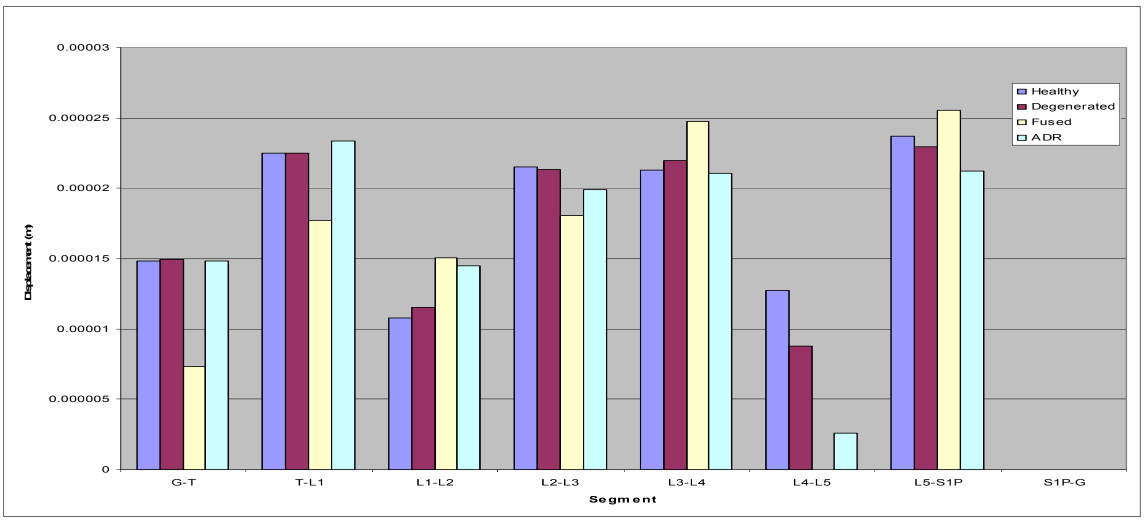

Figure 9-22: Axial response of a Shear-compressive ADR at L4-L5

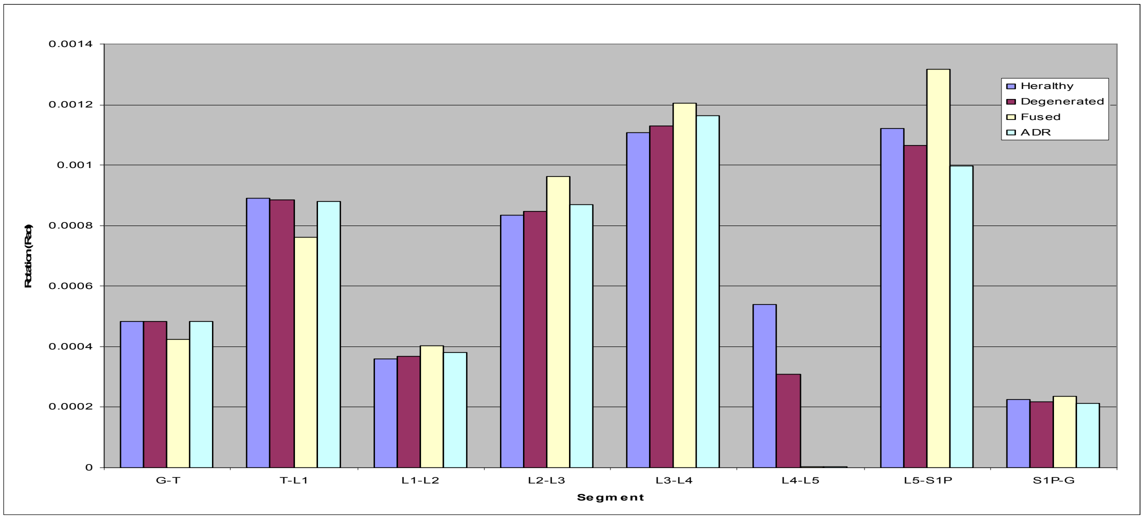

Figure 9-23: Flexion Extension response of a Shear-compressive ADR at L4-L5

9.3.1.2 Compressive-Rotational ADR

Figures 9-24 – 9-26 show the response of the lumbar spine to an impulsive Shear force acting on L3. The figures include the response of a spine with a degenerated disc, fused disc and a compressive-rotational ADR at the L4 – L5 level as well as the response of a healthy spine.

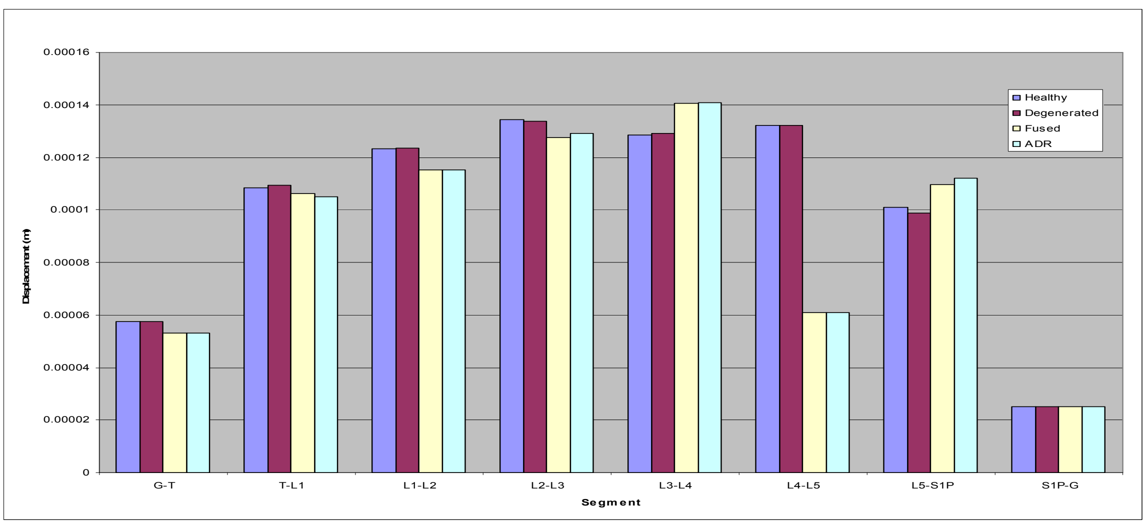

Figure 9-24: Posterior Anterior response of a compressive-rotational ADR at L4-L5

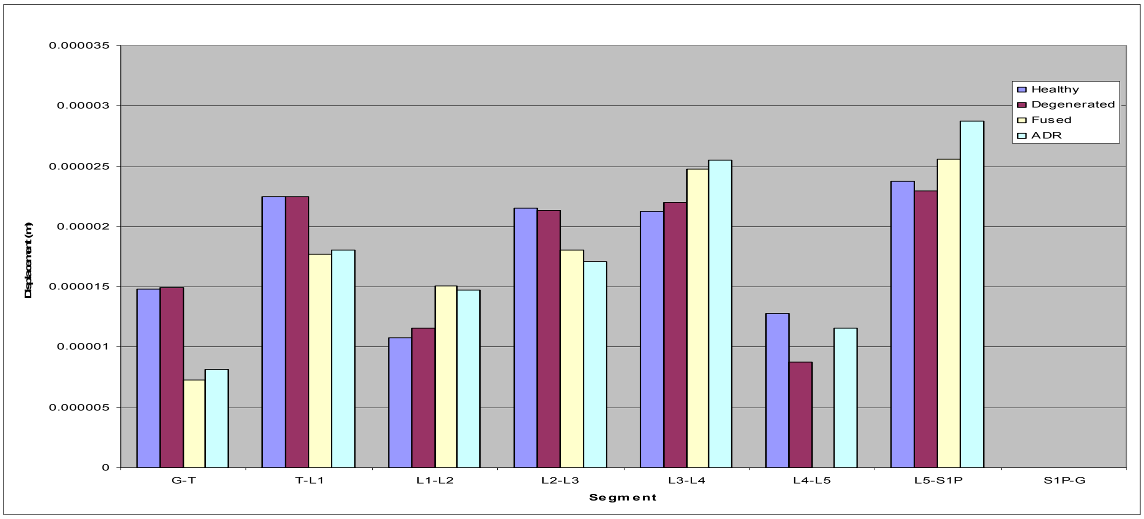

Figure 9-25: Axial response of a compressive-rotational ADR at L4-L5

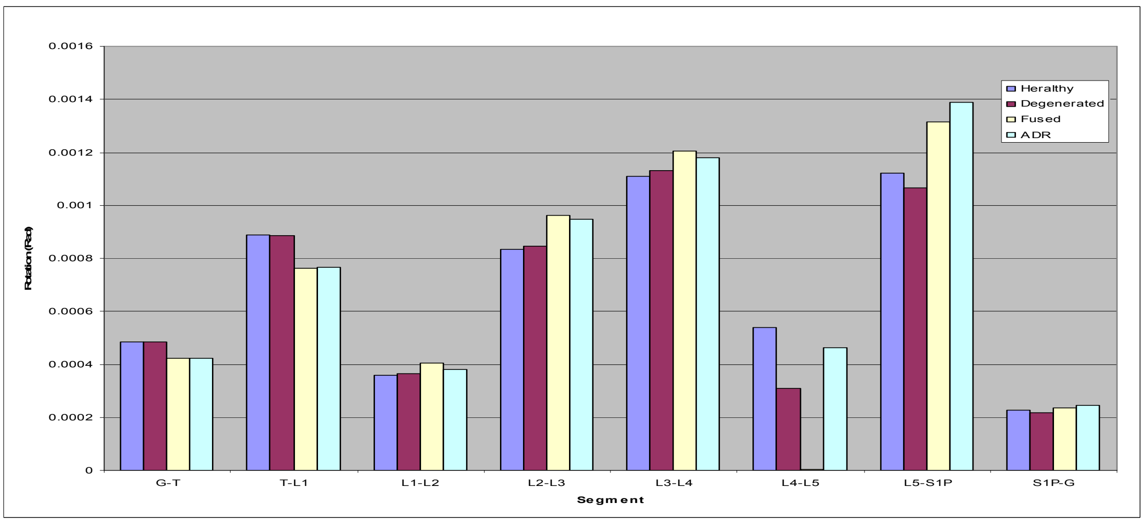

Figure 9-26: Flexion Extension response of a compressive-rotational ADR at L4-L5

9.3.1.3 Shear-Rotational ADR

Figures 9-27 – 9-29 show the response of the lumbar spine to an impulsive Shear force acting on L3. The figures include the response of a spine with a degenerated disc, fused disc and a Shear-rotational ADR at the L4 – L5 level as well as the response of a healthy spine.

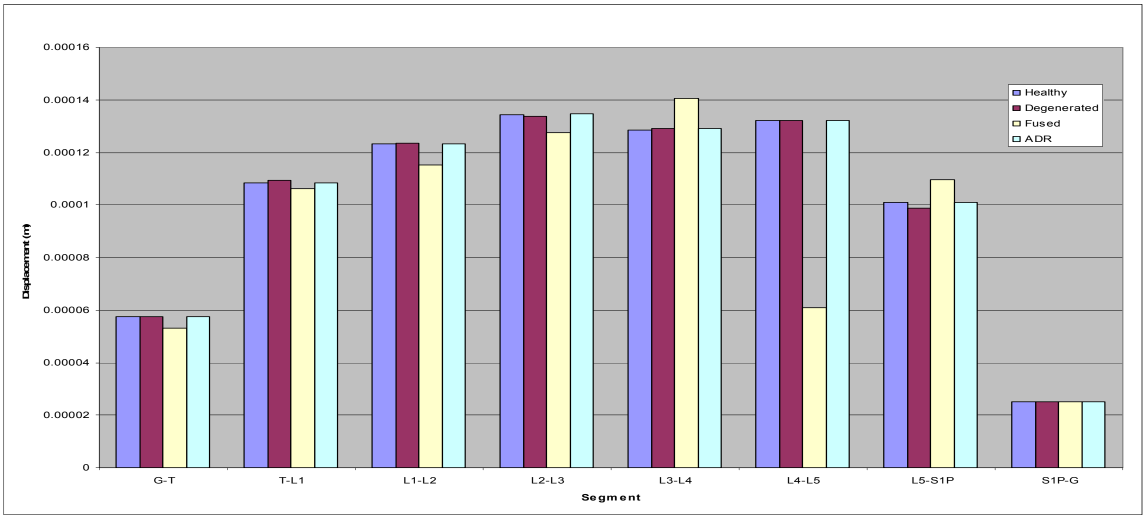

Figure 9-27: Posterior Anterior response of a Shear-rotational ADR at L4-L5

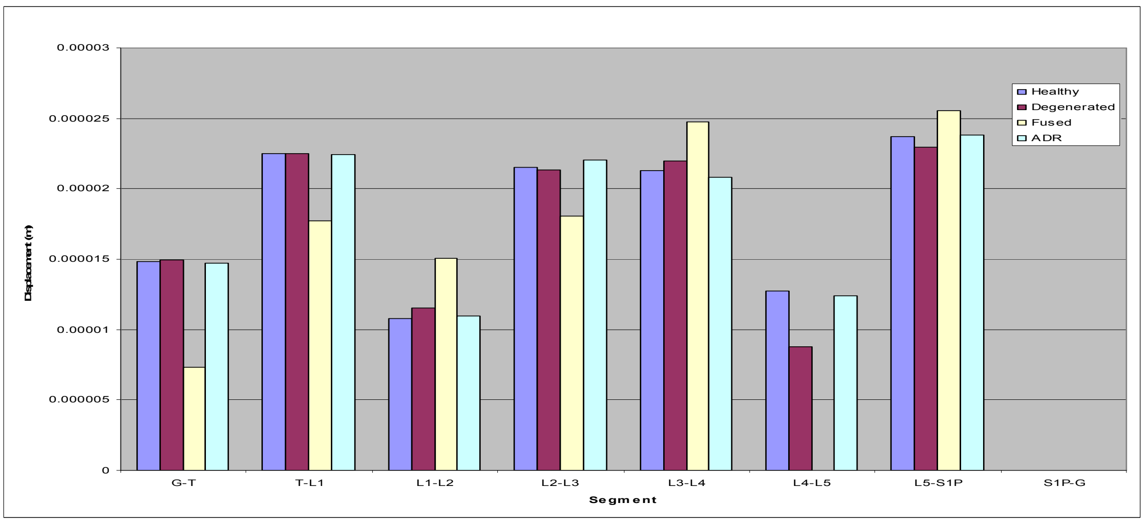

Figure 9-28: Axial response of a Shear-rotational ADR at L4-L5

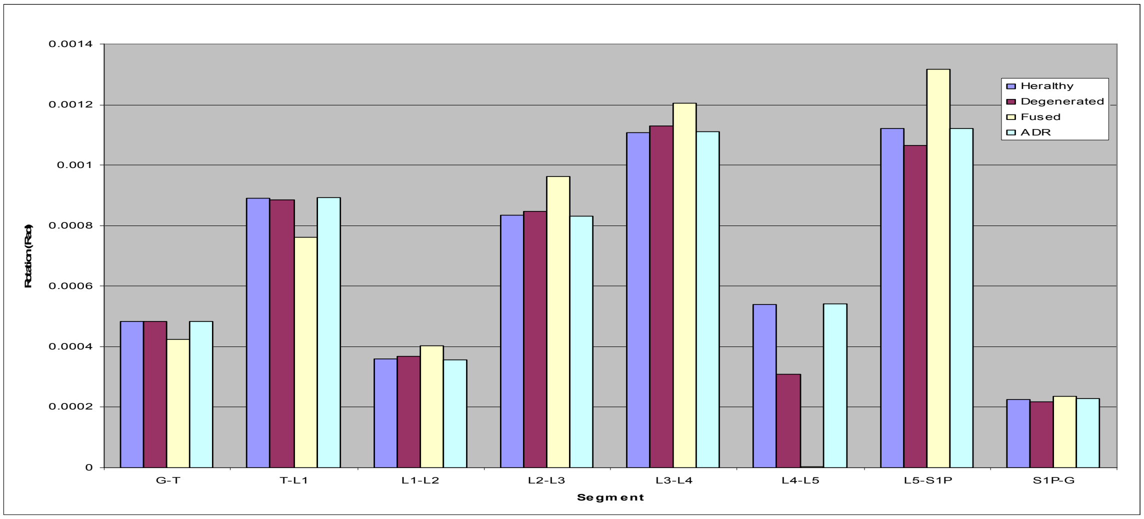

Figure 9-29: Flexion Extension response of a Shear-rotational ADR

9.3.1.4 Result Summary of Two Degree of Freedom L4 – L5 ADR's

Tables 9-7 through 9-9 show a comparative summary of the results obtained for each 2-degree of freedom L4 - L5 ADR case.

Table 9-7: Posterior Anterior intervertebral displacement summary for the 2-DOF L4-L5 ADR cases

	Posterior Anterior Intervertebral Displacement % Difference					
	T-L1	**L1-L2**	**L2-L3**	**L3-L4**	**L4-L5**	**L5-S1P**
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	0.72%	0.21%	-0.46%	0.43%	0.04%	-1.97%
Fused	-1.94%	-6.65%	-5.04%	9.19%	-53.91%	8.80%
Shear-Compressive	1.74%	0.14%	-0.90%	0.83%	0.86%	-5.51%
Compressive-Rotational	-3.15%	-6.48%	-4.03%	9.49%	-53.97%	11.25%
Shear-Rotational	-0.07%	0.03%	0.27%	0.46%	-0.12%	0.02%

Table 9-8: Axial intervertebral displacement summary for the 2-DOF L4-L5 ADR cases

	Axial Intervertebral Displacement % Difference					
	T-L1	**L1-L2**	**L2-L3**	**L3-L4**	**L4-L5**	**L5-S1P**
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	0.00%	6.90%	-0.72%	3.26%	-31.49%	-3.31%
Fused	-21.36%	39.39%	-16.03%	16.32%	-100.00%	7.69%
Shear-Compressive	3.87%	34.16%	-7.47%	-1.11%	-79.80%	-10.62%
Compressive-Rotational	-19.70%	36.28%	-20.43%	19.74%	-9.65%	21.14%
Shear-Rotational	-0.33%	1.42%	2.49%	-2.23%	-3.11%	0.30%

Table 9-9: Flexion Extension intervertebral rotation summary for the 2-DOF L4-L5 ADR cases

	Flexion Extension Intervertebral Rotation % Difference					
	T-L1	**L1-L2**	**L2-L3**	**L3-L4**	**L4-L5**	**L5-S1P**
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	-0.46%	2.24%	1.51%	1.94%	-42.79%	-4.94%
Fused	-14.39%	12.62%	15.30%	8.62%	-99.41%	17.35%
Shear-Compressive	-1.06%	5.98%	4.08%	5.11%	-99.41%	-10.90%
Compressive-Rotational	-13.99%	5.99%	13.54%	6.42%	-14.00%	23.79%
Shear-Rotational	0.28%	-0.45%	-0.36%	0.10%	0.64%	0.05%

9.3.2 L5 – S1 Level Degeneration

The following results reflect the 2 degree of freedom ADR's, fused vertebrae and degenerated disc cases at the L5 – S1 level.

9.3.2.1 Shear-Compressive ADR

Figures 9-30 – 9-32 show the response of the lumbar spine to an impulsive Shear force acting on L3. The figures include the response of a spine with a degenerated disc, fused disc and a Shear-compressive ADR at the L5 – S1 level as well as the response of a healthy spine.

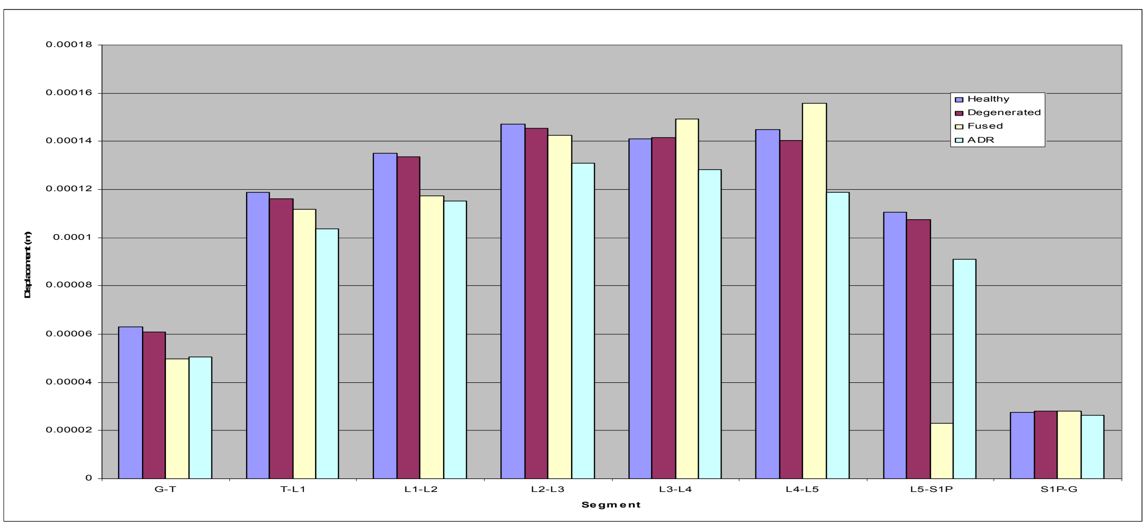

Figure 9-30: Posterior Anterior response of a Shear-compressive ADR at L5-S1

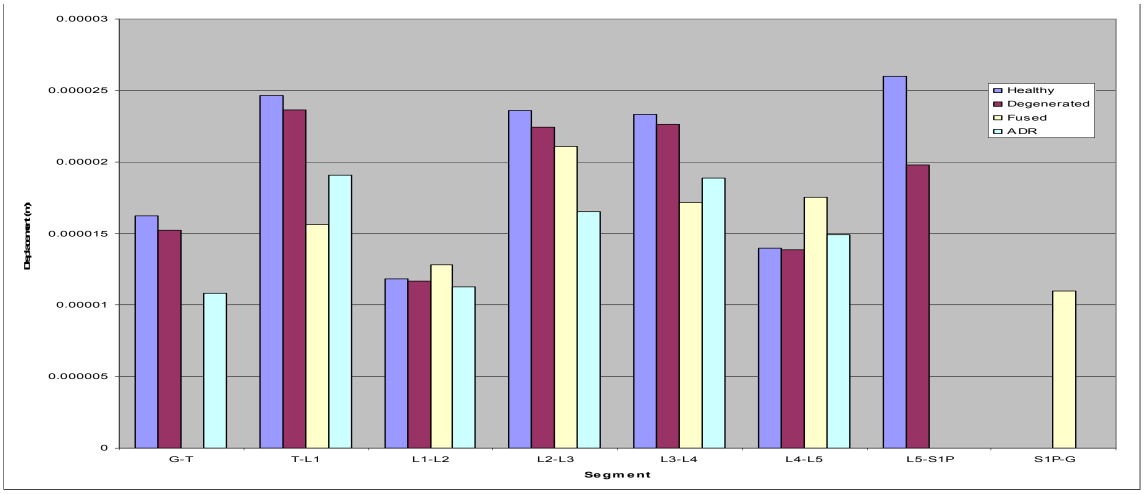

Figure 9-31: Axial response of a Shear-compressive ADR at L5-S1

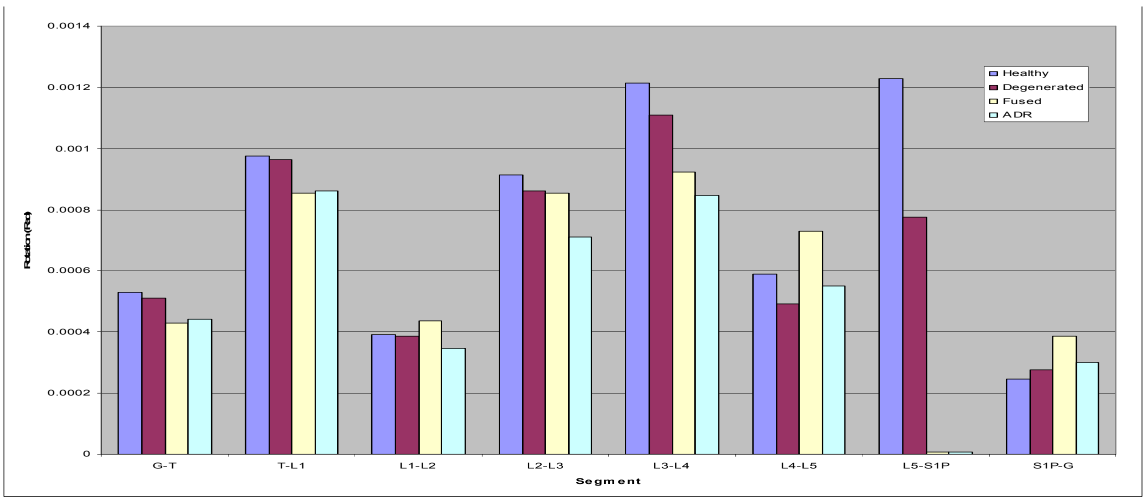

Figure 9-32: Flexion Extension response of a Shear-compressive ADR at L5-S1

9.3.2.2 Compressive-Rotational ADR

Figures 9-33 – 9-35 show the response of the lumbar spine to an impulsive Shear force acting on L3. The figures include the response of a spine with a degenerated disc, fused disc and a compressive-rotational ADR at the L5 – S1 level as well as the response of a healthy spine.

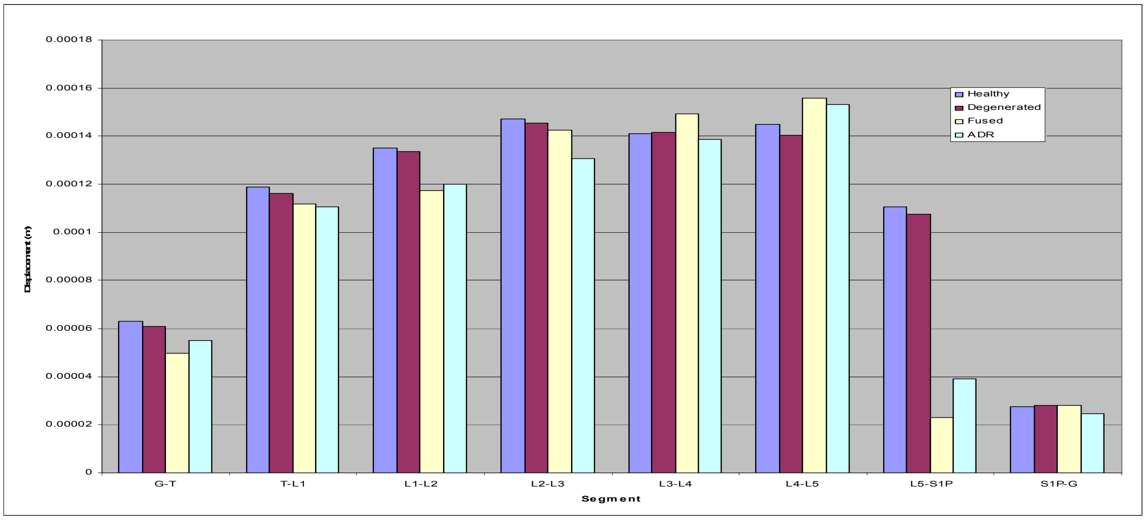

Figure 9-33: Posterior Anterior response of a compressive-rotational ADR at L5-S1

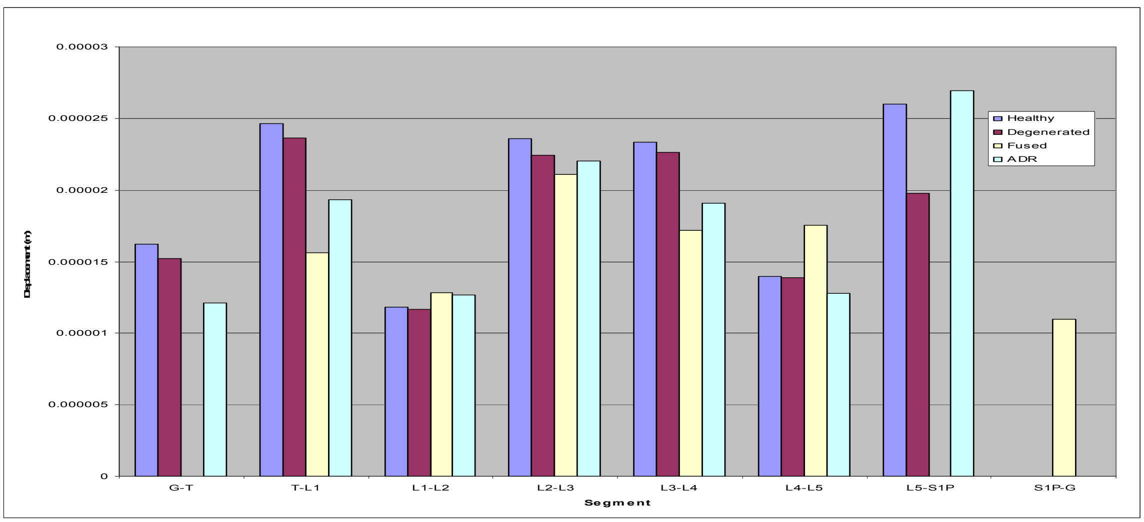

Figure 9-34: Axial response of a compressive-rotational ADR at L5-S1

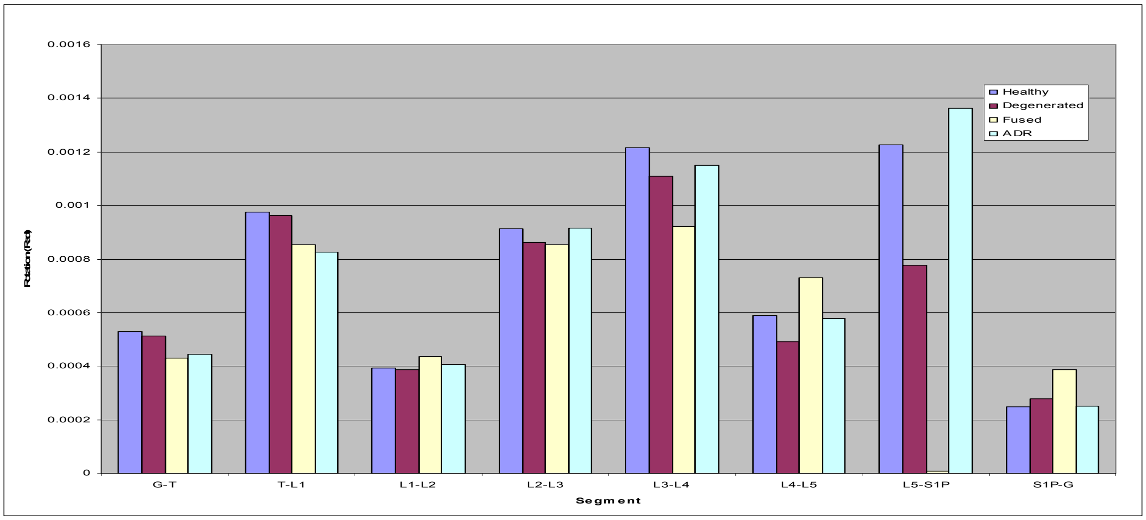

Figure 9-35: Flexion Extension response of a compressive-rotational ADR at L5-S1

9.3.2.3 Shear-Rotational ADR

Figures 9-36 – 9-38 show the response of the lumbar spine to an impulsive Shear force acting on L3. The figures include the response of a spine with a degenerated disc, fused disc and a Shear-rotational ADR at the L5 – S1 level as well as the response of a healthy spine.

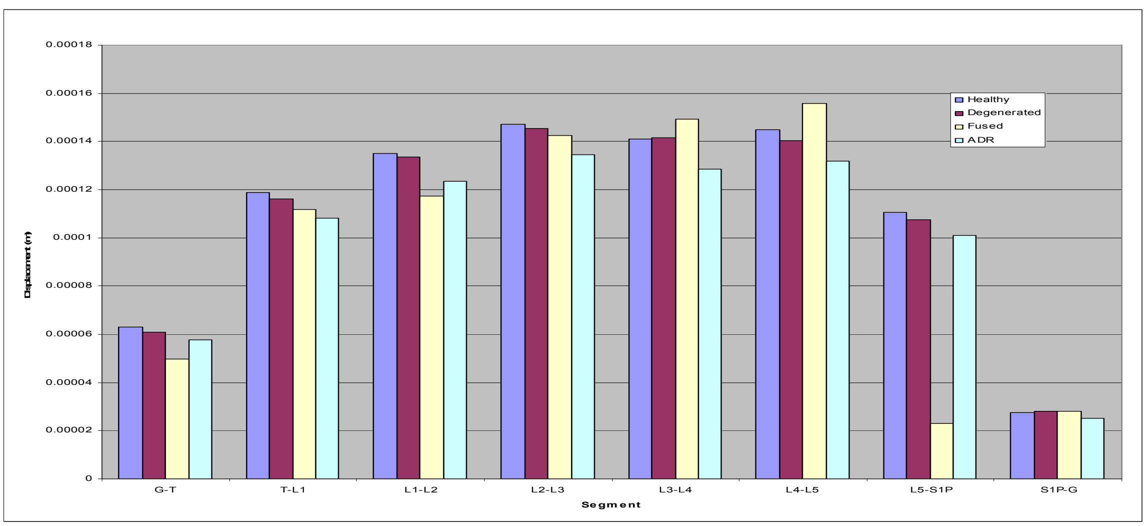

Figure 9-36: Anterior Posterior response of a Shear-rotational ADR at L5-S1

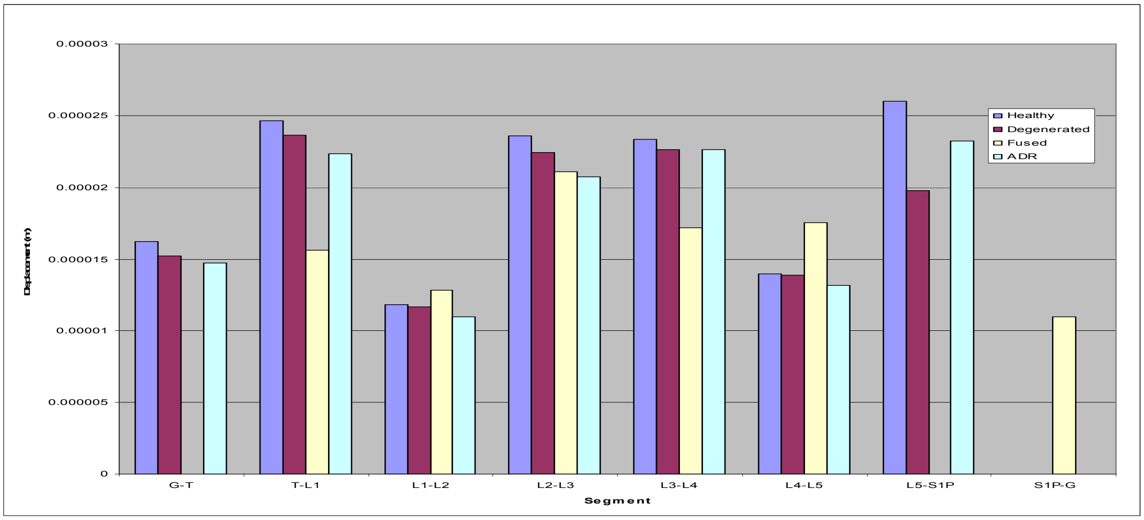

Figure 9-37: Axial response of a Shear-rotational ADR at L5-S1

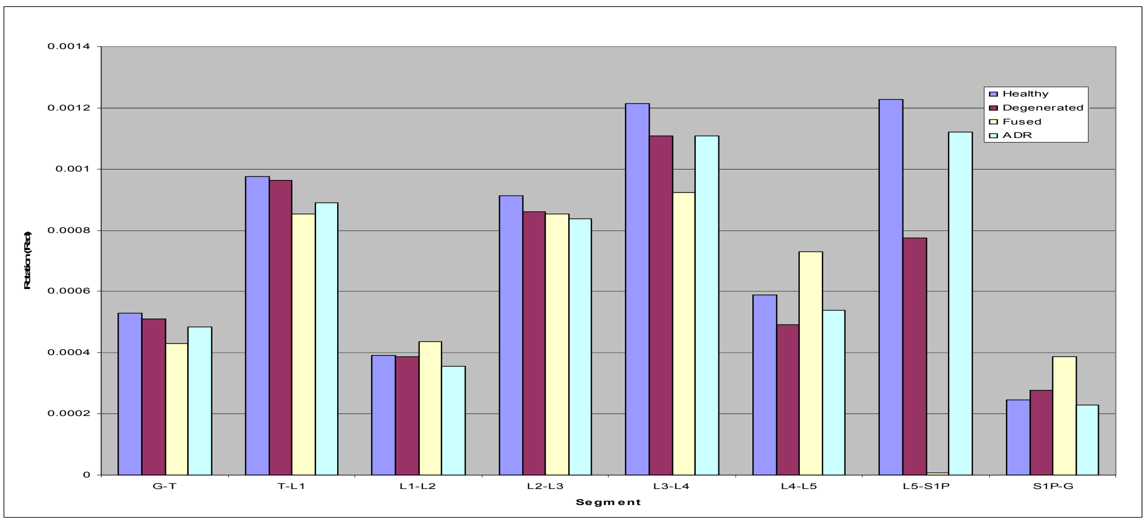

Figure 9-38: Flexion Extension response of a Shear-rotational ADR at L5-S1

9.3.2.4 Result Summary of Two Degree of Freedom L5 – S1 ADR's

Tables 9-10 through 9-12 show a comparative summary of the results obtained for each 2-degree of freedom L5 – S1 ADR case.

Table 9-10: Posterior Anterior intervertebral displacement summary for the 2-DOF L5-S1 ADR cases

	Posterior Anterior Intervertebral Displacement % Difference					
	T-L1	**L1-L2**	**L2-L3**	**L3-L4**	**L4-L5**	**L5-S1P**
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	-2.23%	-1.08%	-1.32%	0.43%	-3.12%	-2.62%
Fused	-5.98%	-13.26%	-3.21%	5.84%	7.53%	-79.05%
Shear-Compressive	-12.61%	-14.67%	-11.17%	-8.95%	-18.00%	-17.54%
Compressive-Rotational	-7.03%	-11.18%	-11.20%	-1.64%	5.60%	-64.65%
Shear-Rotational	-8.89%	-8.65%	-8.65%	-8.78%	-9.08%	-8.49%

Table 9-11: Axial intervertebral displacement summary for the 2-DOF L5-S1 ADR cases

	Axial Intervertebral Displacement % Difference					
	T-L1	**L1-L2**	**L2-L3**	**L3-L4**	**L4-L5**	**L5-S1P**
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	-4.03%	-1.44%	-4.79%	-2.99%	-1.03%	-23.85%
Fused	-36.65%	8.23%	-10.64%	-26.24%	25.36%	-100.00%
Shear-Compressive	-22.69%	-4.88%	-29.88%	-19.03%	6.75%	-100.00%
Compressive-Rotational	-21.64%	6.91%	-6.44%	-18.27%	-8.71%	3.68%
Shear-Rotational	-9.31%	-7.41%	-12.05%	-2.86%	-5.96%	-10.62%

Table 9-12: Flexion Extension intervertebral rotation summary for the 2-DOF L5-S1 ADR cases

	Flexion Extension Intervertebral Rotation % Difference					
	T-L1	**L1-L2**	**L2-L3**	**L3-L4**	**L4-L5**	**L5-S1P**
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	-1.17%	-1.45%	-5.66%	-8.61%	-16.65%	-36.78%
Fused	-12.34%	11.09%	-6.65%	-24.07%	23.67%	-99.37%
Shear-Compressive	-11.69%	-11.67%	-22.24%	-30.32%	-6.47%	-99.39%
Compressive-Rotational	-15.21%	3.75%	0.09%	-5.34%	-2.22%	10.92%
Shear-Rotational	-8.69%	-9.29%	-8.50%	-8.61%	-8.69%	-8.62%

9.4 Three Degree of Freedom Artificial Disc (RMS)

The artificial discs results for the three degree of freedom cases have been divided in two, implanted at L4 – L5 and L5 – S1 levels. The following results show the behavior of the spine with the artificial disc, fused disc and degenerated disc at each level.

9.4.1 L4 – L5 Level Degeneration

Figures 9-39 – 9-41 show the response of the lumbar spine to an impulsive Shear force acting on L3. The figures include the response of a spine with a degenerated disc, fused disc and a full 3-degree of freedom ADR at the L4 – L5 level as well as the response of a healthy spine. It is assumed that the 3-DOF ADR exactly matches the healthy disc, so the results for the ADR and the healthy disc are identical in this section.

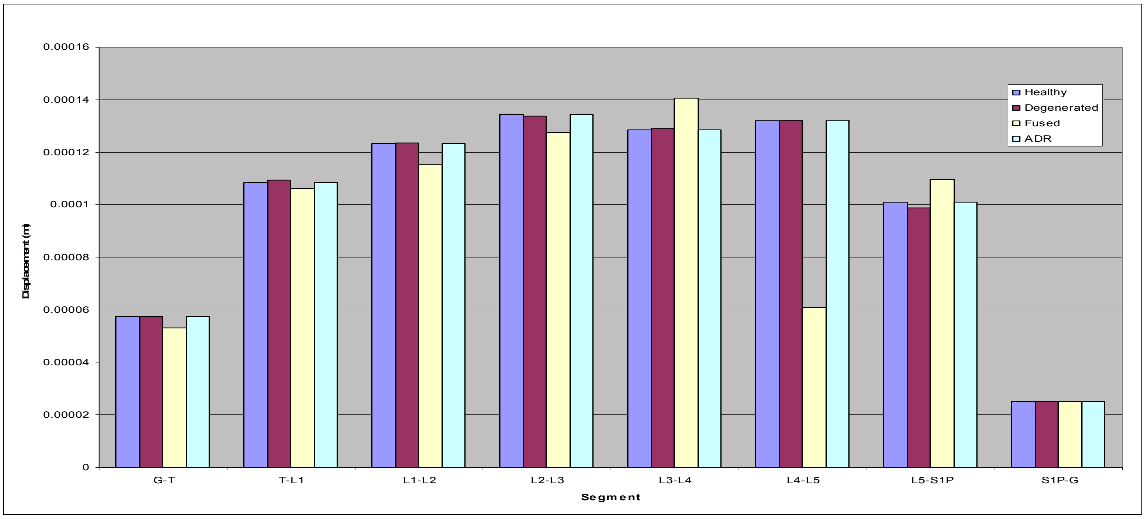

Figure 9-39: Anterior Posterior response of a full 3-degree of freedom ADR at L4-L5

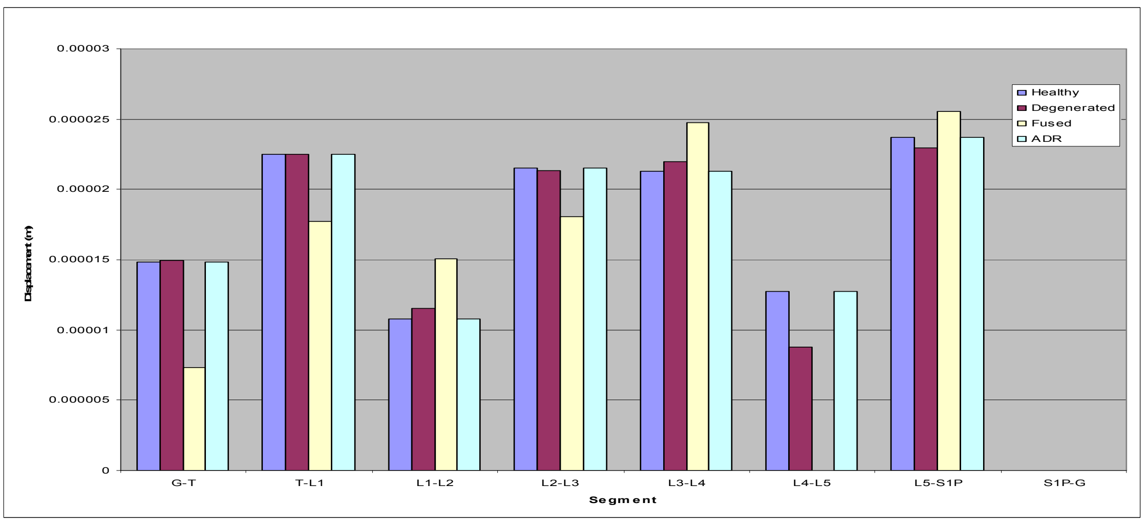

Figure 9-40: Axial response of a full 3-degree of freedom ADR at L4-L5

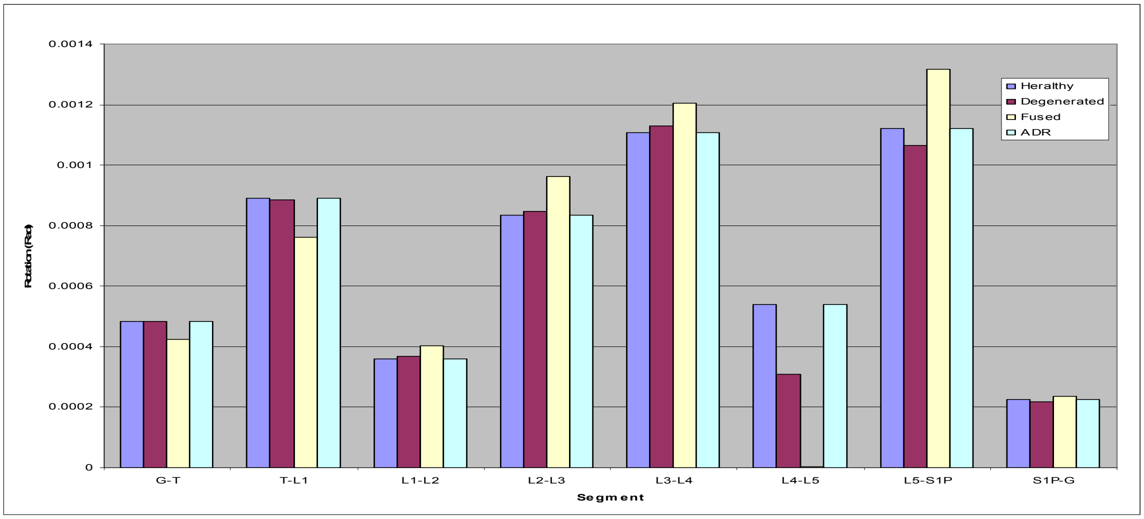

Figure 9-41: Flexion Extension response of a full 3-degree of freedom ADR at L4-L5

9.4.1.1 Result Summary of Three Degree of Freedom L4 – L5 ADR's

Tables 9-13 through 9-15 show a comparative summary of the results obtained for each 3-degree of freedom L4 – L5 ADR case.

Table 9-13: Posterior Anterior intervertebral displacement summary for the 3-DOF L4-L5 ADR case

	Posterior Anterior Intervertebral Displacement % Difference					
	T-L1	L1-L2	L2-L3	L3-L4	L4-L5	L5-S1P
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	0.72%	0.21%	-0.46%	0.43%	0.04%	-1.97%
Fused	-1.94%	-6.65%	-5.04%	9.19%	-53.91%	8.80%
3-DOF	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Table 9-14: Axial intervertebral displacement summary for the 3-DOF L4-L5 ADR case

	Axial Intervertebral Displacement % Difference					
	T-L1	L1-L2	L2-L3	L3-L4	L4-L5	L5-S1P
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	0.00%	6.90%	-0.72%	3.26%	-31.49%	-3.31%
Fused	-21.36%	39.39%	-16.03%	16.32%	-100.00%	7.69%
3-DOF	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Table 9-15: Flexion Extension intervertebral rotation summary for the 3-DOF L4-L5 ADR case

	Flexion Extension Intervertebral Rotation % Difference					
	T-L1	L1-L2	L2-L3	L3-L4	L4-L5	L5-S1P
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	-0.46%	2.24%	1.51%	1.94%	-42.79%	-4.94%
Fused	-14.39%	12.62%	15.30%	8.62%	-99.41%	17.35%
3-DOF	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

9.4.2 L5 – S1 Level Degeneration

Figures 9-42 – 9-44 show the response of the lumbar spine to an impulsive Shear force acting on L3. The figures include the response of a spine with a degenerated disc, fused disc and a full 3-degree of freedom ADR at the L5 – S1 level as well as the response of a healthy spine.

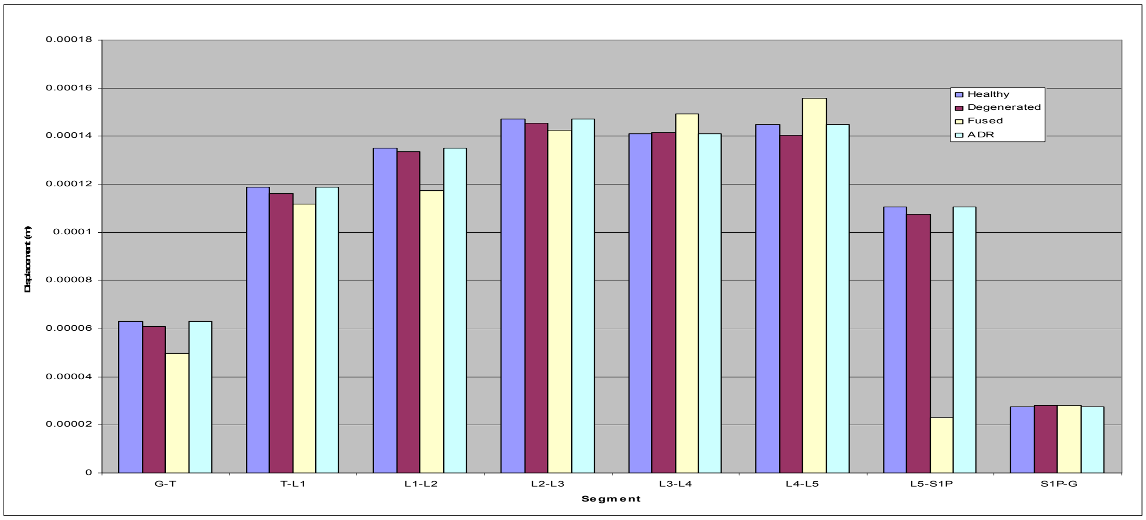

Figure 9-42: Anterior Posterior response of a full 3-degree of freedom ADR at L5-S1

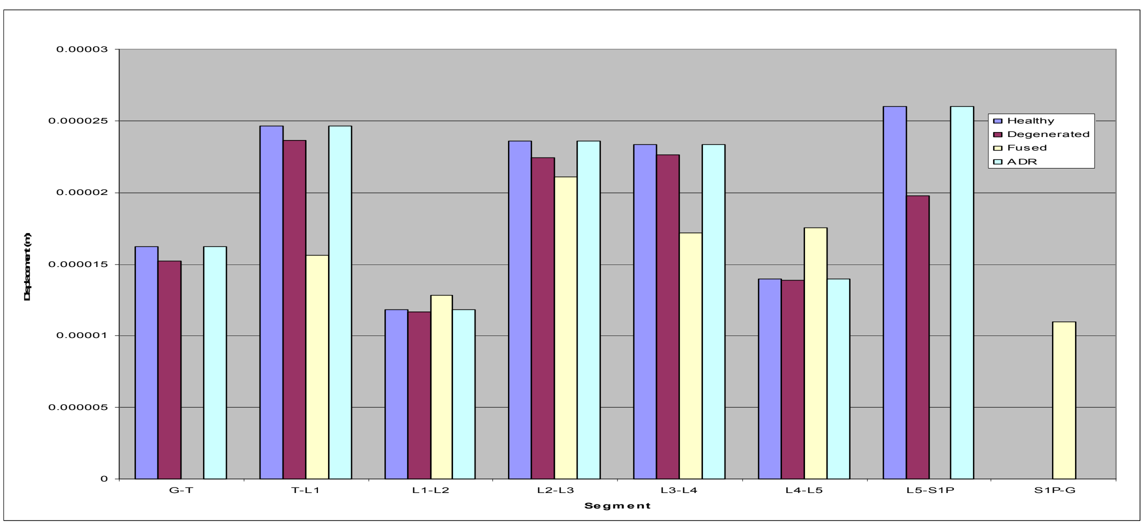

Figure 9-43: Axial response of a full 3-degree of freedom ADR at L5-S1

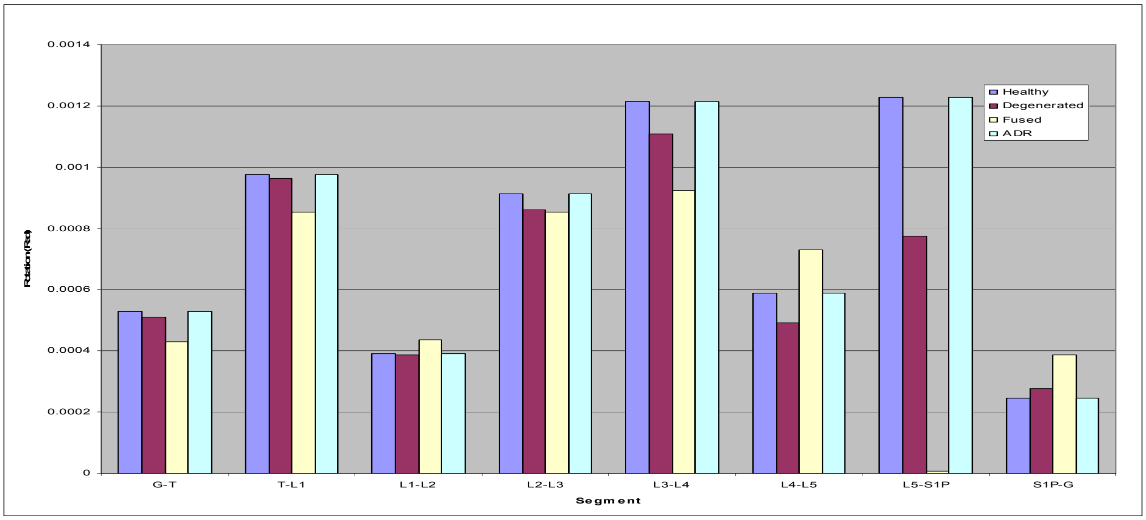

Figure 9-44: Flexion Extension response of a full 3-degree of freedom ADR at L5-S1

9.4.2.1 Result Summary of Three Degree of Freedom L5 – S1 ADR's

Tables 9-16 through 9-18 show a comparative summary of the results obtained for each 3-degree of freedom L5 – S1 ADR case.

Table 9-16: Posterior Anterior intervertebral displacement summary for the 3-DOF L5-S1 ADR case

	Posterior Anterior Intervertebral Displacement % Difference					
	T-L1	**L1-L2**	**L2-L3**	**L3-L4**	**L4-L5**	**L5-S1P**
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	-2.23%	-1.08%	-1.32%	0.43%	-3.12%	-2.62%
Fused	-5.98%	-13.26%	-3.21%	5.84%	7.53%	-79.05%
3-DOF	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Table 9-17: Axial intervertebral displacement summary for the 3-DOF L5-S1 ADR case

	Axial Intervertebral Displacement % Difference					
	T-L1	**L1-L2**	**L2-L3**	**L3-L4**	**L4-L5**	**L5-S1P**
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	-4.03%	-1.44%	-4.79%	-2.99%	-1.03%	-23.85%
Fused	-36.65%	8.23%	-10.64%	-26.24%	25.36%	-100.00%
3-DOF	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Table 9-18: Flexion Extension intervertebral rotation summary for the 3-DOF L5-S1 ADR case

	Flexion Extension Intervertebral Rotation % Difference					
	T-L1	**L1-L2**	**L2-L3**	**L3-L4**	**L4-L5**	**L5-S1P**
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	-1.17%	-1.45%	-5.66%	-8.61%	-16.65%	-36.78%
Fused	-12.34%	11.09%	-6.65%	-24.07%	23.67%	-99.37%
3-DOF	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

9.5 Results Summary (RMS)

The following tables summarize all the results obtained by level of implantation, L4 – L5 and L5 – S1.

9.5.1 L4 – L5 ADR's

Tables 9-19 through 9-21 show a comparative summary of all the results obtained for each ADR case implanted at the L4 – L5 level.

Table 9-19: Posterior Anterior intervertebral displacement summary for all L4-L5 ADR cases

	Posterior Anterior Intervertebral Displacement % Difference					
	T-L1	L1-L2	L2-L3	L3-L4	L4-L5	L5-S1P
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	0.72%	0.21%	-0.46%	0.43%	0.04%	-1.97%
Fused	-1.94%	-6.65%	-5.04%	9.19%	-53.91%	8.80%
Shear	1.71%	0.07%	-0.82%	0.90%	0.71%	-5.26%
Compressive	-1.96%	-6.63%	-5.04%	9.17%	-53.89%	8.77%
Rotational	-3.14%	-6.52%	-4.04%	9.41%	-53.97%	11.28%
Shear-Compressive	1.74%	0.14%	-0.90%	0.83%	0.86%	-5.51%
Compressive-Rotational	-3.15%	-6.48%	-4.03%	9.49%	-53.97%	11.25%
Shear-Rotational	-0.07%	0.03%	0.27%	0.46%	-0.12%	0.02%
3-DOF	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Table 9-20: Axial intervertebral displacement summary for all L4-L5 ADR cases

	Axial Intervertebral Displacement % Difference					
	T-L1	L1-L2	L2-L3	L3-L4	L4-L5	L5-S1P
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	0.00%	6.90%	-0.72%	3.26%	-31.49%	-3.31%
Fused	-21.36%	39.39%	-16.03%	16.32%	-100.00%	7.69%
Shear	5.76%	33.10%	-13.50%	7.44%	-100.00%	-11.62%
Compressive	-18.89%	39.39%	-12.26%	14.72%	-79.80%	7.69%
Rotational	-23.05%	35.22%	-19.98%	16.32%	-16.70%	22.35%
Shear-Compressive	3.87%	34.16%	-7.47%	-1.11%	-79.80%	-10.62%
Compressive-Rotational	-19.70%	36.28%	-20.43%	19.74%	-9.65%	21.14%
Shear-Rotational	-0.33%	1.42%	2.49%	-2.23%	-3.11%	0.30%
3-DOF	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Table 9-21: Flexion Extension intervertebral rotation summary for all L4-L5 ADR cases

	Flexion Extension Intervertebral Rotation % Difference					
	T-L1	L1-L2	L2-L3	L3-L4	L4-L5	L5-S1P
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	-0.46%	2.24%	1.51%	1.94%	-42.79%	-4.94%
Fused	-14.39%	12.62%	15.30%	8.62%	-99.41%	17.35%
Shear	-0.91%	6.40%	3.85%	5.10%	-99.24%	-10.92%
Compressive	-14.41%	12.47%	15.28%	8.63%	-99.17%	17.29%
Rotational	-13.97%	5.63%	13.53%	6.26%	-12.99%	23.95%
Shear-Compressive	-1.06%	5.98%	4.08%	5.11%	-99.41%	-10.90%
Compressive-Rotational	-13.99%	5.99%	13.54%	6.42%	-14.00%	23.79%
Shear-Rotational	0.28%	-0.45%	-0.36%	0.10%	0.64%	0.05%
3-DOF	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

9.5.2 L5 – S1 ADR's

Tables 9-19 through 9-21 show a comparative summary of all the results obtained for each ADR case implanted at the L5 – S1 level.

Table 9-22: Posterior Anterior intervertebral displacement summary for all L5-S1 ADR cases

	Posterior Anterior Intervertebral Displacement % Difference					
	T-L1	L1-L2	L2-L3	L3-L4	L4-L5	L5-S1P
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	-2.23%	-1.08%	-1.32%	0.43%	-3.12%	-2.62%
Fused	-5.98%	-13.26%	-3.21%	5.84%	7.53%	-79.05%
Shear	-12.66%	-14.65%	-11.18%	-8.87%	-18.27%	-16.98%
Compressive	-14.10%	-20.81%	-11.69%	-3.36%	-1.89%	-80.88%
Rotational	-7.02%	-11.18%	-11.21%	-1.60%	5.45%	-64.57%
Shear-Compressive	-12.61%	-14.67%	-11.17%	-8.95%	-18.00%	-17.54%
Compressive-Rotational	-7.03%	-11.18%	-11.20%	-1.64%	5.60%	-64.65%
Shear-Rotational	-8.89%	-8.65%	-8.65%	-8.78%	-9.08%	-8.49%
3-DOF	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Table 9-23: Axial intervertebral displacement summary for all L5-S1 ADR cases

	Axial Intervertebral Displacement % Difference					
	T-L1	L1-L2	L2-L3	L3-L4	L4-L5	L5-S1P
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	-4.03%	-1.44%	-4.79%	-2.99%	-1.03%	-23.85%
Fused	-36.65%	8.23%	-10.64%	-26.24%	25.36%	-100.00%
Shear	-24.13%	0.00%	-32.05%	-18.27%	6.75%	-100.00%
Compressive	-41.70%	-3.63%	-15.53%	-35.92%	-2.41%	-67.82%
Rotational	-21.99%	5.79%	-6.44%	-16.42%	-9.65%	3.21%
Shear-Compressive	-22.69%	-4.88%	-29.88%	-19.03%	6.75%	-100.00%
Compressive-Rotational	-21.64%	6.91%	-6.44%	-18.27%	-8.71%	3.68%
Shear-Rotational	-9.31%	-7.41%	-12.05%	-2.86%	-5.96%	-10.62%
3-DOF	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Table 9-24: Flexion Extension intervertebral rotation summary for all L5-S1 ADR cases

	Flexion Extension Intervertebral Rotation % Difference					
	T-L1	L1-L2	L2-L3	L3-L4	L4-L5	L5-S1P
Healthy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Degenerated	-1.17%	-1.45%	-5.66%	-8.61%	-16.65%	-36.78%
Fused	-12.34%	11.09%	-6.65%	-24.07%	23.67%	-99.37%
Shear	-11.77%	-11.82%	-22.16%	-30.47%	-5.17%	-99.44%
Compressive	-20.09%	1.79%	-14.80%	-30.55%	11.08%	-99.35%
Rotational	-15.28%	3.21%	0.18%	-5.41%	-2.57%	11.08%
Shear-Compressive	-11.69%	-11.67%	-22.24%	-30.32%	-6.47%	-99.39%
Compressive-Rotational	-15.21%	3.75%	0.09%	-5.34%	-2.22%	10.92%
Shear-Rotational	-8.69%	-9.29%	-8.50%	-8.61%	-8.69%	-8.62%
3-DOF	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

9.6 Matlab Code

```
%Function Name 'spine'
function dw = spine(t,w)    %Function Definition 'Spine'

%Initial Conditions in X,Y,Theta dots (1st 21 elements) and X,Y,Theta (last 21 elements)
order
%vx=[0 0 0 1.8414 0 0 0];            %Velocity in the x-direction Thorax - Pelvis
%vy=[0 0 0 0 0 0 0];            %Velocity in the y-direction Thor - Pelv
%vt=[0 0 0 0 0 0 0];            %Velocity in the theta-direction Thor - Pelv
%xd=[0 0 0 0 0 0 0];            %Position in the x-direction Thor - Pelv
%yd=[0 0 0 0 0 0 0];            %Position in the y-direction Thor - Pelv
%td=[0 0 0 0 0 0 0];            %Position in the theta-direction Thor - Pelv
%w = [xd yd td vx vy vt];       %Velocities and Positions IC
%t=[0 10];                      %Time Span


%.........Variables...........


%Masses in Kg
%Thorax, L1, L2, L3, L4, L5, Pelvis-Sacrum
m1=25.9;
m2=0.17;
m3=0.17;
m4=0.114;
m5=0.114;
m6=0.114;
m7=6.02;

%Segment Lengths in meters
%Thorax, L1, L2, L3, L4, L5, Pelvis-Sacrum
l1=0.1240;
l2=0.0355;
l3=0.0375;
l4=0.0390;
l5=0.0400;
l6=0.0390;
l7=0.0410;

%Spring Constants X-Direction (N/m)
%Thorax, L1, L2, L3, L4, L5, Pelvis-Sacrum
kx1=30000;
kx2=50000;
kx3=40000;
kx4=35000;
kx5=30000;
kx6=30000*1;    %Fused Disc Kx6*1000  L4-L5
kx7=45000*1;    %Fused disc kx7*1000  L5-S1
kx8=200000;

%Spring Constants Y-Direction (N/m)
%Thorax, L1, L2, L3, L4, L5, Pelvis-Sacrum
dgny=1;
ky1=1250000;
ky2=640000*dgny;
ky3=620000*dgny;
ky4=600000*dgny;
ky5=525000*dgny;
ky6=450000*dgny;    %Degeneration 0.5, Fused Ky7*1000
ky7=510000*dgny;    %Degeneration 0.5, Fused Ky7*1000
ky8=300000;

%Spring Constants Theta-Direction (Nm/rad)
%Thorax, L1, L2, L3, L4, L5, Pelvis-Sacrum
dgnt=1;
kt1=400;
kt2=160*dgnt;
kt3=140*dgnt;
kt4=120*dgnt;
kt5=100*dgnt;
kt6=80*dgnt;    %Degeneration 2, Fused Kt7*1000
kt7=75*1000;    %Degeneration 2, Fused Kt7*1000
kt8=700;
```

```
%Axial and Torsion Spring Coupling Constant in meters
a=0.02;

%Inertias
I1=(m1*l1^2)/12;
I2=(m2*l2^2)/12;
I3=(m3*l3^2)/12;
I4=(m4*l4^2)/12;
I5=(m5*l5^2)/12;
I6=(m6*l6^2)/12;
I7=(m7*l7^2)/12;

%Mass Matrix
m=[m1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0;
    0 m2 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0;
    0 0 m3 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0;
    0 0 0 m4 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0;
    0 0 0 0 m5 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0;
    0 0 0 0 0 m6 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0;
    0 0 0 0 0 0 m7 0 0 0 0 0 0 0 0 0 0 0 0 0 0;
    0 0 0 0 0 0 0 m1 0 0 0 0 0 0 0 0 0 0 0 0 0;
    0 0 0 0 0 0 0 0 m2 0 0 0 0 0 0 0 0 0 0 0 0;
    0 0 0 0 0 0 0 0 0 m3 0 0 0 0 0 0 0 0 0 0 0;
    0 0 0 0 0 0 0 0 0 0 m4 0 0 0 0 0 0 0 0 0 0;
    0 0 0 0 0 0 0 0 0 0 0 m5 0 0 0 0 0 0 0 0 0;
    0 0 0 0 0 0 0 0 0 0 0 0 m6 0 0 0 0 0 0 0 0;
    0 0 0 0 0 0 0 0 0 0 0 0 0 m7 0 0 0 0 0 0 0;
    0 0 0 0 0 0 0 0 0 0 0 0 0 0 I1 0 0 0 0 0 0;
    0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 I2 0 0 0 0 0;
    0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 I3 0 0 0 0;
    0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 I4 0 0 0;
    0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 I5 0 0;
    0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 I6 0;
    0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 I7;];

%Spring Matrix
k=[kx1+kx2 -kx2 0 0 0 0 0 0 0 0 0 0 0 0 -l1*(kx1-kx2)/2 l2*kx2/2 0 0 0 0 0;
    -kx2 kx2+kx3 -kx3 0 0 0 0 0 0 0 0 0 0 0 -l1*kx2/2 -l2*(kx2-kx3)/2 l3*kx3/2 0 0 0 0;
    0 -kx3 kx3+kx4 -kx4 0 0 0 0 0 0 0 0 0 0 0 -l2*kx3/2 -l3*(kx3-kx4)/2 l4*kx4/2 0 0 0;
    0 0 -kx4 kx4+kx5 -kx5 0 0 0 0 0 0 0 0 0 0 0 -l3*kx4/2 -l4*(kx4-kx5)/2 l5*kx5/2 0 0;
    0 0 0 -kx5 kx5+kx6 -kx6 0 0 0 0 0 0 0 0 0 0 0 -l4*kx5/2 -l5*(kx5-kx6)/2 l6*kx6/2 0;
    0 0 0 0 -kx6 kx6+kx7 -kx7 0 0 0 0 0 0 0 0 0 0 0 -l5*kx6/2 -l6*(kx6-kx7)/2 l7*kx7/2;
    0 0 0 0 0 -kx7 kx7+kx8 0 0 0 0 0 0 0 0 0 0 0 0 -l6*kx7/2 -l7*(kx7-kx8)/2;
    0 0 0 0 0 0 0 ky1+ky2 -ky2 0 0 0 0 0 a*(ky1+ky2) -a*ky2 0 0 0 0 0;
    0 0 0 0 0 0 0 -ky2 ky2+ky3 -ky3 0 0 0 0 -a*ky2 a*(ky2+ky3) -a*ky3 0 0 0 0;
    0 0 0 0 0 0 0 0 -ky3 ky3+ky4 -ky4 0 0 0 0 -a*ky3 a*(ky3+ky4) -a*ky4 0 0 0;
    0 0 0 0 0 0 0 0 0 -ky4 ky4+ky5 -ky5 0 0 0 0 -a*ky4 a*(ky4+ky5) -a*ky5 0 0;
    0 0 0 0 0 0 0 0 0 0 -ky5 ky5+ky6 -ky6 0 0 0 0 -a*ky5 a*(ky5+ky6) -a*ky6 0;
    0 0 0 0 0 0 0 0 0 0 0 -ky6 ky6+ky7 -ky7 0 0 0 0 -a*ky6 a*(ky6+ky7) -a*ky7;
    0 0 0 0 0 0 0 0 0 0 0 0 -ky7 ky7+ky8 0 0 0 0 0 -a*ky7 a*(ky7+ky8);
    -l1*(kx1-kx2)/2 -l1*kx2/2 0 0 0 0 0 a*(ky1+ky2) -a*ky2 0 0 0 0 0
l1^2*(kx1+kx2)/4+kt1+kt2+a^2*(ky1+ky2) l1*l2*kx2/4-kt2-a^2*ky2 0 0 0 0 0;
    l2*kx2/2 -l2*(kx2-kx3)/2 -l2*kx3/2 0 0 0 0 -a*ky2 a*(ky2+ky3) -a*ky3 0 0 0 0
l1*l2*kx2/4-kt2-a^2*ky2 l2^2*(kx2+kx3)/4+kt2+kt3+a^2*(ky2+ky3) l2*l3*kx3/4-kt3-a^2*ky3 0
0 0 0;
    0 l3*kx3/2 -l3*(kx3-kx4)/2 -l3*kx4/2 0 0 0 0 -a*ky3 a*(ky3+ky4) -a*ky4 0 0 0 0
l2*l3*kx3/4-kt3-a^2*ky3 l3^2*(kx3+kx4)/4+kt3+kt4+a^2*(ky3+ky4) l3*l4*kx4/4-kt4-a^2*ky4 0
0 0;
    0 0 l4*kx4/2 -l4*(kx4-kx5)/2 -l4*kx5/2 0 0 0 0 -a*ky4 a*(ky4+ky5) -a*ky5 0 0 0 0
l3*l4*kx4/4-kt4-a^2*ky4 l4^2*(kx4+kx5)/4+kt4+kt5+a^2*(ky4+ky5) l4*l5*kx5/4-kt5-a^2*ky5 0
0;
    0 0 0 l5*kx5/2 -l5*(kx5-kx6)/2 -l5*kx6/2 0 0 0 0 -a*ky5 a*(ky5+ky6) -a*ky6 0 0 0 0
l4*l5*kx5/4-kt5-a^2*ky5 l5^2*(kx5+kx6)/4+kt5+kt6+a^2*(ky5+ky6) l5*l6*kx6/4-kt6-a^2*ky6 0;
    0 0 0 0 l6*kx6/2 -l6*(kx6-kx7)/2 -l6*kx7/2 0 0 0 0 -a*ky6 a*(ky6+ky7) -a*ky7 0 0 0 0
l5*l6*kx6/4-kt6-a^2*ky6 l6^2*(kx6+kx7)/4+kt6+kt7+a^2*(ky6+ky7) l6*l7*kx7/4-kt7-a^2*ky7;
    0 0 0 0 0 l7*kx7/2 -l7*(kx7-kx8)/2 0 0 0 0 0 -a*ky7 a*(ky7+ky8) 0 0 0 0 0
l6*l7*kx7/4-kt7-a^2*ky7 l7^2*(kx7+kx8)/4+kt7+kt8+a^2*(ky7+ky8);];

%Eigenvectors
[V,D]=eig(k,m);

%Normalizing Eigenvectors
for n=1:21
    phi(:,n)=(1/sqrt(V(:,n)'*m*V(:,n)))*V(:,n);
end
```

```
%Natural Frequencies
omegas=sqrt(abs(phi'*k*phi));

%Damping Coefficients
z=0.25; %Critical damping coefficients all equal to 0.25
c=m*phi*2*z*eye(21)*omegas*phi'*m;


%External Forces Applied to L3
ksi=0;
e=0;
fo=0;  %*exp(2*pi()*i*2*t);
fx=fo*cos(ksi*pi()/180);    %Force in the X-direction
fy=fo*sin(ksi*pi()/180);   %Force in the Y-direction
M=fx*e;                     %Moment in the Z-direction
f=[0; 0; 0; fx; 0; 0; 0; 0; 0; 0; fy; 0; 0; 0; 0; 0; 0; M; 0; 0; 0];
mf=inv(m)*f;
g = zeros(21,1);
forces=[g;mf];

%Static Response
X=inv(k)*f;

%State Space Matrix
dots=[zeros(21,21) eye(21); -inv(m)*k -inv(m)*c];


%ODE Function
%function dw = spine(t,w)    %Function Definition 'Spine'
dw = zeros(42,1);            %Column Vector of 42rows
for n=1:42

dw(n)=dots(n,1)*w(1)+dots(n,2)*w(2)+dots(n,3)*w(3)+dots(n,4)*w(4)+dots(n,5)*w(5)+dots(n,6
)*w(6)+dots(n,7)*w(7)+dots(n,8)*w(8)+dots(n,9)*w(9)+dots(n,10)*w(10)+dots(n,11)*w(11)+dot
s(n,12)*w(12)+dots(n,13)*w(13)+dots(n,14)*w(14)+dots(n,15)*w(15)+dots(n,16)*w(16)+dots(n,
17)*w(17)+dots(n,18)*w(18)+dots(n,19)*w(19)+dots(n,20)*w(20)+dots(n,21)*w(21)+dots(n,22)*
w(22)+dots(n,23)*w(23)+dots(n,24)*w(24)+dots(n,25)*w(25)+dots(n,26)*w(26)+dots(n,27)*w(27
)+dots(n,28)*w(28)+dots(n,29)*w(29)+dots(n,30)*w(30)+dots(n,31)*w(31)+dots(n,32)*w(32)+do
ts(n,33)*w(33)+dots(n,34)*w(34)+dots(n,35)*w(35)+dots(n,36)*w(36)+dots(n,37)*w(37)+dots(n
,38)*w(38)+dots(n,39)*w(39)+dots(n,40)*w(40)+dots(n,41)*w(41)+dots(n,42)*w(42)+
forces(n);
end


end
```