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Biomechanical Testing on Cadaveric Spines for Different Treatments that Affect Lumbar Stability

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Biomechanical Testing on Cadaveric Spines for Different

Treatments that Affect Lumbar Stability

by

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Decompression, Functional Spinal Unit (FSU)

DEDICATION

I want to dedicate this thesis to my parents, Nancy and Antonio, and to my sister, Desiree, who have always believed in my dreams and have given me all their support and love to make them come true.

I also want to dedicate this to my husband, Oscar, who has guided me with his unconditional love and support to achieve this important goal in my life.

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Quisiera agradecer a la familia Cristancho Mercado por todo su apoyo y calor humano a lo largo de este hermoso camino. Gracias por abrirme las puertas de su hogar y de su corazón lo que ha sido muy importante para alcanzar este sueño.

I said once that this degree would be "...a trampoline that will give me the tools to contribute to society in a responsible way". You all made this possible and my duties are just beginning.

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ABSTRACT

Stenosis is one of the most common causes for spinal surgery. Laminectomy decompression and fusion are surgical procedures prescribed for this condition. The intention of this work was to investigate the effects of a laminectomy decompression, followed by fusion, on a lumbar functional spinal unit (FSU) through *in vitro* dynamic (±8Nm at 0.125Hz) and quasi-static (±7.5Nm at 0.1Hz) biomechanical tests, for flexion, extension, bending and rotation motions.

Six FSUs where disarticulated from four human cadaveric lumbar spines (63 ± 12 years) and were tested under the following sequence: (1) intact, (2) laminectomy decompression, and (3) Pedicle Screw System (PSS), using a load-displacement controlled system. Dynamic neutral zone (NZ), dynamic neutral zone stiffness (NZS) and the range of motion (ROM) were the parameters evaluated.

Since only 6 FSUs from different spinal levels were used, any effect related to the spinal level could not be evaluated. This limitation enforced to consider normalized data (with respect to intact) as an alternative analysis, but large standard deviations after transforming the data forced us to contemplate this "a pilot study".

Dynamic testing revealed that there were no significant differences in the neutral zone magnitude for any motion after a laminectomy decompression, while its magnitude for flexion-extension was significantly affected by PSS treatment ($p<0.004$). The change in dynamic NZ (normalized data) was significantly different ($p<0.03$) after both treatments for flexion-extension motion. The reduction in stiffness (normalized data) for

extension after a laminectomy, and the increase in stiffness (normalized data) for flexion and extension after PSS treatment, were both significant ($p<0.03$ and $p<0.05$, respectively). The ROM were not statistically significant for the three treatments, but normalized data showed significant differences ($p<0.05$) for all motions, except for right bending after laminectomy and right rotation after PSS.

Non-normalized data from quasi-static testing didn't show any statistically significant difference between the treatments for any motion. Normalized data suggested significant differences for the change in ROM for all motions at multiple load conditions, especially for flexion and extension.

This pilot study suggests there may be a considerable effect of a laminectomy on the stability of a lumbar FSU. Dynamic data suggested the changes in neutral zone stiffness triggered by a laminectomy procedure may be significant for extension. PSS treatment increased segment's NZ stiffness by more than double. The changes in ROM from quasi-static loading caused by a laminectomy decompression may be significant as well, especially for flexion (20%) and extension (greater than 10%).

It is suggested that further studies involving spine biomechanics should consider and report, but not be limited to the following variables: exposure time of the specimen to room temperature, preservation and testing conditions, ligaments and joints conditions, testing protocol, and loading history.

CHAPTER 1: INTRODUCTION

1.1. Significance

Back pain has lately become one of the most common complaints among the adult population. According to the National Center for Health Statistics (2006) more than one-quarter of the adults' respondents reported to have suffered back pain in the past 3 months. Similarly, Vallfors states on one of his works (as cited on the American Chiropractic Association [ACA], 2011) that eighty percent of the population claim to have experienced back pain at some point of their life.

Low back pain can be caused by a variety of reasons, such as mechanical instability, soft tissue injury, bone degeneration, and spinal stenosis. Stenosis is the most common cause for spine surgery and its incidence in older adults is expected to increase over time (Deyo, 2010; Backstrom, Whitman, & Flynn, 2011). Common treatments for this condition are decompression, or decompression coupled with fusion (Kaner, Sasani, Oktenoglu, Aydin, & Ozer, 2010; Dimar, Djurasovic, & Carreon, 2005).

Biomechanical testing has become a valuable instrument for spinal research; It provides information about the vertebral column behavior when is exposed to different loading conditions, including activities of daily living, work related activities, aging, injuries, and degenerative processes. In addition, *in vitro* biomechanical data is commonly included as part of the standard testing protocol for testing new surgical procedures and implants. The viscoelastic behavior of the spine explains how the displacements achieved when certain loads are applied are highly dependent on the load's rate; because of that, *in* vitro testing can involve dynamic and/or quasi-static loading, at controlled rates. Either animal or human cadaveric models can be used, although human models are preferred since the limitation of extrapolating the outcomes is less contradictory.

The goal of any surgical procedure is to have the best outcomes through a minimally invasive procedure, as well as a short recovery time. The wide variety of decompression techniques include minimal resections, such as unilateral laminotomy, and more invasive procedures, such as bilateral facetectomy combined with laminectomy (Zander, Rohlmann, Klöckner, & Bergmann, 2003). The extent of the resection for achieving an adequate decompression would depend on the severity of the stenosis and the surgeon's criterion.

It has been demonstrated that a complete laminectomy (which includes the resection of the spinous process, the lamina and both supraspinous and interspinous ligaments) can be effectively performed, in terms of decompression, without compromising the integrity of the facet joints (Musacchio et al., 2007). However, *in vitro* biomechanical data about intervertebral motion, using human cadaveric models, when a laminectomy itself has been performed, could not be found.

The actual data available about the effects of a lumbar laminectomy is controversial. Zander et al. (2003) developed a mathematical model that intended to evaluate the effects of a laminectomy on lumbar stability, but their procedure included the removal of the facet capsular ligament (facetectomy), which should not be compared to a laminectomy alone. Likewise, Lee & Teo (2004) developed a three dimensional finite element (FE) model of an L2-L3 segment, where the effects of the laminectomy and facetectomy were evaluated. In this study, the posterior elements were resected following the subsequent order: (1) unilateral laminectomy, (2) unilateral facetectomy, (3) bilateral laminectomy, (4) bilateral facetectomy. Once again, it is not appropriate to consider the outcomes of treatment (3) as the effects of a laminectomy itself since the segment was previously subjected to a unilateral facetectomy. However, this study suggests that unilateral laminectomy may cause some kinematic effects and annulus stress.

Regarding animal models, Kulkarni et al. (2007) investigated the post-laminectomy effects for lumbar intraforaminal spinal nerve adhesion in a rodent's *in vitro* model, finding quantifiable spinal nerve fibrosis after laminectomy, but no biomechanical data in terms of intervertebral motion was reported. Likewise, an *in vitro* study conducted by Rao et al (2002) was intended to compare the kinematic effects in calf spines of a bilateral laminotomy and a laminectomy, but this last procedure implied the excision of the medial portion of the facet joint capsule, which makes the laminectomy procedure refutable. Additionally, it is recognized in this work the possible overestimation in the influence of supraspinous and interspinous ligaments for flexion when extrapolating results to human cadaveric models, since the calf spines has longer spinous processes than human spines.

Since the existence of data regarding the biomechanical effects of a laminectomy decompression on the lumbar spine is limited, and the data is controversial due to different procedures described as a laminectomy, the need of *in vitro* biomechanical testing to investigate the effects of this procedure in human cadaveric lumbar spinal segments arose.

1.2. Objectives

The scope of this study is to evaluate the biomechanical effects, through *in vitro* testing, of a laminectomy decompression on a lumbar functional spinal unit (FSU) as a treatment for spinal stenosis. Also, the effect of fusion (using the “gold standard” system: pedicle screw) as an alternative for stabilization after decompression is evaluated.

1.3. Experimental Design

A load-displacement machine, designed for 6 DOF spine testing by VG Innovations, LLC., was used to perform dynamic (±8Nm at 0.125Hz) and quasi-static (±7.5Nm at 0.1Hz) loading tests on six lumbar functional spinal units (FSUs) that underwent three different treatments: (1) intact/control, (2) laminectomy decompression and (3) pedicle screw system (PSS).

1.4. Limitations

The availability of human cadaveric specimens was limited. Only four lumbar spines were available for this study. In addition, the condition of some spinal levels were not ideal (i.e. presence of osteophyte discs, osteoporotic conditions), which forced the reduction on the number of samples. These limitations led to utilizing six Functional Spinal Units (FSUs) from different levels: one L1-L2, one L2-L3, one L3-L4, one L4-L5 and two L5-S1 segments. Having a restricted number of samples from different spinal levels limited the conclusions related to spinal level, as well as the power of the data analysis.

CHAPTER 2: LITERATURE REVIEW

2.1. Spine Anatomy

2.1.1. Overview

The human spine is responsible for the motion between the pelvis, trunk, and head. It allows weight transfer in the form of compressive, tensile and bending load, originated by daily body motions, and it also serves as protection to the spinal cord. (White & Panjabi, 1990)

The spine consists of 24 articulated vertebrae (7 cervical, 12 thoracic and 5 lumbar) and 8 to 9 fused vertebrae (5 sacral and 3 or 4 coccygeal segments), as illustrated in Figure 2.1. Each cervical, thoracic and lumbar vertebra is articulated with their adjacent vertebrae by a cartilaginous joint (intervertebral disc) that serves as shock (also heat) absorber, and allows holding the vertebral bodies together. Ligaments and muscles are also part of the structure that gives the spine its stability. (White & Panjabi, 1990)

One particular functional feature of the spine is its natural curvatures (Figure 2.1). In the sagittal plane, the spine has 4 normal curvatures: concave posteriorly (lordosis) on the cervical and lumbar region and concave anteriorly (kyphosis) on the thoracic, sacral and coccygeal regions. These anatomical curvatures contribute to the vertebral column's stability, its stiffness and flexibility, which are fundamental for absorbing different forces to which it is habitually exposed. (White & Panjabi, 1990)

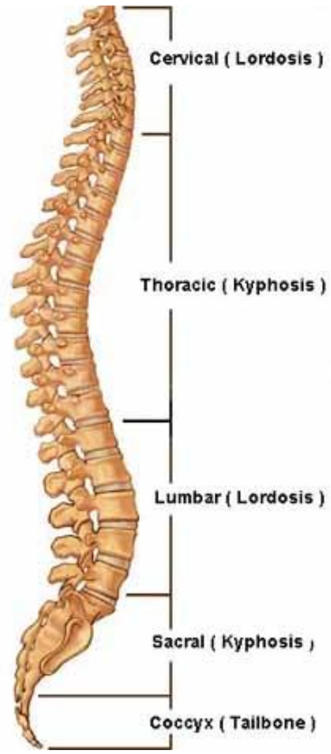
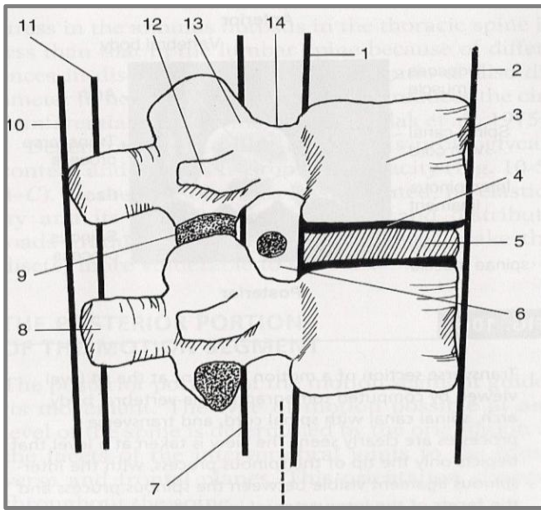


Figure 2.1. Lateral View of the Spinal Column–*Only Bone Structure and Intervertebral Disc are Shown*. (Spine Universe, 2010 (Public Domain))

2.1.2. Functional Spinal Unit

A functional spinal unit (FSU) is known as the smallest motion segment that can demonstrate biomechanical properties of the spine (Figure 2.2). It consists of two adjacent vertebrae, the intervertebral disc between the two, and interconnecting ligaments. (Nordin & Frankel, 2001)



1. Longitudinal Ligament (posterior).
2. Longitudinal Ligament (anterior).
3. Vertebral Body.
4. Cartilaginous end plate.
5. Intervertebral disc.
6. Intervertebral foramen (with nerve root)
7. Ligamentum flavum.
8. Spinous process.
9. Intervertebral Joint (facet joint).
10. Supraspinous ligament.
11. Interspinous ligament.
12. Transverse process (intertransverse ligament not shown).
13. Arch.
14. Vertebral canal.

Figure 2.2. Schematic Representation of a Lumbar FSU Spine-Sagittal View. (adaptation from Nordin & Frankel, 2001)

2.1.2.1. The Vertebra

With the exception of the first cervical vertebra, which does not have a body, the vertebral body is the bone structure of a FSU. Common characteristics of a typical vertebra are the vertebral body (anterior segment), the neutral arch (posterior segment- which enclose the vertebral foramen) and the seven processes (four articular, two transverse and one spinous). (Moore, Agur & Dalley, 2011)

Each vertebra’s anatomy is unique but they share common features that are highly related to their location. The lumbar region, for example, is exposed to greater loads which justifies wider and thicker vertebral bodies, when comparing to those on the thoracic and cervical regions (Nordin & Franke, 2001). Figures 2.3, 2.4 and 2.5 illustrate a typical cervical, thoracic and lumbar vertebra, respectively.

The sacrum, composed by five fused vertebrae, gives the strength and stability to the pelvis. Its most superior vertebra (S1) articulates with the inferior articular process of the last lumbar vertebra (L5). (Moore, Agur & Dalley, 2011)

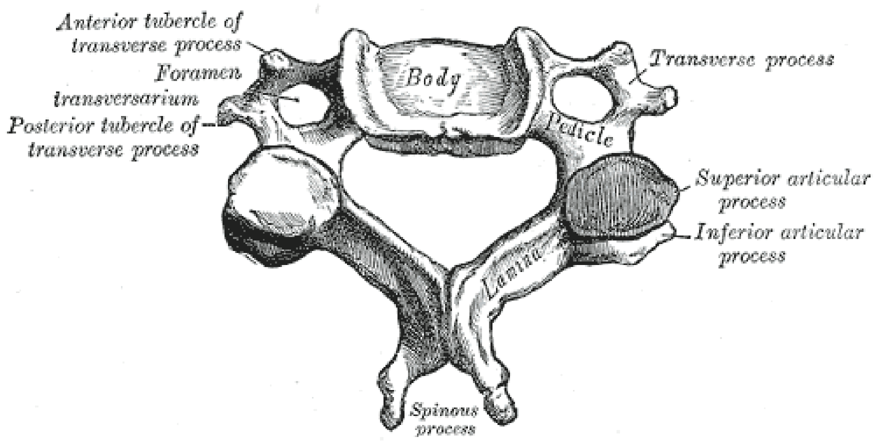


Figure 2.3. Representation of a Typical Cervical Vertebra. (Gray, 1918 (Public Domain))

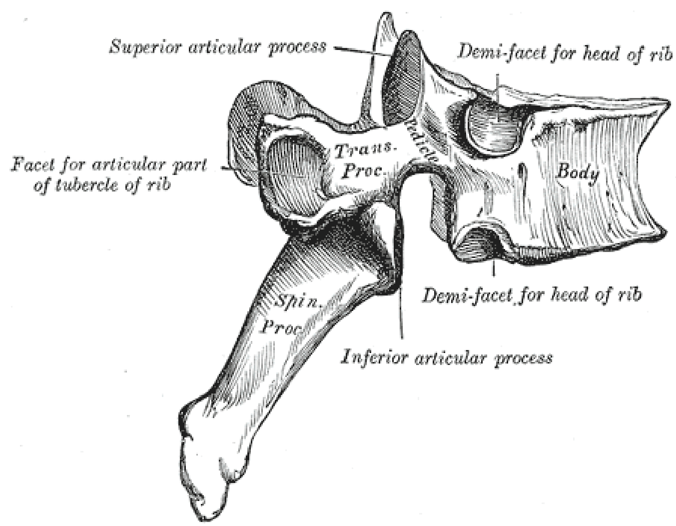


Figure 2.4. Representation of a Typical Thoracic Vertebra. (Gray, 1918 (Public Domain))

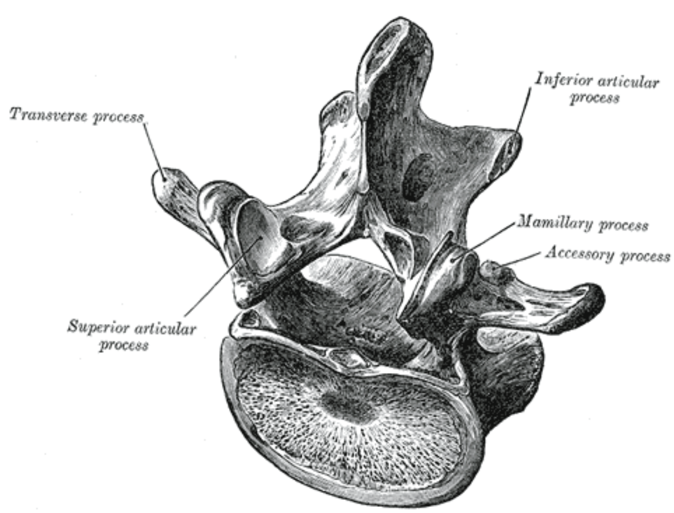


Figure 2.5. Representation of a Typical Lumbar Vertebra. (Gray, 1918 (Public Domain))

2.1.2.2. The Intervertebral Disc

The intervertebral disc is a fibrocartilage that articulates two adjacent vertebrae. Its main function is to act as a shock absorber of all loading, especially compressive loads, to which the trunk is exposed (White & Panjabi, 1990). It is also important for maintaining the space between vertebrae, allowing the nerve roots from the spinal cord to expand to the rest of the body.

Regarding its composition, an intervertebral disc consists of an inner gelatinous structure, nucleus pulposus, and an outer fibrocartilage structure, annulus fibrosus (Figure 2.6). Due to its important role on withstanding complex loads, its degeneration is critical for the spine motion.

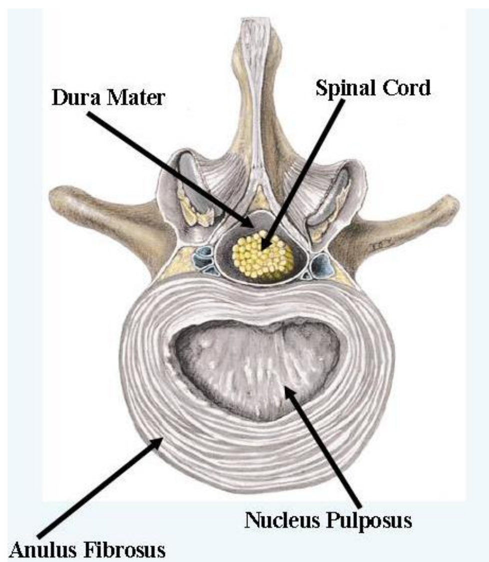


Figure 2.6. Representation of an Intervertebral Disc Anatomy. (Lahr, 2003, (Public Domain))

There is no intervertebral disc between the two first cervical vertebrae (C1 and C2), and the last functional disc is located between the last lumbar vertebrae (L5) and the first fused sacral vertebra (S1). The thickness of an intervertebral disc is associated with the range of motion to which it is exposed; hence to the region it is located. Lumbar and cervical intervertebral discs are thicker, while the thinnest discs can be found at the superior thoracic region. (Moore, Agur & Dalley, 2011)

With aging, the nucleus pulposus becomes dry and granular due to the loss of elastin and the gain of collagen, which make it stiffer and more resistant to deformation. Likewise, the annulus becomes thicker and begins to develop fissures and cavities. (Moore, Agur & Dalley, 2011)

A common condition for low back pain is known as herniated disc, where the nucleus pulposus protrudes into or through the annulus causing compression on longitudinal ligaments and/or the spinal cord, usually posterior-lateral. Localized pain is triggered by the pressure produced by the herniated disc on the longitudinal ligaments and from local inflammation, while chronic pain results from compression on the spinal cord. This condition usually requires surgical intervention. (Moore, Agur & Dalley, 2011)

2.1.2.3. Ligaments

Ligaments are uniaxial structures that respond effectively to loads applied along the direction of their fibers (White III & Panjabi, 1990). They can extend to one or more adjacent vertebra, depending on its nature and location. Among the main features of ligaments in a FSU is to bring stability to the vertebral column, as well as protect the spinal cord by limiting the range of motion (White III & Panjabi, 1990). The ligaments considered on a FSU are illustrated in Figure 2.7.

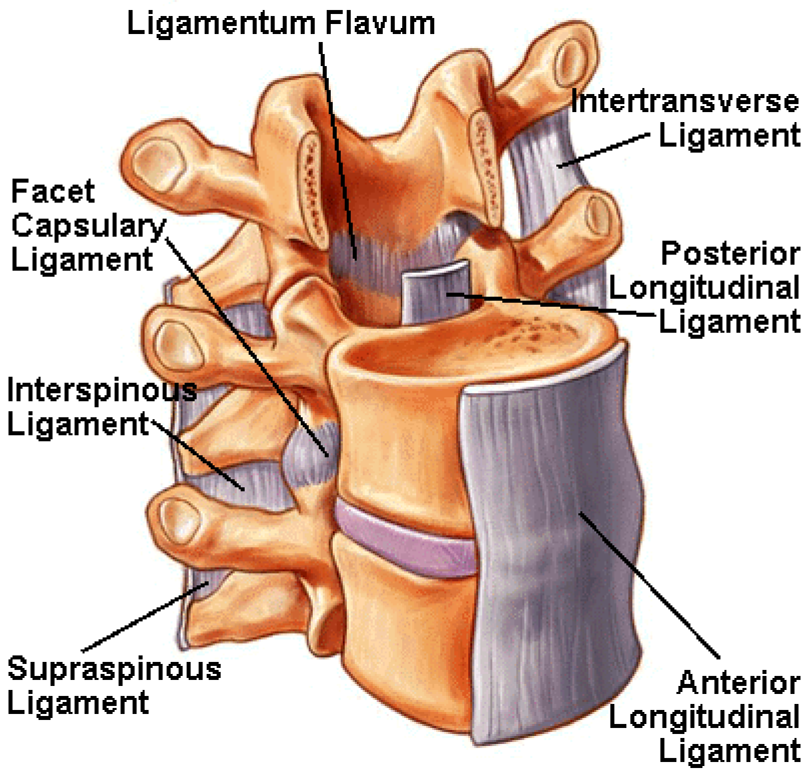


Figure 2.7. Representation of Ligaments in a Segment of the Spine. (Spine Universe, 2011 (Public Domain))

Each ligament in a FSU has distinct features and is responsible for reacting at the presence of specific loads. They are known as (Moore, Agur & Dalley, 2011):

- *Ligamentum flavum.* It extends vertically from lamina to lamina, helping the vertebral column maintain its natural curvature, as well as assisting on straightening after flexing. It also prevents excessive separation between the laminae to protect the intervertebral disc from injury.
- *Posterior longitudinal ligament.* It extends from the second cervical vertebra (C2) to the sacrum. Its main function is to prevent hyper-flexion of the vertebral column, as well as posterior herniation of the intervertebral disc.

- *Anterior longitudinal ligament.* It extends from the sacrum to the occipital bone anterior to the foramen magnum. It limits the extension of the vertebral column and also gives stability to the intervertebral joints.
- *Joint capsule.* It surrounds the articular surface of the zygapophysial joints (facets). It is responsible for gliding movements between the articular processes.
- *Intertransverse ligament.* It connects the transverse processes of adjacent vertebrae. It is very thin and membranous on the lumbar region, fibrous on the thoracic region and composed by scattered fibers in the cervical region.
- *Interspinous ligament.* It connects the spinous processes of adjacent vertebrae. It has an important role during flexion (Yogananda, Kumerasan, & Pintar, 2001).
- *Supraspinous ligament.* It merges from the median ligament of the neck (nuchal ligament) and it connects the apices of spinous processes of adjacent vertebrae. It is considered a strong structure, compared to the Interspinous ligament.

2.2. Spinal Stenosis

Spinal stenosis is characterized by a narrow (stenotic) vertebral foramen at one or more vertebrae. It may cause the compression of one or more spinal nerve root located at the vertebral canal, or the compression of any nerve leaving the neural foramina. Even severe anatomical spinal stenosis could be asymptomatic (Weinstein et al., 2007).

Lumbar stenosis is the most common reason for lumbar surgery in adults over the age of 65 (Weinstein et al., 2007). It can be either primary (congenital or postnatal developed) or secondary (resulting from degenerative changes, trauma, infection or surgery) (Genevay & Atlas, 2010). Foraminal stenosis, narrowing of the neural foramen at one or more segments, can be either caused by a disc split or osteophytes formation (Genevay & Atlas, 2010).

Treatments for lumbar stenosis can be either surgical or non-surgical. Recent studies suggest that surgery is more effective (Genevay & Atlas, 2010). A common surgical treatment for lumbar spine stenosis is a decompressive laminectomy (Mimran & Henn, 2005; Dimar et al., 2005; Kaner et al., 2010). This procedure consists of the resection of the entire laminae of the vertebra, as well as the spinous process, ligamentum flavum, and the supraspinous and interspinous ligaments (Mimran & Henn, 2005), as illustrated in Figure 2.8. More than one vertebra can be involved in this treatment and it is also prescribed for recurrent disc displacements, retained intervertebral disc fragment, adjacent level stenosis and postoperative instability with adjacent level stenosis (Hulen, 2008).

This procedure is considered a minimal invasive surgery and can be performed in a regular operating room. After all preoperative preparation, the first step is to determine the level that will be treated, and fluoroscopy is commonly used for this approach. The second step consists on creating a channel through which the procedure will be performed. There is a wide variety of instruments used for this purpose and they are generally offered as a “surgical kit” (i.e. tubular retractor system by METRx). The third step implies the removal of the laminae, using a high-speed air drill and an operative microscope and/or endoscopy to guarantee excellent illumination and visibility. (Mimran & Henn, 2005)

Occasionally a lumbar decompression is followed by fusion. According to a recent study by Reid et al. (2011), posteriolateral fusion (PLF) is more widely accepted than direct posterior spinal fusion nowadays (PSF). Pedicle screw systems (PSS) is the standard method for PLF (Figure 2.9), which consists on fixing screws to the pedicles of two adjacent vertebrae and bound them by rods, crosslinks and connectors (Reid, Johnson & Wang, 2011).

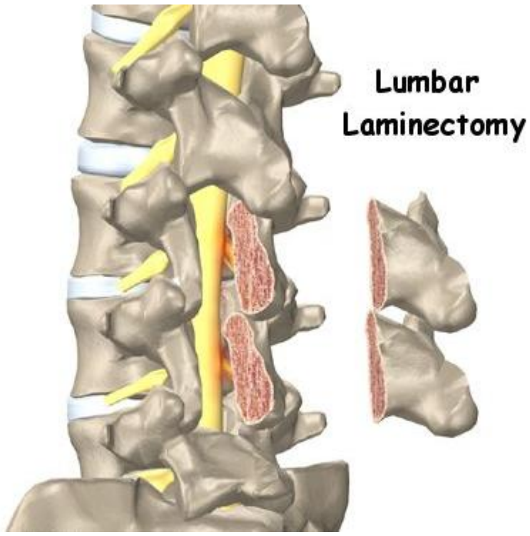
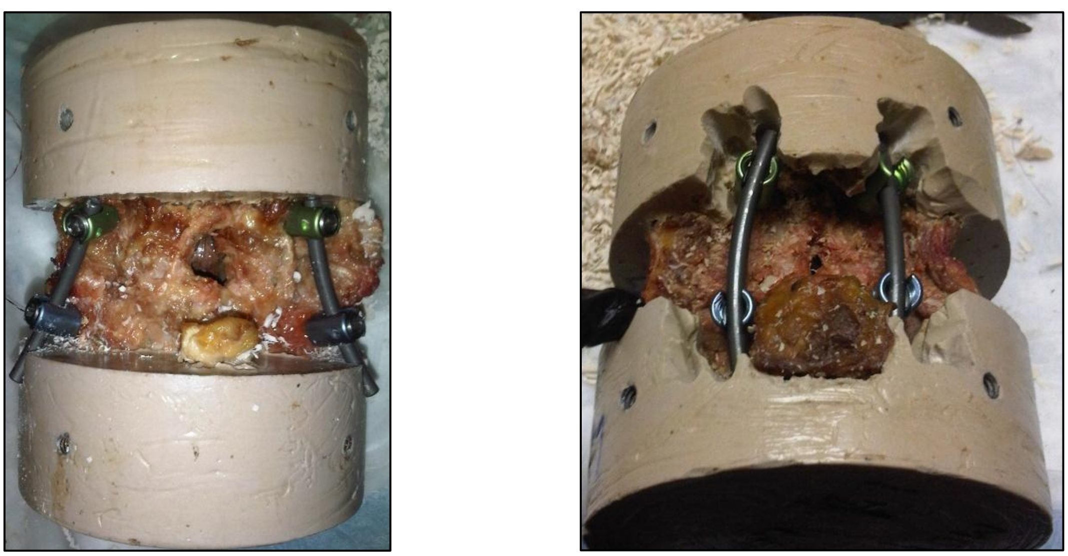


Figure 2.8. Illustration of a Two-Levels Lumbar Laminectomy. (Orthogate, 2006, (Public Domain))



(A) (B)

Figure 2.9. Alphatech Pedicle Screw System. *(A): L5-S1 Segment, (B): L1-L2 Segment*

Some researchers affirm that spinal fusion negatively affects adjacent spinal levels by promoting degeneration due to the restricted motion in the fused segment(s) (Bono & Brick, 2007; Goel, et al. 2007). However, a common argument made for fusing spinal segments after decompression is that fusion helps to minimize the chance of instability that could eventually lead to slippage of the disc and stenosis (Mardjetko, Connolly, & Shott, 1994; Bono & Brick, 2007).

2.3. Biomechanics of the Spine

When discussing about spine biomechanics, it is important to define a coordinate system to which all possible motions would be referred. Figure 2.10 defines a three-dimensional, right-handed, orthogonal coordinate system (according to ISO 2631) where all motions (flexion, extension, right/left bending and right/left rotation) are illustrated. Here X-axis refers to ventral (forward), Y-axis to the left and Z-axis refers to cranial (above).

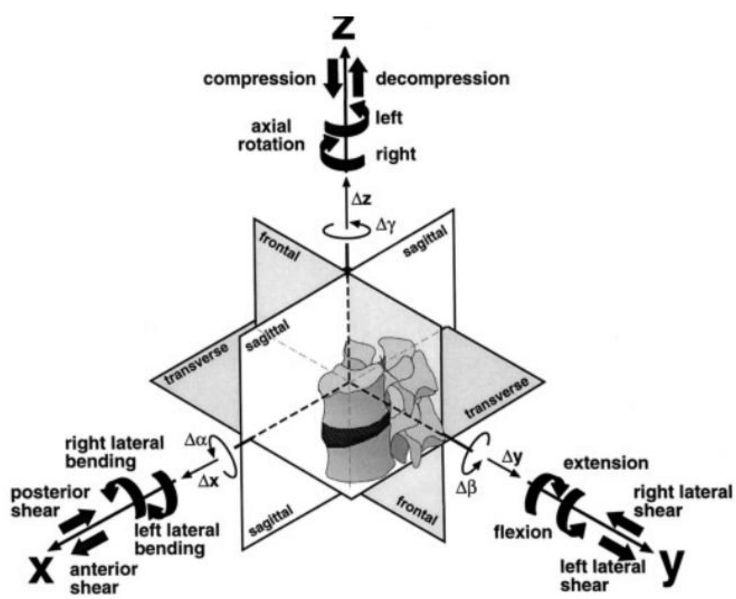


Figure 2.10. Three-Dimensional Coordinate System to Reference FSU Motions. (Wilke, Wenger, Claes, 1998)

The spine could be considered as a structure composed by multiple FSUs, hence its behavior can be seen as a composite of each FSU's actions. The biomechanical properties of a FSU mainly depend on the physical properties of its components (intervertebral disc, ligaments and articular joints). A typical load-displacement curve experience by any FSU is shown in Figure 2.11.

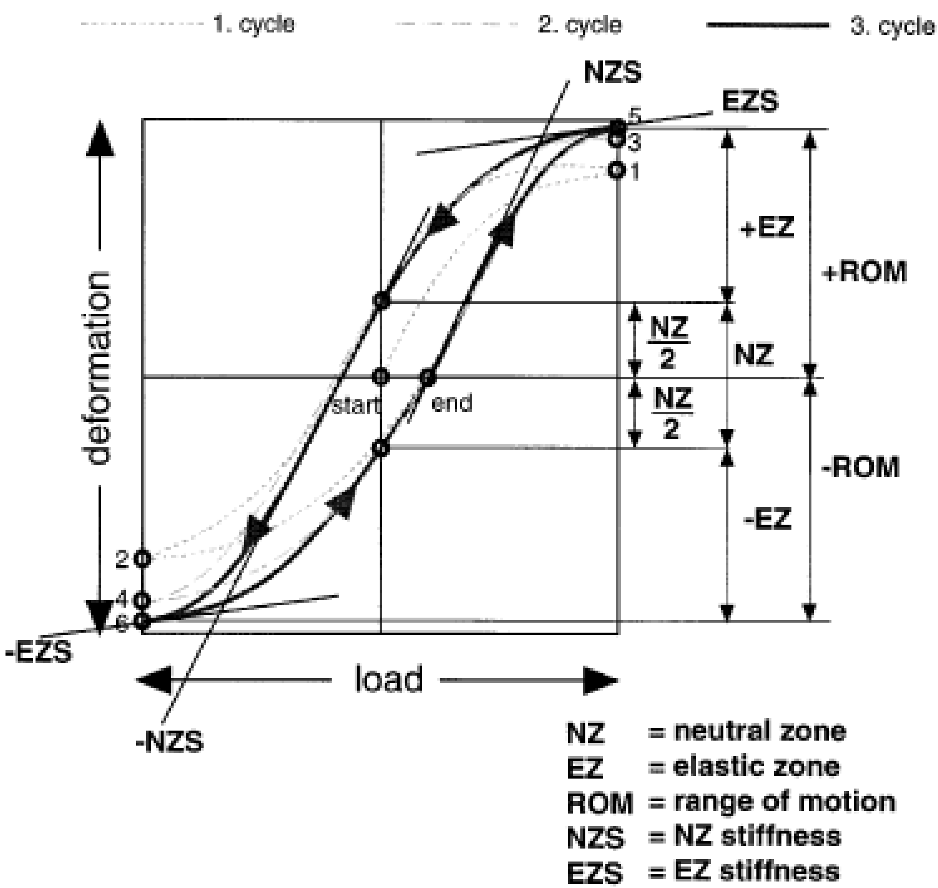


Figure 2.11. Representation of a Load-Displacement Curve with Continuous Changing Load. (Wilke, Wenger, Claes, 1998)

A typical load-displacement curve for a FSU reveals the viscoelastic (non-linear) behavior of the vertebral column. At small loads, the displacement increases more rapidly (i.e. region neighboring the neutral zone) than it does for larger loads (i.e. elastic zone). The following definitions can be conceptualized from Figure 2.11 (Wilke, Wenger, Claes, 1998):

- *Neutral Zone (NZ).* It is defined as the difference in displacement (angulation) at "zero" load between two phases of motion. It represents the range over which the specimen moves essentially free.
- *Elastic Zone (EZ).* Deformation measured from the end of the neutral zone (NZ) to the point of maximal physiological load.
- *Range of Motion (ROM).* It describes the sum of the neutral zone and the elastic zone in one direction of motion.
- *Neutral Zone Stiffness (NZS).* The stiffness measured at the neutral zone by taking the slope of the linear portion around the neutral position[1].
- *Elastic Zone Stiffness (EZS).* The stiffness measured at the linear portion around the elastic deformation zone[1].

In vitro biomechanical testing normally includes the evaluation of some or all of the parameters mentioned above. They could give useful information when evaluating changes in spine biomechanics due to an injury or degeneration.

Both dynamic and quasi-static loading conditions provide substantial information about the biomechanics of the spine. When testing dynamically, there is a closer approximation to what the behavior of the spine would be during Activities of Daily Living (ADL). Most daily tasks performed by a person imply dynamic motion of the vertebral column. However, quasi-static testing allows the analysis of the creep phenomenon

[1] Technically, the stiffness is the inverse of the slope of the linear portion of the curves, from Figure 2.11.

demonstrated by the spine (due to its viscoelastic properties), which shows how when a load is being held constant, the strain increases over time.

2.3.1. The Vertebra

Cervical, thoracic and lumbar vertebrae share common features that have been previously discussed, but the increment in size and mass from the first cervical to the last lumbar have a reason for being: the compressive load increases as we move to lower levels. Likewise, the alignment of the facet joints governs the mechanical behavior of a vertebra, and their orientation can significantly differ between the three regions of the spine. Furthermore, the facet joints orientation has been identified as an important sign for different pathologies of the intervertebral disc. (White & Pajabi, 1990)

Another parameter for describing a vertebra's biomechanics is the stress of failure (strength), which is directly related to bone density. In general, aging has shown to induce osseous tissue's diminution, thus, the vertebra decreases in strength.

2.3.2. Intervertebral Disc

The disc is mainly exposed to compressive loads, although it can be subjected to other types of stress during physiological motion (depending on its location). The disc exhibits time-dependent properties (i.e. viscoelasticity); hence it is important to categorize the loads in order to describe the biomechanical properties of the disc. These loads are mainly distinguished by their amplitude and duration, being the two categories: (1) low amplitude/long duration and (2) high amplitude/short duration. (White & Panjabi, 1990)

Being both elasticity and viscosity characteristics of an intervertebral disc, the creep and stress relaxation phenomenon (illustrated in Figure 2.12) can be exhibited, depending on the type of load applied. Creep occurs when a constant stress (load) is displayed and, as a result, the strain increases over time. While stress relaxation phenomenon takes place when a constant strain is applied and the result is a decrement of the stress over time.

The viscoelastic properties of a disc can be altered by degeneration, therefore the ability of responding to certain loads and attenuating shocks. It has been observed that the creep response of an intervertebral disc is highly related to the degree of its degeneration, where a non-degenerated disc creeps gradually reaches its final deformation after a long period of time when comparing with a degenerated disc (cited on White & Panjabi, 1990).

Another important phenomenon that is present in the intervertebral disc behavior is hysteresis, which is defined by the loss of energy when exposed to cyclic loads. It has been shown that lower lumbar discs experience larger hysteresis than other regions. The hysteresis exhibited by an intervertebral disc decreases when it is loaded a second time, which suggests that the vertebral column is less protected against cyclic loading. (White & Panjabi, 1990)

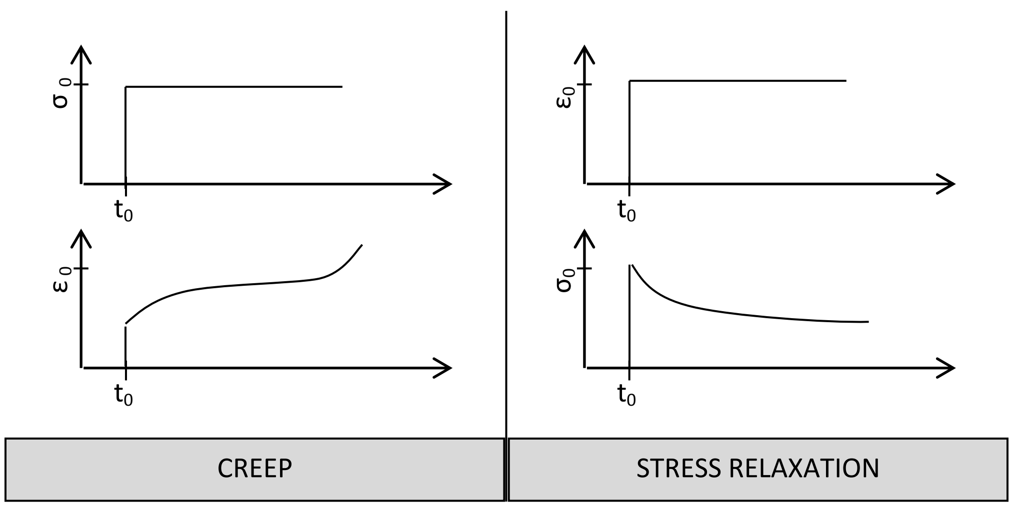


Figure 2.12. Creep and Stress Relaxation Phenomenon.

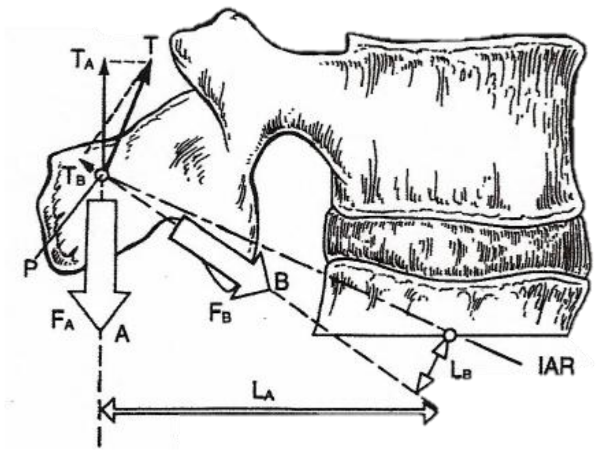
2.3.3. Ligaments

Due to the complex anatomy of ligaments, they can develop tension as a response of tensile resistance from external loads of different natures; although they are most effective when subjected to uniaxial loads (White & Pajabi, 1990). Compared to the intervertebral disc, the ligaments are more subjected to tension loads while a disc is designated more for compressive loads.

The resistance a ligament exerts against a load depends on the magnitude and rate at which the load is applied. Anterior longitudinal ligament, as well as the interspinous ligament, exerts higher resistance than the posterior longitudinal ligament located at the center of rotation. (Yoganand a, Kumerasan, & Pintar, 2001)

In terms of biomechanics, a ligament that offers a smaller lever arm would provide less stability than one with a larger lever arm. In other words, the resistance of a ligament in a vertebra is proportional to the force being applied and to the lever arm (i.e. resistance=**F**orce X **L**ever.arm **–**cross product), as long as the force (tension) is applied on the instantaneous axis of rotation, as illustrated in Figure 2.13. The resistance exerted by two different oriented ligaments (F_A X L_A, resistance of ligament A, and F_B X L_B resistance of ligament B), which have the same mechanical properties, would be greater for the one that has a greater lever arm (assuming the ligaments apply equal force). (White & Panjabi, 1990)

A typical load-displacement curve of a ligament is illustrated in Figure 2.14. Two major areas are identified: physiological and traumatic range. The physiological range is constituted by the neutral and elastic zone (NZ and EZ), which have been defined before (please refer to *biomechanics of the spine*). It is important to mention that, according to Figure 2.14., the neutral zone (NZ) is the displacement achieved when a small load (very close to zero) is applied, while other authors refer to the NZ as the displacement achieved when a zero load is applied.



T: tension
F: Force
L: length
A, B: Ligaments
P: Point of attachment for ligaments
IAR: Instantaneous axis of Rotation

Figure 2.13. Stabilizing Function of a Spinal Ligament. (Adaptation from White & Panjabi, 1990)

The ligaments do not provide crucial stability when the vertebral column is close or within the neutral zone but they do for higher strains, i.e. away from NZ (Panjabi, 1992). Goel et al. (as cited on Tai et al., 2008) suggest that the supraspinous ligament plays an important role during flexion. Likewise, the intertransverse ligaments have mechanical significance in the thoracic region while they have been found less important for the lumbar region due to small cross-sectional size (White & Panjabi, 1990).

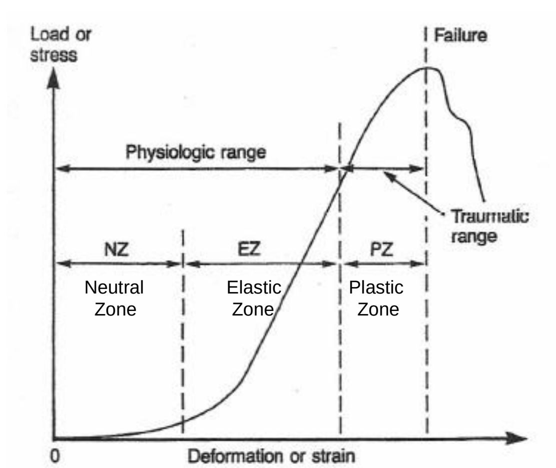


Figure 2.14. Typical Load-Displacement Curve of a Ligament. (Adaptation from White & Panjabi, 1990)

The ligamentum flavum allows large amounts of flexion without achieving a permanent deformation due to its high percentage of elastic fibers, while the capsular ligaments (facet joints) play an important role during flexion for the cervical region. (White & Panjabi, 1990)

CHAPTER 3: MATERIALS AND METHODS

3.1. Specimen Selection and Preservation

Four frozen human lumbar spines, with no previous surgery and suitable for research, were obtained from multiple approved research donor tissue organizations. The donors group consisted of 2 females and 2 males, with an average age of 63 ± 12 years.

In order to identify any major abnormality, such as intervertebral disc osteophytes and fissures to the vertebral bodies, the spines were visually inspected and dual-energy x-ray absorptiometry scans were performed to asses bone mineral density (BMD), Specimens with a BMD score lower than 0.700gr/cm^2 were considered at high-risk of osteoporosis, hence were excluded and replaced. The average score of BMD was 0.941 ± 0.169 gr/cm^2.

The inspection of the specimens served to identify the best Functional Spinal Units (FSU) that would be disarticulated and used for the study. Specimens were thawed at room temperature (23±1°C) for about 24 hours and then disarticulated. Muscles and adipose tissue were removed, carefully preserving the disc, ligaments and posterior elements of the respective selected segment. Each FSU was inspected and only a selected subset was judged acceptable for inclusion in this study. The group of FSUs consisted of L1-L2, L3-L4 and L5-S1 segments from *specimen 1*, L4-L5 from *specimen 2*, L5-S1 from *specimen 3*, and L2-L3 segment from *specimen 4*.

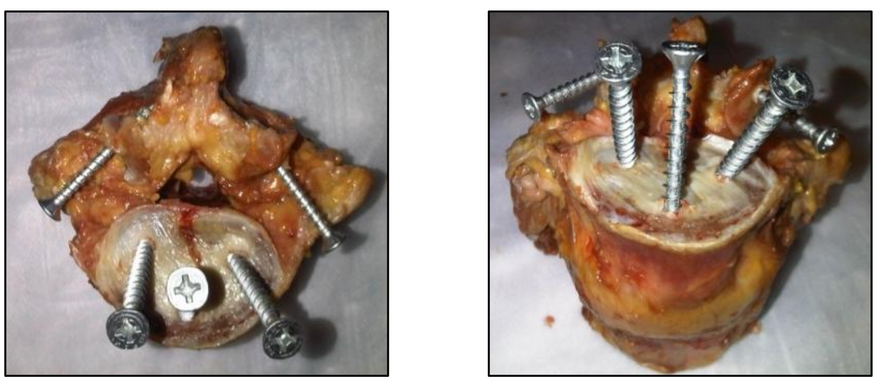
Specimens were sprayed with distilled water, covered with soaked gauzes and preserved in a freezer at -30°C. They were thawed at 4°C for 8-12 hours and set at room temperature (23±1°C) for 30 min before testing.

3.2. Specimen Preparation

The specimen preparation protocol was developed by VG Innovations, LLC and used with only minor modifications in this study. This reflected and extensive analysis of protocols employed in similar studies.

To anchor the FSU, three 2'' screws (size 10) were placed in the vertebral body and two 1'' screws (size 8) in each articular facet joint of the superior vertebra, using a screwdriver. In some cases, it was necessary to drill a small hole before placing the screws to facilitate fixation. It was essential to achieve a good fixation at the first attempt, so we avoided having loose screws as a consequence of screwing in and out. Additionally, it was taken into account that the screws placed in the vertebral body would not go deeper than the height of the vertebral body, since it would have damaged the intervertebral disc. Once the screws were in place, we verified all screws were securely fastened (Figure 3.1). Likewise, screws were placed in the inferior vertebra (3 in the vertebral body and 2 in the inferior facet joints).

Two molds were constructed with two aluminum plates (6'' x 6'' x 0.25'') and dishes (OD-6.3'', ID-6'', height-2''), where each plate was screwed to each dish using four 10'' threaded bar (Figure 3.2a). Four ¼-20x2'' pan head screws were placed horizontally into the holes of the dishes and wing nuts were placed at 1 inch on each screw, to help securing the specimen to the testing machine. At this point, the FSU was placed in the inferior mold, making sure the spinous process was aligned with one of the threaded bars. The orientation was given by the centers of rotation so that they would coincide with the drive shafts of the testing machine (Figure 3.2b). Also, the disc was lined up parallel to the base of the frame. These alignments were necessary to ensure all loads would be applied at the right planes. In some cases, it was necessary to elevate the spinal segment by using bolt nuts at the bottom of the screws located on the vertebral body. After filling the inferior mold with a polyester resin mixture, we let it set for 30min. Then, the 4 threaded bars were removed (Figure 3.3a) and the assembly (dish and spine anchored to the polyester resin) was flipped upside down through another 4 threaded bars which were attached to the superior mold. Four bolt nuts placed on the threaded bar gave the correct position (height) to the FSU (Figure 3.3b). The dish was filled with the polyester resin mixture and the specimen was removed from the dishes after 30 minutes (Figure 3.4).



(A) (B)

Figure 3.1. Representation of Screws' Position in One Side of a FSU. *(A): Superior view. (B): Anterior-superior view.*

(A) (B)

Figure 3.2. Settings for Specimen's Fixation. *(A): Mold Configuration. (B): Specimen's Position for Achieving Correct Fixation.*

(A) (B)

Figure 3.3. Specimen's Fixation Process. *(A): First Step Finished (Inferior Vertebra Anchored to Polyester resin Mixture). (B): Second Step's Configuration (Superior Vertebra Fixation).*

(A) (B)

Figure 3.4. Representation of a Segment Fixed to Polyester Resin Bases. (*A): Anterior View. (B): Posterior View.*

3.3. Testing Machine and Set-Up

3.3.1. Testing Machine Description

A load-displacement machine designed for 6DOF spine testing by *VG Innovations, LLC* was used for testing the specimens under flexion/extension, lateral bending and axial rotation (Figure 3.5). This machine consists of three *Brushless AC servo motor* (model N0400-101-B-000), combined with a planetary reduction gear box, and two fixation frames (superior and inferior). Two motors are anchored to the upper frame, one provides rotation about z-axis and the other rotation about y-axis (please refer to Figure 2.10). The third motor is attached to the lower frame and it also provides rotation about the y-axis. To achieve rotation about the x-axis (i.e. flexion/extension), it is necessary to rotate the specimen 90 degrees; for this reason, flexion/extension and lateral bending tests had to be performed one at the time, while axial rotation can be performed no matter how the specimen is placed on the machine. Both dynamic and quasi-static tests can be performed, by choosing either moment or displacements rates that are controlled by *Electronic Spine Tester VGI*, software developed for the spine tester (Figure 3.6).

The moments applied to the specimen are measured through strain gauges (precision of 0.01Nm) located directly on the drive shafts coupled to the dishes that holds the specimen (Figure 3.7), using the following relation:

$$T = (V[v] + OF[v]) \times SF \qquad \text{(Equation 3.1)}$$

where **V[v]** is the voltage reading from the strain gauges at a specific tension, **OF[v]** is the voltage reading from the strain gauges when no torque is being applied and **SF** is the scaling factor determined by the calibration of the strain gauges.

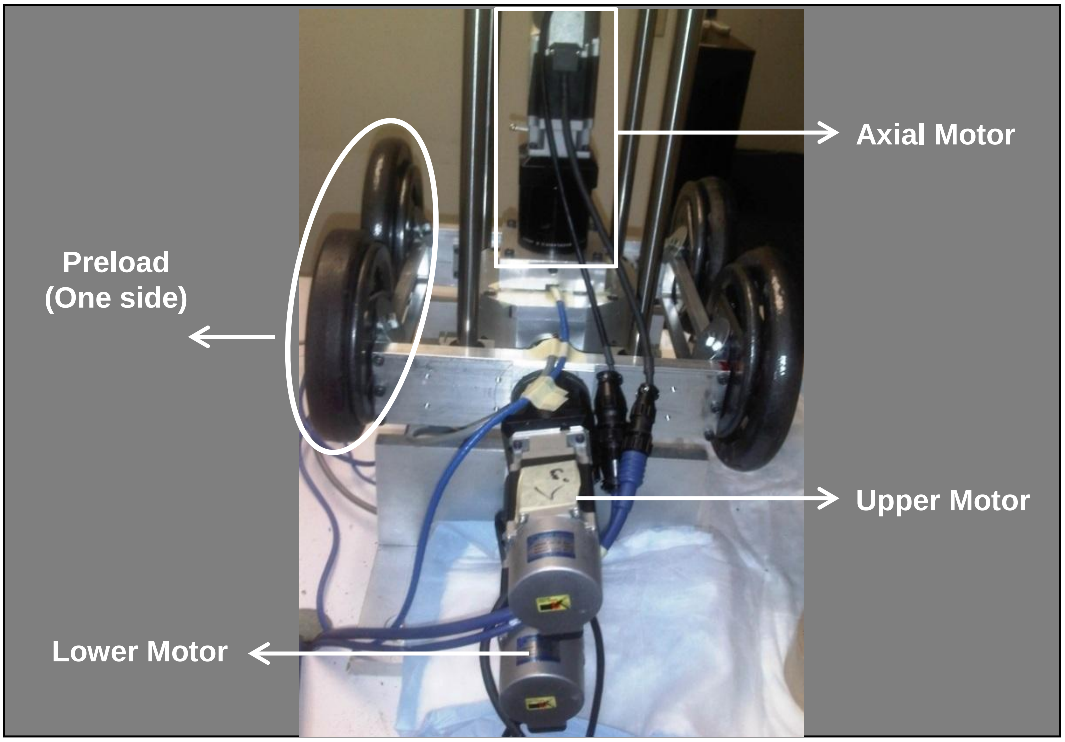


Figure 3.5. Testing Machine with Preload.

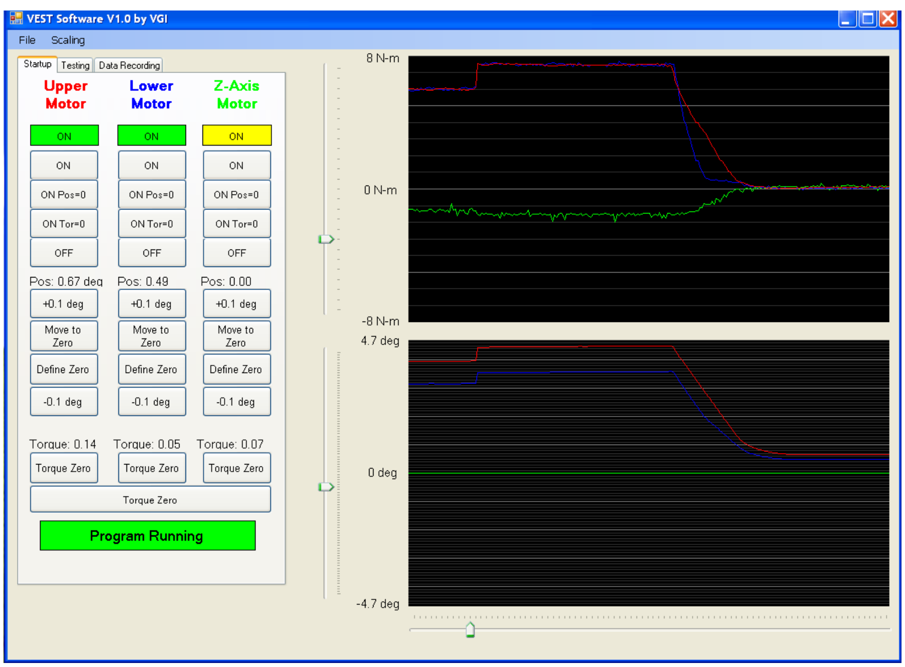
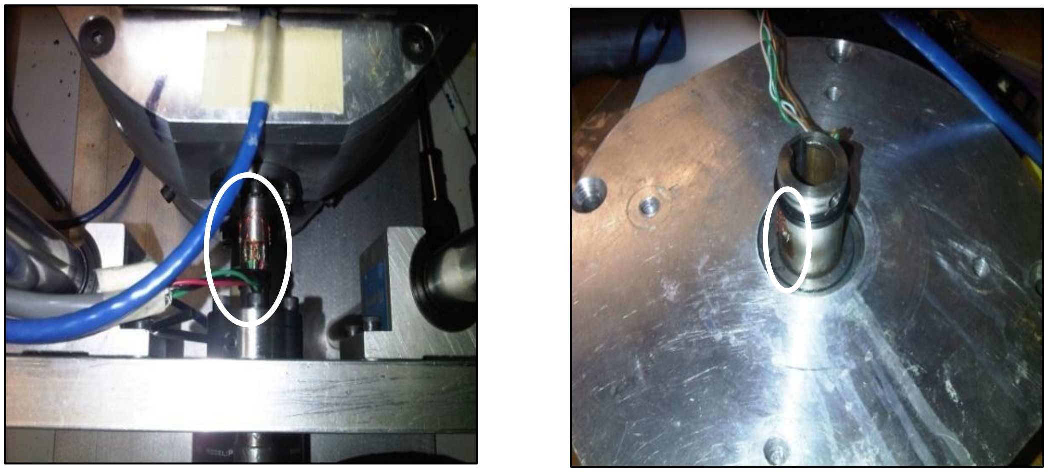


Figure 3.6. Representative Output (User Interface) from a Regular Quasi-Static Loading Test.



(A) (B)

Figure 3.7. Strain Gauges. *(A): Upper Motor Strain Gauge-superior. (B): Axial Motor Strain Gauge-1 of 2.*

The displacements values come directly from the motor (precision of 0.01 degree) as a measurement of the degrees rotated by the shaft when applying a certain moment. Figures 3.8 and 3.9 show a representation of a typical plot of the outcome for a dynamic and quasi-static test, respectively. For any testing the variables measured were: time, torque and displacement.

For dynamic testing, the change in displacement triggered by a continuous (dynamically) change in torque (Figure 3.8) was plotted. However, quasi-static data was used to create two different plots: torque vs. time (not shown) and displacement vs. time (Figure 3.9). The first plot was used to ensure the desired moments were being achieved for each step, while the second plot was our actual graph of interest. Occasionally, data from last step of quasi-static tests were estimated from a “print-screen” shoot (Figure 3.6), due to a minor software issue. Thus, the data when this issue was encountered looked like last step for PSS shown in Figure 3.9.

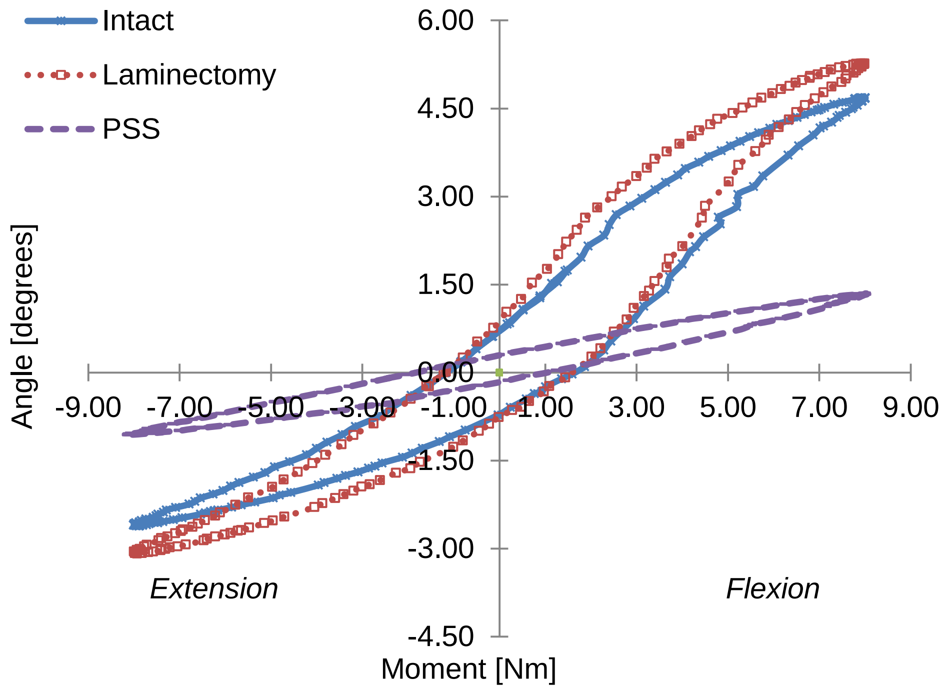


Figure 3.8. Representative Flexion-Extension Results for Intact, Laminectomy and PSS Treatments, under Dynamic Load.

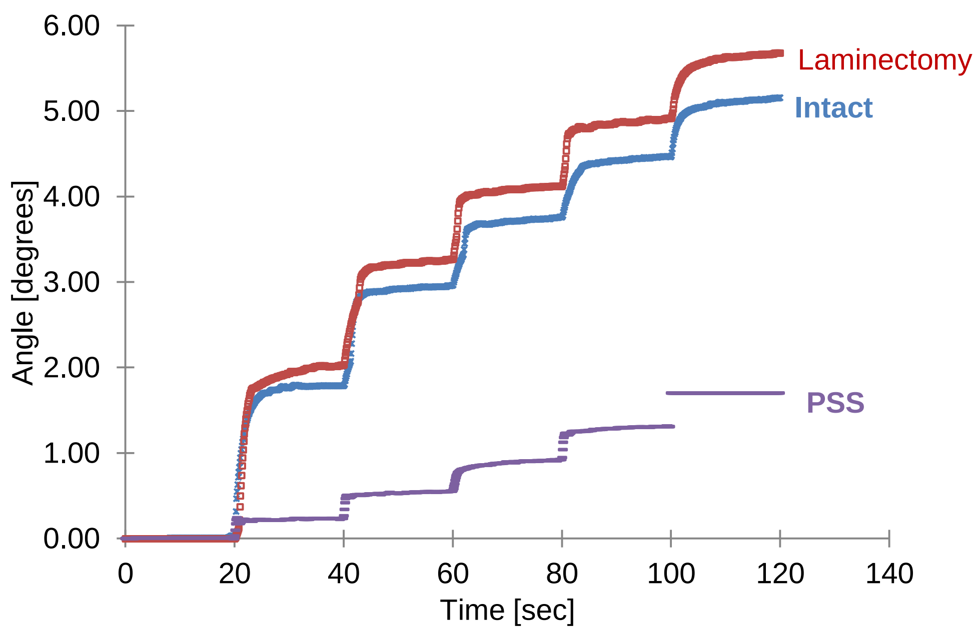


Figure 3.9. Representative Right Bending Results for Intact, Laminectomy and PSS Treatments, under Quasi-Static Loads.

3.3.2. Testing Set-Up

The FSU was anchored to the testing machine by using 4 screws threaded to both superior and inferior polyester resin bases. The first test performed was flexion/extension (dynamic followed by quasi-static testing), and then the specimen was rotated 90 degrees clockwise for testing lateral bending and axial rotation (both dynamic and quasi-static testing as well). It was important to be consistent with the position of the specimen to be able to analyze adequately the output data. All screws holding the specimen on the machine were well tight to avoid any unwanted vibration. Figure 3.10 shows the configuration of the specimen on the testing machine for performing lateral bending and axial rotation tests.

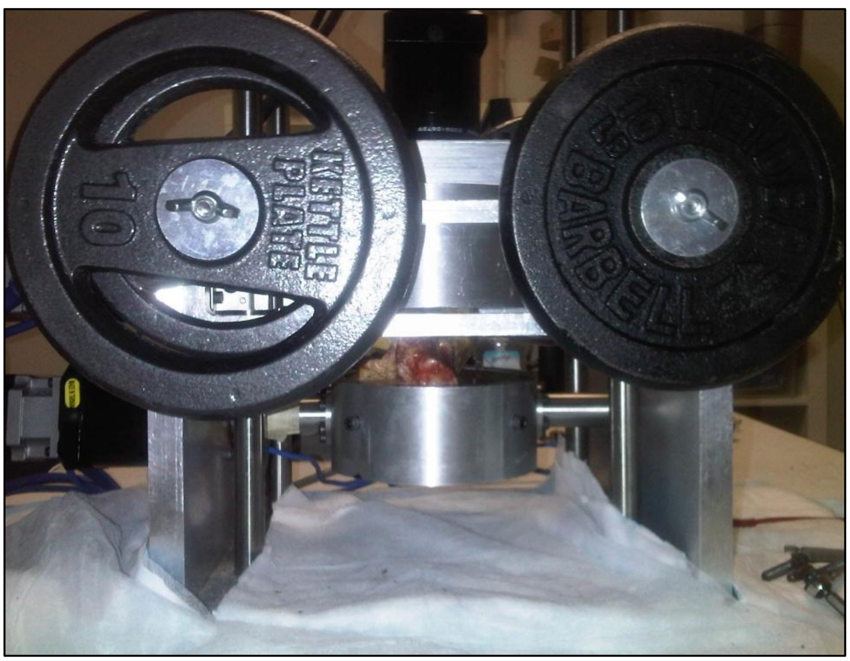


Figure 3.10. Specimen Configuration on Testing Machine for Lateral Bending and Axial Rotation Tests.

A compressive pre-load of 398.3 N was applied to the FSU during all tests, considering that previous publications suggest 400N (Voronov et al., 2009; Phillips et al. 2009).

In order to define the pre-load, we needed to consider the following calculation:

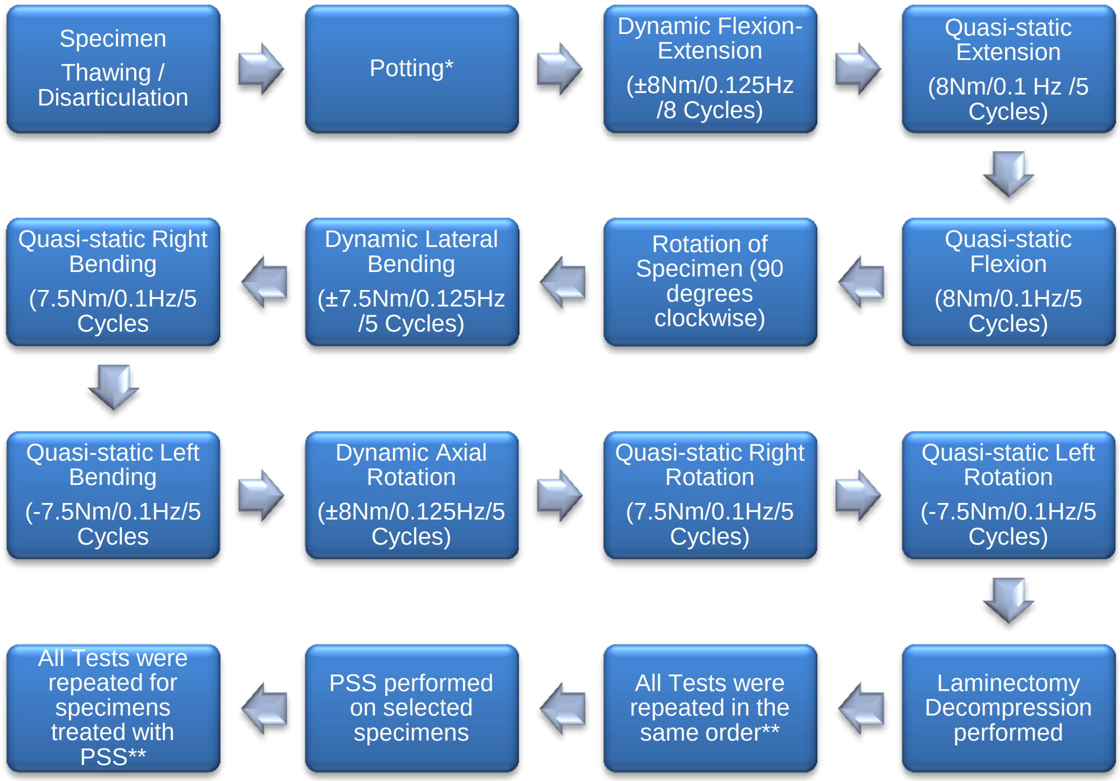
$$\vec{F} = m\vec{g} \rightarrow m = \frac{\vec{F}}{\vec{g}} = \frac{400[N]}{9.81[\mathrm{m}/s^2]} = 40.8\ [Kg] \qquad \text{(Equation 3.2)}$$

The superior frame of the machine weighted 16.3 kg, which made us needed to add 24.5 kg to reach the required preload (400N). 5.7 kg of weight were added to each corner of the superior frame, and one 1.1 kg weight to the opposite side of the upper motor location (using a 0.45 kg clamp). The total weight added was 24.3 kg. The corners' weights were hold with hexagon head bolts, wing nuts and washers (please refer to Figure 3.5 and 3.10). This configuration led to 40.6 Kg, which resulted in a preload of 398.3 N.

3.4. Testing Protocol

All tests were performed at room temperature (23±1°C) Each FSU was subjected to both dynamic and quasi-static loads for all treatments. Dynamic tests were performed using a moment of ±8Nm at a rate of 0.125Hz, for 5 cycles. The only case where 8 cycles were performed when testing dynamically was for intact condition under flexion-extension (very first test for each specimen), allowing the specimen to pre-condition. All cycles were recorded and the last cycle was used for the analysis.

Quasi-static tests were performed using a moment of ±7.5Nm at a frequency of 0.1 Hz, for 5 steps. Each step represented an increment of 1.5Nm of moment, where the displacements achieved were estimated by taking 80±30 data points at the linear portion of each step. Figure 3.11 outlines the overall process to which each specimen was submitted.



*Occasionally, the specimen was preserved at 4°C for 8-12 hours after potting and testing
**Dynamic flexion-extension was performed for 5 cycles instead of 8

Figure 3.11. Schematization of the Overall Process for Testing a Specimen.

Laminectomy decompression was achieved in all FSU by resecting the entire laminae of the vertebra, the spinous process, ligamentum flavum, and the supraspinous and interspinous ligaments, preserving intact the facet joints (Figure 3.12b).

Alphatech PSS was only attained in three specimens (Figure 3.12c) since other specimens were not suitable for this procedure due to a bad bone condition.

Table 3.1 summarizes the different procedures' time that implied the specimen being exposed to room temperature (23±1°C). From this table we can estimate that the total testing time for a specimen that underwent intact, laminectomy decompression and PSS treatments was, in average, less than 7hrs, and less than 3hrs for a specimen that was not treated with PSS.

(A) (B) (C)

Figure 3.12. Posterior Elements of a FSU. *(A): Intact. (B): Laminectomy Decompression. (C): PSS.*

Table 3.1. Average Time for Different Procedures.

Procedure	Average time [min]
Thawing*	1400 ± 120
Disarticulation/potting*	300 ± 60
Laminectomy Decompression*	30 ± 10
PSS Procedure*	169 ± 23
Set of Biomechanical Tests-One Treatment*	45 ± 13

*The Error Represents the Standard Deviation (SD) for n=6
**The Error Represents the Standard Deviation (SD) for n=3

3.5. Data Collection & Analysis

3.5.1. Dynamic Analysis

According to the Neutral Zone (NZ) definition, the displacement when there is no torque being applied (0 Nm) should be the same for both flexion and extension, as well as for right/left bending and right/left axial rotation (please refer to Figure 2.11). Therefore, the defined NZ for each specimen was calculated from the dynamic tests for each treatment, and all dynamic data was adjusted so the displacement at zero torque would be half of the NZ (NZ/2). Figure 3.13 shows a typical flexion-extension result without the adjustment of the NZ and Figure 3.14 represents the plot for the adjusted data.

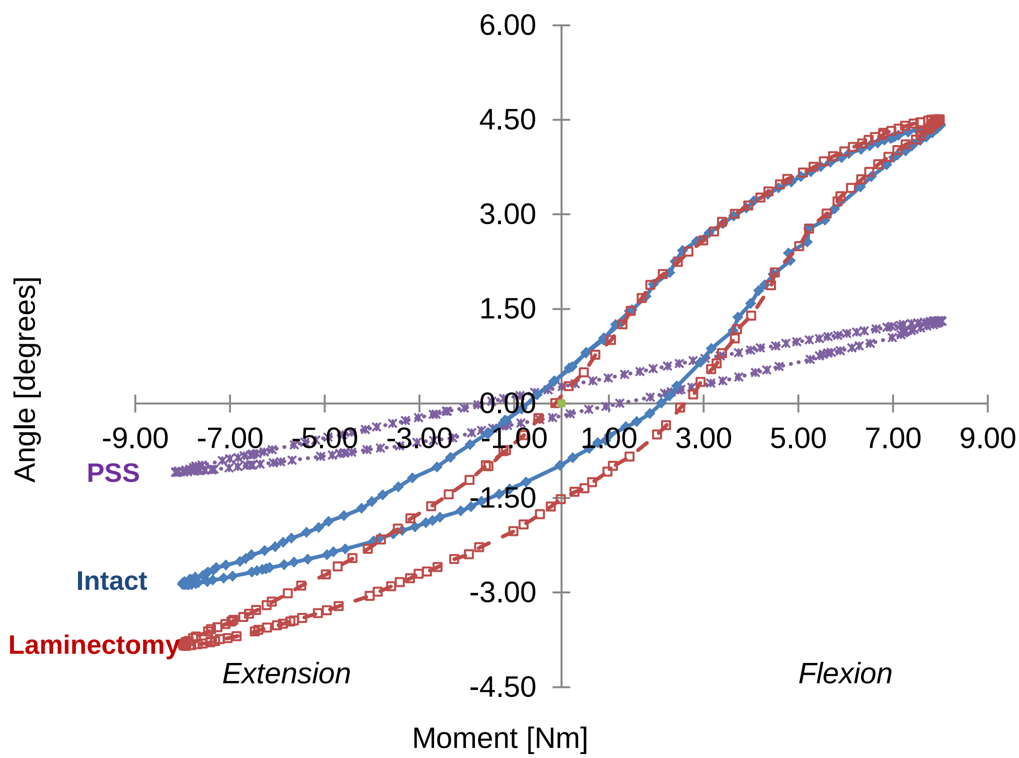


Figure 3.13. Representative Flexion-Extension Results for Intact, Laminectomy and PSS Treatments (without NZ Adjustment).

The dynamic Neutral Zone Stiffness (NZS) was calculated to evaluate the impact of a laminectomy procedure and PSS treatment on the flexibility of a FSU. The NZS was estimated as the inverse of the slope of the linear portion of the load-displacement curves, around the neutral position (Phillips et al., 2009).

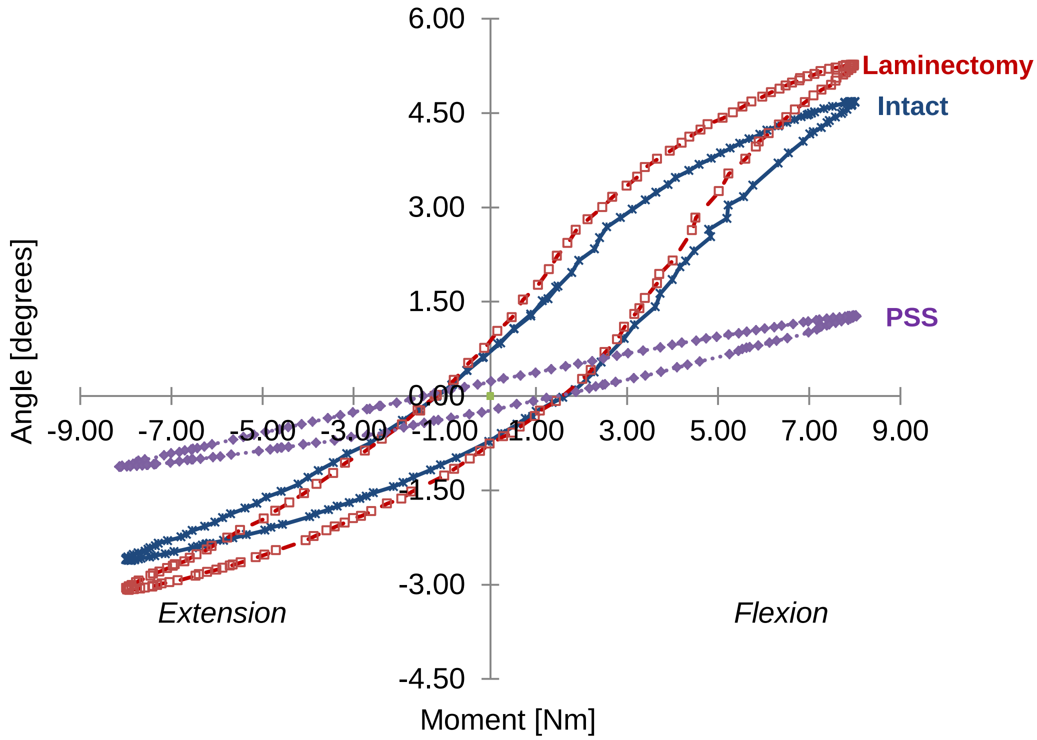


Figure 3.14. Representative Flexion-Extension Results for Intact, Laminectomy and PSS Treatments (with NZ Adjustment)

Since the range of motion for different levels of the spine could differ from each other, the data was also normalized with respect to the initial condition (intact-control). Therefore, the changes in stiffness triggered by laminectomy and PSS treatments were evaluated.

3.5.2. Quasi-Static Analysis

Analogously to the dynamic analysis, all quasi-static data was presented in terms of ROM as well as normalized with respect to intact condition. In this sense, the parameters presented for quasi-static testing were absolute range of motion and the change in ROM triggered by the laminectomy and PSS treatments. The changes in

ROM were estimated with the ratios from laminectomy displacement versus intact displacement and PSS displacement versus intact displacement, at certain loads.

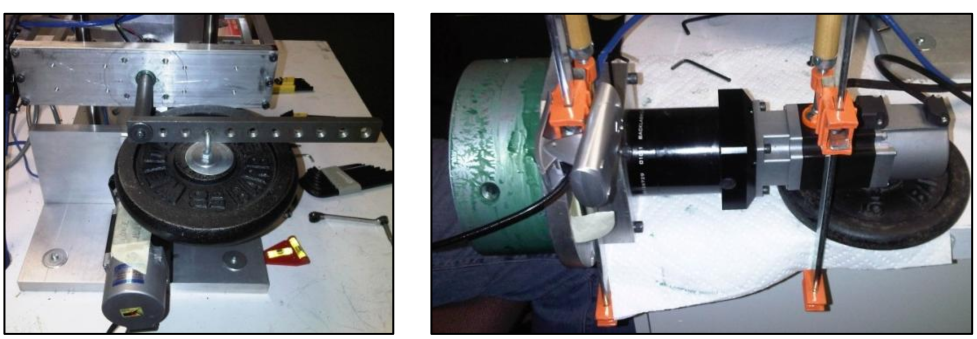
3.6. Instrument Calibration & Method Validation

3.6.1. Calibration

As it has been mentioned, the displacements were obtained from strain gauges readings. These strain gauges were calibrated using a lever arm fixed directly to the shaft where the gauges were located (Figure 3.15). The arm consisted on a 24cm "L" shape steel bar (0.45 Kg of weight) that contained 10 equidistant holes (23mm). A 4.54 kg weight and the physic principle of moment of a force were used to measure the torque (as strain gauges voltage) produced by the weight at each hole, using the following relationship:

$$\vec{M}[Nm] = \vec{r}[m] \times \vec{F}[N] = \vec{r} \times (m\vec{g}) \qquad \text{(Equation 3.3)}$$

where **r[m]** is the distance from where the torque is being measured to where the weight is being placed and **F[N]** is the force exerted by the weight.



(A) (B)

Figure 3.15. Calibration of Strain Gauges. *(A): Upper Motor Lever Arm and Weight Configuration. (B): Axial Motor Position for Performing Calibration.*

Since the strain gauges reading unit is voltage, a relationship voltage-moment was defined. By this, it was possible to identify the specific voltage reading for known moments, and compute the SF and OF variables (from Equation 3.1), for each motor.

3.6.2. Method Validation

A PVC pipe (ID-3/4'' and 8'' of length) was fixed to polyester resin bases (replicating specimen's setting) and tested reproducing specimen's protocol. This PVC sample was tested under dynamic and quasi-static loads (both bending and axial) after the strain gauges' calibration, as well as at the beginning of a testing day. This allowed us to validate the accuracy of the measurements and to detect any error on the data recorded. Table 3.2 summarizes the average displacements at specific torques when a quasi-static test was performed using the PVC pipe sample. Moreover, the precision of the torque reading (from output files) was analyzed (Table 3.3).

Table 3.2. Average Displacement of PVC Pipe for Specific Moments.

Moment [Nm]	Right Bending [degrees]	Left Bending [degrees]	Right Rotation [degrees]	Left Rotation [degrees]
1.50	0.37 ± 0.02	0.36 ± 0.02	0.28 ± 0.01	0.27 ± 0.01
3.00	0.79 ± 0.02	0.75 ± 0.02	0.72 ± 0.01	0.71 ± 0.01
4.50	1.20 ±0.02	1.17 ± 0.02	1.22 ± 0.01	1.19 ± 0.01
6.00	1.61 ± 0.02	1.57 ±0.02	1.69 ± 0.01	1.68 ± 0.01
7.50	2.02 ± 0.02	2.00 ± 0.02	2.15 ± 0.01	2.16 ± 0.01

Note: Errors represent standard deviation (repeated measurements, n=5)

Table 3.3. Average Moment for PVC Pipe Testing for Torques of Interest.

Moment [Nm]	Right Bending [Nm]	Left Bending [Nm]	Right Rotation [Nm]	Left Rotation [Nm]
1.50	1.47 ± 0.02	1.49 ± 0.01	1.49 ± 0.01	1.50 ± 0.01
3.00	2.97 ± 0.01	2.98 ± 0.02	2.99 ± 0.01	2.99 ± 0.32
4.50	4.48 ± 0.02	4.47 ± 0.01	4.49 ± 0.01	4.48 ± 0.54
6.00	5.97 ± 0.01	5.98 ± 0.01	5.99 ± 0.01	5.98 ± 0.76
7.50	7.50 ± 0.01	7.49 ± 0.01	7.49 ± 0.01	7.49 ± 0.97

Note: Errors represent standard deviation (repeated measurement n=5)

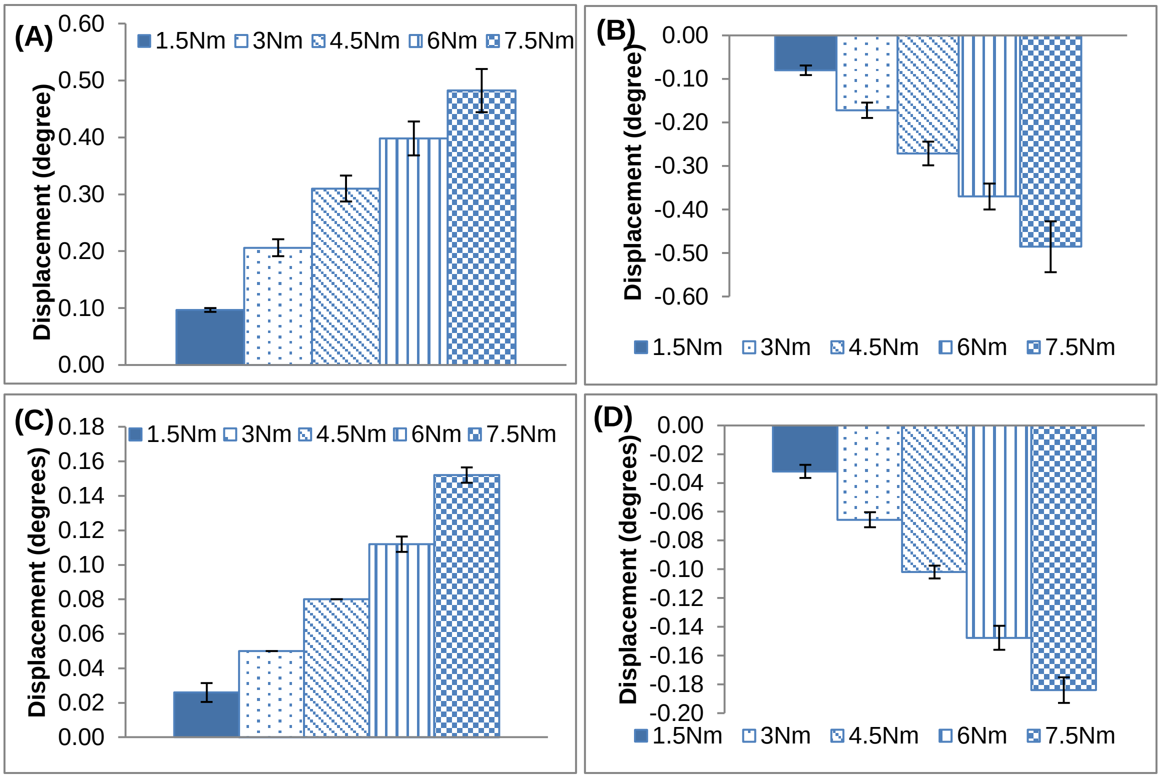
Likewise, a square steel bar (2''x2''x6'') was covered with polyester resin for creating a stiffer model as an additional validation protocol. The idea of using a stiffer sample was to verify that torques applied when small displacements were achieved were accurate. This also allowed us to verify both horizontal motors, used for testing bending and flexion/extension, were achieving the same torque for the same (small) displacements. The results are summarized in Table 3.4 (torque variation) and Figure 3.16 (displacement variation).

Table 3.4. Average Moment for Steel Column for Torques of Interest.

Moment [Nm]	Right Bending [Nm]	Left Bending [Nm]	Right Rotation [Nm]	Left Rotation [Nm]
1.50	1.46 ± 0.02	1.51 ± 0.02	1.55 ± 0.09	1.48 ± 0.07
3.00	3.00 ± 0.02	3.00 ± 0.03	2.98 ± 0.03	2.00 ± 0.06
4.50	4.50 ± 0.02	4.49 ± 0.03	4.59 ± 0.03	4.67 ± 0.05
6.00	6.00 ± 0.03	6.01 ± 0.02	5.93 ± 0.04	5.98 ± 0.07
7.50	7.50 ± 0.00	7.50 ± 0.01	7.45 ± 0.04	7.44 ± 0.05

Note: Errors represent standard deviation (repeated measurement n=5)

The results when testing the rigid column were reproducible. Moreover, the displacements, in average, were very similar for both right and left bending, as well as for right and left axial rotation. Similar results were observed when testing the PVC pipe.



Note: All error bars represent standard deviations (repeated measurements, n=5)

Figure 3.16. Average Displacements when Testing Steel Column. *(A): Right Bending. (B): Left Bending. (C): Right Rotation. (D): Left Rotation.*

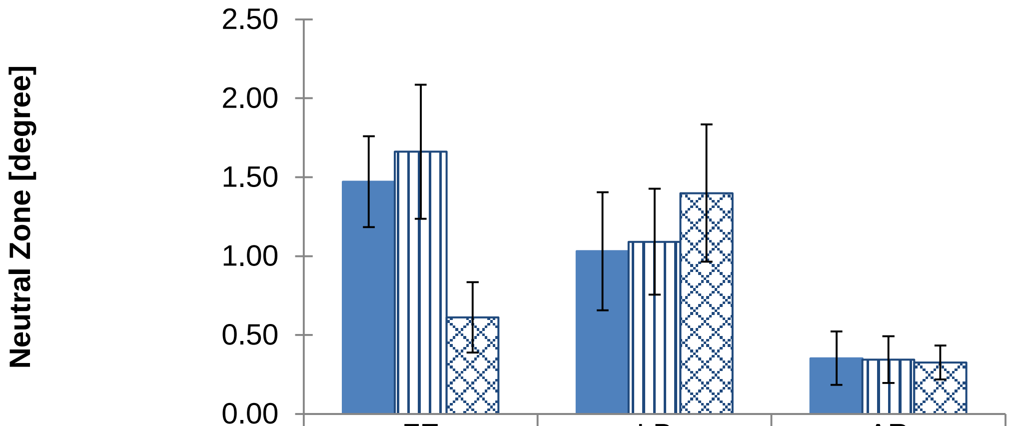
3.7. Statistical Analysis

A one-way analysis of variance (ANOVA), followed by a Post-Hoc Tukey and Waller-Duncan tests, was conducted (SAS 9.2) to evaluate the differences in range of motion among all treatments, using a significance level of 0.05. Likewise, one- (H_0: $\mu \geq 1$ or H_0: $\mu \leq 1$) and two-tailed (H_0: $\mu = 1$) t-tests were performed to evaluate the change in ROM (ratios with respect to intact condition), using a significance level of 0.05. All experimental data is presented as a mean ± standard deviation.

CHAPTER 4: RESULTS

4.1. Dynamic Testing Results

The dynamic neutral zone (NZ) was calculated for all treatments, from the dynamic testing, and the values are presented in Figure 4.1.



	FE	LB	AR
Intact (n=6)	1.47	1.03	0.35
Laminectomy (n=6)	1.66	1.09	0.34
PSS (n=3)	0.61	1.40	0.33

All error bars represent ±SD

Figure 4.1. Average of Neutral Zone Values for all Treatments.

All the results from the dynamic testing presented on this chapter were previously corrected so the displacements at zero torque were distributed as half of the NZ (please refer to explanation on sub-section *3.5.2 Data Collection*). It is important to mention that each specimen data was corrected with their unique NZ value (by specimen, by motion, by treatment).

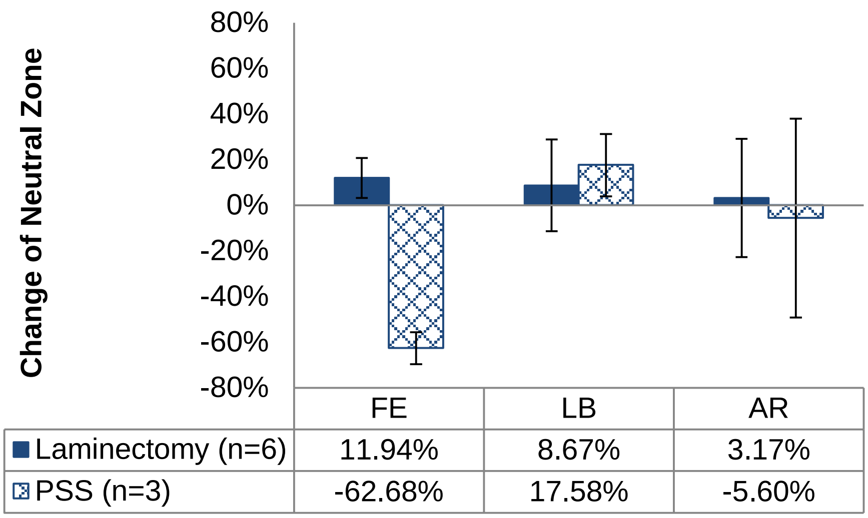
A one-way ANOVA analysis, followed by Post-Hoc Tukey and Waller-Duncan tests, was conducted to evaluate any statistically significant difference between the neutral zone values for all treatments. P-values for these tests are listed in Table 4.1.

Table 4.1. Output Summary from One-Way ANOVA Test (α=0.05) when Comparing Dynamic Neutral Zones (Degrees) for All Motions and Treatments.

	α=0.05		
	ANOVA (p-value)	Tukey	Duncan-Waller
Flexion-Extension	0.0031	C ≠ A, C ≠ B	C ≠ A, C ≠ B
Lateral Bending	0.3808	ND	ND
Axial Rotation	0.9696	ND	ND

A= Intact, B = Laminectomy Decompression, C = PSS
ND = No differences

Dynamic NZ data was normalized (Figure 4.2) and a two-tailed t-test (H_0: μ=1, α=0.05) was conducted to evaluate the significance of change in NZ after performing a laminectomy decompression. Likewise, the change in NZ after PSS treatment was evaluated. The results from these t-tests are presented in Table 4.2.



All error bars represent ±SD

Figure 4.2. Average Change of Dynamic Neutral Zone after Laminectomy and PSS Treatments.

Table 4.2. P-Values from Two-Tailed T-Test (H_0: μ=1, α=0.05) when Evaluating Change of Dynamic NZ (Degrees) with Respect to Intact.

	Laminectomy (n=6)	PSS (n=3)
Flexion-Extension	**0.021**	**0.004**
Lateral Bending	0.339	0.156
Axial Rotation	0.777	0.844

The dynamic neutral zone stiffness (NZS) for flexion and extension motions were estimated as the inverse of the slope of the linear portion of the load-displacement curve, as illustrated in Figure 4.3.

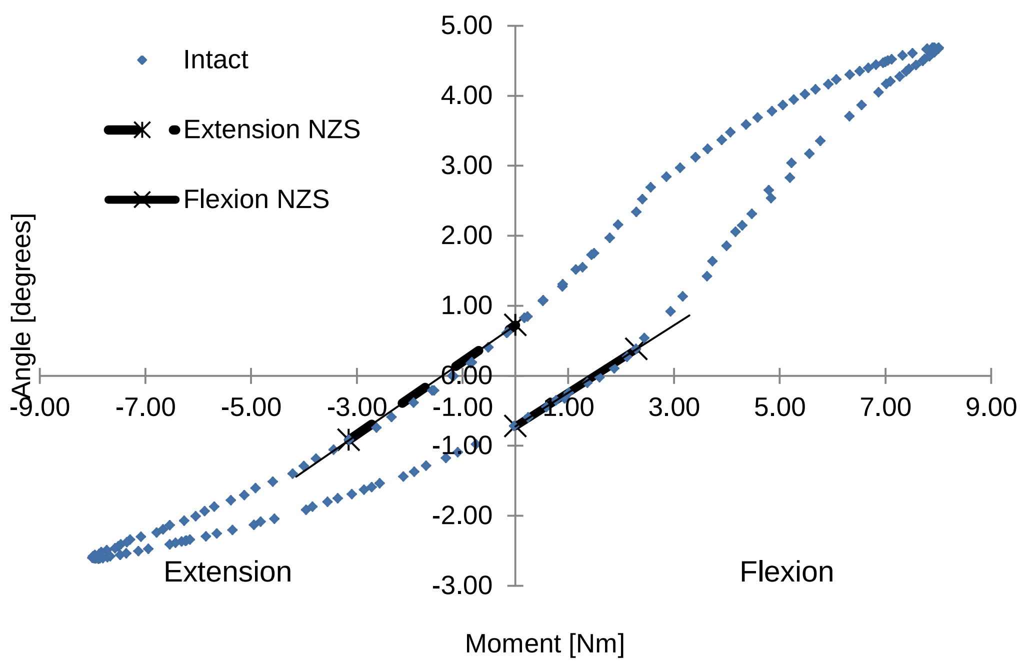
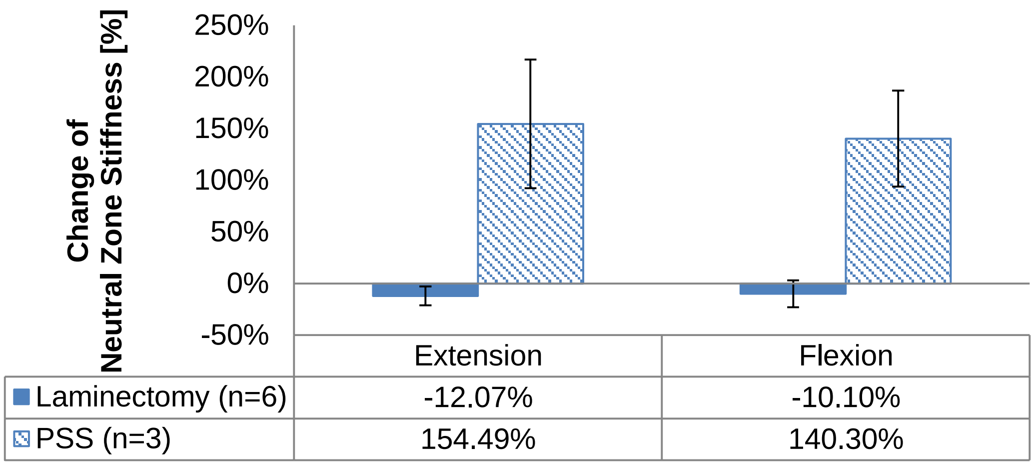


Figure 4.3. Representative Dynamic Flexion-Extension Load-Displacement Curve for Intact Treatment, and the Respective Neutral Zone Stiffness (Inverse of Slope of Linear Portion).

The change of dynamic NZS for flexion and extension after performing a laminectomy and PSS on a FSU were estimated and are summarized in Figure 4.4.

Table 4.3 presents the p-values obtained when a two-tailed t-test (H_0: μ=1, α=0.05) was conducted to evaluate the change of dynamic NZS triggered by these two treatments.



All error bars represent ±SD

Figure 4.4. Average Change of Neutral Zone Stiffness for Flexion-Extension under Dynamic Load.

Table 4.3. P-Values from Two-Tailed T-Test (H_0: μ=1, α=0.05) when Comparing Change of Dynamic Neutral Zone Stiffness for Flexion-Extension Motions.

	Extension	Flexion
Laminectomy (n=6)	**0.0259**	0.1181
PSS (n=3)	**0.0497**	**0.0353**

The range of motion (ROM) achieved by all segments (at 8Nm of moment) for each treatment are summarized in Table 4.4, and the statistical output from performing a one-way ANOVA analysis, followed by post-hoc Tukey and Ducan-Waller tests, on this data are presented in Table 4.5. The percentage changes of ROM after a laminectomy and PSS treatments were also calculated and results are shown in Table 4.6; Statistical test outputs are summarized in Table 4.7.

Table 4.4. Range of Motion Values for Intact, Laminectomy and PSS Treatment, at 8Nm.

	Intact [degree]	Laminectomy [degree]	PSS [degree]
Extension	2.75 ± 0.74	3.39 ± 1.08	1.72 ± 0.73
Flexion*	5.29 ± 1.69	5.98 ± 2.26	1.51 ± 0.31
Right Bending	4.30 ± 1.93	4.59 ± 2.00	2.62 ± 1.13
Left Bending	4.69 ± 2.75	4.82 ± 2.67	2.15 ± 0.82
Right Rotation	1.09 ± 0.32	1.21 ± 0.36	0.85 ± 0.30
Left Rotation	1.03 ± 0.22	1.10 ± 0.22	0.78 ± 0.30

Note: Errors represent standard deviations
*One specimen could not reach 8Nm for intact and laminectomy treatments, due to Machine Limitation. Therefore, n=5 for these two treatments for flexion motion.

Table 4.5. Output Summary from One-Way ANOVA Test (α=0.05) when Comparing ROM (Degrees), at 8Nm, for All Treatments.

	Intact (n=6) /Laminectomy (n=6) / PSS (n=3)		
	ANOVA (p-value)	**Tukey**	**Duncan-Waller**
Extension	0.0630	ND	C ≠ B
Flexion*	0.0433	C ≠ B	C ≠ A, C ≠ B
Right Bending	0.3349	ND	ND
Left Bending	0.3075	ND	ND
Right Rotation	0.1921	ND	ND
Left Rotation	0.2038	ND	ND

Errors represent standard deviations
A=Intact, B=Laminectomy, C=PSS
ND=No Difference
*n=5 for Intact and Laminectomy treatments for flexion motion

Table 4.6. Percentage Change of Range of Motion.

	Laminectomy VS Intact (n=6)	PSS VS Intact (n=3)
Extension	24.08% ± 29.88%	-35.43% ± 19.48%
Flexion*	10.12% ± 13.20%	-71.80% ± 0.16%
Right Bending	8.08% ± 14.26%	-42.26% ± 25.65%
Left Bending	4.75% ± 4.42%	-62.85% ± 6.00%
Right Rotation	12.36% ± 9.85%	-25.26% ± 10.97%
Left Rotation	7.10% ± 6.59%	-27.76% ± 19.23%

Note: Errors represent standard deviations
*One specimen could not reach 8Nm for intact and laminectomy treatments, due to a Machine Limitation. Therefore, n=5 for Intact and laminectomy treatments while n=2 for PSS treatment, for flexion motion.

Table 4.7. P-Values from One-Tailed T-Test (α=0.05) when Evaluating Change of ROM (Degrees) on Normalized Data (with Respect to Intact).

	P-VALUES (α=0.05)	
	Intact VS Laminectomy (n=6, H_0: μ≤1, α=0.05)	Intact VS PSS (n=3, H_0: μ≥1, α=0.05)
Extension	**0.0158**	**<0.0001**
Flexion*	**0.0158**	**0.0027**
Right Bending	0.0740	**0.0057**
Left Bending	**0.0016**	**<0.0001**
Right Rotation	**0.0011**	0.4567
Left Rotation	**0.0013**	**0.0060**

*n=5 for Laminectomy VS Intact and n=2 for PSS VS Intact for flexion motion.

In comparison to intact condition, the PSS showed a significant reduction in NZ for flexion-extension motion ($p<0.004$) while the effect of a laminectomy treatment was not significant for any motion (Figure 4.1). However, after normalizing the data, the change in NZ was significantly different ($p<0.03$) after both laminectomy and PSS treatments for flexion-extension (Figure 4.2).

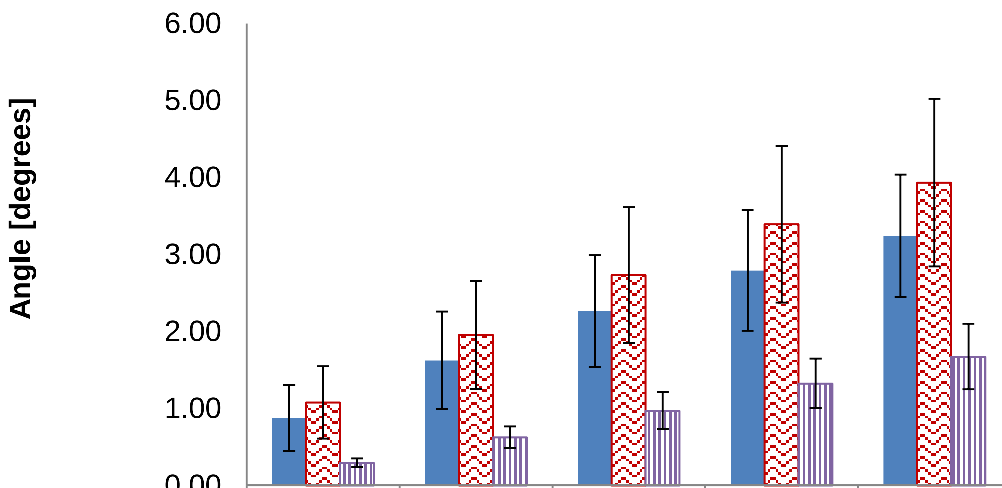
In terms of stiffness, the laminectomy decompression triggered a significant reduction on the dynamic neutral zone stiffness for extension ($p<0.03$), while PSS increased it significantly ($p<0.05$) for both flexion and extension (Figure 4.4).

The changes in ROM were not statistically significant when compared to intact (Table 4.4) but after normalization of the data (Table 4.6), significant differences ($p<0.05$) were found for all motions after treating the FSU with a laminectomy decompression and PSS, except for right bending (after laminectomy decompression) and right rotation (after PSS). It is important to mention that high standard deviations where observed among normalized data.

4.2. Quasi-Static Testing Results

The displacements measured for the three treatments under quasi-static loading are summarized in Figure 4.5, 4.6, 4.7, 4.8, 4.9 and 4.10 for extension, flexion, right and left bending, and right and left rotation, respectively.

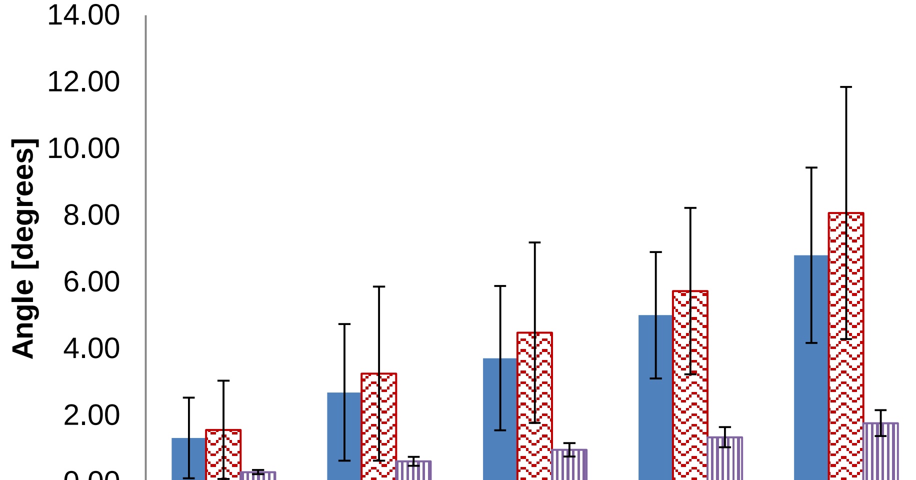
Likewise, Table 4.8, 4.9 and 4.10 present the statistical results from performing a one-way ANOVA test, followed by post-hoc tests Tukey and Ducan-Waller, on the displacements from quasi-static testing.



	1.50 Nm	3.00 Nm	4.50 Nm	6.00 Nm	7.50 Nm
Intact (n=6)	0.87	1.62	2.27	2.79	3.24
Laminectomy (n=6)	1.08	1.96	2.73	3.39	3.93
PSS (n=3)	0.29	0.62	0.97	1.32	1.67

All error bars represent ±SD

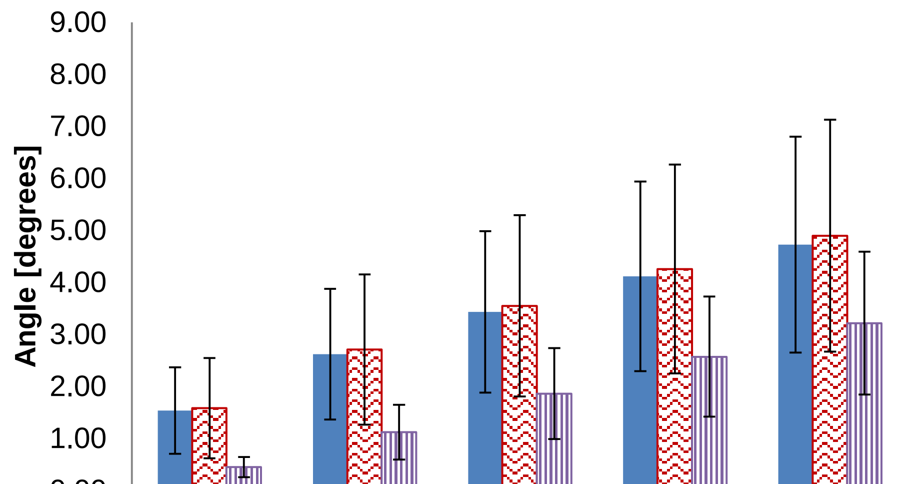
Figure 4.5. Extension Displacements for Quasi-Static Loading (f= 0.1Hz).



	1.50 Nm	3.00 Nm	4.50 Nm	6.00 Nm	7.50 Nm
Intact (n=6)	1.32	2.69	3.71	5.00	6.80
Laminectomy (n=6)	1.57	3.25	4.48	5.73	8.07
PSS (n=3)	0.30	0.62	0.97	1.34	1.77

All error bars represent ±SD

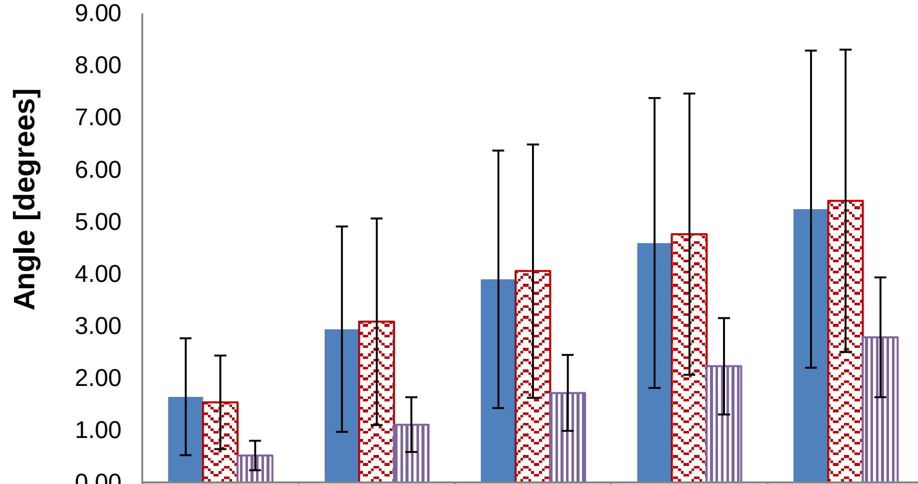
Figure 4.6. Flexion Displacements for Quasi-Static Loading (*ƒ*= 0.1Hz).



	1.50 Nm	3.00 Nm	4.50 Nm	6.00 Nm	7.50 Nm
Intact (n=6)	1.53	2.62	3.43	4.12	4.72
Laminectomy (n=6)	1.58	2.71	3.55	4.26	4.90
PSS (n=3)	0.45	1.12	1.86	2.57	3.22

All error bars represent ±SD

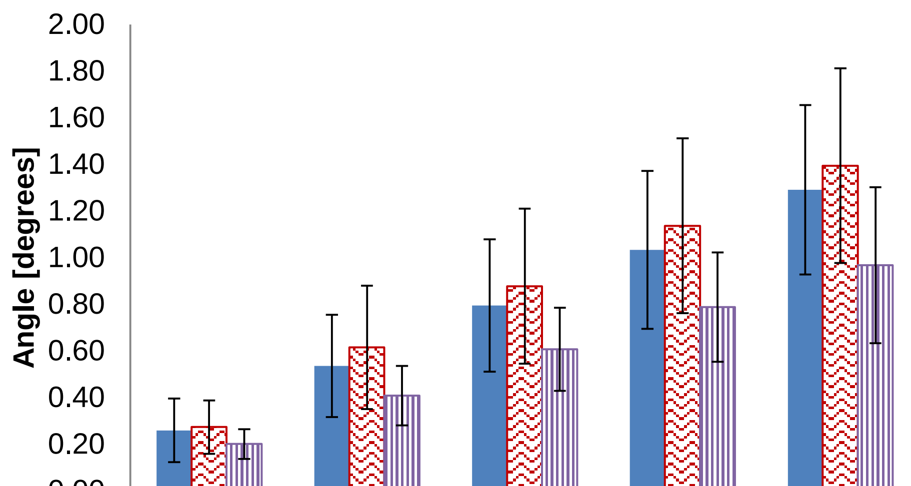
Figure 4.7. Right Bending Displacements for Quasi-Static Loading (*ƒ*= 0.1Hz).



	1.50 Nm	3.00 Nm	4.50 Nm	6.00 Nm	7.50 Nm
Intact (n=6)	1.64	2.94	3.90	4.59	5.24
Laminectomy (n=6)	1.54	3.09	4.06	4.76	5.40
PSS (n=3)	0.52	1.11	1.72	2.23	2.79

All error bars represent ±SD

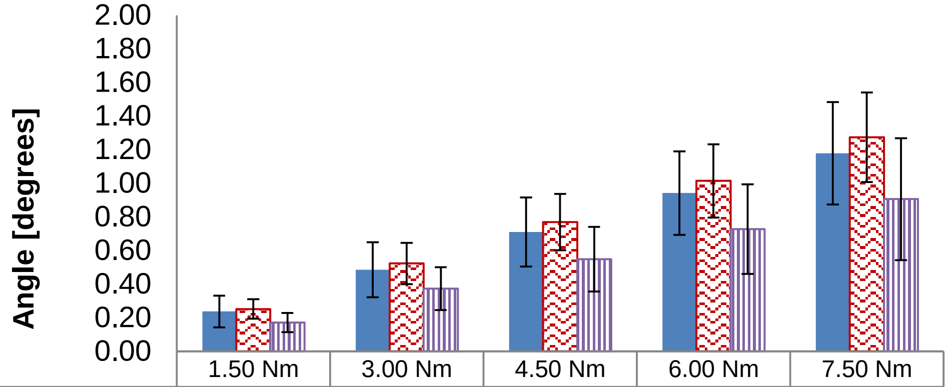
Figure 4.8. Left Bending Displacements for Quasi-Static Loading (f= 0.1Hz).



	1.50 Nm	3.00 Nm	4.50 Nm	6.00 Nm	7.50 Nm
Intact (n=6)	0.26	0.54	0.79	1.03	1.29
Laminectomy (n=6)	0.27	0.62	0.88	1.14	1.39
PSS (n=3)	0.20	0.41	0.61	0.79	0.97

All error bars represent ±SD

Figure 4.9. Right Rotation Displacements for Quasi-Static Loading (f= 0.1Hz).



	1.50 Nm	3.00 Nm	4.50 Nm	6.00 Nm	7.50 Nm
Intact (n=6)	0.24	0.49	0.71	0.94	1.18
Laminectomy (n=6)	0.25	0.52	0.77	1.01	1.27
PSS (n=3)	0.17	0.37	0.55	0.73	0.91

All error bars represent ±SD

Figure 4.10. Left Rotation Displacements for Quasi-Static Loading (f= 0.1Hz).

Table 4.8. Output Summary from One-Way ANOVA Test (α=0.05) Performed on Flexion and Extension Motions (Degree) for Quasi-Static Testing.

	Extension			Flexion		
Moment [Nm]	p value	Tukey	Duncan-Waller	p value	Tukey	Duncan-Waller
1.50	0.0571	C ≠ B	C ≠ A	0.3649	ND	ND
3.00	0.0297	C ≠ B	C ≠ B, C ≠ A	0.2530	ND	ND
4.50	0.0186	C ≠ B	C ≠ B, C ≠ A	0.1221	ND	ND
6.00	0.0149	C ≠ B	C ≠ B, C ≠ A	0.0275	C ≠ B	C ≠ B, C ≠ A
7.50	0.0124	C ≠ B	C ≠ B, C ≠ A	0.033	C ≠ B	C ≠ B, C ≠ A

Note: Errors represent standard deviations
A=Intact, B=Laminectomy, C=PSS
ND=No Difference

Table 4.9. Output Summary from One-Way ANOVA Test (α=0.05) Performed on Right and Left Bending (Degree) for Quasi-Static Testing.

	Right Bending			Left Bending		
Moment [Nm]	p value	Tukey	Duncan-Waller	p value	Tukey	Duncan-Waller
1.50	0.1570	ND	ND	0.2023	ND	ND
3.00	0.2023	ND	ND	0.3045	ND	ND
4.50	0.2999	ND	ND	0.3787	ND	ND
6.00	0.4107	ND	ND	0.4603	ND	ND
7.50	0.4971	ND	ND	0.5158	ND	ND

Note: Errors represent standard deviations
A=Intact, B=Laminectomy, C=PSS
ND=No Difference

Table 4.10. Output Summary from One-Way ANOVA Test (α=0.05) Performed on Right and Left Rotation (Degree) for Quasi-Static Testing.

	Right Rotation			Left Rotation		
Moment [Nm]	p value	Tukey	Duncan_Waller	p value	Tukey	Duncan_Waller
1.50	0.6837	ND	ND	0.3401	ND	ND
3.00	0.4591	ND	ND	0.3596	ND	ND
4.50	0.4458	ND	ND	0.2879	ND	ND
6.00	0.3768	ND	ND	0.2728	ND	ND
7.50	0.3183	ND	ND	0.2596	ND	ND

Note: Errors represent standard deviations
A=Intact, B=Laminectomy, C=PSS
ND=No Difference

Similarly, a one-tailed t-test (H_0: μ≤1, α=0.05, d.f.=6) was conducted on normalized quasi-static data (with respect to intact) to evaluate the significance of changes in motion as a result of performing a laminectomy decompression on a lumbar FSU. This data is shown in Table 4.11 and outputs from statistical tests are presented in Table 4.12.

Table 4.11. Percentage Change of Motion after Laminectomy Decompression (n=6).

Moment [Nm]	Extension	Flexion
1.50	25.15% ± 26.34%	15.52% ± 15.12%
3.00	21.81% ± 24.94%	18.10% ± 17.26%
4.50	21.26% ± 24.46%	19.15% ± 15.44%
6.00	21.79% ± 22.76%	12.25% ± 12.23%
7.50	21.33% ± 20.64%	15.96% ± 12.72%
	Right Bending	Left Bending
1.50	3.89% ± 23.18%	1.04% ± 14.22%
3.00	3.53% ± 19.50%	6.92% ± 4.32%
4.50	3.88% ± 17.52%	6.42% ± 4.94%
6.00	4.08% ± 16.47%	6.22% ± 5.51%
7.50	4.67% ± 15.52%	5.83% ± 6.20%
	Right Rotation	Left Rotation
1.50	9.47% ± 14.50%	11.44% ± 18.43%
3.00	14.11% ± 5.59%	10.69% ± 12.96%
4.50	10.62% ± 10.15%	10.25% ± 10.08%
6.00	10.98% ± 9.73%	8.97% ± 7.57%
7.50	8.65% ± 10.73%	9.47% ± 7.96%

Note: Errors represent standard deviations

Table 4.12. P-Values from One-Tailed T-Test (H_0: $\mu \leq 1$, $\alpha=0.05$, d.f.=6) when Comparing Change of ROM after Laminectomy Decompression with Intact Condition.

Moment [Nm]	Extension	Flexion	Right Bending	Left Bending	Right Rotation	Left Rotation
1.50	**0.027**	**0.032**	0.349	0.432	0.085	0.094
3.00	**0.025**	**0.043**	0.338	**0.006**	**0.001**	0.050
4.50	**0.014**	**0.043**	0.305	**0.012**	**0.025**	**0.028**
6.00	**0.029**	**0.033**	0.285	**0.020**	**0.020**	**0.017**
7.50	**0.014**	**0.026**	0.247	**0.035**	0.053	**0.017**

Likewise, a one-tailed t-test (H_0: $\mu \geq 1$, $\alpha=0.05$, d.f.=3) was performed to evaluate the change in ROM on a lumbar FSU triggered by PSS treatment. Normalized data is presented in Table 4.13 and results from statistical tests are shown in Table 4.14.

Table 4.13. Percentage Change of Motion after PSS Treatment (n=3).

Moment [Nm]	Extension	Flexion
1.50	-57.75% ± 10.16%	-38.93% ± 23.78%
3.00	-54.22% ± 11.99%	-48.74% ± 19.12%
4.50	-51.16% ± 12.84%	-55.55% ± 16.27%
6.00	-47.84% ± 12.77%	-66.88% ± 7.81%
7.50	-45.19% ± 12.81%	-73.58% ± 5.66%
	Right Bending	Left Bending
1.50	-73.80% ± 11.62%	-74.72% ± 1.84%
3.00	-60.86% ± 18.30%	-69.83% ± 1.72%
4.50	-49.73% ± 22.98%	-64.32% ± 3.85%
6.00	-41.95% ± 25.38%	-60.56% ± 5.62%
7.50	-36.55% ± 26.64%	-56.94% ± 6.66%
	Right Rotation	Left Rotation
1.50	-23.27% ± 26.39%	-27.27%± 7.99%
3.00	-24.08% ± 10.78%	-24.37% ± 9.77%
4.50	-24.55% ± 5.75%	-24.70% ± 14.62%
6.00	-24.83% ± 10.68%	-24.53% ± 19.21%
7.50	-29.59% ± 12.49%	-25.60% ± 24.51%

Note: Errors represent standard deviations

Table 4.14. P-Values from One-Tailed T-Test (H_0: μ≥1, α=0.05, d.f.=3) when Comparing Change of ROM after PSS with Intact Condition.

Moment [Nm]	Extension	Flexion	Right Bending	Left Bending	Right Rotation	Left Rotation
1.50	0.053	**0.005**	**0.004**	**<0.001**	0.133	**0.014**
3.00	**0.024**	**0.008**	**0.014**	**<0.001**	**0.030**	**0.025**
4.50	**0.014**	**0.010**	**0.032**	**<0.001**	**0.009**	**0.050**
6.00	**0.002**	**0.012**	0.052	**<0.001**	**0.028**	0.079
7.50	**0.001**	**0.013**	0.070	**<0.001**	**0.027**	0.106

In general terms, laminectomy decompression seems to cause instability on a lumbar FSU, while fusion (PSS) limits the ROM beyond intact (anatomical) condition. These behaviors were observed during all quasi-static tests (Figure 4.5 to 4.10) for all motions, with the exception of left bending at 1.5Nm after a laminectomy decompression. Any of the differences in ROM triggered by either a laminectomy decompression or PSS treatment were statistically significant ($p>0.05$). However, once data was normalized, these differences became significant for flexion and extension at any load (with the exception of PSS at 1.5Nm –Table 4.14) and for all other motion at some specific loads; although high standard deviations were encountered.

CHAPTER 5: DISCUSSION

For this research, only 6 FSUs met the criteria for this study: one L1-L2, one L2-L3, one L3-L4, one L4-L5 and two L5-S1 segments. Given the limited number of samples from different specimens for the same level, it was not possible to evaluate any effect related to the spinal level. This fact makes difficult to lead strong conclusions about the biomechanical effects of performing a laminectomy decompression on a lumbar FSU. However, some useful biomechanical observations and conclusions can still be provided.

A study conducted by Gay et al. (2006) on dynamic and quasi-static biomechanics of lumbar FSUs also recognizes the limitation of having FSUs from multiple lumbar spinal levels. However, they only used one L5-S1 segment (from 15 FSUs), which has been shown to have different biomechanical behavior than other lumbar levels, they addressed. For our study, two L5-S1 FSUs were used, which represents 33.3% of our samples.

One-way ANOVA, followed by post-hoc Tukey and Duncan-Waller tests, was performed to evaluate the difference in ROM for both dynamic and quasi-static data, as well as the effect of these treatments on dynamic NZ and NZS. Additionally, data was normalized (with respect to intact) and these ratios (laminectomy/intact and PSS/intact) were tested to be statistically significant different from 1 (intact/intact), by using two-tailed t-test (for estimating changes on dynamic NZ and NZS) and one-tailed t-test (for analyzing changes in ROM).

This additional analysis of using ratios was initially considered a better approach for analyzing the data since we were dealing with different spinal levels, and our number of sample was limited (n=6). It is well recognized that comparing ratios implicitly considers the assumption of the effects of the treatments being the same for all spinal levels, which could be seen as an important limitation. The concern about the veracity of this assumption arose when recognizing large standard deviations for normalized data (as shown in Table 4.6 and 4.11). This large variability could be either due to particular characteristics of the specimens, which become remarkable when having a small sample (6 FSU from 4 specimens), or due to the effects of the treatments being, in fact, different for each spinal level. This last hypothesis would contradict our initial assumption but we certainly acknowledge that the only accurate way for testing this possibility would be by performing a study with a larger number of FSUs from different lumbar spinal levels. Thus, specimens could be grouped by level and be compared.

Even though further studies are necessary to validate the results presented on this work, important considerations that need to be addressed before performing any biomechanical spine testing were identified. They are:

- *Time specimen has been exposed to room temperature*. It is important to carefully report how long the specimen has been out of the freezer. Even though thawing out the specimen at room temperature has been shown to have little effect on the biomechanical behavior of a disc and bone, over time exposure could have considerable effects on the specimen's properties (Wilke, Wenger & Claes, 1998). In this study, the exposure time could have affected bone specimen's condition, being a possible explanation for not being able to perform PSS on 3, of the 6, FSUs. Even though testing time (including all treatments) was reasonable for a specimen than underwent the three treatments (less than 7 hours), thawing, disarticulating and potting time (Table 3.1) could have been reduced. It is important to mention that our protocol was in line with previous publications which have reported thawing periods of 24hrs (Voronov et al., 2009). Moreover, all specimens satisfied a minimal bone mineral density (>0.070 gr/cm^2), however it is important to mention that the 3 FSUs where PSS were performed came from the donor that had the higher BMD (1.111 gr/cm^2). This may suggest the request of more than one test for measuring BMD, or being more conservative when selecting the inclusion parameter. Previous *in vivo* study has shown there is a stretch relationship between BMD and failure of pedicle screws fixation for values below 0.674 ± 0.104 g/cm^2 (Okuyama et. al, 2001). Even though our inclusion parameter was BMD>0.700g.cm^2, it is suggested to be more conservative in further studies since *in vitro* conditions could be considered more critical for bone degradation.

- *Preconditioning*. It is necessary to precondition the specimen to minimize viscoelastic behavior and obtain reproducible data (Wilker, Wenger & Claes, 1998). In our case, we summited the specimen to 8 steps during the first dynamic testing and only the last step was considered for the analysis.
- *Zero positions*. It is important to be consistent with the "zero mark" (initial position-degrees) in order to make measurements comparable. It is recommended not to change the reference system any time during testing. If there is a well understanding of the process, the data can always be referenced to a different coordinate system after collected. Changing our "zero mark" during testing could potentially incur important errors. Moreover, the NZ is defined for each specimen and for each treatment, and the loading history of the specimen could change its magnitude; therefore, it is important to report under what

condition(s) this parameter is estimated. Although the NZ concept has been widely used for quasi-static data, this could be an important parameter for dynamic testing. Dynamic and Quasi-Static data should be carefully distinguished.

- *Disc Condition*. The condition and hydration of the intervertebral disc is determinant for the motion's pattern during loading. A specimen with an evident osteophyte disc (L3-L4) was tested (data not included for analysis) and the ROM for intact condition during dynamic testing (±8Nm, 0.125Hz) was observed limited (1.5 and <1.5 degrees for flexion and extension, respectively), presumably related to disc's condition. The high stiffness of the disc may have not allowed the laminectomy effects be significant since the motion was already preceded, in a higher portion than normal, by the condition of the disc. In this sense, when testing any treatment that may cause destabilization, it is important to evaluate and report the condition of all joints and ligaments of the spinal segment, to avoid results being misleading. From this experience, it is suggested to incorporate intradiscal pressure sensors during spinal testing to evaluate the performance of the disc at any time, and combine this information with displacements data to support any biomechanical conclusion. This procedure was attempted during this work by placing miniature pressure transducers (Model 060; Precision Measurement Company, Ann Arbor, MI) in the nucleus of the FSU, through the mid-sagittal plane, but not enough data was gathered to be presented. The transducer moved during testing, which required testing different techniques for implanting the sensor into the specimen. The final and most accurate technique consisted on inserting a 2mm of diameter cannula through the mid-sagittal plane into the disc. Then, a sewing thread was notched to the wire of the transducer by making multiple knots (one over the other) which would prevent the knots go through the 2mm cannula. The other end of the thread had a needle which was inserted through the cannula. Once the needle would leave the disc, it was carefully pulled until the sensor would reach the middle of the nucleus. At this point, the cannula was removed and the sensor's performance was evaluated by observing its reading when manually moving the specimen in different directions. Then, one end of the sewing thread would be hold in place by the multiple knots (by preventing penetration of the knots into the disc) while the other end was gently tensioned and taped to the upper frame of the FSU (after removing the needle). In this sense, we reduced significantly the misplaced of the sensor (caused by internal pressure changes) during testing. Thus, accurate readings of the pressure at the nucleus were achieved. From this preliminary data, a presumable correlation was observed: laminectomy decompression triggers a pressure increase in the nucleus of the FSU for flexion and extension motions. Animal models have shown there is a significant pressure increase in the nucleus after laminectomy for flexion and lateral bending motions, while there is no significant increase for extension and axial rotation (Rao et al., 2002). Further studies are necessary to objectively evaluate the effects of a laminectomy on the intradiscal pressure, having a constant monitoring of the sensor's position.

- *Orientation of FSU*. Potting procedure depends on the final configuration the specimen will adopt on the machine since its orientation will be determined by the right distribution of the load on the sample. A recent study conducted by Campbell-Kyureghyan et al. (2011) has shown how segment orientation has an important effect on failure strength, stress and strain. Then, it is important to report the orientation of the specimen and the distribution of the load during testing, even when the data is normalized. Also, once the specimen has been potted, it is important to let the polyester resin frames cool down enough before testing to avoid any relative motion between the specimen and the frames.

It is important to recognize that saline solution is the most common solution used for keeping spine cadaveric models moist, and during this work the solution used for this application was distilled water. This could have speeded up the degradation of the tissues, although any study to support this hypothesis was found.

Acknowledging that all factors mentioned above could have a significant effect on the variability of the data, important observations related to specific tests performed during this work are mentioned below.

5.1. Dynamic Testing

The Neutral Zone (NZ) is usually measured during quasi-static testing as the residual deformation achieved 30s after removing a define load (Gay et al., 2006). It has been addressed that the size of the NZ may vary with the loading history of the specimen, although the relationship of this quasi-static factor with dynamic parameters is not well-known (Gay et al., 2006). We have measured the NZ from dynamic testing data and the loading history of each specimen before testing could be considered the same, since we always performed all tests in the same order and allowed the specimen to rest between treatments (while performing either a laminectomy or PSS procedure).

In one hand, Figure 4.1 shows how a laminectomy may have an effect on the dynamic neutral zone of a lumbar FSU during flexion-extension motion but Table 4.1 supports that there is not enough evidence to conclude the differences are statistically significant, when using a significance level of .05. However, PSS treatment showed to have a significant effect on the size of the dynamic neutral zone for flexion-extension motion, while for lateral bending showed to be larger than intact and laminectomy conditions. Two possible explanations for this phenomenon could be that, one, this treatment was performed in 3 of the 6 FSUs (which means the average presented for this treatment was from 3 samples, while for intact and laminectomy were calculated from 6 FSUs) and, two, the exposure time could have also affected tissue integrity, specially bone quality that could have impacted PSS fixation.

On the other hand, normalized data (Figure 4.2) showed there is a significant effect of both treatments on the dynamic NZ for flexion-extension motion ($p<0.05$), as shown in Table 4.2. If we assume there are significant differences within the biomechanics of different spinal levels, the variation within the results, between non-normalized data (Table 4.1) and normalized data (Table 4.2), may be due to the fact of taking an average from different spinal levels for non-normalized data (Figure 4.1). Most spinal biomechanics studies involve multisegmental spine specimens or FSUs that are used to compare different treatments against intact (control) conditions, but it is not a concern if there is any difference when testing individual FSUs from different spinal levels. Some studies have evaluated the effects of specimen length on monosegmental motion behavior (Kettler et al., 2000) but no study that evaluates the difference within spinal levels when tested alone has been found.

The change in dynamic Neutral Zone Stiffness (NZS) for dynamic flexion-extension was significant ($p<0.05$), except for flexion after laminectomy treatment, as shown in Table 4.3. The results here obtained where fusion increases segmental stiffness for flexion-extension motion, when compared to intact condition, has been shown in previous studies (Phillips et al., 2009). It is important to mention some studies wrongly refer to the neutral zone stiffness as the slope of the linear portion of a load-displacement curve (Wilke et al., 1998; Phillips et al, 2009). The slope actually measures flexibility (i.e. degree/moment) while its inverse is what represents stiffness values (i.e. moment/degree).

The decrease in stiffness for extension, as well as the increase in the NZ for flexion-extension motion, after destabilization (i.e. laminectomy decompression) implies a higher stress on spinal segment, which may lead to pain due to a higher demand on musculature activity in order to maintain stability during daily motion (Phillips et al., 2009).

Regarding ROM analysis, some discrepancy was observed between non-normalized and normalized data, as it was for dynamic NZ analysis. Table 4.5 shows there is not enough evidence to presume that any of the two treatments have an effect on intact condition, while Table 4.7 supports the effect of a laminectomy being statistically significant ($p<0.05$) for all motions, except for right bending ($p=0.074$). The results from normalized data for PSS treatment for flexion motion (Table 4.7) are not conclusive since only two samples were used for this case; a physical limitation of the testing machine did not allowed testing one of the specimens under intact and laminectomy conditions at 8Nm.

5.2. Quasi-Static Testing

From Figure 4.5 to Figure 4.10 it can be seen how the average displacement for all loading and motions increased after performing a laminectomy decompression (except for left bending at 1.5Nm) and decreased after implementation of PSS, when compared to intact condition. The large standard deviation may be a consequence of using different spinal levels or to intrinsic characteristics of the specimens that are remarked when using a small number of samples. When evaluating the changes in ROM after the laminectomy decompression, there was not enough evidence to presume its effect being significant for any motion, when compared to intact condition (Table 4.8, 4.9 and 4.10). However, according to the output from a Duncan-Waller post-hoc test, PSS may have an effect on intact conditions for extension and flexion motions, at specific loadings: 3.0, 4.5, 6.0 and 7.5Nm for extension and 6.0 to 7.0 Nm for flexion. An important limitation of Duncan-Waller post-hoc test is the lack of controlling Type I error, which could wrongly accept the null hypothesis of no difference between the means, which becomes more critical when having a small number of samples.

An important observation is that the ROM of the destabilized segment was closer to intact than when treated with PSS. This may be one of the reasons why there are different opinions about fusion being a good optional treatment after decompression.

After normalizing ROM data and comparing the effects of the laminectomy and PSS treatments with intact condition, results indicated significant differences, at more than one loading condition, for all motions ($p<0.05$), except for right bending after performing the laminectomy (Table 4.12). These results were consistent with dynamic ROM discussed above. Furthermore, PSS seemed to significantly limit ($p<0.05$) the ROM for most loading conditions under all motions (Table 4.14).

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

When testing spine biomechanics it is important to report all variables that may have an effect on the results. Among the most important variables found during this work were: exposure time of the specimen to room temperature, preservation and testing conditions (i.e. temperatures), inclusion parameters (i.e. sample characterization), ligaments and joint conditions, testing protocol and loading history.

The most important limitation found during this work was having a small number of FSUs from different spinal levels. On one hand, knowing that different spinal levels could have different biomechanical properties made difficult to study them altogether. On the other hand, normalizing this data brings the assumption of the effects of all treatments (laminectomy and PSS) being the same for all spinal levels. The high standard deviation observed among normalized data may suggest this assumption is improper, although this large variability could also be consequence of having a small number of samples (6 FSUs). Further studies should consider a power analysis to determine a reasonable number of FSUs from different spinal levels to evaluate these hypotheses. From this pilot study, an educated estimation of number of samples would be 6 whole lumbar spines (which lead to 18 FSUs, 6 from each spinal level).

This pilot study suggests there may be a considerable effect of the laminectomy on the stability of a lumbar FSU. Dynamic data suggested the changes in neutral zone stiffness may be significant for extension motion after performing a laminectomy, when compared to intact condition. PSS showed to increase segment's stiffness by more than double. Moreover, changes in quasi-static displacements caused by a laminectomy decompression may be significant as well, especially for flexion (20%) and extension (greater than 10%).

In vitro studies provide valuable information but long-term consequences should not be underestimated. For this reason, *in vitro* studies should be integrated with *in vivo* studies (i.e. retrospective studies), when possible. Even if further *in vitro* studies show there is no significant destabilization of the spine after performing a laminectomy decompression, there are clinical studies that have shown that decompressive laminectomy may contribute to segmental instability which forces some patients to go back to surgery looking for a stabilization system. This fact could have several reasons but should be, indeed, considered before making any strong conclusion about the effects of this treatment on the stability of the spine.

It is recommended that further studies that aim to evaluate the effects of a laminectomy decompression in cadaveric human models include multisegmental spinal samples (at least 6 complete lumbar spines) since these more closely resemble *in vivo* situations. Moreover, this would allow analyzing the contribution of this surgical procedure in adjacent levels. These segments could be later dissected in FSUs (about 18 FSUs from 6 lumbar spines) and tested individually to have more information about this treatment.

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APPENDICES

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Figure A.1. Copyright Permission for Figures 2.10 and 2.11

Appendix B. Original (Raw) Data

Table B.1. Dynamic Extension and Flexion Data.

		EXTENSION		FLEXION	
Specimen	Treatment	Moment [Nm]	Displacement [degree]	Moment [Nm]	Displacement [degree]
1	Intact	7.96	2.57	8.00	4.67
2	Intact	8.04	2.21	7.78	4.77
3	Intact	7.98	3.09		
4	Intact	8.03	2.11	7.94	3.28
5	Intact	7.91	2.42	7.97	5.93
6	Intact	7.92	4.07	7.97	7.80
1	Laminectomy	7.93	3.04	7.94	5.24
2	Laminectomy	7.97	2.35	7.57	4.42
3	Laminectomy	8.00	3.39		
4	Laminectomy	7.99	2.25	7.86	3.58
5	Laminectomy	7.92	4.45	7.96	7.82
6	Laminectomy	7.99	4.88	7.90	8.85
1	PSS	8.08	1.11	7.96	1.31
2	PSS	7.96	1.52	7.95	1.35
3	PSS	7.95	2.53	7.99	1.87
1	Intact	7.47	2.41	7.45	4.38
2	Intact	7.45	1.99	7.58	4.47
3	Intact	7.43	2.80	7.56	11.64
4	Intact	7.55	1.98	7.51	3.12
5	Intact	7.55	2.27	7.58	5.77
6	Intact	7.54	3.95	7.54	7.62
1	Laminectomy	7.40	2.83	7.49	4.95
2	Laminectomy	7.45	2.10	7.57	4.42
3	Laminectomy	7.49	3.15	7.03	11.81
4	Laminectomy	7.59	2.11	7.54	3.24
5	Laminectomy	7.55	4.30	7.55	7.67
6	Laminectomy	7.34	4.59	7.47	8.71
1	PSS	7.58	1.94	7.45	1.21
2	PSS	7.51	1.38	7.49	1.24
3	PSS	7.45	1.54	7.55	1.72

Appendix B (Continued)

Table B.2. Dynamic Lateral Bending Data.

		RIGHT BENDING		LEFT BENDING	
Specimen	Treatment	Moment [Nm]	Displacement [degree]	Moment [Nm]	Displacement [degree]
1	Intact	7.97	4.27	7.98	6.01
2	Intact	7.90	4.66	7.84	8.13
3	Intact	8.00	4.85	8.06	3.39
4	Intact	7.94	2.38	7.95	1.53
5	Intact	7.95	2.19	7.99	2.04
6	Intact	7.92	7.46	7.94	7.03
1	Laminectomy	7.96	4.15	7.94	6.24
2	Laminectomy	7.99	5.11	7.93	7.99
3	Laminectomy	7.96	5.23	7.96	3.63
4	Laminectomy	7.98	2.23	8	1.70
5	Laminectomy	7.95	2.94	8.01	2.17
6	Laminectomy	7.93	7.89	7.92	7.17
1	PSS	7.92	2.88	7.9	2.64
2	PSS	7.96	3.60	7.92	2.62
3	PSS	8.05	1.39	8.02	1.20
1	Intact	7.44	4.07	7.54	5.77
2	Intact	7.65	4.50	7.46	7.95
3	Intact	7.46	4.58	7.46	3.19
4	Intact	7.43	2.23	7.57	1.44
5	Intact	7.58	2.10	7.48	1.92
6	Intact	7.51	7.22	7.51	6.78
1	Laminectomy	7.45	3.90	7.5	6.22
2	Laminectomy	7.51	4.92	7.47	7.79
3	Laminectomy	7.48	4.98	7.56	3.47
4	Laminectomy	7.51	2.08	7.47	1.56
5	Laminectomy	7.5	2.80	7.51	2.05
6	Laminectomy	7.47	7.52	7.54	6.92
1	PSS	7.65	2.71	7.44	2.65
2	PSS	7.54	3.34	7.44	2.45
3	PSS	7.46	1.24	7.42	1.07

Appendix B (Continued)

Table B.3. Dynamic Axial Rotation Data.

		RIGHT ROTATION		LEFT ROTATION	
Specimen	Treatment	Moment [Nm]	Displacement [degree]	Moment [Nm]	Displacement [degree]
1	Intact	8.12	1.48	7.95	1.30
2	Intact	7.99	1.06	7.98	1.11
3	Intact	8.00	0.86	8.06	0.83
4	Intact	8.00	1.37	8.00	1.20
5	Intact	8.03	0.61	8.03	0.71
6	Intact	8.02	1.15	8.01	1.03
1	Laminectomy	7.90	1.80	7.89	1.40
2	Laminectomy	7.97	1.12	7.95	1.11
3	Laminectomy	7.94	0.98	7.97	0.97
4	Laminectomy	8.00	1.42	8.06	1.20
5	Laminectomy	8.03	0.77	8.04	0.75
6	Laminectomy	8.09	1.18	8.01	1.16
1	PSS	7.9	1.20	7.92	1.12
2	PSS	7.99	0.66	8.07	0.56
3	PSS	7.90	7.90	7.97	0.67
1	Intact	7.48	1.44	7.49	1.22
2	Intact	7.45	0.99	7.63	1.03
3	Intact	7.43	0.80	7.55	0.84
4	Intact	7.55	1.29	7.45	1.11
5	Intact	7.51	0.57	7.51	0.65
6	Intact	7.46	1.04	7.45	0.96
1	Laminectomy	7.54	1.72	7.55	1.33
2	Laminectomy	7.48	0.97	7.51	1.03
3	Laminectomy	7.43	0.91	7.54	0.90
4	Laminectomy	7.46	1.37	7.43	1.13
5	Laminectomy	7.51	0.72	7.51	0.70
6	Laminectomy	7.49	1.10	7.55	1.07
1	PSS	7.55	1.11	7.42	1.02
2	PSS	7.48	0.62	7.67	0.55
3	PSS	7.42	0.65	7.52	0.60

Appendix B (Continued)

Table B.4. Quasi-Static Flexion and Extension Data.

ID	Moment [Nm]	FLEXION INT [degree]	FLEXION LD [degree]	FLEXION PSS [degree]	EXTENSION INT [degree]	EXTENSION LD [degree]	EXTENSION PSS [degree]
1	7.50	5.21	6.01	1.50	3.10	3.64	1.25
2		5.22	4.98	1.59	2.81	3.01	1.67
3		11.07	14.40	2.21	3.25	4.20	2.10
4		3.90	4.34		2.50	2.54	
5		6.90	8.87		3.00	4.77	
6		8.50	9.80		4.78	5.44	
1	6.00	4.31	5.05	1.11	2.66	3.16	1.00
2		3.00	2.81	1.24	2.32	2.45	1.33
3		5.20	5.51	1.68	2.67	3.51	1.65
4		3.25	3.63		2.17	2.19	
5		6.34	8.25		2.60	4.24	
6		7.92	9.10		4.33	4.82	
1	4.50	3.02	3.53	0.79	2.14	2.53	0.73
2		1.86	1.81	0.92	1.80	1.87	0.97
3		2.07	2.92	1.19	2.08	2.78	1.21
4		2.55	2.84		1.74	1.75	
5		5.66	7.47		2.13	3.50	
6		7.12	8.29		3.70	3.97	
1	3.00	1.62	1.84		1.50	1.78	0.48
2		1.11	1.07		1.21	1.26	0.62
3		1.12	1.58		1.42	1.93	0.77
4		1.76	1.84	0.49	1.16	1.21	
5		4.62	6.25	0.61	1.57	2.60	
6		5.90	6.92	0.76	2.87	2.95	
1	1.50	0.67	0.73		0.77	0.92	0.24
2		0.45	0.42		0.61	0.65	0.30
3		0.44	0.60		0.73	1.00	0.35
4		0.74	0.82	0.23	0.53	0.60	
5		2.25	2.92	0.31	0.89	1.53	
6		3.37	3.90	0.36	1.71	1.75	

*ID=Specimen IID
INT=Intact
LD=Laminectomy Decompression
PSS=Pedicle Screw System

Appendix B (Continued)

Table B.5. Quasi-Static Lateral Bending Data.

ID	Moment [Nm]	RIGHT BENDING INT [degree]	RIGHT BENDING LD [degree]	RIGHT BENDING PSS [degree]	LEFT BENDING INT [degree]	LEFT BENDING LD [degree]	LEFT BENDING PSS [degree]
1	7.50	4.87	3.92	3.58	6.70	7.09	3.40
2		5.23	5.60	4.37	9.00	8.77	3.50
3		5.11	5.64	1.70	3.70	4.03	1.46
4		2.60	2.51		1.80	2.06	
5		2.44	3.10		2.33	2.52	
6		8.10	8.62		7.94	7.95	
1	6.00	4.22	3.27	2.86	5.89	6.34	2.69
2		4.61	4.93	3.55	8.14	8.03	2.84
3		4.44	4.88	1.30	3.09	3.39	1.17
4		2.21	2.11		1.49	1.67	
5		2.14	2.71		1.98	2.15	
6		7.07	7.63		6.98	6.99	
1	4.50	3.51	2.59	2.09	5.06	5.49	2.00
2		3.87	4.20	2.60	7.13	7.10	2.26
3		3.72	4.09	0.90	2.50	2.72	0.89
4		1.75	1.68		1.16	1.29	
5		1.80	2.26		1.62	1.78	
6		5.94	6.45		5.91	5.96	
1	3.00	2.71	1.84	1.25	3.87	4.19	1.23
2		2.97	3.30	1.57	5.50	5.62	1.56
3		2.94	3.24	0.54	1.77	1.93	0.54
4		1.13	1.10		0.75	0.82	
5		1.39	1.73		1.18	1.33	
6		4.60	5.05		4.58	4.64	
1	1.50	1.65	0.97	0.53	2.17	2.18	0.55
2		1.74	2.03	0.59	2.89	2.44	0.78
3		1.78	2.01	0.23	0.95	1.06	0.22
4		0.46	0.48		0.38	0.41	
5		0.76	0.93		0.65	0.77	
6		2.80	3.08		2.82	2.36	

*ID=Specimen IID
INT=Intact
LD=Laminectomy Decompression
PSS=Pedicle Screw System

Appendix B (Continued)

Table B.6. Quasi-Static Axial Rotation.

		RIGHT ROTATION			LEFT ROTATION		
ID	Moment [Nm]	INT [degree]	LD [degree]	PSS [degree]	INT [degree]	LD [degree]	PSS [degree]
1	7.50	1.70	2.01	1.35	1.50	1.58	1.31
2		1.30	1.25	0.73	1.30	1.30	0.60
3		1.09	1.12	0.82	0.90	1.06	0.81
4		1.60	1.72		1.47	1.50	
5		0.69	0.86		0.75	0.87	
6		1.37	1.40		1.15	1.33	
1	6.00	1.41	1.67	1.06	1.20	1.25	1.03
2		1.01	0.99	0.65	0.99	1.05	0.53
3		0.76	0.87	0.65	0.72	0.86	0.62
4		1.37	1.47		1.22	1.21	
5		0.55	0.68		0.61	0.67	
6		1.10	1.15		0.91	1.05	
1	4.50	1.11	1.35	0.81	0.90	0.94	0.77
2		0.76	0.71	0.55	0.75	0.81	0.44
3		0.57	0.66	0.46	0.53	0.66	0.44
4		1.12	1.20		0.97	0.93	
5		0.42	0.49		0.45	0.51	
6		0.79	0.87		0.65	0.77	
1	3.00	0.81	1.00	0.54	0.62	0.63	0.52
2		0.45	0.49	0.40	0.50	0.53	0.33
3		0.39	0.45	0.29	0.35	0.46	0.28
4		0.80	0.88		0.73	0.68	
5		0.29	0.31		0.30	0.34	
6		0.47	0.56		0.41	0.50	
1	1.50	0.48	0.44	0.27	0.30	0.29	0.24
2		0.19	0.23	0.20	0.23	0.24	0.15
3		0.20	0.22	0.14	0.17	0.23	0.13
4		0.37	0.39		0.39	0.34	
5		0.15	0.15		0.13	0.17	
6		0.17	0.21		0.19	0.24	

*ID=Specimen IID
INT=Intact
LD=Laminectomy Decompression
PSS=Pedicle Screw System