3D Facet Joint Kinematics *In-vivo* and Spinal Degeneration and Its Correlation to the Lower Back Pain

BY

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THESIS

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This thesis is dedicated to my mother, Viera Simonova and my father, Ladislav Simon, without their support and unconditional love it would never have been accomplished.

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SUMMARY

Low back pain affects almost every adult individual at some point in his or her life. The lifetime occurrence of low back pain in the United States is about 70% to 85%, making it the number two reason for doctor visits (after the common cold)[2]. Low back pain is also the primary cause of disability in individuals under the age of 40[1]. In the United States alone direct costs for treating back pain are estimated at $50 billion annually [1]. In addition to the direct costs for treating low back pain, indirect costs such as disability and lost productivity at work cannot be ignored. Low back pain is the most costly musculoskeletal disease in industrialized countries today [3].

The morphological changes in the intervertebral disc, vertebral body, and facet joints are believed to be the major contributing factors in low back pain etiology. It has been hypothesized that degenerative changes of both articulating structures in the lumbar spine (intervertebral disc and facet joints) may significantly alter motion patterns (defined by segmental range of motion) of the lumbar spine. Facet joints are paired synovial articulations which play a major role in constraining motion in the segmental unit and morphological changes to the facet joint may decrease their constraining function, subsequently leading to instability of the whole motion segment. It was hypothesized that the presence of spinal degenerative changes causes spinal instability that is believed to be associated with low back pain.

Kinematic parameters such as range of motion are necessary to evaluate instability. Traditionally, spinal kinematics is studied with reference to intervertebral disc. Complex three-dimensional facet surface geometry and small size pose challenges for kinematic analysis. Recent advancements in medical imaging allow researchers to study *in-vivo* three-dimensional characteristics of those smaller, complex structures.

The aim of this study was to develop a three-dimensional *in-vivo* kinematic model in order to evaluate facet joint range of motion, and correlate it with degenerative changes in the lumbar spine and symptoms of the low back pain. Degeneration induced alteration in facet joint kinematics has been reported to be the greatest in torsion[30]. In this study, 91 volunteers were scanned using conventional CT

scanner in the neutral position and under torsion. Three-dimensional information on subject-specific lumbar anatomy was evaluated.

The study was subdivided into three parts: *in-vivo* kinematic model of the lumbar facet joint motion and its validation; evaluation of the degenerative changes in the lumbar spine; and correlation of kinematic parameters with degenerative changes and symptoms of low back pain.

A novel noninvasive *in-vivo* method was introduced to measure lumbar facet joint segmental rotations and translations in six degrees of freedom. The method presented in this study is a combination of an anatomically relevant local coordinate system definition and their spatial transformations. Results indicated the motion coupling during torsion. Facet joint kinematics are dependent on the level of the lumbar spine and kinematic parameters were different between genders. The accuracy of the CT-based geometry was previously determined with a mean absolute translation error less than 0.1mm and a mean absolute rotation error less than 0.2°. Facet joint surface geometry is the key input to the model. The surface identification match between two observers has been determined at 98±3.9%.

A combination of conventional, clinical methods and newly developed methods was used to quantify spinal degeneration. The relationship between spinal degeneration and age was clearly demonstrated. Additionally, using a novel quantitative method, the early occurrence of localized disc degeneration in the posterior portion was demonstrated. Facet joint osteoarthritis was similarly related to age. The results also revealed a strong level dependency in facet osteoarthritis development. Facet joint space narrowing, as an indication of the osteoarthritis progression, was also localized in the inferior portion of the facet joint in the subject at their thirties. Comparison of qualitative (clinical) and quantitative methods for evaluation of degeneration showed a very strong correlation among them.

Correlation of spinal degeneration and facet kinematics to the symptom showed significant differences between symptomatic and healthy subjects. It has been shown that degeneration is

significantly larger in subjects with low back pain. Similarly subjects with low back pain showed significantly different patterns of kinematic parameters.

The present study for the first time investigated the effect of degenerative changes on segmental range of motion *in-vivo* with respect to the presence of the low back pain. The results demonstrated the influence of degenerative changes on the alteration of segmental motion. Rotational and translational instability have been demonstrated to be larger in the group of subjects with low back pain.

I. Project Rationale and Study Design

1. Significance

Low back pain is one of the most common ailments. It affects almost every adult individual at some point in his or her life. The lifetime occurrence of low back pain in the United States is about 70% to 85%, with 10% to 20% experiencing chronic low back pain [1], making it the number two reason for doctor visits (after the common cold) [2]. Low back pain is also the primary cause of disability in individuals under the age of 40[1]. Cost related to low back pain diagnosis and treatment despite technological advances presents a major socioeconomic burden on the Western societies[3]. In the United States alone direct costs for treating back pain are estimated at $50 billion annually [1]. In addition to the direct costs for treating low back pain, indirect costs such as disability and lost productivity at work cannot be ignored. Low back pain is the most costly musculoskeletal disease in industrialized countries today [3].

Our principal long-term goal is to develop novel methods to diagnose and treat low back pain problems resulting from segmental instability and degenerative changes in the spinal column. Back related pain is a well-recognized problem. However, its etiology is unknown for most types of low back pain. It is widely accepted that segmental instability of the lumbar spine and degenerative changes are major factors in the etiology of persistent low back pain. In general, instability can be defined as excessive motion beyond normal constraints, causing either compression or stretching of the soft tissues (neural elements, ligaments, joint capsule) which have a significant number of pain receptors[4]. Degenerative changes, natural to all living tissues, are also believed to result in increased segmental motion. However, due to a lack of a standardized diagnostic method, the definition of instability remains controversial. Due to those facts it is not surprising that many of the present treatments are relatively ineffective [2]. There is a need to define accurate kinematic parameters describing motion in the spinal

column and relate them to the progression of the degeneration in healthy subjects and individuals who experience low back pain.

The anatomic changes in the intervertebral disc, vertebral body, and facet joints associated with instability are not clearly known, and their relationship to pain is even more elusive. There have been numerous studies done on instability and the influence of degeneration on spinal biomechanics[4]. Degenerative changes in the lumbar spine affect the intervertebral disc and facet joints. It has been hypothesized that degenerative changes of both articulating structures may significantly alter segmental motion characteristics. Kinematic parameters such as range of motion are necessary to evaluate instability and are normally related to the motion of the intervertebral disc. The effect of disc degeneration on kinematics has been also reported by numerous studies [5-8]. Facet joints play a major role in constraining motion in the segmental unit and morphological changes to the facet joint may cause decrease in their constraining function, subsequently leading to instability of the whole motion segment. There is currently no complex work published addressing this issue to the best of the author's knowledge. Recently, facet joints have received attention as a potential cause of low back pain. Facet joint osteoarthritis has been considered as a potential source of low back pain and disability and contributes to 15-45% of chronic low back pain[9]. Due to this fact, it is believed that facet joint osteoarthritis might be a potential trigger of low back pain and cause disability.

There is a paucity of data regarding the kinematics of the facet joint primarily because the size of the facet joint and its complex three-dimensional geometry pose challenges for kinematic analysis. Advancements in medical imaging allow us to study *in-vivo* three-dimensional characteristics of these smaller, complex structures. The aim of this study was to develop a precise three-dimensional rigid body model of the facet joint kinematics able to evaluate facet joint motion parameters, based on facet joint surface geometry and expressed on an anatomically relevant reference frame. The obtained model was used to evaluate the effect of spinal degenerative changes and the presence of low back pain on arthro-kinematics.

2. Background

2.1. Anatomy of the human spine – motion segment

The spine is a mechanical structure that transfers the weights resulting from bending moments of the head and trunk and the weights being lifted to the pelvis. It also allows body motions and protects the spinal cord from damage caused by non-physiological motions and trauma. It consists of seven cervical vertebrae, twelve thoracic vertebrae, five lumbar vertebrae, five fused sacral vertebrae, and three to four fused coccygeal segments (Figure I-1). In the sagittal plane, the spine generally appears as curved convex anteriorly in the cervical and lumbar regions and convex posteriorly in the thoracic and sacral regions – forming cervical lordosis, thoroacic kyphosis, lumbar lordosis and sacral kyphosis. Normal curvature of the spine has a mechanical basis. Curved structure of the spinal column helps to maintain adequate stiffness and stability of the column, while increasing its flexibility and shock-absorbing capacity[10]. Individual vertebrae articulate with each other in a controlled manner through a complex of joints and active (muscles) and passive (ligaments) constraints. Most freedom of motion is experienced by the cervical spine, followed by the lumbar spine.

The motion segment is the smallest segment of the spine that exhibits biomechanical characteristics similar to those of the entire spine. It consists of two adjacent vertebrae, an intervertebral disc, facet articulations and the connecting ligamentous tissues (Figure I-2). It is the smallest unit representing the general mechanical behavior in a given region of the spine. The entire spine might be decomposed into multiple motion segments connected in series, and the mechanical characteristics of the spine can be approximated as a composite of the behaviors of the individual motion segments. Changes to the physical properties of individual parts of the motion segment (vertebrae, intervertebral disc, facet joint and ligaments) may lead to the alterations in motion characteristics within the motion segment, and alternate motion characteristics of adjacent motion segments and of the entire spine. Motion is conventionally described in terms relative to the subjacent vertebra. For a kinematic analysis it is useful to alter conventional subdivision of the spine taking into consideration local uniqueness of the structures. In

our case, it is important to distinguish between separate regions of the lumbar spine: lumbar region (L1-L5) and lumbosacral regions (L5-S1). Anatomy, kinematics and kinetics of lumbosacral region is significantly different from the lumbar region of the spine[10].

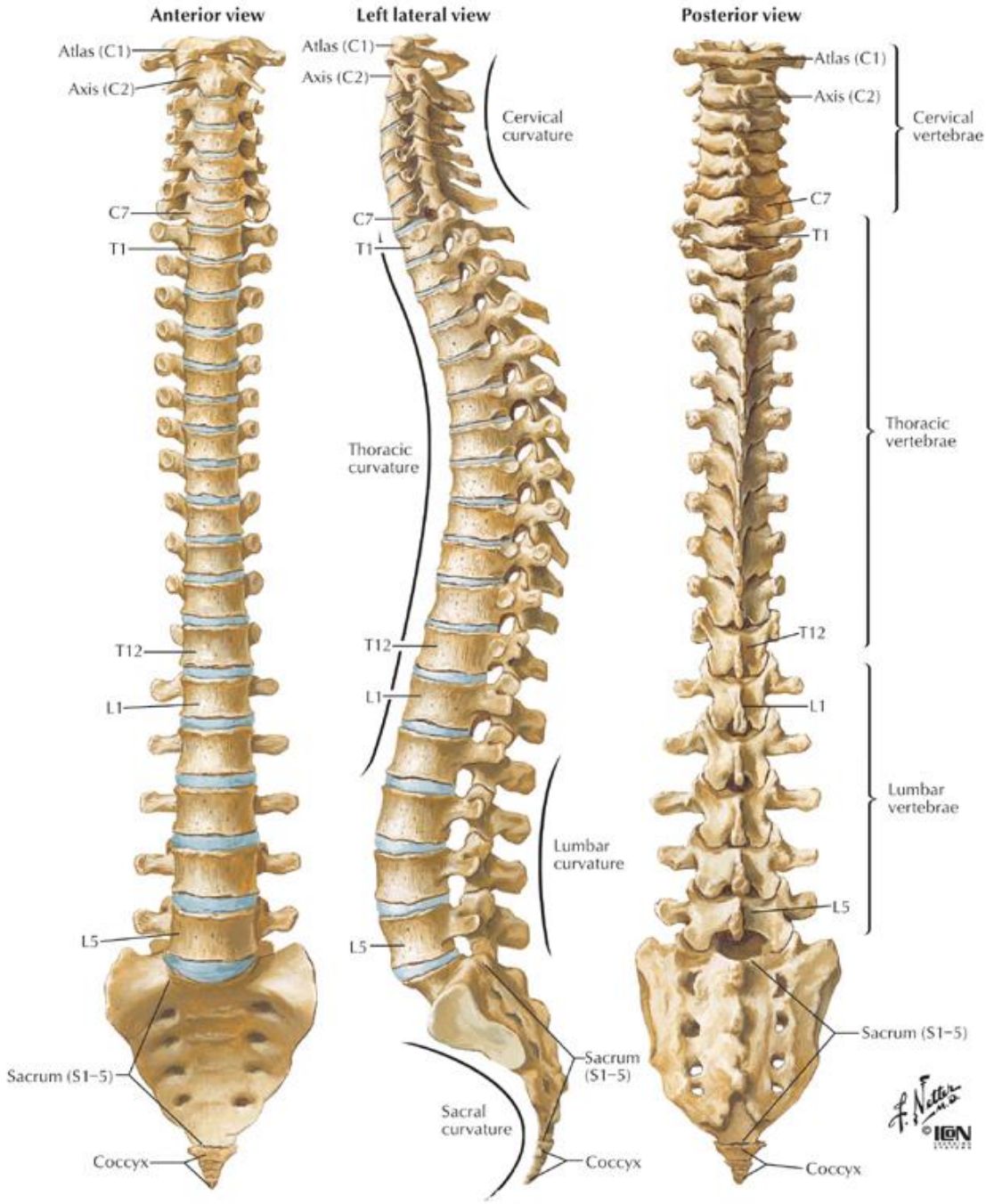


Figure I-1: Human spine[11]

Figure I-2: Lumbar motion segment[11]

2.1.1 Lumbar vertebrae

A vertebra consists of an anterior mass of bone consisting of a vertebral body and a posterior ring known as the neural arch (Figure I-3). The vertebral body is the main load bearing structure of the lumbar vertebra. The vertebral body is a roughly cylindrical mass formed by an external cortical shell surrounding the inner cancellous bone. The cranial and caudal surfaces of the vertebral body are covered with the vertebral end-plates, structures composed of hyaline cartilage that separates the other two components of the disc from the vertebral body. The neural arch is attached to the dorsolateral aspects (posterior wall) of the body and consists of two pedicles and two laminae from which arise seven processes: spinous process, superior and inferior articulating processes of the zygapophysial joints and the left and right transverse processes. Laminae connect the spinous process to the rest of the posterior element while pedicles connect the posterior element to the vertebral body. The superior and inferior articulating surfaces mate respectively with the inferior articulating process of the superior vertebra and the superior articulating process of the inferior vertebra, forming the facet joints.

2.1.2 Intervertebral disc

The intervertebral disc is the soft tissue structure that lies between the adjacent vertebral bodies (Figure I-4). It is subjected to a considerable variety of forces and moments, binds the adjacent vertebrae, transfers load from one vertebra to the other and allows the movement of spine. It is also responsible for carrying majority of the compressive load to which the trunk is subjected. The intervertebral disc is comprised of three distinct areas: the nucleus pulposus, annulus fibrosus and cartilaginous endplate. The nucleus puplosus is a located in the central area of the intervertebral disc, between adjacent endplates and forms the gelatinous core of the disc. It consists of an irregular network of collagen (type II) and elastin fibers surrounded with a proteoglycan and water matrix. The nucleus acts as a shock absorbing, deformable sphere that transfers compressive forces to the annulus and endplates. The annulus fibrosus consists of approximately twenty concentric lamellae of highly organized collagen fibers (type I) surrounding nucleus. The annulus fibers in the inner zone of the disc are attached to the cartilaginous endplates, whereas fibers in the outer zone of the disc are attached directly into the osseous tissue of the vertebral body.

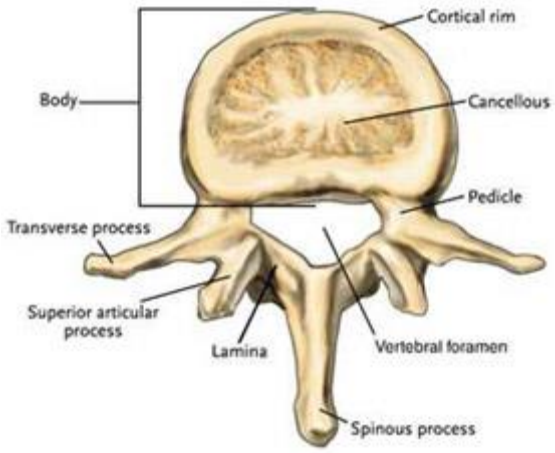


Figure I-3: Lumbar vertebrae[11]

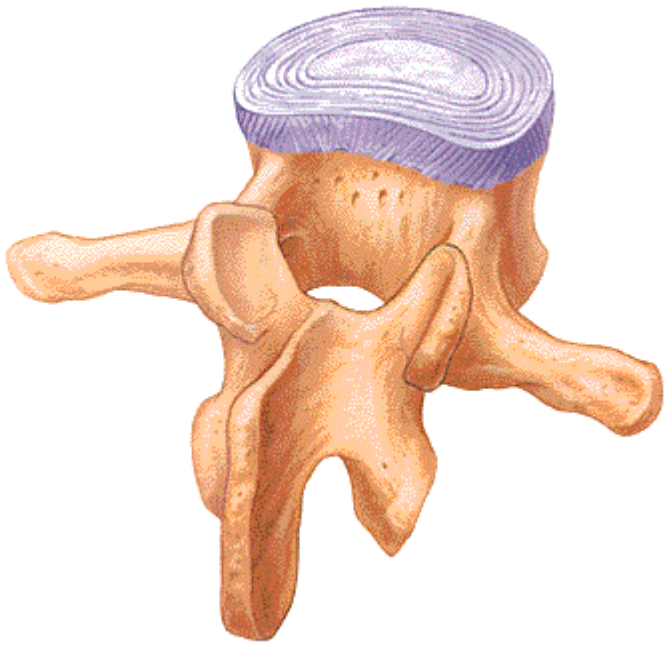


Figure I-4: Lumbar intervertebral disc[11]

2.1.3 Facet joint

The zygapophyseal, or facet joints are synovial joints in the spine that play an important role in controlling kinematics of the motion segment and transmitting load in the spine (Figure I-5) [12]. At each spinal level, there is a pair of facet joints located on the postero-lateral aspects of each motion segment. Their influence on spinal motion rises from specific shape and position within the human spine as well as their orientation in space. While the intervertebral disc allows for motion in all planes, the lumbar facet joints are restricted by their geometry, orientation, and capsular attachments. Orientation of the lumbar spine facet joint plane gradually changes from more sagittally oriented joints in the upper lumbar spine to more coronally oriented joints in the lower lumbar spine [10]. Previous studies have reported the overall significance of the facet joint orientation in the upper lumbar spine is to provide resistance to axial rotation, whereas in lower lumbar spine, the more coronally oriented surfaces provide resistance to flexion and extension[13]. The facet joints viewed on axial imaging parallel to the intervertebral disc space approximates a “C” or “J” shape with congruent geometry[12]. The shape and orientation of the lumbar FJ determines the role it plays in protecting the spine against excessive motion (15) as well as in load bearing

within the motion segment. From a biomechanical perspective it is understood that there is a direct relationship between facet joint surface geometry and load transmission. Load distribution properties of the facet joint depend mainly on morphometric factors such as size, position and orientation. Alteration of geometry of any surface will change its load distribution. During normal motion, FJ surfaces come into contact and share the transferred load in order to stabilize spinal column. The largest motion experienced by the lumbar spine was cumulatively (L1-L5) 57 degrees in flexion/extension motion, reported by Punjabi and White[10].

Facet joints are typical diarthrodial joints with cartilage surfaces that provide a low-friction interface to facilitate motion of the spine. Joints are covered with hyaline cartilage overlying subchondral bone, a synovial membrane and a joint capsule. Each joint is enclosed in a fibrous capsule. The joint capsule is richly supplied with sensory innervations: mechanoreceptors in the joint capsule and nociceptors surrounding blood vessels. The most painful stimuli to a joint are twisting, tearing, and stretching of the joint capsule of surrounding ligaments.

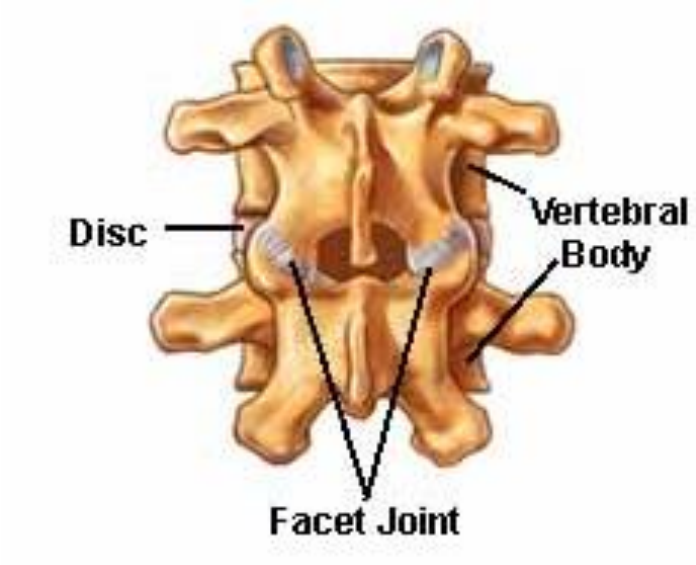


Figure I-5: Lumbar facet joint[11]

2.1.4 Spinal ligaments

Two adjacent vertebral bodies are connected together with an intervertebral disc and seven individual ligaments (Figure I-6). The anterior longitudinal ligament connects vertebral bodies through firm attachments to the anterior edges of individual vertebral bodies. The posterior longitudinal ligament is attached similarly as its anterior counterpart on the posterior side of the vertebral body within the spinal canal. The ligamentum flavum connects the laminae borders of two adjacent vertebrae. The intertransverse ligaments pass between the transverse processes at each lumbar level. The interspinous ligaments connect adjacent processes through attachments at top and apex of each process. The supraspinous ligament attaches along spinous process at each level. Finally, the capsular ligaments are attached beyond the margins of the adjacent articular process forming a facet joint outer capsule. Ligaments are uni-axial structures, whose load-bearing capacity is the largest along the direction of its fibers. This characteristic makes ligaments resistant to tensile load, while weak to bear compressive loads. The individual ligaments provide tensile resistance to external loads by developing tension. The spinal ligaments are richly supplied with sensory innervations such as mechanoreceptors and nociceptors surrounding blood vessels.

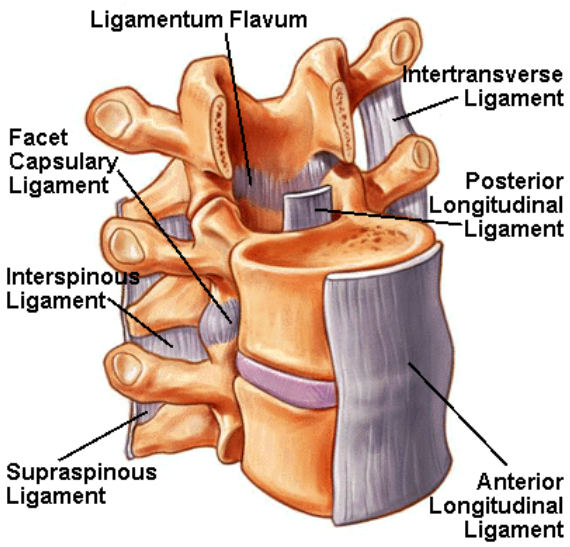


Figure I-6: Spinal ligaments[11]

2.2. Low back pain

Low back pain is the discomfort experienced in the lumbar region of the spine. Causes of low back pain are varied. Structures of the lumbar spine that can cause low back pain include muscles, ligaments, vertebral bodies, facet joints and intervertebral discs. There is a large overlap of nerve supply to all of these structures in the spinal column making it nearly impossible for the brain to distinguish between irritations from one structure versus another. Low back pain can be classified into three types: axial (mechanical back pain), radicular and referred pain. Axial back pain may be due to nerve, ligament or muscle irritation, or lesions of the bones. Radicular pain is characterized by radiation into the lower extremity and it is most frequently caused by nerve compression by a herniated disc or spinal stenosis. Referred neural pain is caused by a source different from nerve compression and has radiation into the buttock. Low back pain can either be acute, subacute or chronic in duration.

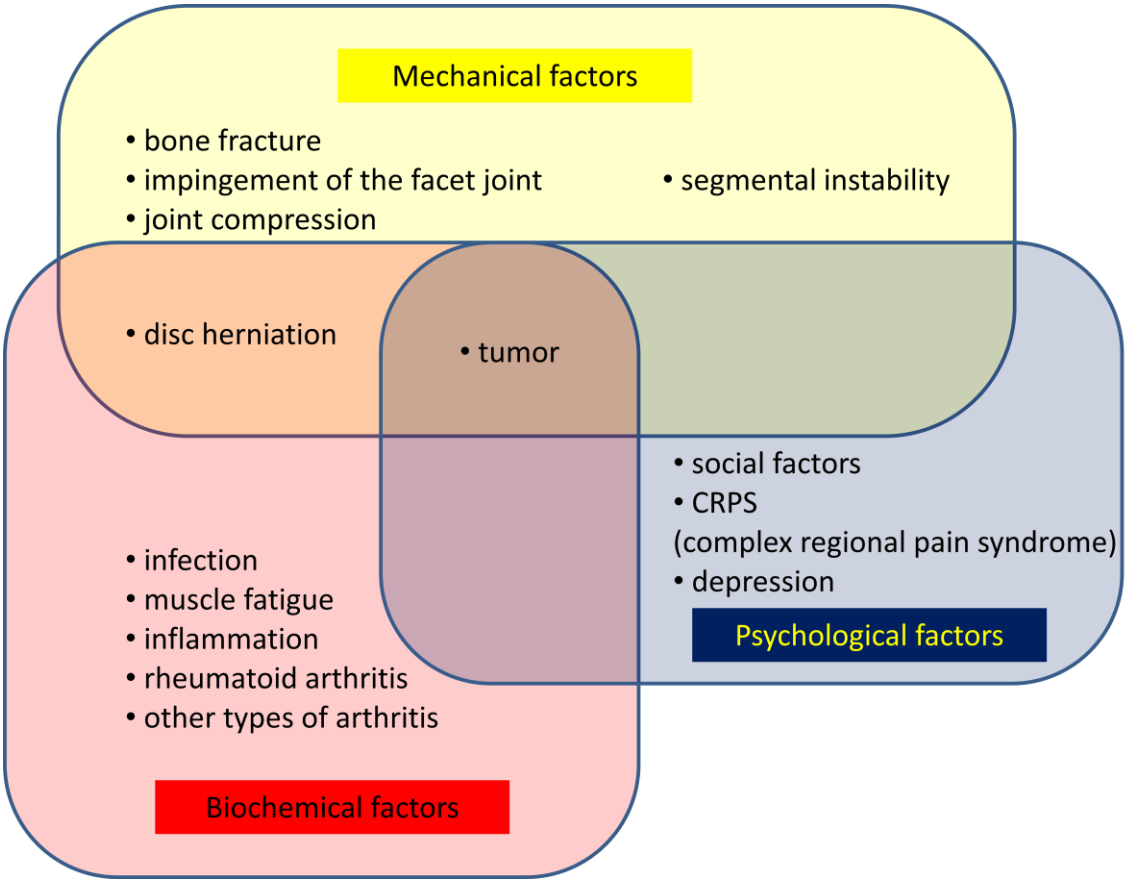


Figure I-7: Factors effecting etiology of low back pain [14]

The etiology of low back pain is not fully understood. Three major groups of factors that have an effect on the etiology of low back pain (Figure I-7) and their interactions have been identified in clinical practice. There is a strong believe that lumbar disc disease causes persistent back pain and leads to disc herniation and radicular pain[15]. However, many individuals with apparent disc disease on MRI images are non-symptomatic[16]. Segmental instability of the lumbar spine is another common cause of low back pain. However, the concept of segmental instability is controversial. The criteria for diagnosis are not generally accepted, and therefore the diagnosis often is made based upon vague clinical symptoms, imprecise radiographic findings of degenerative changes in the intervertebral discs and facet joints, and abnormal vertebral motions. Again, the presence of advanced degenerative changes to spinal structures does not necessarily mean the presence of pain symptoms. Because of these unknown variables, the results of treatment are often unpredictable and the efficacy of different treatment modalities is difficult to assess.

2.3. Segmental instability

Spinal segmental stability is an ability of individual vertebrae to maintain their relationship and limit their relative displacements during physiologic postures and loads[17]. Each spinal segment consists of intervertebral disc and a pair of facet joints forming together a "three-joint complex". Degeneration of three-joint complex affects the stability of the motion segment[18] and causes alterations in segmental motion. Kirkaldy-Willis and Farfan defined three stages of spinal degeneration[18,63]: dysfunction, instability, and stabilization. Degeneration in any of the articulating structures in the motion segment influences the other two and subsequently the biomechanics of the whole complex. Definition of clinical segmental instability is unclear. Panjabi and White defined clinical instability as the loss of the ability of the spine under physiologic loads to maintain its pattern of displacement so that there is no initial or additional neurological deficit, no major deformity, and no incapacitating pain[10]. From a biomechanical point of view, clinical instability can be defined as an abnormal response to applied loads characterized kinematically by abnormal movement in the motion segment beyond normal constraints[19]. Motion

abnormality can be explained by alterations to the restraining structures that, if damaged or lax, will lend to altered equilibrium and thus instability[20].

3. Materials and Methods

3.1. Study subjects

A total of 105 volunteers participated in this IRB approved study (IRB Approval No. 00042801) and each subject signed an approved informed consent form. All subjects were screened for presence of low back pain and preexisting lumbar spine pathology and were asked to fill out the National Spine Network (NSN) outcome questionnaire (see Appendix B: National Spine Network outcome questionnaire) to obtain detailed information that may affect spine condition, such as health condition, occupation, and activity levels. Subjects with low back pain were categorized as symptomatic subjects with inclusion criteria defined as recurrent low back pain with at least two episodes of at least 6 weeks. In addition, symptomatic patients were asked to evaluate their pain based on the analog visual scale from 1 to 10. Exclusion criteria for the symptomatic group were prior surgery for back pain, age > 60 years, claustrophobia or other contraindication to magnetic resonance (MR) and CT imaging, severe osteoporosis, severe disc collapse at multiple levels, severe central or spinal stenosis, destructive process involving the spine, litigation, or compensation proceedings, extreme obesity, congenital spine defects, and previous spinal injury. Healthy subjects were categorized as non-symptomatic subjects with exclusion criteria for the non-symptomatic group defined by the presence of the low back pain, previous spinal surgery, history of low back pain, age 60 years, obesity, and claustrophobia or other contraindication to MR and CT imaging. Fourteen volunteers were excluded from further analysis due to spondylolisthesis, spondylolysis, sacralization, lumbarization, and malformation of vertebrae. In consequence, a total of 91 subjects (50 males and 41 females, age range: 23–59 years, mean ± SD: 36.5 ± 10.0 years) were used for the analyses (Table I-1).

Subject anthropometric analysis revealed an average BMI index being 27.5 kg/m^2 (Table I-2). BMI index represents the measure of deviation of an individual's body weight from normal or desirable for a person of his or her height. Observed deviations of BMI index may be result of excessive body fat,

however it also might represent other factors such as muscularity or ethnic variations. According to WHO, a value of BMI index larger than 30 kg/m^2 represents obesity.

Table I-1: Subjects groups

	non-symptomatic		symptomatic	
	Male (30)	Female (28)	Male (20)	Female (13)
20s	9	10	3	2
30s	11	10	9	5
40s	8	6	3	3
50s	2	2	5	3

Table I-2: Anthropometric data of study subjects

	Weight (kg)	Height (m)	BMI (kg/m^2)
NF	65.7±16.1	1.61±0.08	25.2±6.1
NM	80.3±10.3	1.76±0.07	26±2.9
SF	69.6±21.3	1.59±0.08	27±4.8
SM	84.4±14.8	1.73±0.09	28.5±6.7

3.2. Dynamic computed tomography

In order to study kinematic parameters as well as morphology of the lumbar spine, every study subject was CT scanned in multiple positions. Each individual was positioned in a body restraint and loading apparatus (**T**orso **R**otation **C**ontrol **A**pparatus) in the supine position in the gantry of the Computed tomography (CT) scanner (Figure I-8). Each subject was scanned in two positions: neutral and rotated position (50 degrees to the right) using a CT scanner (Volume Zoom, Siemens, Malvern). The torso, pelvis and thighs of each subject was held using custom made hip and chest restraints, which allow lumbar spine movements while preventing hip and sacroiliac joint rotation. The neutral position of the lumbar spine was determined based on a "scout" CT scan, adjusting the middle axis of the pelvis to be parallel to the axis of rotation.

CT images were acquired in an axial view with the following scanning parameters (see Appendix A: Dynamic CT scan protocol): PA at 1.0 mm contiguous slices, pixel size 0.395mm, at 120 kV, AEC 350 mAs, 20 cm field of view, 512 x 512 matrix through the lumbar spine (T12-Sacrum). The images were stored in Digital Imaging and Communication in Medicine (DICOM) format then transferred to personal computers for analysis.

To reduce the risk of ionizing radiation the scanning parameters were adjusted to reduce exposure. At 40 mAs and 120 kV, the estimated dose of radiation is 0.125 rads (in the core) to 0.25 rads (on the surface). For one CT study subjects received in average less than 2 rads.

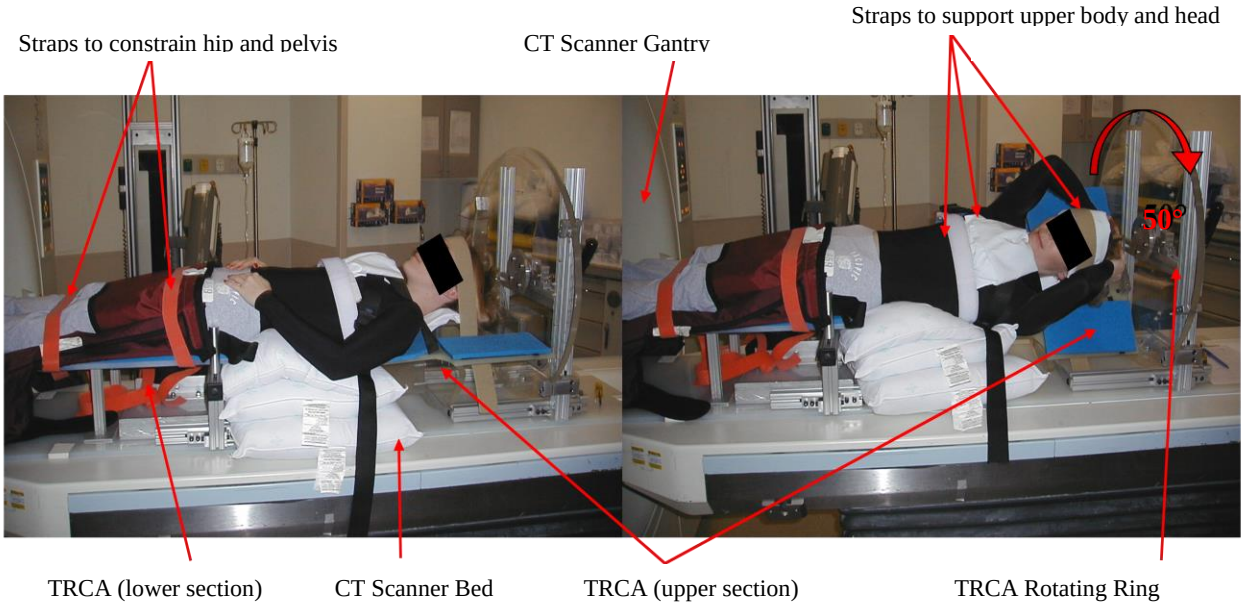


Figure I-8: CT scanning using TRCA (left- neutral position, right - rotated position)[21,22]

3.3. Magnetic resonance imaging

Magnetic resonance (MR) imaging was performed with T2-weighted sequences [repeat time/echo time (TR/TE): 2000/80 ms, 18.0 cm Field Of View (FOV), 512 × 512 matrix, 0.352 mm pixel size] using a 1.5T clinical MR imaging scanner (Signa1.5T, General Electric, Milwaukee, WI). Scans were performed at 2.67mm intervals (see Appendix A: MR scan protocol). The scanner gantry was tilted to

produce a scan through the plane of the disc at each intervertebral disc level. The images were stored in DICOM format for further analysis.

3.4. Three-dimensional CT computer models

Recent advancements in imaging modalities made it possible to obtain an *in-vivo* three-dimensional geometrical representation of the human anatomy. New CT scanners offer highly accurate spatial volume resolution without significant distortion while minimizing the radiation dose exposure. These advancements allowed the transition from a widely used two-dimensional based kinematic measurement to an *in-vivo* three-dimensional geometrical representation, and also acquire much higher precision and repeatability.

Precision is the key in studying small and complex structures such as the facet joint for which current two-dimensional methods are not sufficient. In this study various methods were developed in order to obtain a precise representation of bone geometry.

3.4.1 Vertebrae geometry

CT image data were imported in DICOM format to a three-dimensional reconstruction software Mimics (Materialise, Ann Arbor, MI). Based on visual observation, the value of the Hounsfield Unit (HU) representing the cortical shell of vertebrae was selected as a threshold level to define the cutoff between soft tissue and bone[21, 22]. The same threshold level was applied to all images of the same individual in both positions. Segmentation procedure followed the protocol (see Appendix A: Three-dimensional CT model segmentation protocol) in order to assure the consistency. The spinal geometry in both positions was precisely, manually segmented and the result was exported as an individual point-cloud file for each vertebrae (Figure I-9). A total of 910 individual vertebrae were obtained and used in the further analysis.

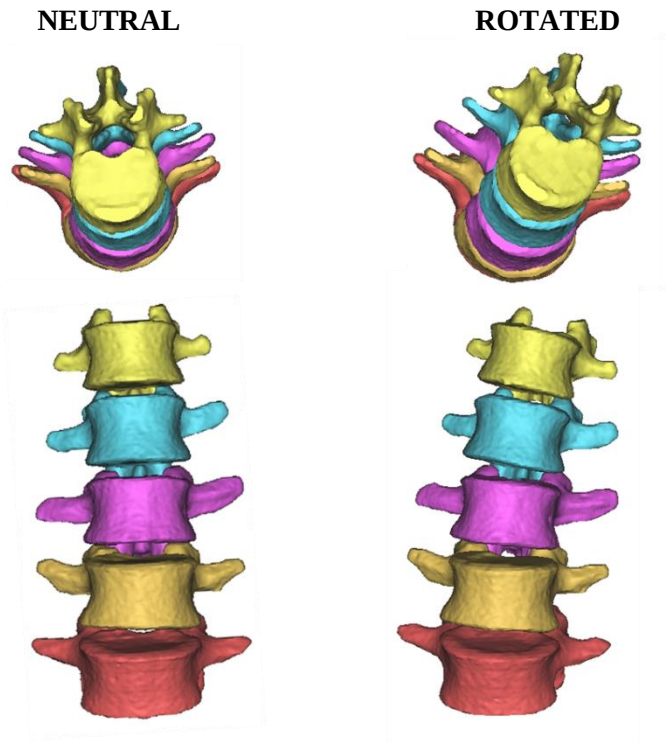


Figure I-9: 3D model of the human lumbar spine (in neutral and rotated position)

3.4.2 Posterior wall segmentation

The dorsolateral aspect of the vertebral body, the posterior wall, is a relatively flat surface of the vertebral body (Figure I-3). It can be defined as the area in between the pedicles and superior and inferior endplates at every spinal level.

To determine the posterior wall area, a custom-written software was created in Microsoft Visual C++ 2005 with Microsoft Foundation Class programming environment (Microsoft Corp., Redmond, WA). The posterior wall of each vertebral body in both studied positions was precisely extracted from the original point-cloud of the entire vertebra by defining the area in between two pedicles (Figure I-10)[23]. The results were saved as individual point-cloud files for each posterior wall. A total of 910 posterior walls were created following the protocol (see Appendix A: Posterior wall model segmentation protocol) in order to assure the consistency of the method. Three dimensional definition of the posterior wall was used to define a vertebral body specific local coordinate system. This local coordinate system was used to

identify the principal spatial orientation of each vertebra and also to define the local coordinate system for individual facet joints.

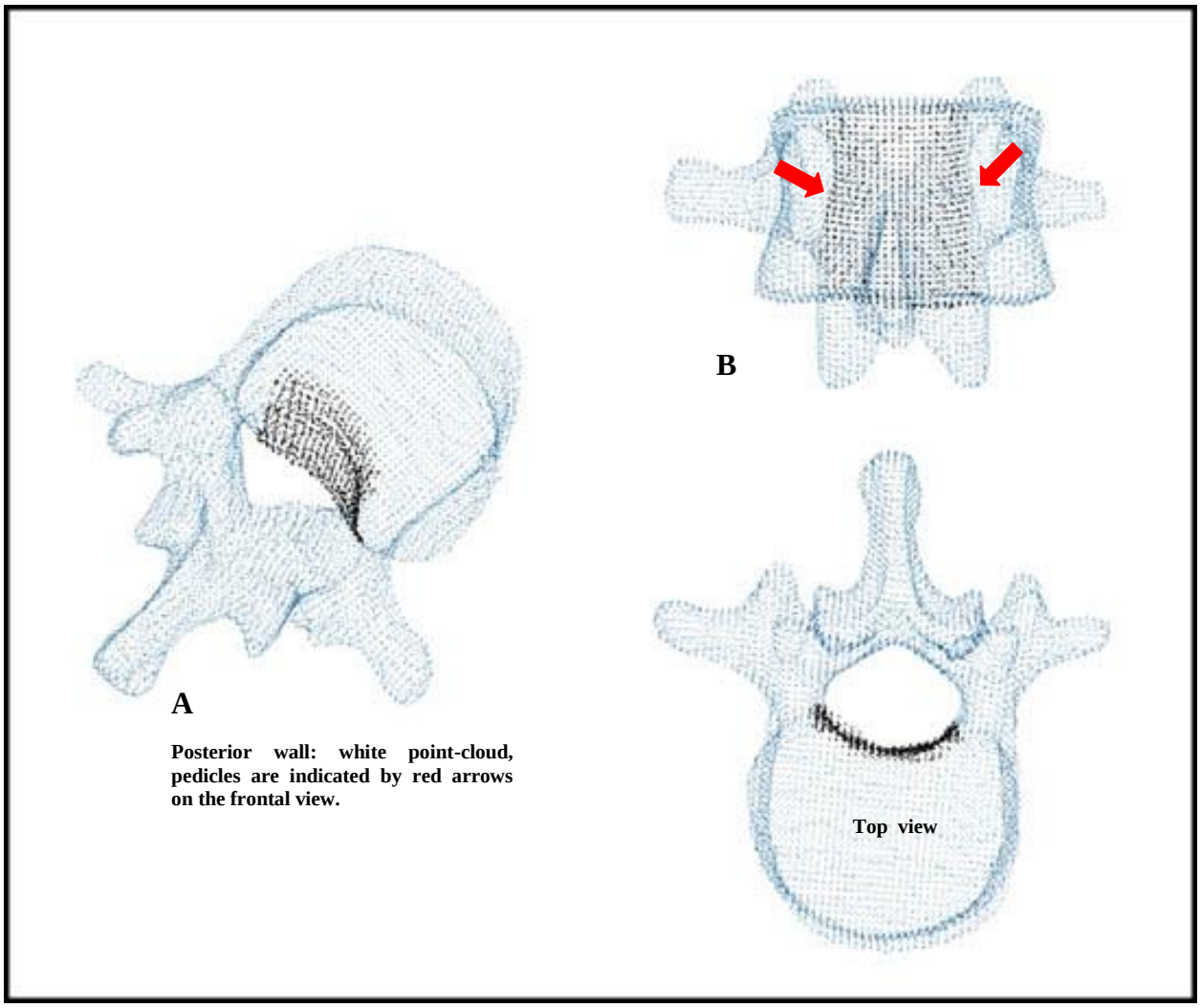


Figure I-10: Posterior wall segmentation

3.4.3 Endplate segmentation

The intervertebral disc is attached to the adjacent vertebral bodies in the most inferior/superior region of the vertebra, the intervertebral endplates.

The model of the intervertebral disc, a set of endplates at each level, was created by precise segmentation of the individual endplate surfaces (Figure I-11). Each endplate surface was segmented from original vertebral body point-cloud using the custom-written software identical to one previously used for posterior wall segmentation. Resultant endplates were saved as point-cloud files. A total of 1456 endplates were created following the standardized protocol (see Appendix A: Endplate model segmentation protocol)[24]. Three-dimensional endplate models were used to evaluate disc height distribution in the further analysis.

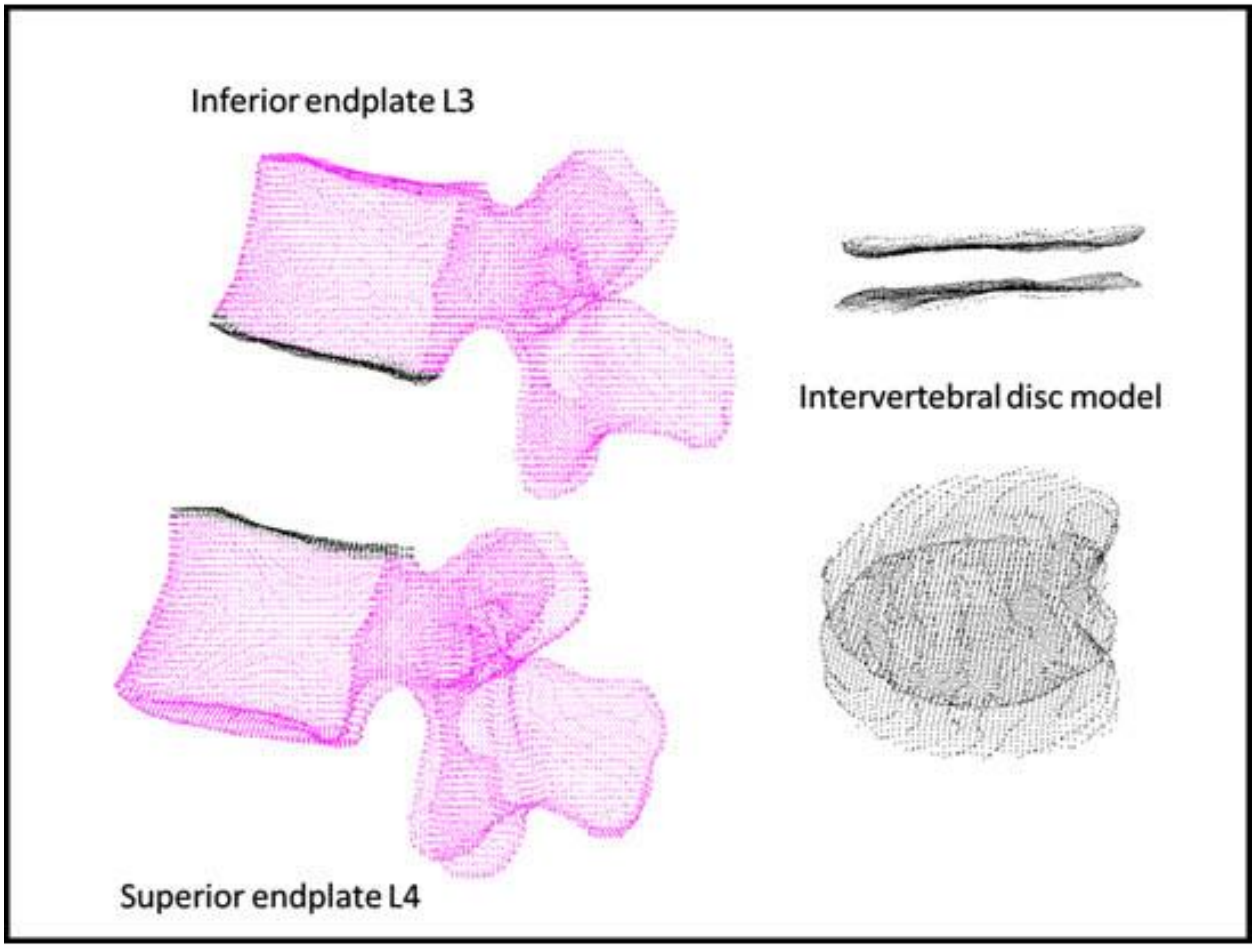
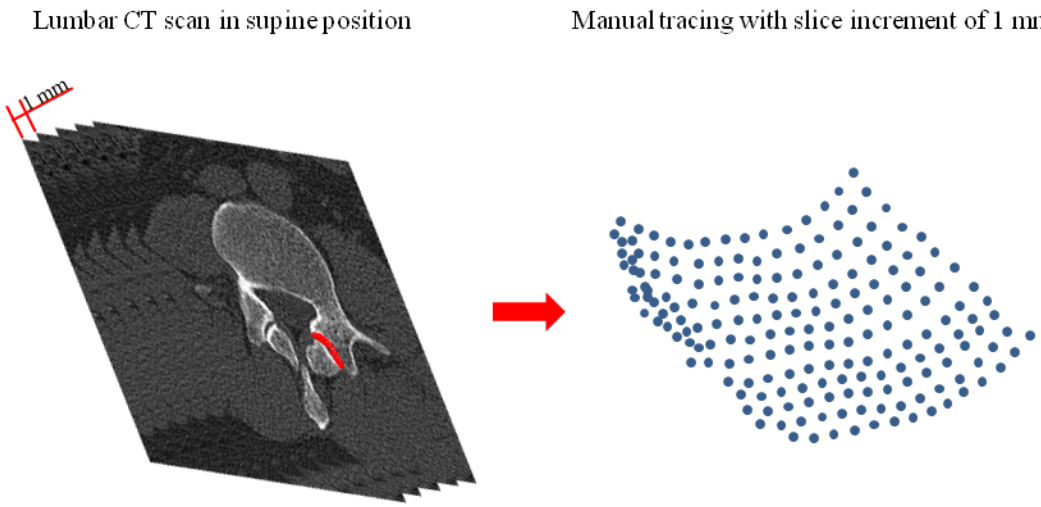


Figure I-11: Endplate segmentation[67]

3.4.4 Facet joint surface geometry

Raw CT imaging data corresponding to facet joints were post-processed in the axial plane at 1.0-mm slice thickness. Facet joint surfaces were traced from those axial DICOM images (Figure I-12) in a custom-written program (MV C++) using a tablet digitizer (Wacom Intuos 3; Wacom, Saitama, Japan). This procedure consists of a manual selection of the pixels representing the edge of the subchondral bone plate at the facet joint surface on an axial CT image. Particular care was taken to identify and exclude ostophyte formations from the joint surface. Traced surfaces were exported as a point-cloud. The tracing methodology was previously described by Otsuka et al[25]. Segmentation procedures followed the standardized protocol (see Appendix A: Facet joint surface tracing protocol).



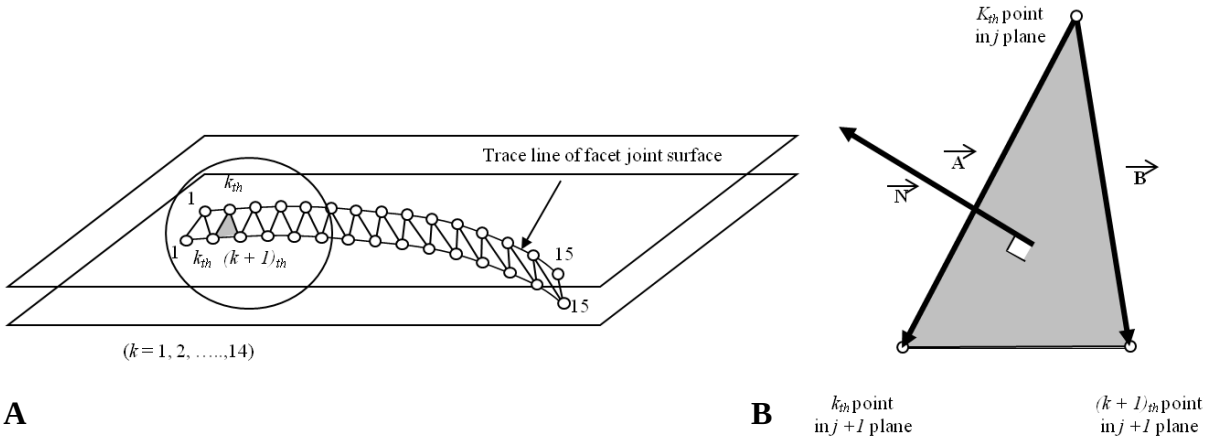
A: a stack of axial CT images corresponding to FJs at one spinal level (red – trace line)

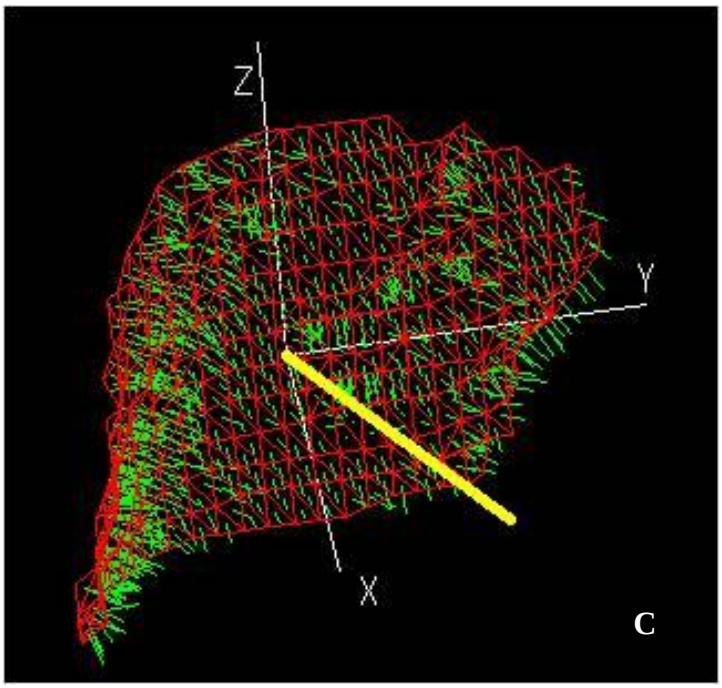
B: 3D point-cloud of the facet joint surface

Figure I-12: Facet joint surface tracing

Subsequently, triangular surface meshes were created from point-cloud data in the custom-written program (MV C++). Polygons between individual points were created by using 2 adjacent points in one plane (j or $j+1$) and 1 point in the adjacent plane ($j+1$ or j) (Figure I-13 A,B). The entire facet joint surface was modeled with the resulting polygon elements. A normal vector was calculated for each mesh element and a mean normal vector of all normal vectors was calculated through the entire surface (Figure I-13 C). The facet joint surface area center was defined from the original point-cloud and the average

normal vector was set to originate at this point. A total of 2912 individual facet joint surface models were created and exported as point-cloud data sets. Calculating normal vectors and area centers required human operator interaction. In order to standardize the procedure every facet joint surface model was processed following the outlined protocol (see Appendix A: Facet joint normal vector calculation protocol). Definitions of facet joint geometry and orientation parameters present a key input for a kinematic model as well as evaluation of the facet joint space width in the further analysis.





A: Meshing procedure: polygons were created by using 2 adjacent points in one plane (j or j+1) and 1 point in the adjacent plane (j +1 or j). The entire facet joint surface was modeled with the resulting polygon elements.

B: Normal vector and area center: of each polygon was defined using vector algebra based on the polygon size and orientation.

C: **Facet joint surface model** oriented in the global CT based coordinate system: polygon mesh (red) of the facet surface with normal vectors of each polygon (green) and average normal vector of the entire surface (yellow)

Figure I-13: Facet joint surface model[25, 26]

3.5. Statistical analysis

Statistical analysis will be carried out using SPSS statistical tool package (IBM, Armonk, New York). Significance level will be set to ALPHA = 0.05 for all statistical tests. Normality will be tested using histograms and descriptive statistics. All results and plots will be presented with mean value ± standard deviation, unless the overall trend is presented (in such a case standard deviations will be listed in tabular form).

Comparison of two independent groups with the same count will utilize a paired *t*-test for non-nominal variables that are statistically normal. Comparison of three or more independent groups with the same count will be carried out using one-way analysis of variance (ANOVA) with a Fischer's post-hoc test to determine differences. Categorical data will be evaluated using a chi-square test of association comparing two or more independent groups with respect to percentages. Relationships between pairs of continuous, scale variables will be investigated with correlation coefficients. If neither of the two variables being correlated has a statistically normal distribution, the nonparametric Spearman correlation will be used. If at least one of the pair of variables has a statistically normal distribution, the Pearson correlation will be obtained.

4. Study Design

The purpose of this study was to investigate the correlation between segmental instability of facet joints, natural degenerative process and low back pain symptom.

The stated problem was decomposed into an evaluation of kinematic parameters of the facet joint; a morphology evaluation of individual parts of the motion segment; and the subsequent correlation of new variables with symptoms of low back pain (Figure I-14). In order to bring a significant contribution and innovation into the field, the study was designed under the following criteria:

1. a three-dimensional approach to kinematic and morphology analysis
2. validation of human factor influence
3. standardization of every procedure
4. clinically relevant quantification of degenerative changes
5. subject-specific models
6. minimized error

High resolution imaging modalities made it possible to obtain an *in-vivo* three-dimensional, subject specific geometrical representation of the lumbar anatomy. The bone signal from the conventional clinical CT scanner represents superior information with very high accuracy and repeatability[27-29]. This study aimed to develop new, advanced methods while minimizing an error. This can be achieved by minimizing the study inputs to variables whose accuracy is well established (CT), and validation is easily manageable (human interaction). There are only two types of inputs in this study: human geometry (from clinical imaging) and qualified decision made by an operator. Human factor might have a significant influence on any type of measurement. To overcome this issue, algorithms developed in this study were of semi-automatic nature and an influence of observer was evaluated using well-established statistical methods.

4.1. Specific Aim I:

Kinematic model

Spinal kinematics has been studied in terms of a "three-joint complex", which consists of an intervertebral disc and two facet joints. Kinematic parameters of the spine are usually established on a coordinate system based on the vertebral body. The rotations and translations of one vertebral body with respect to another vertebral body are expressed in this coordinate system. Recently, attention has been shifted towards the definition of kinematic parameters of individual parts rather than whole complex. Facet joints play an important role in the motion coupling of the spine. Facet surface geometry, position and orientation within the lumbar spine predetermined their kinematic function. An early work by Adams and Hutton defined the functional anatomy of the facet joint, stating that facets are not well suited to resist compressive forces[20], however their three-dimensional orientation predetermines the facet joint to resist high torsion. Later, Fujiwara et al. reported alterations in kinematics due to degeneration to be the greatest in torsion[30]. Trunk torsion is an important epidemiological factor for low back pain[21, 22]. For studying kinematics of the facet joint, it seems that torsion might be a key loading direction especially when degeneration is a concern. The principal goal of this study is to establish a new method able to describe facet joint motion characteristics during torsion based on an anatomically relevant reference frame of the facet joint using a subject-specific, image-based method.

Aim Ia:

To develop a rigid body facet joint kinematics model based on in-vivo dynamic three-dimensional CT image-based models during torsion.

This aim will be accomplished by developing the following algorithms: an algorithm for semi-automatic calculation of the facet joint local coordinate system and an algorithm for calculation of facet joint segmental range of motion projected in local coordinate system of the facet joint.

Position and orientation of the facet joint are essential to define kinematic parameters of the joint articulation. Their definition with respect to vertebral body is a challenging task. In order to minimize an error introduced by human factors a semi-automated method to define a facet-specific coordinate system with position and orientation based purely on input facet geometry will be developed. Segmental motion will be evaluated using standard mathematical formulations previously developed for the study of human joints kinematics.

Hypotheses behind this work are that facet joint kinematic is level dependent. Due to the morphological differences (size) between male and female; facet joint kinematics is gender dependent.

Validation of kinematic model

Kinematic parameters have value only if they are represented in an objective and repeatable manner. Geometry of the facet joint surface and posterior wall are the most sensitive inputs to the model. Previously, our group validated the accuracy of the dynamic CT geometrical method, using ceramic beads and cadaveric vertebrae rigidly fixed to high precision x- tables, with a mean absolute translation error of 0.1 mm and a mean absolute rotation error to be less than 0.2°[21, 22]. However, this validation can serve as assurance of dynamic CT based three-dimensional models (vertebral bodies, posterior walls, intervertebral endplates), further validation is necessary for the facet joint surface geometry.

Aim Ib:

To validate the precision of the CT based facet joint kinematic model.

This aim will be accomplished by evaluating precision of the main input to the model – facet joint surface geometry and the influence of human factor. Validation will be performed by calculating precision under a set of repeatability conditions for measurement (the same measurement procedure, operators, measuring system, and operating conditions over a short period of time).

4.2. Specific Aim II.

Quantitative and qualitative evaluation of spinal degeneration

Degeneration of the spine is a natural process developing throughout lifetime. Morphological changes resulting from degeneration process are believed to lead to spinal instability and subsequently cause low back pain. Every structure in the human spine experiences degeneration to certain extent, however, intervertebral disc and facet degeneration are believed to have the most significant effect on alterations in segmental motion[31]. Clinically, there are several well-established grading methods to assess the extent of degeneration process in intervertebral discs and facet joints. However, those methods are subjective in nature and might be inaccurate as the evaluation is based on two-dimensional "representative" picture of the studied structure. There is an acute need to develop novel, three-dimensional methods able to quantify the progression of the spinal degeneration.

Aim II:

To investigate the relationships between degenerative changes in the intervertebral disc and the facet joint.

This aim will be accomplished by developing a three-dimensional method to objectively quantify the parameters of spinal degeneration in the intervertebral disc (disc height measurement) and in the facet joint (facet joint space width measurement). Additionally, conventional methods for grading degenerative process will be used and validated using parametric statistics.

The intervertebral disc and facet joints are biomechanically important structures that maintain segmental stability in the lumbar spine. Thus, it is reasonable to hypothesis that spinal degenerative changes are significantly correlated with torsional instability and that kinematic parameters are degeneration grade dependent. To address those questions it is necessary to quantify spinal degeneration. There are numerous grading systems available to assess the extent of degenerative changes. Grading systems significantly differ and are subjective in nature. This study aimed to evaluate spinal degeneration

using conventional methods and objectively quantify degenerative process in the intervertebral disc and facet joint.

Hypotheses for this aim include: degeneration in the human lumbar spine is age-dependent. Degeneration in the intervertebral disc and facet joint differs with level.

Although numerous studies in the past showed that disc degeneration may precede facet joint osteoarthritis[3233], recent macroscopic studies on facet joint degeneration using cadaveric specimens demonstrated early initiation of facet degeneration and did not support the correlation between the facet degeneration and intervertebral degeneration[34]. In light of this fact, the correlation between the facet joint degeneration and intervertebral disc degeneration will be also evaluated.

4.3. Specific Aim III.

Instability in the motion segment initiated by progression of the spinal degeneration is believed to cause low back pain[18]. The exact mechanism remains unknown due to lack of clinical data and overall controversy to support this hypothesis. Robust quantification of the "pain" must be developed and factors that influence presence of the low back pain must be identified.

Aim III:

To investigate the effects of spinal degeneration on kinematic parameters of the lumbar facet joint in torsion and their relationship to low back pain.

This Aim will be accomplished by establishing a relationship between facet joint kinematic parameters (range of motion), spinal degeneration parameters, and presence of pain symptoms. Conventional statistical methods will be used. The power of individual covariates will be evaluated.

The *hypothesis* behind this aim is that there are significant differences in segmental motion and parameters of spinal degeneration between non-symptomatic and symptomatic groups of volunteers.

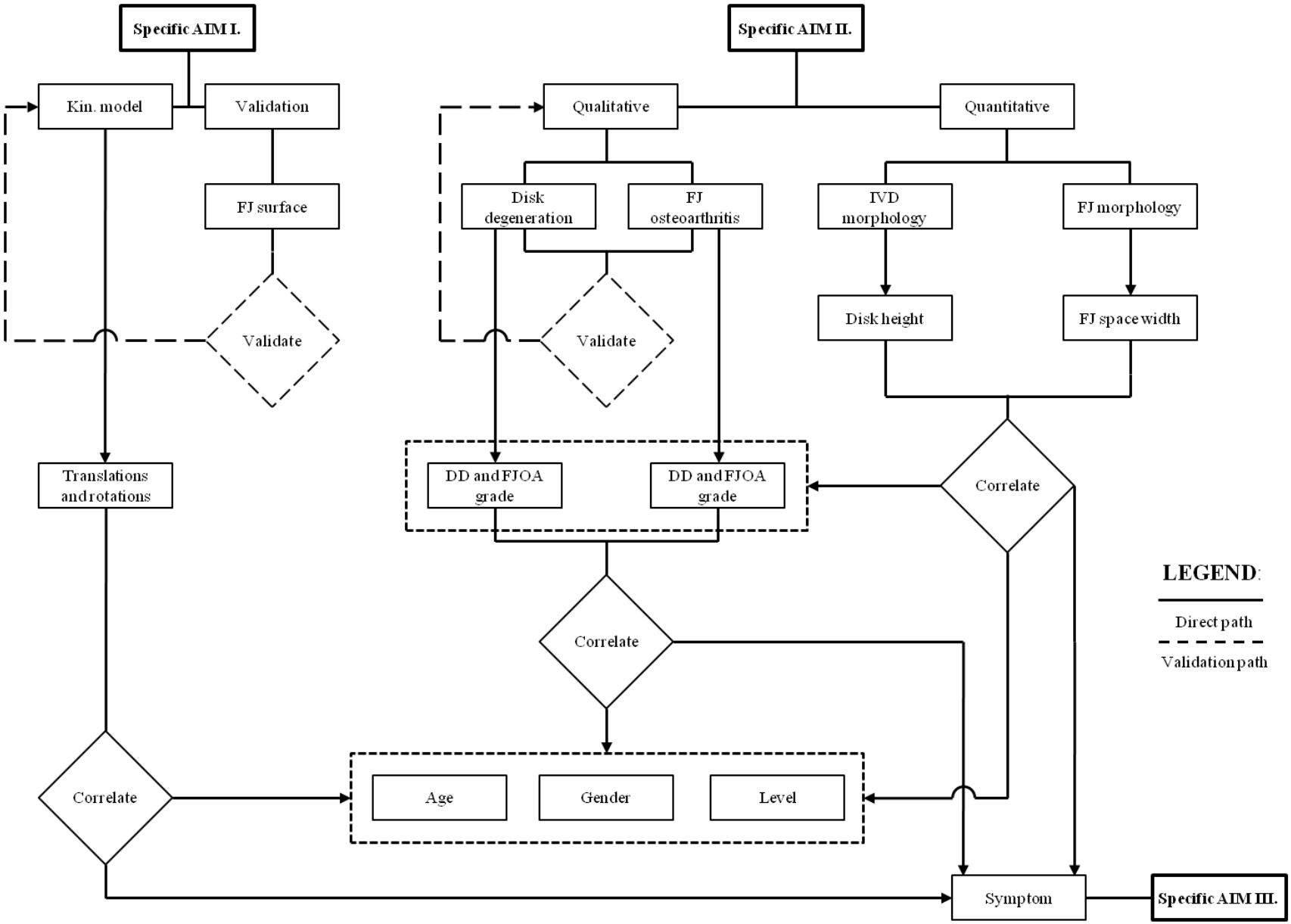


Figure I-14: Study design

II. Facet joint kinematic model

1. Background

Accurate description of the motion experienced by two segments forming a joint is of increasing interest in medicine, biomechanics and bioengineering. A precise understanding of joint motion is essential in orthopedic implant design and can also facilitate treatment of various joint diseases, as well as supply information to improve the joint exercises in professional training and rehabilitation.

Human joints are formed by "linkages" of body segments and their motion is determined by the surface geometry and the structure of the joint[35]. Every human joint permits a total of six degrees of freedom to some extent. Degree of freedom is a fundamental concept in studying biomechanical systems. It expresses the number of parameters that determine the state of a physical system. The experimental studies of joint motion engage measuring a set of motion parameters whose selection is based on certain simplifying assumptions concerning joint geometry. Human joints are commonly modeled as simplified structures allowing three or fewer degrees of freedom (revolute, planar, spherical joint). Those models are able to evaluate an overall motion of the joint in principal directions defined by joint geometry, however are insufficient to study joints with complex geometry and joints whose motion is "general" in nature. In theory, every decrease of joint's degrees of freedom in the model decreases the accuracy of the measured motion[35]. A methodology able to measure motion of two segments forming a joint without removing any degree of the freedom from the model is required and will be further described in this chapter.

Motion parameters for kinematic analysis must be obtained independently with respect to individual parts of the motion couple. The experimental methods in biomechanics involve two distinct designs based on the state of the study subject. Measuring motion in living subjects – *in-vivo* and measuring motion in post-mortem subjects – *in-vitro*. While the first mentioned method allows us to measure physiological motion, the accuracy of such an approach might be limited. The second approach allows us to measure joint motion with high accuracy; however the motion might not correspond to a true

physiological range. Selection of an experimental method is usually a function of the simplifying assumptions which can be made in order to achieve the desired outcome.

In this study, focus was given on evaluating the relationship between low back pain and segmental instability resulting from degenerative changes in the human lumbar spine. As pain is included in the study hypothesis, it is necessary to use *in-vivo* experimental design. Accuracy of the measured kinematic parameters was assured by using an image-based approach. This approach compares relative motions captured by imaging modality in different positions.

A three-dimensional, image-based, subject-specific kinematic model of the *in-vivo* lumbar facet joint was developed. The kinematic model consists of developing the following algorithms: an algorithm for semi-automatic calculation of the facet joint local coordinate system and an algorithm for calculation of facet joint segmental range of motion (ROM) projected in local coordinate system of the facet joint.

1.1. Spinal kinematics

Conventionally, spinal motion is analyzed by comparing the relative motion between two coordinate systems "rigidly" attached to each of the part of the motion segment. Under the assumption of rigidity, structural strength of vertebral bodies is sufficient and any deformation can be neglected. Relative motion is defined by the set of rigid transformations. The rotations and translations of one vertebral body with respect to another vertebral body are expressed in vertebral body coordinate system. Calculating coordinate system transformations is a well established method applicable in two, as well as three-dimensions.

1.2. Current concepts for evaluating *in-vivo* spinal kinematics

1.2.1 Two-dimensional dynamic flexion/extension radiographs

A simple technique using dynamic radiographs has been described in numerous *in-vivo* lumbar kinematic studies. Dupuis et al. suggested the measurement of segmental rotation and translational motion from the flexion-extension radiographs [36]. Although those techniques were once considered a standard in

studying spinal segmental motion, sagittal dynamic radiographs have been found inaccurate for studying segmental motion, with error ranging from 1-4 mm[37][38].

1.2.2 Biplanar stereoradiography

Li et al. used MR imaging in combination with a dual-fluoroscope to estimate kinematic parameters[39]. This approach was closer to the true three-dimensional assessment, however, problems associated with two to three-dimensional registration and virtual transformation caused the method to never be fully accepted.

1.2.3 Invasive techniques

Techniques proposed by Punjabi and Pope [40, 41]involved direct measurement of three-dimensional range of motion using accelerometers directly connected to spinous process via pin represents true kinematic measurement with high accuracy. However, the invasive nature of the measurement limits its use with human subjects.

1.2.4 Dynamic CT/MR based techniques

Advancements in imaging modalities and wide spread accessibility made it possible to obtain *in-vivo*, three-dimensional, displacement controlled image data on the lumbar spine. Various methods have been developed to calculate image-based kinematic parameters of the lumbar spine motion with six degree of freedom. The methods are similar in nature; the input is a three-dimensional representation of the osseous structures and analysis is done by comparing the relative motion between two coordinate systems. There are some conceptual differences between methods, however. Classical methods compare relative motion between two coordinate systems that are virtually "rigidly" connected to the individual vertebras. The method developed by Lim et al. [42] and later by Inoue et al.[21, 22] tracks changes of eigen vectors defined on the individual vertebrae. A vertebral body in the neutral position was virtually rotated and translated towards the vertebrae in rotated position controlling for a volume being merged by both of them.

1.3. Current concepts for evaluating human lumbar facet joint kinematics

None of the above mentioned techniques will be suitable for the study of human lumbar facet joint kinematics due to the limiting factors of the facet joint size and its complex shape.

There is very little data available on the motion patterns of lumbar facet joints. The earliest cadaveric work done by Adams and Hutton defined basic concepts of biomechanical function of the facet joint[20]. The facet joint is a complex structure with level specific geometry. Due to the previously mentioned facts, kinematic modeling requires a precise facet-surface-based coordinate system definition. To the best of author's knowledge, there are only two previous works published in the literature that described image based facet joint kinematics. The first study by Kozanek et al. described a three-dimensional model of the lumbar facet joint *in-vivo* using a combination of MR and a dual-floroscopic imaging systems. However, the small, aged study group, the conventional resolution of the MR, the two-dimensional nature of dual-floroscopic imaging and the two to three-dimensional registration post-processing limited the study outcome[43]. Also, subjects were asked to freely move through their range of motion which adss an additional factor of the variability in voluntary efforts that the subject applies at the time of examination. Another study done by Jegapragasan et al. aimed to characterize the ROM of the facet joint *in-vitro*[44]. The definition of the facet-based coordinate system used in this study does not implement the influence of degeneration of the facet surface. The principal component analysis would not be sufficient for complex alterations of the facet joint surface geometry and would not allow sufficient within and between subject comparisons.

2. Materials and Methods

2.1. Coordinate system definition

In order to solve any kinematic problem associated with the relative motion between two rigid bodies, it is necessary to define two sets of subject specific coordinate systems. One of the bodies can be considered fixed and the other body can be considered to move relative to the first. The musculoskeletal components have no plan of symmetry thus the rectangular coordinate system is the most convenient[35]. With respect to general convention, a right-handed coordinate system was applied in the entire analysis.

In both *in-vivo* and *in-vitro* experiments on the human spine, conventionally a set of non-vectorial values – angles are reported; typically Euler angles with three values or directional cosines with nine non-vectorial values. For either of them, there is a prerequisite: an anatomical coordinate system. The coordinate system generally used for the kinematic modeling of the human spine covers the frontal, sagittal and transverse anatomical planes. Resultant angles can therefore represent principal motions in those planes: axial rotation (transverse), lateral bending (frontal), and flexion/extension (sagittal). Interpretation of such a result might be convenient and clinically relevant, but from an engineering point of view, it possesses an error that might lead to describing the motion in the planes that do not reflect the actual rotary axis of the joints. Also, reproducibility of the results might be reduced by the subjective variations of the axis location. Facet joints, on the other hand, are not oriented with reference to the anatomical planes. In fact, there is a significant variation in facet orientation with the segmental level [45, 46]. Thus, a facet joint surface based local coordinate system has to be implemented into the analysis.

2.1.1 Global coordinate system

A global coordinate system was defined by the CT scanner in the middle plane of the three-dimensional scanning view of the lumbar spine (L1-L5) (Figure II-1). This coordinate system acts as an absolute, fixed three-dimensional frame. Every point in the fixed body can be uniquely defined in terms of the global coordinate system.

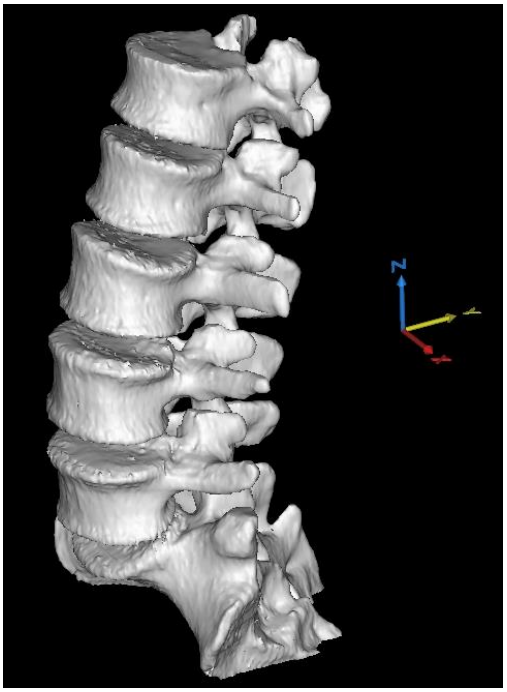


Figure II-1: Global coordinate system

2.1.2 Posterior wall based local coordinate system

A local coordinate system was set on the surface of the vertebral body. The posterior wall of each vertebral body was precisely extracted from the original point-cloud following previously described methodology (see 3.4.2 Posterior wall segmentation). A local coordinate system was established by three orthogonal eigenvectors (Figure II-2). Those were obtained by post-processing posterior wall point-cloud in custom-written software (MV C++) that uses the generalized power method for principal component analysis. A total of 910 sets of posterior wall local coordinate systems were calculated following the standardized protocol (see Appendix A: Posterior wall LCS calculation protocol). The posterior wall based local coordinate system is used to identify the spatial orientation of each vertebra (see Figure II-2) and also to define the local coordinate system of individual facet joints.

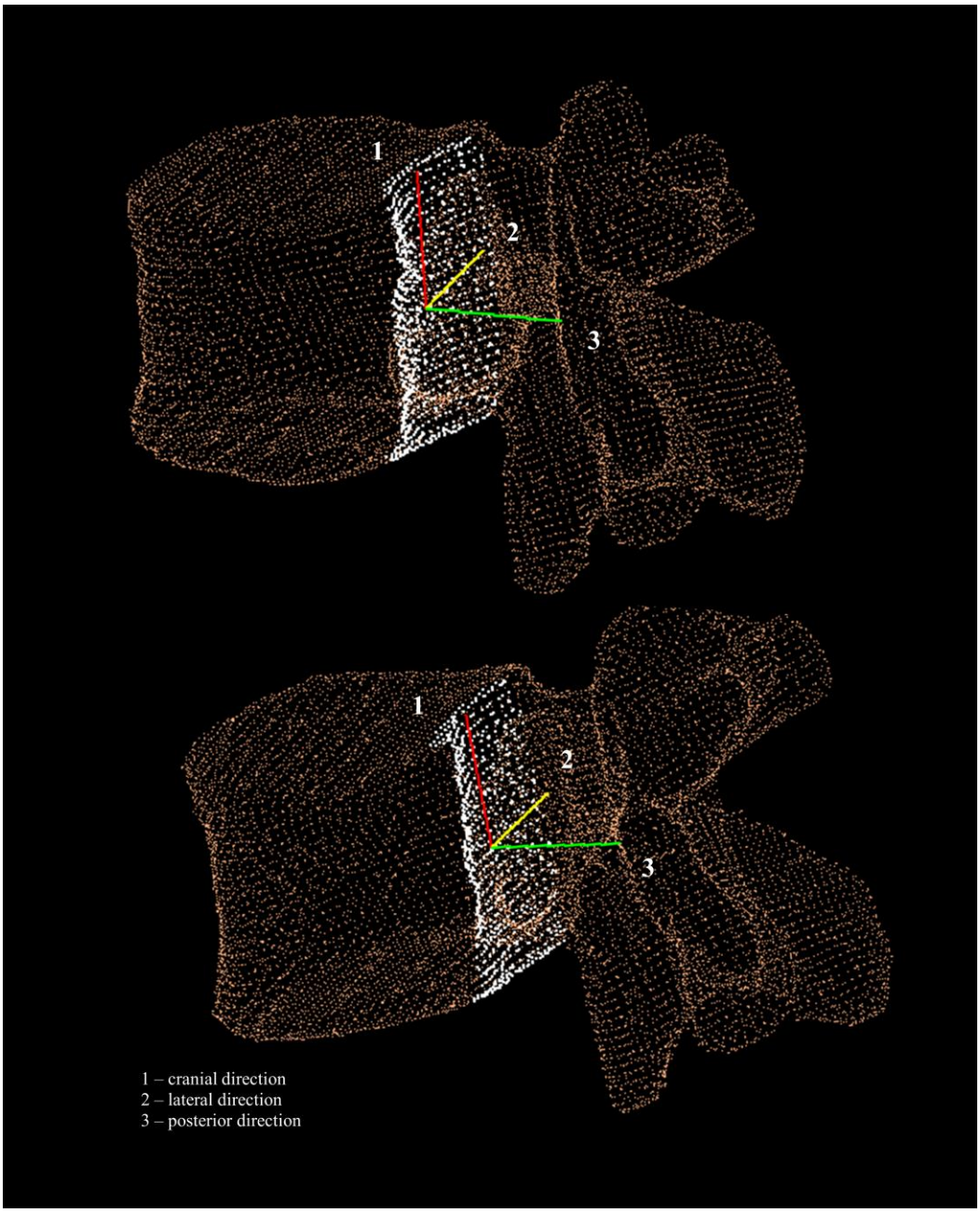


Figure II-2: Posterior wall based local coordinate system

2.1.3 Facet joint surface based local coordinate system

Spatial definition of facet joint position and orientation is essential for an accurate description of facet articulation. A local coordinate system was set in order to establish kinematic parameters of the

facet joint (Figure II-3). A facet specific local coordinate system was established using the average normal surface vector of the facet joint (see 3.4.3 Facet joint surface segmentation) (Figure I-13) and the eigenvector of the posterior wall pointing towards the posterior direction (Figure II-2). The first coordinate was defined as an average normal vector of the entire surface; the second coordinate was determined as a cross product of the average normal vector of the facet joint and the least principle eigenvector of the posterior wall (3 – posterior direction). The third coordinate was determined by the cross product between the first and the second vectors. All three vectors were transformed into vectors with unit length.

A facet joint local coordinate system was established for each facet joint in both positions independently. A total of 2912 individual facet joint local coordinate systems were calculated.

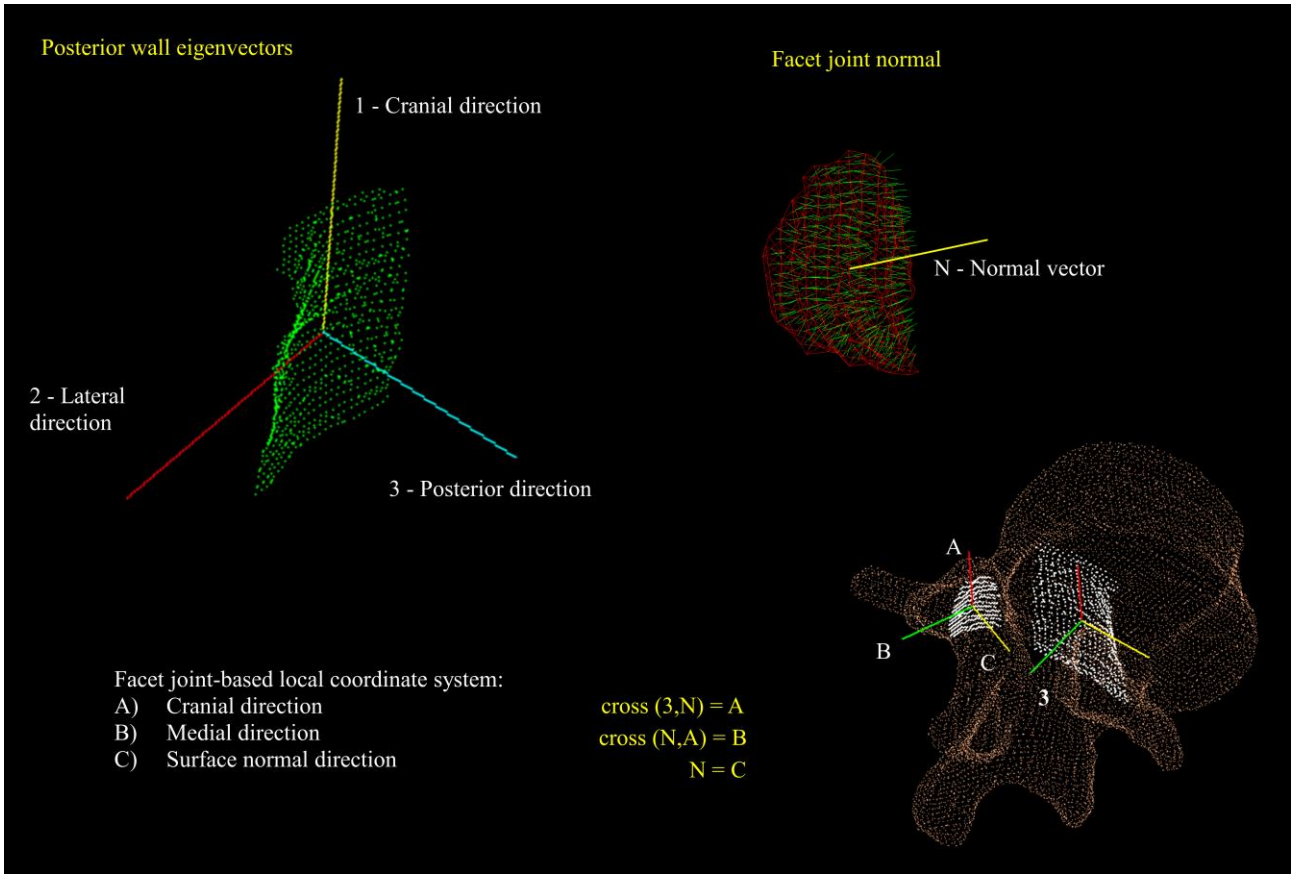


Figure II-3: Facet joint local coordinate system

2.2. Kinematic model

The aim was to develop an objective and repeatable kinematic model in order to allow within and between subject comparisons. Kinematic analysis attempts to define the relative motion between two rigid bodies. This is achieved by defining the solution for two basic problems: 1. to define a unique description of the instantaneous position of one body relative to another body – position analysis; and 2. to define a unique description of the displacement when one body moves from position 1 to position 2 relative to the other body – displacement analysis.

Position analysis is based on the theory from the previous subchapter: the hierarchy of coordinate systems. A rigid body in space has six degrees of freedom, thus a unique position for every point within the rigid body can be described by the coordinates in the global reference system. The orientation of the body with respect to the global reference system can be described by the set of angles (3 for Euler, 9 for directional cosines) which together determine the rotation of the body from the global coordinate reference.

Analogously, displacement analysis can be approached using the same principle of coordinate system hierarchy. A right-handed local coordinate system is "rigidly" attached/defined on the moving body. Displacement of the moving body will be defined relative to this fixed coordinate system. Position of any arbitrary point on the moving body can be described in terms of coordinates in the global reference in every instance.

In case of facet joint kinematics, input to the model is based on "real" geometrical data obtained from CT images in two different positions (neutral, right 50°). Kinematic parameters can be easily calculated by relative changes in positions and orientations of the opposing surfaces. To achieve this goal the theoretical knowledge of coordinate transformation for biomechanics of joints defined by Kinzel[35] was used. Using local coordinate systems defined on each individual facet joint surface in both positions (Figure II-4: Coordinate transformation) it was possible to calculate the transformational matrix and

subsequent Euler angles (ZXY convention). Matlab (MathWorks, Natick, MA) was used to carry out the transformation.

2.2.1 Coordinate transformation

The instantaneous relationship between two coordinate systems is defined by determining a transformation that take the representation of an arbitrary vector in one system and convert it to its representation in the other. In theory, there are three basic non-vectorial principles used in mechanical practice: directional cosines, Euler angles and Euler parameters. The approach used in this study is a combination of first two principles.

In general, when we consider two orthogonal, right-handed coordinate systems $C_o(x_o, y_o, z_o)$ and $C_n(x_n, y_n, z_n)$ (C_o is old coordinate system and C_n is new coordinate system) and arbitrary point P, it is true, that point P can be represented in both coordinate systems as follows:

$$P_o = [x_o \quad y_o \quad z_o \quad 1]^T$$

$$P_n = [x_n \quad y_n \quad z_n \quad 1]^T$$

Transformation of the point is expressed by transformation matrix M_{no} as follows:

$$P_n = M_{no} . P_o$$

Transformation Matrix M_{no} written in generalized form:

$$M_{no} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} R & S \\ 0 & 1 \end{bmatrix}$$

R – rotational sub-matrix

S – translational sub-matrix

Alternatively, represented by the unit vector product:

$$M_{no} = \begin{bmatrix} (i_n . i_o) & (i_n . j_o) & (i_n . k_o) & (\overline{O_n O_o} . i_n) \\ (j_n . i_o) & (j_n . j_o) & (j_n . k_o) & (\overline{O_n O_o} . j_n) \\ (k_n . i_o) & (k_n . j_o) & (k_n . k_o) & (\overline{O_n O_o} . k_n) \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

And, finally represented by directional cosines:

$$M_{no} = \begin{bmatrix} \cos(\widehat{x_n, x_o}) & \cos(\widehat{x_n, y_o}) & \cos(\widehat{x_n, z_o}) & x_n^{(O_o)} \\ \cos(\widehat{y_n, x_o}) & \cos(\widehat{y_n, y_o}) & \cos(\widehat{y_n, z_o}) & y_n^{(O_o)} \\ \cos(\widehat{z_n, x_o}) & \cos(\widehat{z_n, y_o}) & \cos(\widehat{z_n, z_o}) & z_n^{(O_o)} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Here (i_n, j_n, k_n) are the unit vectors of the axes of the new coordinate system. (i_o, j_o, k_o) are the unit vectors of the axes of the old coordinate system. O_n and O_o are the origins of the new and old coordinate systems.

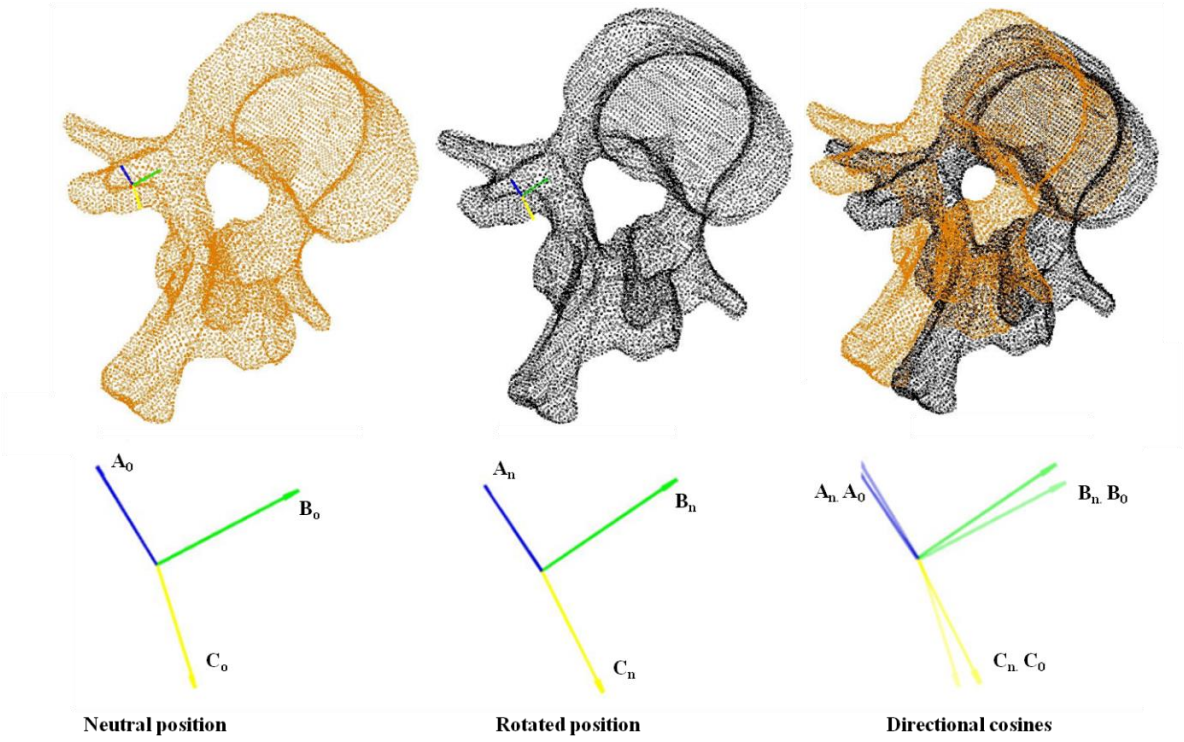


Figure II-4: Coordinate transformation

If local coordinate system defined on the facet joint in neutral position is considered to be C_o and the local coordinate system defined on the facet joint in the rotated position to be C_n (Figure II-4), then coordinate transformation of the facet joint based coordinate system is defined by the set of equations above. Knowing the unit vectors of the coordinate systems, we can obtain directional cosines by product operation of two unit vectors as described in M_{no}. Translations defined in the fourth column of the matrix M_{no} are obtained from the position data of the area center of the facet join (see 3.4.3 Facet joint surface segmentation).

Nine angles of directional cosines define the relationship between the two systems. However, it is important to outline that only three of these angles are independent. That leads us to assume that each of the components of the rotation part of the transformation matrix (R) can be expressed in terms of some set of three independent variables namely Euler angles.

2.2.2 Euler angles

Euler angles are the most commonly utilized rotational coordinates in biomechanics used to describe the orientation of a rigid body. A theorem developed by Leonhard Euler hold that any arbitrarily oriented reference frame may be placed in alignment with any other reference frame by three successive rotations about the axes of the reference frame.

There are several conventions for the order of the Euler angles, depending on the axes about which the rotations are carried out first. The convention for selecting angle order used within our group for all spinal application is ZXY. The first and principal rotation is about the body z-axis, followed by the rotation about the body x axis [0;π] and finally, the third rotation about the body y-axis.

Resultant Euler angles derived from this convention are as follows:

$$R = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} = \begin{bmatrix} \cos(\widehat{x_n, x_o}) & \cos(\widehat{x_n, y_o}) & \cos(\widehat{x_n, z_o}) \\ \cos(\widehat{y_n, x_o}) & \cos(\widehat{y_n, y_o}) & \cos(\widehat{y_n, z_o}) \\ \cos(\widehat{z_n, x_o}) & \cos(\widehat{z_n, y_o}) & \cos(\widehat{z_n, z_o}) \end{bmatrix}$$

$$R = \begin{bmatrix} \cos y \,.\, cos\ z - sin\ x \,.\sin y \,.\sin z & -\cos x \,.\sin z & \cos z \,.\sin y + \cos y \,.\sin x \,.\sin z \\ \cos z \,.\sin x \,.\sin y + \cos y \,.\sin z & \cos x \,.\cos z & -\cos y \,.\cos z \,.\sin x + \sin y \,.\sin z \\ -\cos x \,.\sin y & \sin x & \cos x \,.\cos y \end{bmatrix}$$

The directional cosines matrix, based on the product of two coordinate systems, is equal to linear combination in ZXY convention. The resultant Euler angles are:

$$\theta_x = \text{asin}(a_{32})$$

$$\theta_y = \text{atan}\,2(-a_{31}, a_{33})$$

$$\theta_z = \text{atan}2\,(-a_{12}, a_{22})$$

Resultant Euler angles can be interpreted as rotations along the axis of the facet joint surface. Angle θx represents an angle along the lateral axis of the facet joint surface and rotation can be approximated as lateral bending motion. Angle θy represents rotation along the surface normal and the motion it represents can be approximated as flexion/extension. And, θz represents rotation along cranial axis of the facet joint and can be approximated as axial rotation.

2.2.3 Segmental range of motion

Resultant rotations and translations are calculated in terms relative to the subjacent vertebra for facet joint at L1L2, L2L3, L3L4, and L4L5 levels.

2.3. Statistical evaluation

Mean values and standard deviations were reported for every analysis. Histogram was plotted for every dependent variable to assure normal distribution.

Rotational and translational ROM on the right and left facet joint were compared using unpaired t-test. It was assumed that both sides are normally distributed and thus carry the same variation.

Significant differences of rotations and translations were analyzed using a one-way ANOVA and post-hoc Fisher test to determine differences based on spinal level, age, gender and direction of motion.

Level was considered a baseline independent variable, as it has been proven that due to the facet joint surface geometry, position and orientation the level dependency exists[45, 46].

3. Results

The entire study group (n = 91) was analyzed for rotation and translation. Rotations and translations were evaluated with reference to the axis along which they occurred. Rotational and translational ROM were compared around/along cranial-caudal, lateral and normal axis of the facet joint, resulting with rotations in axial rotation, lateral bending, and flexion/extension; and translations in cranial/caudal, anterior-posterior, and medial/lateral direction.

3.1. Facet joint rotational ROM

The magnitude of absolute rotation was evaluated for normality per each loading direction. Histogram proved normal distribution within each loading direction (Figure II-5, Figure II-6, and 7). Descriptive statistics supporting the evidence of normal distribution for lateral bend was 4.28 ±5.34 degrees; flexion/extension was 0.41±5.43 degrees; and axial rotation was 13.12±4.61degrees.

The unpaired t-test showed no overall significant difference between the right and left side for lateral bend ($p = 0.811$) and axial rotation ($p = 0.305$). Flexion/extension showed significant difference with $p = 0.033$, however the mean values of rotation were -0.004±5.49 for right side and 0.599±5.21for left side respectively. Results showed that flexion/extension motion was the least principal and varied the most. The normal axis orientation of the facet specific coordinate system, especially in degenerated cases might have an influence on the side differences. Projection of the overall magnitude of rotation in the normal direction tends to be variable from case to case and to be minimal (below 1 degree), which may indicate that such a small value is too close to random error of the method. As there was no “reasonable” statistical difference between right and left facet joint side, all following analyses of rotation do not use side as grouping factor.

3.2. Absolute rotational ROM

At first, rotations were evaluated in their absolute values (Figure II-8). Torsion of the trunk was achieved by coupled rotations around the cranial-caudal axis of the facet joint and lateral axis of the facet joint. Rotation along axis of the facet normal was negligible. The primary absolute rotation was in axial rotation, followed by coupled rotation in lateral direction. Results showed significant differences ($p<0.0001$) between all three studied directions and at all five levels (L1-L5). Analysis of differences within the loading direction showed significant difference ($p<0.0001$) between all spinal levels for lateral bending and axial rotation. There was no significant difference between levels for flexion/extension. Both lateral bending and axial rotation have a decreasing tendency as spinal level decreases. During torsion, coupled lateral bending experienced the paradoxical motion in the lower level at L4L5.

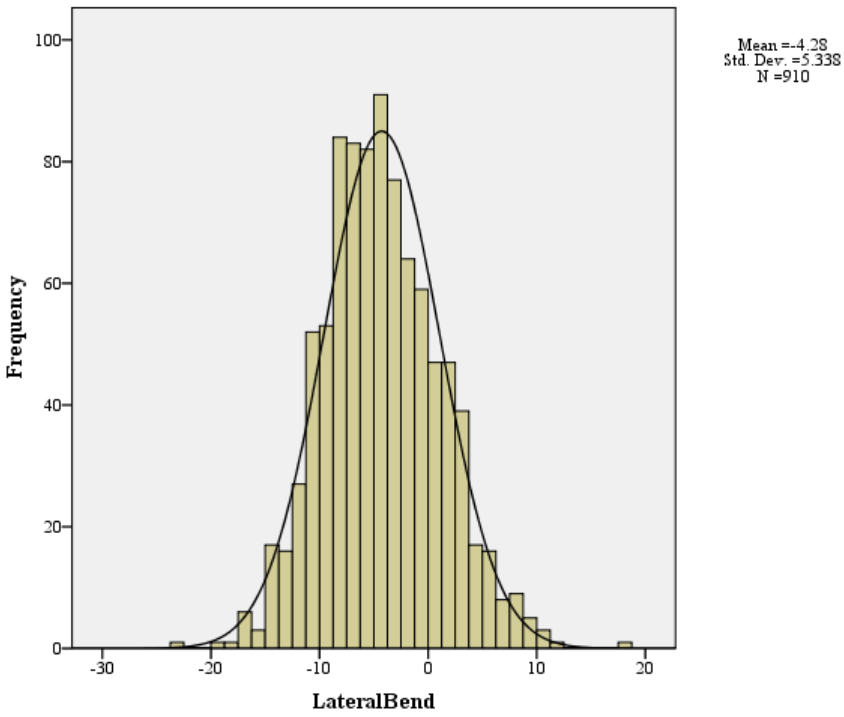


Figure II-5: Histogram Lateral Bending - rotation

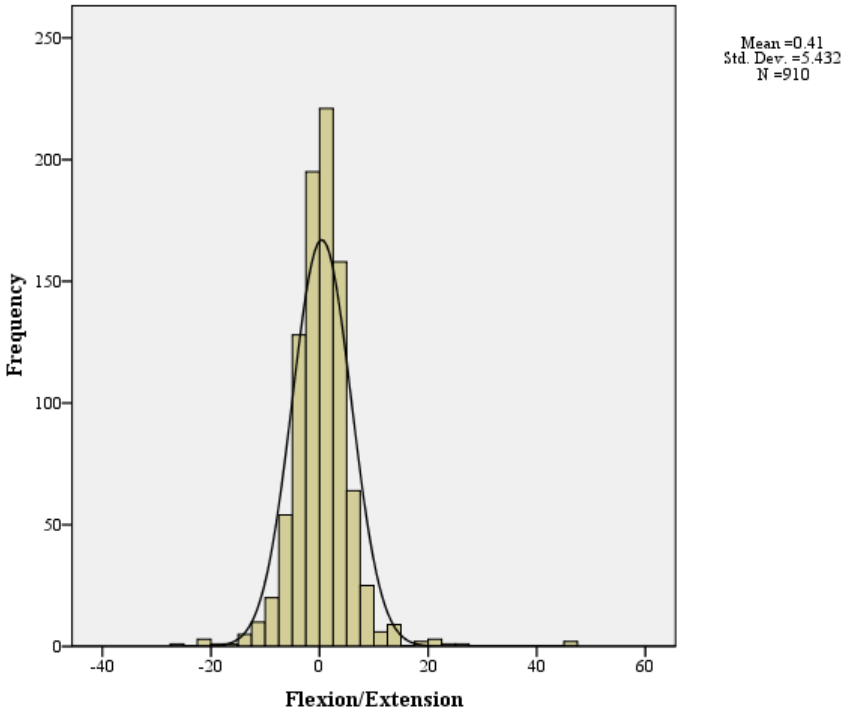


Figure II-6:Histogram Flexion/Extension – rotation

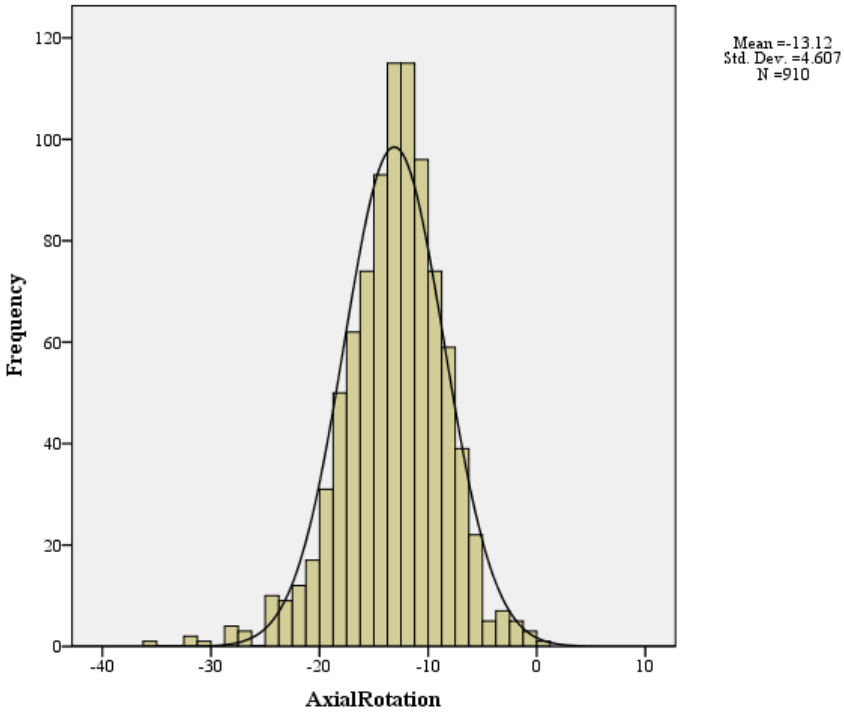


Figure II-7: Histogram Axial Rotation - rotation

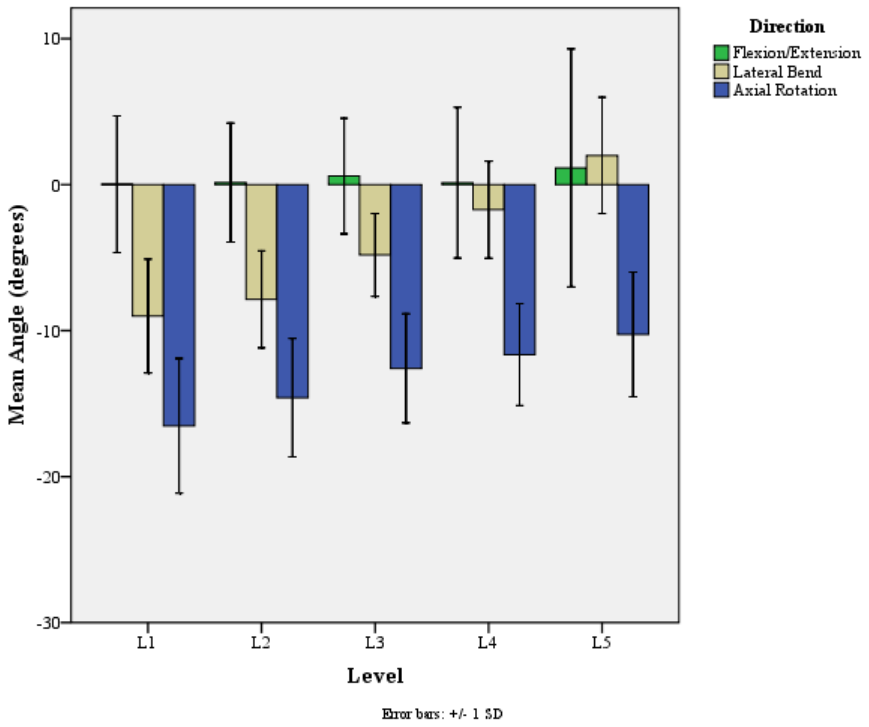


Figure II-8: Absolute rotational ROM

3.3. Segmental rotational ROM

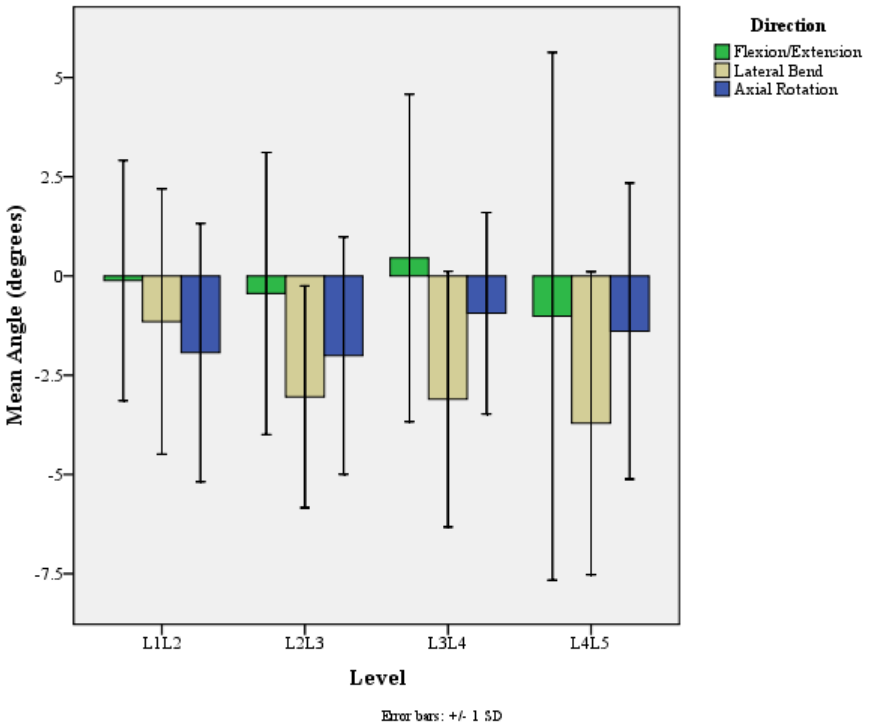


Figure II-9: Segmental rotational ROM

Analysis of the spinal level influence revealed a level dependency for lateral bending and axial rotation. Average values and standard deviations are listed in the table below.

Table II-1: Segmental rational ROM – level effect

Level	Direction	N	Mean	SD
L1L2	Axial Rotation	182	-1.93	3.254
	Flexion/Extension	182	-.11	3.027
	Lateral Bend	182	-1.15	3.342
	Total	546	-1.06	3.290
L2L3	Axial Rotation	182	-2.01	2.990
	Flexion/Extension	182	-.44	3.554
	Lateral Bend	182	-3.04	2.793
	Total	546	-1.83	3.302
L3L4	Axial Rotation	182	-.94	2.539
	Flexion/Extension	182	.45	4.127
	Lateral Bend	182	-3.10	3.222
	Total	546	-1.20	3.659
L4L5	Axial Rotation	182	-1.39	3.729
	Flexion/Extension	182	-1.01	6.648
	Lateral Bend	182	-3.71	3.817
	Total	546	-2.04	5.055

Segmental rotations in axial and lateral direction were coupled (Figure II-9). In general, upper lumbar motion segments (L1L2, L2L3) showed greater axial rotation compared with the lower levels (L3L4, L4L5), while lower lumbar segments exhibited larger lateral bending. In axial rotation, differences in levels were significant between L1L2, L2L3, and L3L4 ($p=0.001$). There were also significant differences between segmental rotational ROM at L1L2 and all remaining levels at lateral bending ($p<0.0001$).

3.3.1 Effect of AGE on facet joint rotational range of motion

Average values and standard deviations of the rotational ROM with reference to age are listed in the table below:

Table II-2: Segmental rational ROM – age effect

Age	Direction	N	Mean	SD
20	Axial Rotation	192	-1.83	2.729
	Flexion/Extension	192	.03	5.066
	Lateral Bend	192	-2.68	3.142
	Total	576	-1.49	3.944
30	Axial Rotation	280	-1.56	2.989
	Flexion/Extension	280	.07	4.137
	Lateral Bend	280	-2.67	3.671
	Total	840	-1.39	3.796
40	Axial Rotation	160	-1.08	3.248
	Flexion/Extension	160	-1.13	4.599
	Lateral Bend	160	-2.69	2.968
	Total	480	-1.64	3.743
50	Axial Rotation	96	-1.85	4.235
	Flexion/Extension	96	-.48	4.612
	Lateral Bend	96	-3.23	4.040
	Total	288	-1.85	4.432

(a) Flexion/extension rotational ROM – age effect

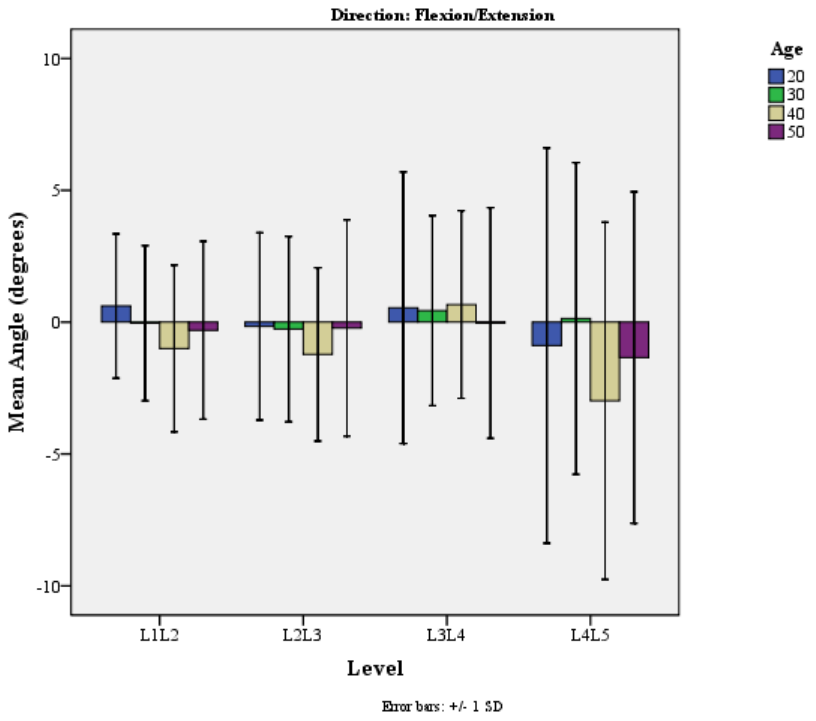


Figure II-10: Flexion/extension rotational ROM – age effect

Age was not a significant variable to explain the variability of the segmental ROM in flexion/extension. Neither was the combined effect of age and level significant.

(b) Lateral bending rotational ROM – age effect

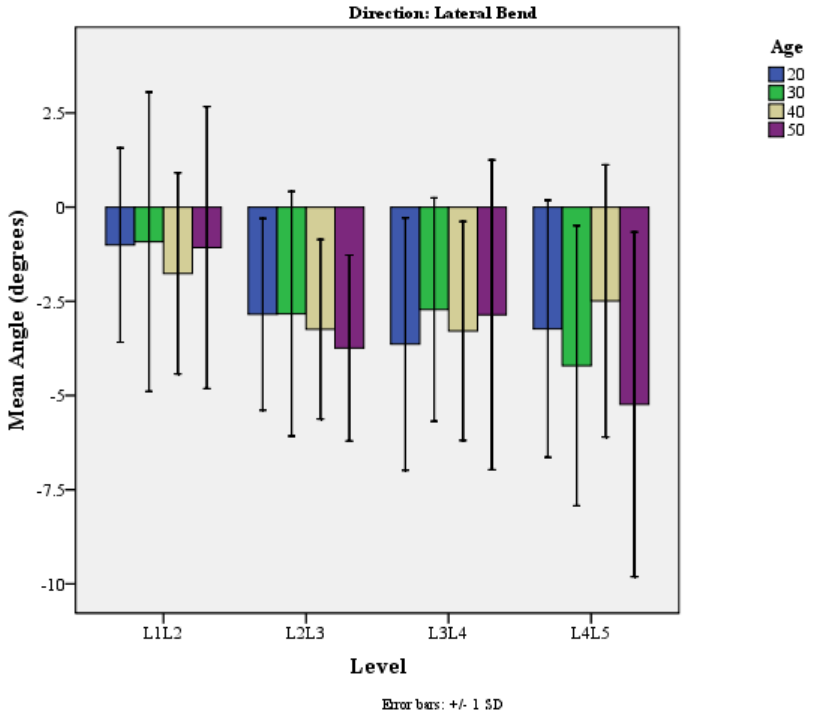


Figure II-11: Lateral bending rotational ROM - age effect

In lateral bending, the general tendency of rotational ROM to increase with age can be seen (Figure II-11). However none of the age groups were significantly different from the other. Combined effect of age and level revealed significance only at L4L5 between 40s and 50s (p=0.05).

(c) Axial rotation rotational ROM – age effect

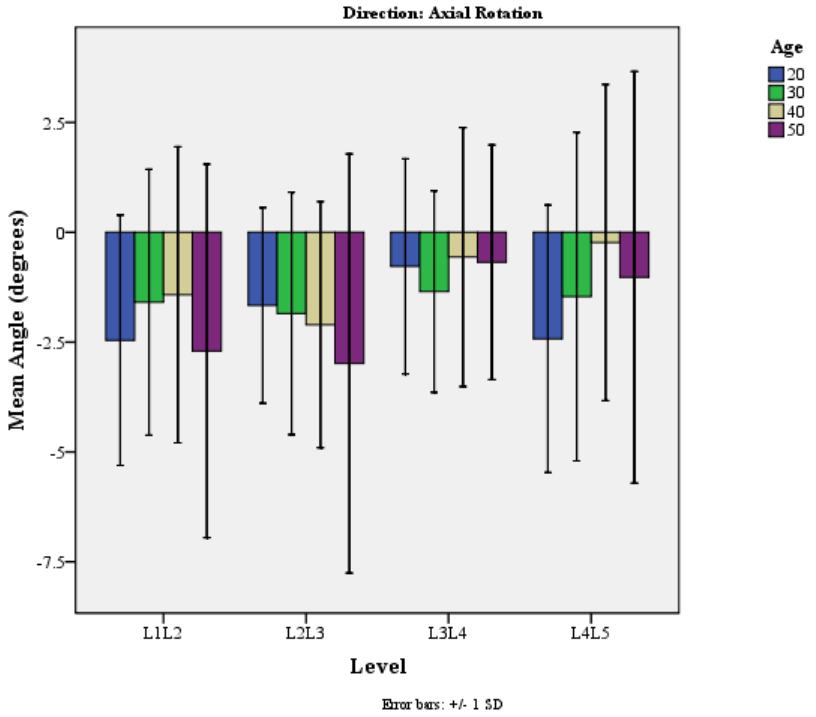


Figure II-12: Axial rotation rotational ROM – age effect

In axial rotation, the tendency of increasing rotational ROM with age can be seen at upper spinal level, with reverse tendency in the lower spinal level (Figure II-12). Significant differences have been observed between 20s and 40s ($p=0.028$). Combining the effect of age and level revealed significant differences only at L4L5 between 20s and 50s ($p=0.05$) and at L4L5 between 20s and 40s ($p=0.013$).

3.3.1 Effect of GENDER on facet joint rotational range of motion

Average values and standard deviations of the rotational ROM with respect to gender are listed in the table below:

Table II-3: Segmental rotational ROM - gender effect

Gender	Direction	N	Mean	SD
Female	Axial Rotation	328	-1.58	3.436
	Flexion/Extension	328	-.68	4.850
	Lateral Bend	328	-3.13	3.647
	Total	984	-1.80	4.147
Male	Axial Rotation	400	-1.55	2.959
	Flexion/Extension	400	.05	4.319
	Lateral Bend	400	-2.44	3.239
	Total	1200	-1.31	3.698

(a) Flexion/extension rotational ROM – gender effect

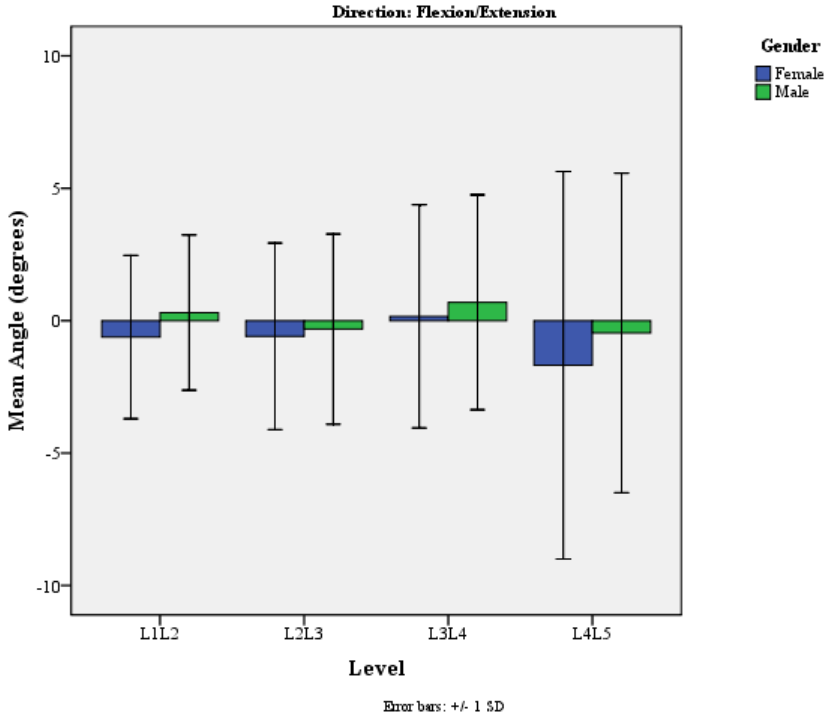


Figure II-13: Flexion/Extension rotational ROM - gender effect

Flexion/extension rotational ROM did not reveal any gender related differences.

(b) Lateral bending rotational ROM – gender effect

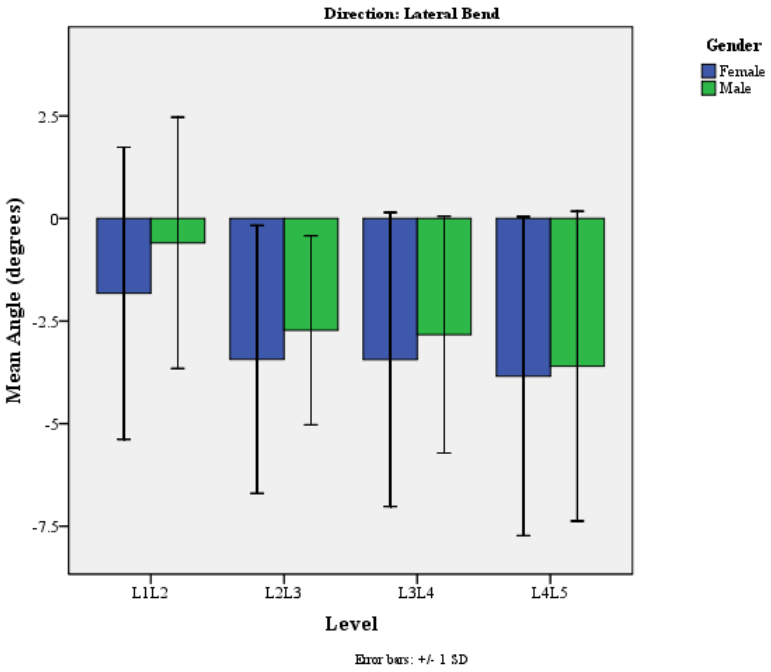


Figure II-14: Lateral bending rotational ROM - gender effect

(c) Axial rotation rotational ROM – gender effect

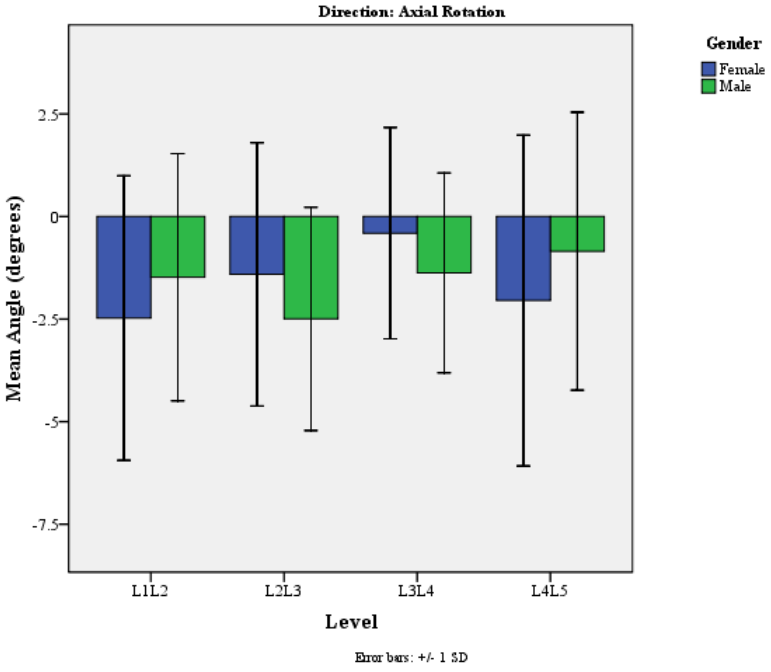


Figure II-15: Axial rotation rotational ROM - gender effect

Presence of the gender as independent variable in the model showed significant difference in both lateral bending ($p=0.0303$) and axial rotation ($p=0.0066$). The combined effect of gender and level showed significant differences between male and female at every level in case of axial rotation (Figure II-14). In case of lateral bending, the difference was significant only at L1L2 (Figure II-15).

3.4. Facet joint translational ROM

The magnitudes of segmental translations were evaluated for normality per each loading direction. Histograms proved normal distribution within each loading direction (Figure II-16, 17, and 18). Descriptive statistics supporting the evidence of normal distribution were for medial/lateral translation 0.59 ±0.72 mm; anterior/posterior translation 0.22±0.83 mm; and cranial/caudal translation 0.32±0.59 mm.

The unpaired t-test showed a strong significant difference between the right and left side for all studied directions ($p <0.0001$).

3.5. Segmental translational ROM

Translations in all three loading directions were evaluated for each side independently with respect to the spinal level. Average values and standard deviations of the translational ROM with reference to level, loading direction, and side are listed in the Table II-4.

The influence of level on translational ROM was evaluated individually for each side in the statistical model with level as the independent variable. The effect of age and gender in combination with level was also evaluated.

The effect of level on translational ROM showed significant differences between levels (Figure II-19, and 20). On the left side at anterior/posterior translation, differences were observed between L1L2, L2L3 and L4L5 ($p=0.01$ and $p=0.1$). A difference was also observed on the right side at the cranial/caudal direction between L1L2 and L4L5 ($p<0.0001$) and L2L3 and L4L5 ($p=0.012$).

Table II-4: Segmental translational ROM – level effect

		Left side			Right side		
Level	Direction	Mean	N	SD	Mean	N	Std. Deviation
L1L2	Anterior/Posterior	.174	91	.6518	.174	91	.6518
	Cranial/Caudal	.302	91	.5779	.302	91	.5779
	Medial/Lateral	.757	91	.4145	.757	91	.4145
	Total	.411	273	.6090	.411	273	.6090
L2L3	Anterior/Posterior	.082	91	.7116	.082	91	.7116
	Cranial/Caudal	.249	91	.5922	.249	91	.5922
	Medial/Lateral	.731	91	.5044	.731	91	.5044
	Total	.354	273	.6660	.354	273	.6660
L3L4	Anterior/Posterior	-.007	91	.7322	-.007	91	.7322
	Cranial/Caudal	.159	91	.4740	.159	91	.4740
	Medial/Lateral	.668	91	.4484	.668	91	.4484
	Total	.274	273	.6332	.274	273	.6332
L4L5	Anterior/Posterior	-.186	91	.7055	-.186	91	.7055
	Cranial/Caudal	.222	91	.5446	.222	91	.5446
	Medial/Lateral	.616	91	.5967	.616	91	.5967
	Total	.218	273	.6988	.218	273	.6988

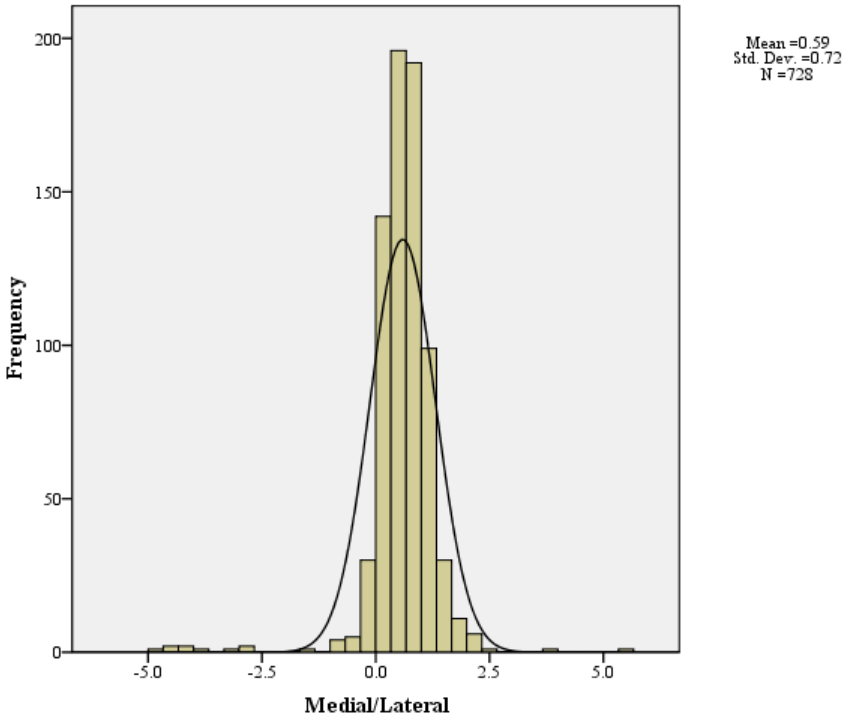


Figure II-16: Histogram medial/lateral translation

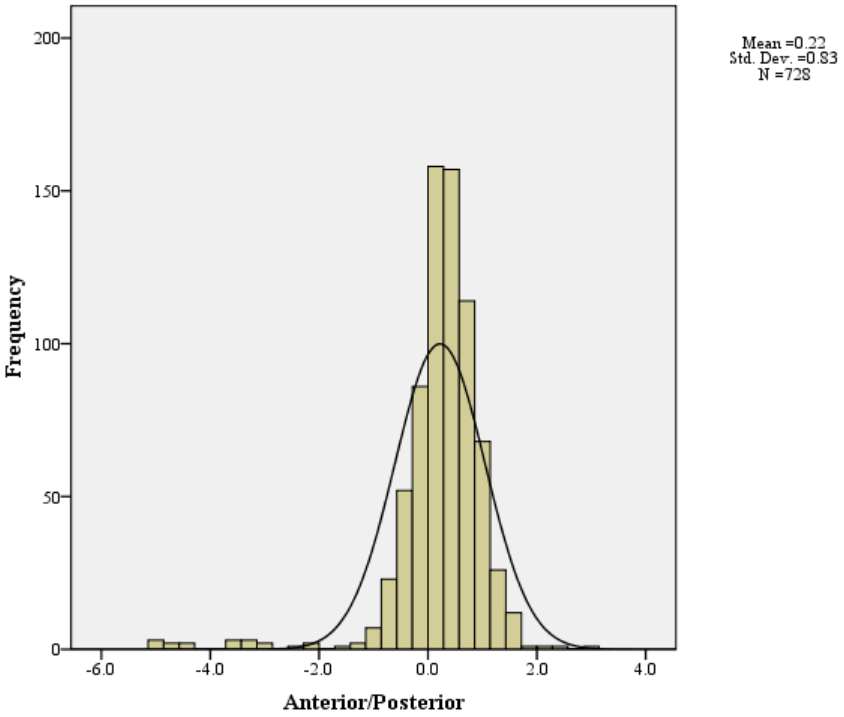


Figure II-17: Histogram anterior/posterior translation

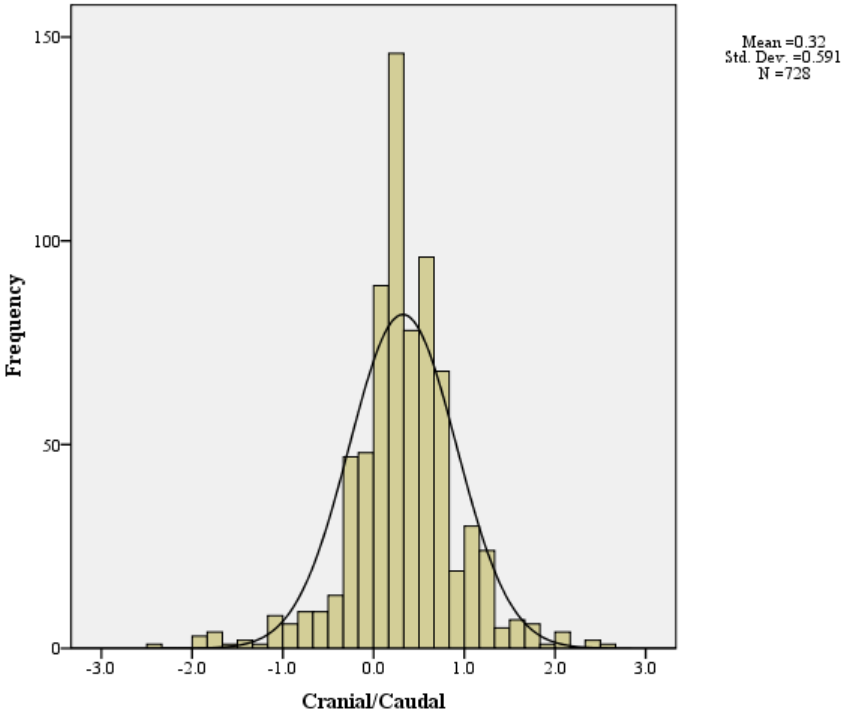


Figure II-18: Histogram cranial/caudal translation

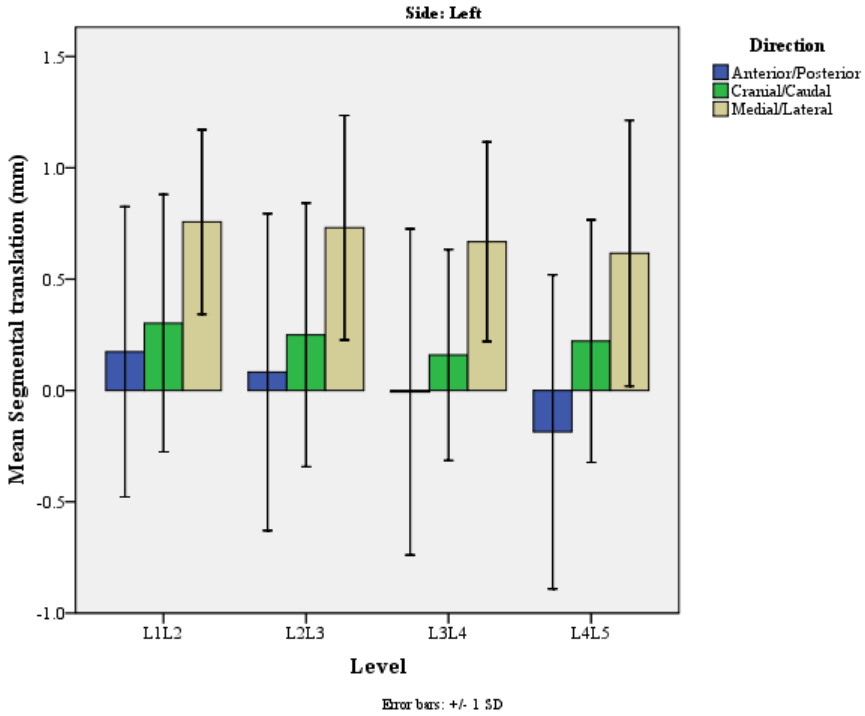


Figure II-19: Segmental translational ROM - left side

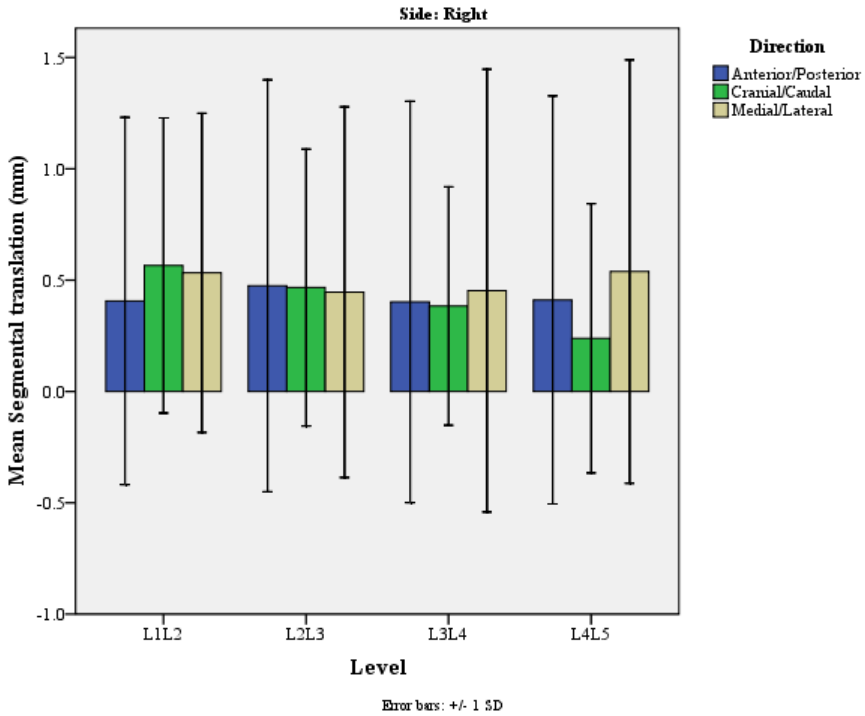


Figure II-20: Segmental translational ROM - right side

Left side showed gradual decrease in translation for all three directions as level decreased.

3.5.1 Effect of AGE on facet joint translation range of motion

There were significant differences between the age groups at various levels throughout all three loading directions (Figure II-21). Changes were more significant at the right side and at cranial/caudal loading direction at both sides. Results indicate the gradual decrease of translational ROM in cranial/caudal direction at the right side as age progress.

3.5.2 Effect of GENDER on facet joint translational range of motion

There were no significant differences with gender on the left side (Figure II-22). The right side showed differences between genders at anterior/posterior translation ($p=0.0056$) and cranial/caudal translation ($p=0.0033$).

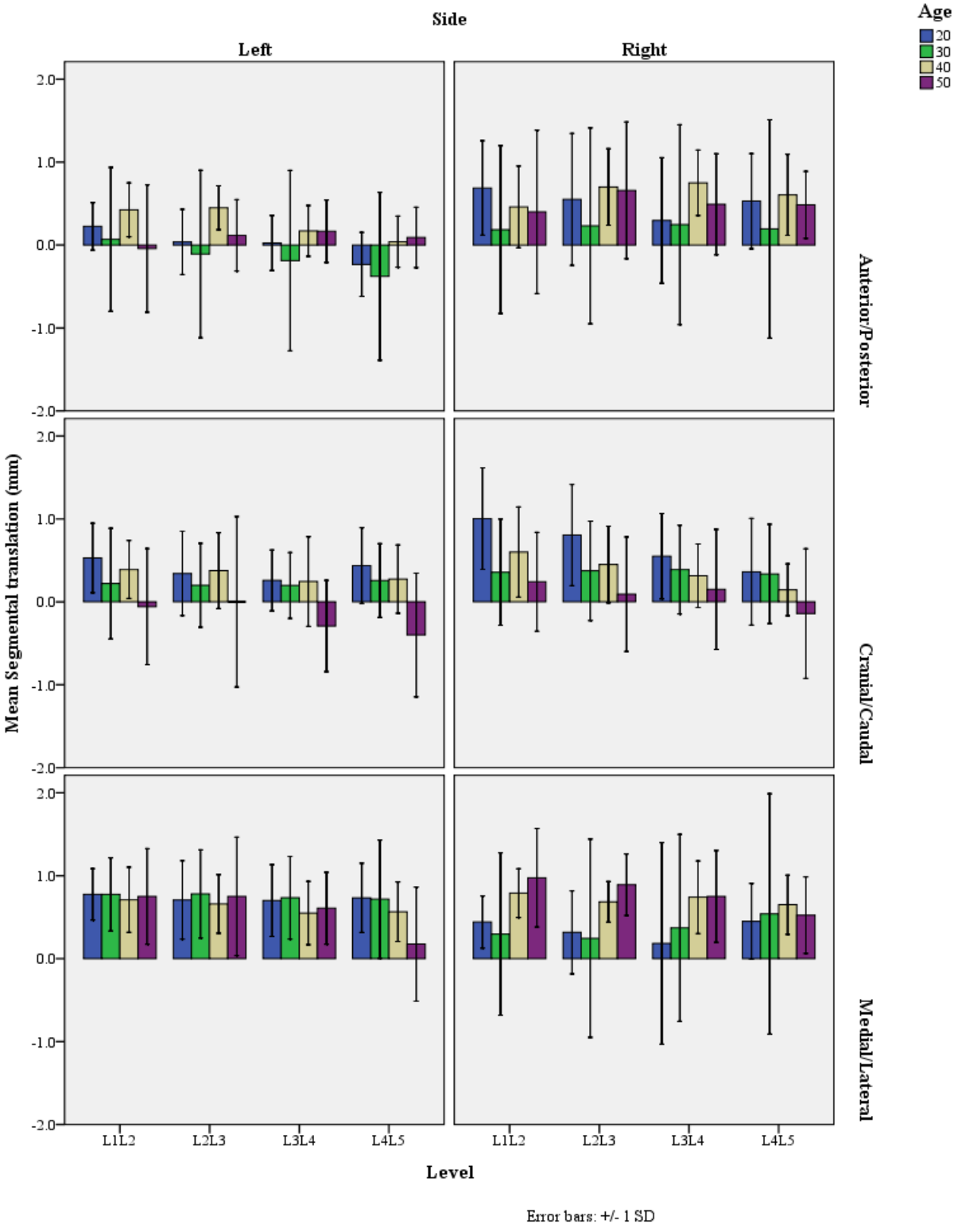


Figure II-21: Segmental translational ROM - age effect

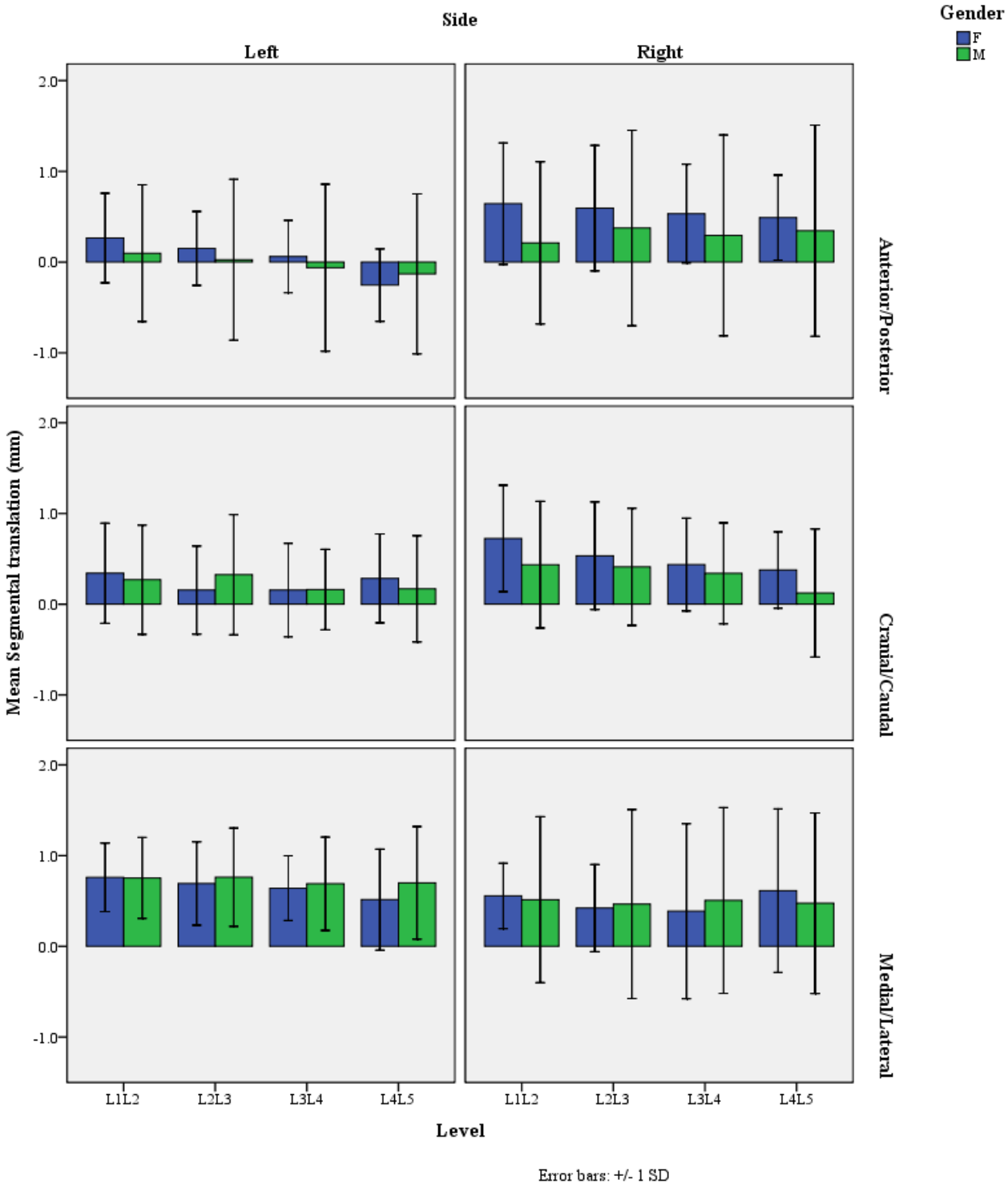


Figure II-22: Segmental translational ROM - gender and side

4. Conclusion and Discussion

In this work, a novel noninvasive *in-vivo* method was introduced to measure lumbar facet joint segmental rotations and translations in six DOF. This method is a combination of an anatomically relevant local coordinate system definition and their spatial transformations. Definition of the coordinate system is an essential step and in case of the facet joint, due to facet complex geometry and small size, a very challenging task. The principal goal of this study was to establish a new method able to describe facet joint motion characteristics during torsion based on an anatomically relevant reference frame of the facet joint using a subject-specific, image-based method.

In order to define spatial position and orientation of individual facet joints with respect to the body, a method describing three-dimensional alignment of the lumbar spine has been developed. Using geometry of the posterior wall of individual vertebral bodies it was possible to determine a spatial relationship between vertebral body and the facet joint at every level. The method utilizing Eigen vector algebra made it feasible to identify the principal orientation of each vertebra. This information was a baseline in determining a local coordinate system of the individual facet joint surfaces. The difference in orientation of the lumbar facet joint is a well-studied phenomenon[45, 46]. To address the variability of facet orientation, each facet coordinate system was aligned with respect to its natural orientation.

Segmental motion was evaluated using standard mathematical formulations previously developed for the study of human joints kinematics. Innovation was achieved by expressing calculated segmental motions in anatomically relevant facet based coordinate system. Interpretation of such results is more intuitive as motions are described in terms of facet joint surface specific axes.

A review of literature reveals that very little data has been reported on facet joint kinematics. Cadaveric study by Adams and Hutton[20] defined basic mechanical function of the facet joint but did not quantify their motion. Kozanek et. al[43] used a dual-floroscope and MR-based approach to measure *in-vivo* kinematics of the facet joint in various weight-bearing positions. The methodology reported in this study

used local coordinate system transformation approach, similar to the one utilized in this study. The resultant kinematic parameters were expressed in the facet-based coordinate system. Jegapragasan et. al[44] used seven cadaveric spines to evaluate facet-based kinematic parameters. The definition of the facet-based coordinate system used in his study does not implement the influence of degeneration of the facet surface. Morphological changes due to degeneration in the facet joint might significantly alter the shape of the facet joint surface, which is the only input to the local coordinate system definition. The principal component analysis would not be sufficient for complex alterations of the facet joint surface geometry and would not allow sufficient within and between subject comparisons.

Results of this study showed the absence of significant difference between sides indicating that the methodology developed in this study was correct. Deviations in flexion/extension motion can be explained by the small magnitude of the motion in this direction. Orientation of the flexion/extension axis is fully dependent on the facet joint surface. Resultant rotational ROMs measured in this axis were of small magnitudes and thus might be close to the random error resulting from surface segmentation and CT accuracy. An evaluation of repeatability will be carried out in the next chapter.

Overall, the results of this study indicate that facets undergo coupled motion during torsion. Absolute rotations along axial and lateral axis showed significant differences between them ($p<0.0001$) at every studied level. The largest absolute axial and lateral rotation was measured at L1 and decreased with level. Level has been identified as a major covariate in explaining variation of the rotational ROM. Segmental rotations showed significant differences between upper and lower levels in axial rotation. This finding is in contrast with Kozanek's results[43]. There are several reasons that may explain the variation. First, Kozanek used a facet-specific coordinate system with an axis predefined by anatomical planes. The kinematic model described in this study defines the cranial axis with reference to the spatial position of the vertebral body rather than the anatomical plane, thus cranial axis is corrected for natural spinal lordosis at every level. Second, the study group evaluated in this chapter consists of both symptomatic and non-symptomatic subjects. In Kozanek's study, only non-symptomatic subjects were evaluated. The

presence of symptoms may explain variations between the results. Third, Kozanek scanned subjects in the vertical position with the pelvis of the subjects not fixed during imaging. As there was no constraint to prevent hip and sacroiliac joint rotation to occur, rotational compensation between the joints might have taken place. On the other hand, segmental rotation in lateral bending was the greatest at L4L5 (-3.71±3t8 degree) and decreased in upper levels (L1L2: -1.15±3.3 degree).

The effect of age on the rotational ROM in lateral bending showed an increasing trend, however significant difference was not found between the age groups. For axial rotation age has been identified as a significant variable ($p=0.028$). Particular changes were observed at L4L5 between the second decade and the fourth and fifth decade. Influence of age will be reevaluated with respect to degenerative changes in the fourth chapter. Age may be an important factor; however it was not significant in this analysis. Perhaps multiple regressions with other factors, such as measures of degenerative changes will show more significance on segmental ROM.

Significant difference of gender was observed in both principal directions. It has been hypothesized that the effect of spinal degeneration on the segmental motion characteristics may be different in male and female spines because degenerative processes, particularly the osteoarthritic changes in facet joints, can be different between genders[30]. Also, morphological gender differences in the human lumbar spine might play an important role in explaining the difference in segmental ROM. A study done by Nachemson and Schults[47] indicates that biomechanical and kinematic studies on the human lumbar spine should be interpreted with gender considerations.

Segmental translations were evaluated independently for each side. Three distinct translations were reported, each corresponding to translation along one of the facet joint coordinate axis. Jegapragasan et al[44]. showed in his study that difference in magnitudes exists between vertebral body-based coordinate system translations and facet joint-based coordinate system translations. Thus, facet translations cannot be

derived from the vertebral body translations. Defining the amount of facet joint translation is a clinically very important procedure, as it can clarify the contribution of the facet joints in segmental instability.

The aim of this section was to develop a rigid body facet joint kinematics model based on *in-vivo* dynamic three-dimensional CT image-based models during torsion. Results, reported here are, to the author's knowledge, unique as they are based on large study sample (n=91), and interpreted in facet-specific coordinate system. Results also show that torsion of the lumbar spine resulted in complex coupled motions in the facet joint. This work is an important step to better understanding more the functional anatomy of the facet joint and role it plays in low back pain.

III. Validation of kinematic model

1. Background – three-dimensional surface based modeling

Acute need to study human biomechanics *in-vivo* in combination with recent advancements in medical imaging allowed three-dimensional geometric modeling of various anatomical structures. The geometric modeling of surfaces is of central importance for any image-based kinematic evaluation of the rigid body motions. Surfaces are usually extracted from two-dimensional images in order to quantify joint kinematics and dynamics in normal, pathological, and surgically reconstructed conditions.

For the previously described kinematic model, there is only one potential source of error: the three-dimensional CT model of the lumbar spine. Spinal geometry is the only input to the model, thus its accuracy has to be assessed together with precision or repeatability of the used methods. The accuracy of the Dynamic CT geometry has been previously evaluated *in-vitro* using a phantom with eight precision ceramic balls. The phantom was positioned on a high precision four-degree of freedom table (Suruga Seiki, Japan) and scanned using a CT scanner at five translated positions in x-direction (0.1 mm increments), and at ten translated positions in z-direction (0.1 mm increments) and ten rotated positions about x-axis (0.1° increments). Accuracy of the obtained geometry-based vertebral motion was determined with mean absolute translation error less than 0.1mm and mean absolute rotation error less than 0.2°. However, even with the high accuracy obtained, it is essential to validate precision.

The superficial cortical shell of each individual facet joint is extracted from sequential CT slices. The segmentation procedures involved thresholding, image algebra, and user interaction (pixel selection) to define each facet joint surface. As previously described, facet joint surface models have been modeled as a triangular polygon mesh based on three-dimensional CT point-cloud. Quantification of facet joint kinematics is technically challenging due to its small size, complex shape, and tight articulation of the individual surfaces. The geometry of the facet joint surface is the most sensitive input to the image-based kinematic model. Surfaces of every individual facet joint have been traced by an experienced spine

surgeon from axial DICOM images in a custom-written program using a tablet digitizer. The tracing methodology was previously described in the first chapter (see I-3.4.3 Facet joint surface segmentation) following the protocol listed in the appendix (see Appendix A: Facet joint surface tracing protocol). During the segmentation procedure, particular care was taken to identify and exclude osteophyte and cyst formations from the traced joint surface. A total of 2912 individual facet joint surfaces (in both studied positions) have been traced and transformed into a uniform, three-dimensional point-cloud. Obtained surface models represent precise facet geometry that was used as a single input for a kinematic evaluation of facet motion.

In scientific research it is necessary to define deviation in two measured quantities in terms of measurement accuracy and measurement precision. Measurement accuracy is defined as the closeness of agreement between a measured quantity value and a true quantity value of a measured. Measurement precision is defined as the closeness of agreement between measured quantity values obtained by replicate measurements on the same or similar objects under specified conditions and is usually expressed numerically as standard deviation or variance under the specified conditions of measurement (repeatability and reproducibility conditions).

Due to the methodology of measurement used in this study, it can be concluded that values were obtained indirectly, by a computational procedure from observed data. Validation was performed by calculating precision under a set of repeatability conditions of measurement (the same measurement procedure, operators, measuring system, and operating conditions over a short period of time).

2. Materials and Methods

Quality of the facet joint surface trace is the key parameter to be validated in order to have a stable and reliable kinematic model. It is essential that individual facet joint surfaces have been traced in a repeatable way. The tracing method used in this study is semi-automatic, involving a human operator making a qualified decision on individual pixel selection. Decision has to be made particularly about atypical and pathological alterations of the facet surface. The facet joint undergoes degenerative changes similar to other synovial joints in human body[31]. The study group evaluated in this work engages subjects ranging from 21-59 years old, thus we can assume the presence of facet joint osteoarthritis. In general, a joint osteoarthritis expresses with articular cartilage degeneration, facet hypertrophy, subchondral bone sclerosis, osteophyte formation and focal erosion[48, 49]. CT is the preferred method for studying facet joint surface due to the high accuracy and superior contrast between bony structures and the surrounding soft tissues. Also, CT clearly delineates abnormalities including articular hyperthropy, osteophyte formation, vacuum joint phenomenon, synovial and subchondral cyst, subchondral bone sclerosis and calcification of surrounding soft tissue[28, 29, 50]. A well-trained operator has to be able to exactly identify the facet surface and also be able to exclude structures that are not part of the articulating couple. Exclusion methodology is subjective in nature, and thus it is necessary to make a set of rigorous conditions and recommendations between the operators. In this study, care has been taken to identify and exclude osteophyte and cyst formations within the facet joint. Those formations can be seen on CT axial slice; however evaluation of their shape, size and function within articulating couple remains subjective. Tischer et al. reported occurrence of the osteophyte formation to be most frequent on the latero-dorsal margin of the superior facet joint surface where the dorsal capsule attaches[51]. Fewer osteophytes were seen in the caudal margin of the inferior facet joint and cranial margin of the superior facet joint.

Twelve randomly selected subjects from the original study group were stratified based on their age, gender and symptom (Table III-1). The validation study group consisted out of 6 subjects younger than 40 years and 6 subjects older than 40 years old; 6 male subjects and 6 female subjects; and 8 non-

symptomatic subjects and 4 symptomatic subjects. Eight individual facet joints (left side only) have been traced from identical DICOM set of slices by two qualified operators and resultant point-clouds have been exported (Figure III-1) as previously described (see I - 3.4.4 Facet joint surface geometry). A total of 96 facet joint surfaces (inferior, superior) traced independently by two operators were included in this validation.

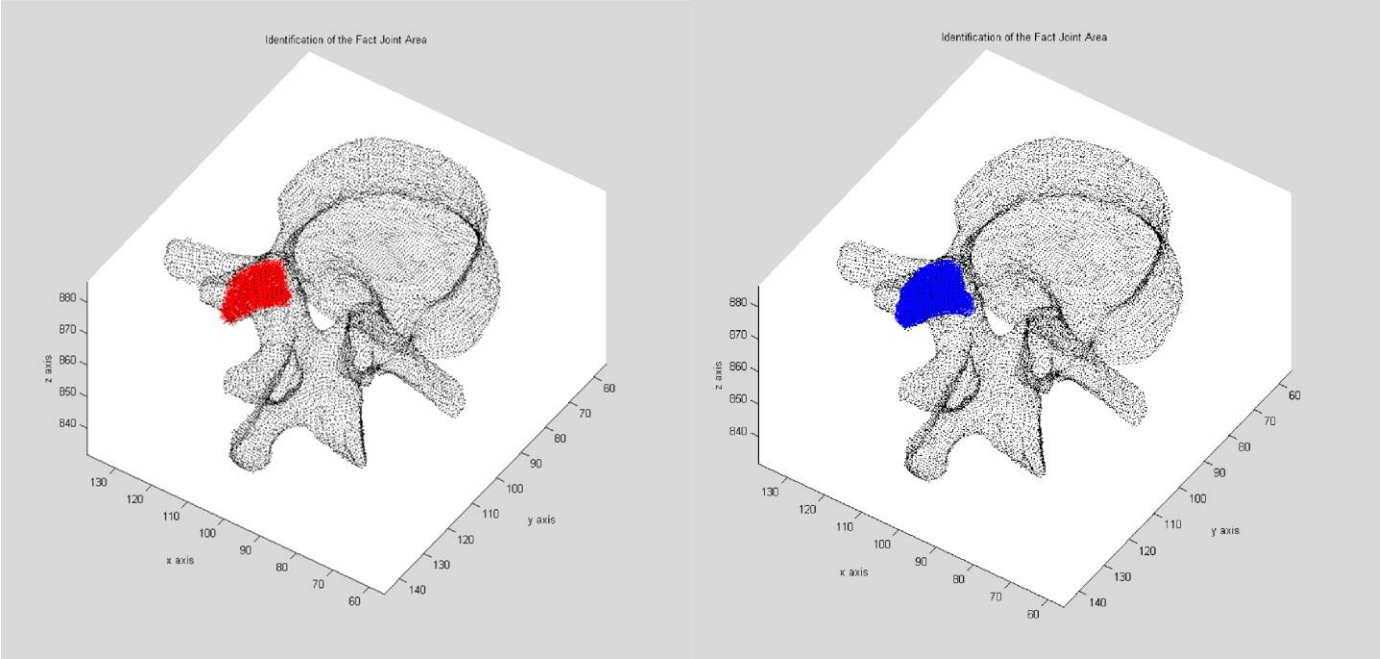


Figure III-1: A pair of identical facet joint surfaces traced by two operators

Table III-1: Validation sample strata

	Male		Female	
	<40 years	>40 years	<40 years	>40 years
Symptom	1	1	1	1
Non-Symptom	2	2	2	2

Validation of two procedures was performed. Firstly, a visual validation of the overlap match was used. Secondly, the parameters defined on individual surfaces were compared.

2.1. Facet joint surface tracing repeatability

2.2. Facet joint surface tracing repeatability

Evaluation of surface tracing repeatability was conducted using the following parameters calculated from a pair of identical facet joint surfaces traced by two qualified operators: 1. surface identification – overlap (%); and 2. pixel selection precision – in-plane evaluation (mean ± SD).

Evaluation of above mentioned parameters was selected in order to assess whether decision over pixel selection has been made based on qualified criteria or pixel was selected randomly. As can be seen from Figure III-2 a; visual validation was assessed by superimposition of two identical surfaces traced by two operators. On the Figure III-2 b, c, and d visual two-dimensional match/overlap of two surfaces can be seen in XY, ZY and ZX plane respectively. Elements (x and o) used in the figure represent pixels which were precisely selected from axial CT slices of the facet joint surface. In terms of the two-dimensional visual validation, it can be concluded that two surfaces represent a fair match; however it is necessary to evaluate spatial distances between them. Measure of point-to-point distance represents quantification of error and can be used to express the amount of variation as well as give us more information on its occurrence and distribution. Influence of age and presence of low back pain was also taken into consideration as a progression of facet joint degeneration has an influence on facet joint surface quality.

2.2.1 Surface identification

Surface identification was evaluated using a computational algorithm that identified individual pixels of the studied surface pair that did not overlap. Each pair of facet joint surfaces has been imported into custom-written program (MV C++). Surfaces were superimposed in a way that the surface traced by operator A was considered a reference. Using the least distance algorithm, every single pixel of the reference surface was assigned a pixel of the opposing surface controlling for distance between them to be minimal (zero in ideal case). The cut off value for acceptable distance was set to be 1.5 mm. If the

distance between two pixels was larger or equal to 1.5 mm, the pixel of reference surface was considered to be a non-identified surface. Pixel-to-pixel distance was plotted on a distribution color-coded map in the three-dimensional surface of each facet joint (Figure III-4). White color on the figure indicates non-identified surface. Surface identification was evaluated by comparing percentage of overlap between all studied cases (n=96). Mean values as standard deviations were reported as precision/repeatability. Additionally, influence of age and symptoms were evaluated.

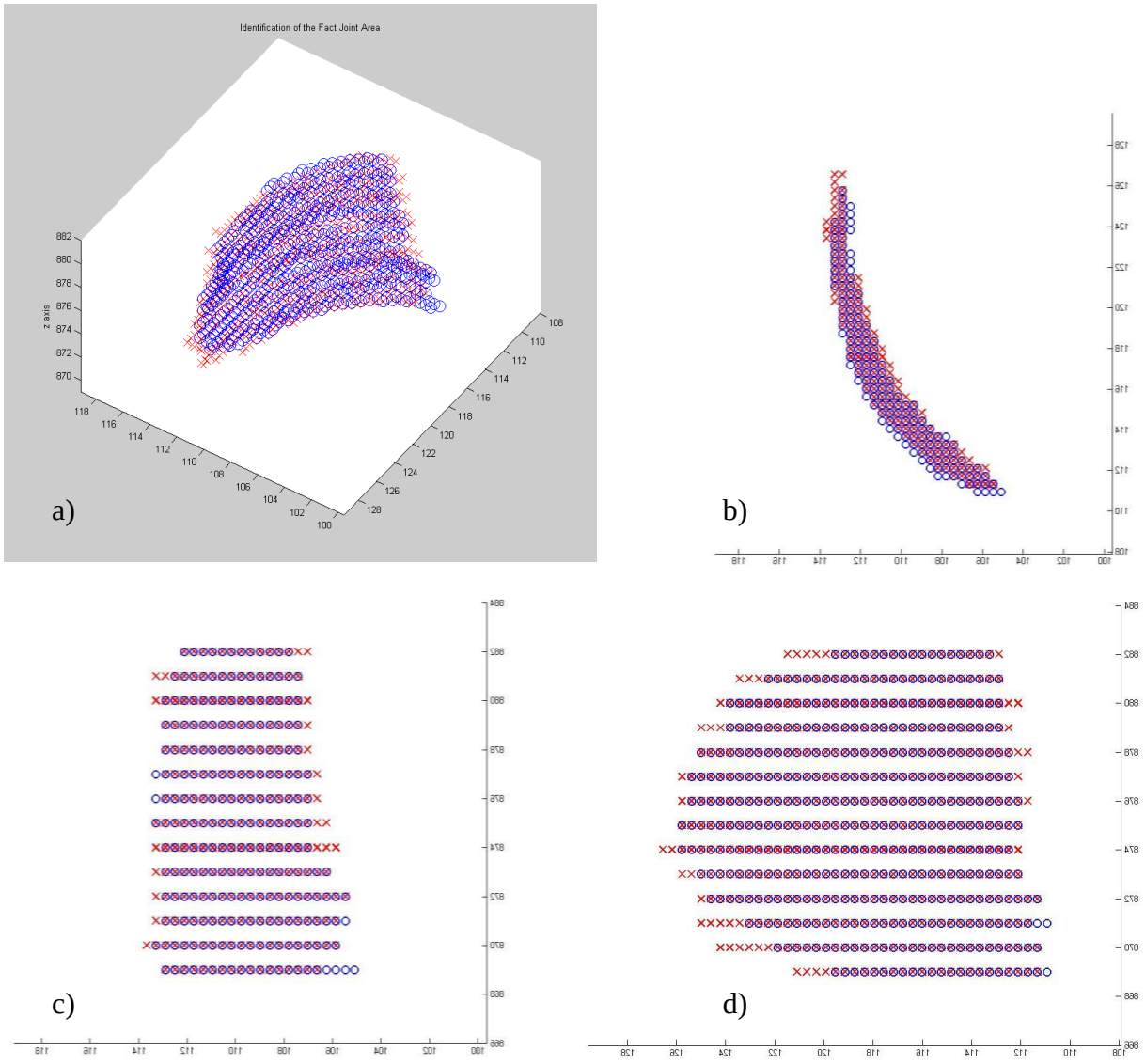


Figure III-2: Surface overlap

2.2.2 Precision of in-plane pixel selection

Previous analysis showed what percentage of the surface was identified by both operators. Repeatability of surface tracing should also include an analysis that addresses the question, to what extent the match between two operators was achieved when the surface was properly identified. Figure III-3: In-plane pixel selection shows the in-plane image of pixel selection during the tracing procedure. Using an algorithm similar to the one described for surface identification; analysis of in-plane pixel selection was utilized. The difference was that there was no control for minimal distance between two surfaces. Thus, every pixel has been paired with the closest neighbor in the opposing surface. Similarly, distance between two superimposed surfaces was measured using custom-written algorithm. Measured distances were recorded and statistically evaluated. Mean and standard deviations were presented. Additionally, distribution of pixel error was quantified showing percent of pixel difference between two observers.

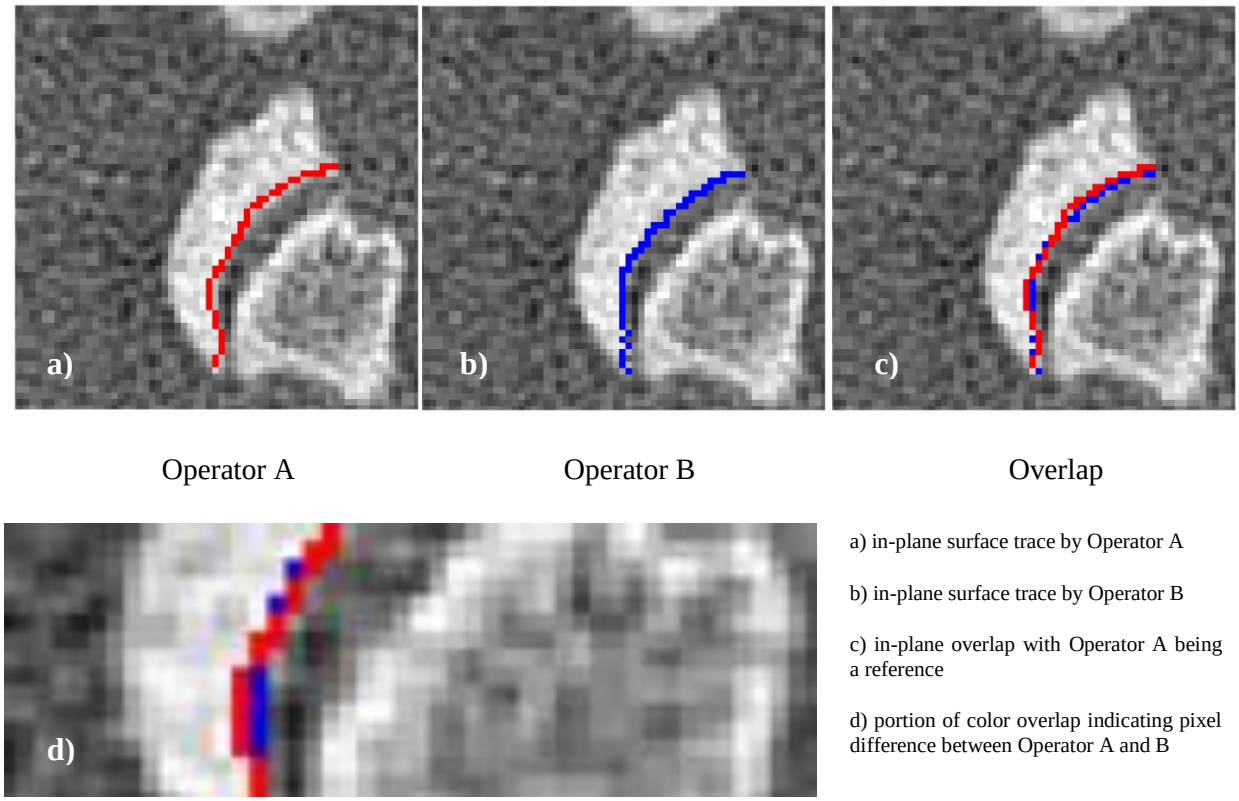


Figure III-3: In-plane pixel selection

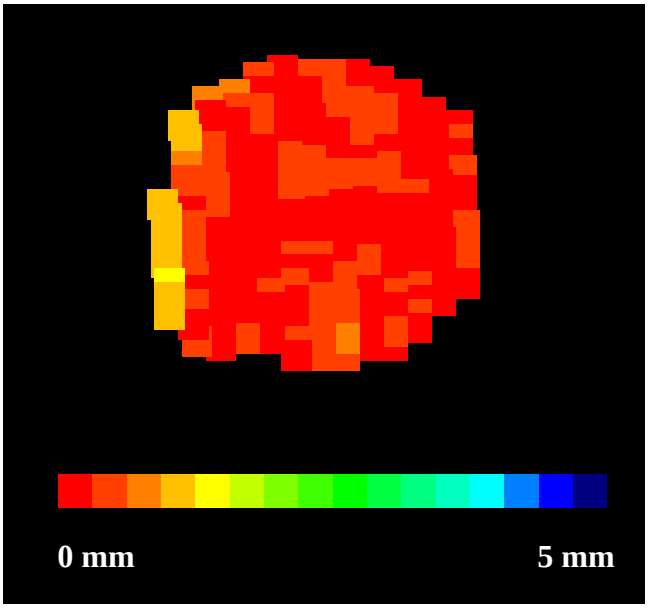


Figure III-4: Pixel-to-pixel distance color map

2.3. Facet joint surface meshing repeatability

Flow of the process creating subject specific three-dimensional facet joint surface models previously described in the first chapter (see I - 3.4.4 Facet joint surface geometry) involved the facet joint surface tracing procedure and the facet joint surface meshing procedure. Influence of human factor on tracing has been described in the previous subchapter. Although meshing is a semi-automatic procedure where triangular surface meshes are created from point-cloud data in the custom-written program, calculation of the average normal vector of the facet surface requires human interaction. The facet is a paired joint, which has two opposing surfaces articulating. The normal vector of a general surface cannot be defined uniquely, as there are always two solutions – identical in magnitude, and position, but opposite in direction. The facet surface is relatively flat, thus, it is necessary for an operator to select the principal direction out of the facet surface in which the normal vector is directed. This operation involves changes in the polygon mesh of the surface. These changes may bring into the model unwanted random error that can alter the direction of the normal vector, additionally shifting the origin of the normal vector – surface area center.

In order to establish repeatability of the surface meshing algorithm, independently calculated average normal vectors and area centers from both operators were compared.

While the mean difference of the area centers was easily compared, difference in the mean normal vectors between two surfaces was assessed by calculating an angle between each pair of mean normal vectors. Mean and standard deviations were reported and they represent precision/repeatability of the method.

3. Results

3.1. Surface identification

There was almost perfect surface identification observed in this validation study throughout the validation group. Out of 96 studied cases there were 50 pairs of surfaces with perfect 100% pixel overlap. Only in three cases was the overlap was lower than 85%, but it never decreased below 82% overlap (Figure III-5). Precision or repeatability of tracing was 98±3.9 % (mean±SD).

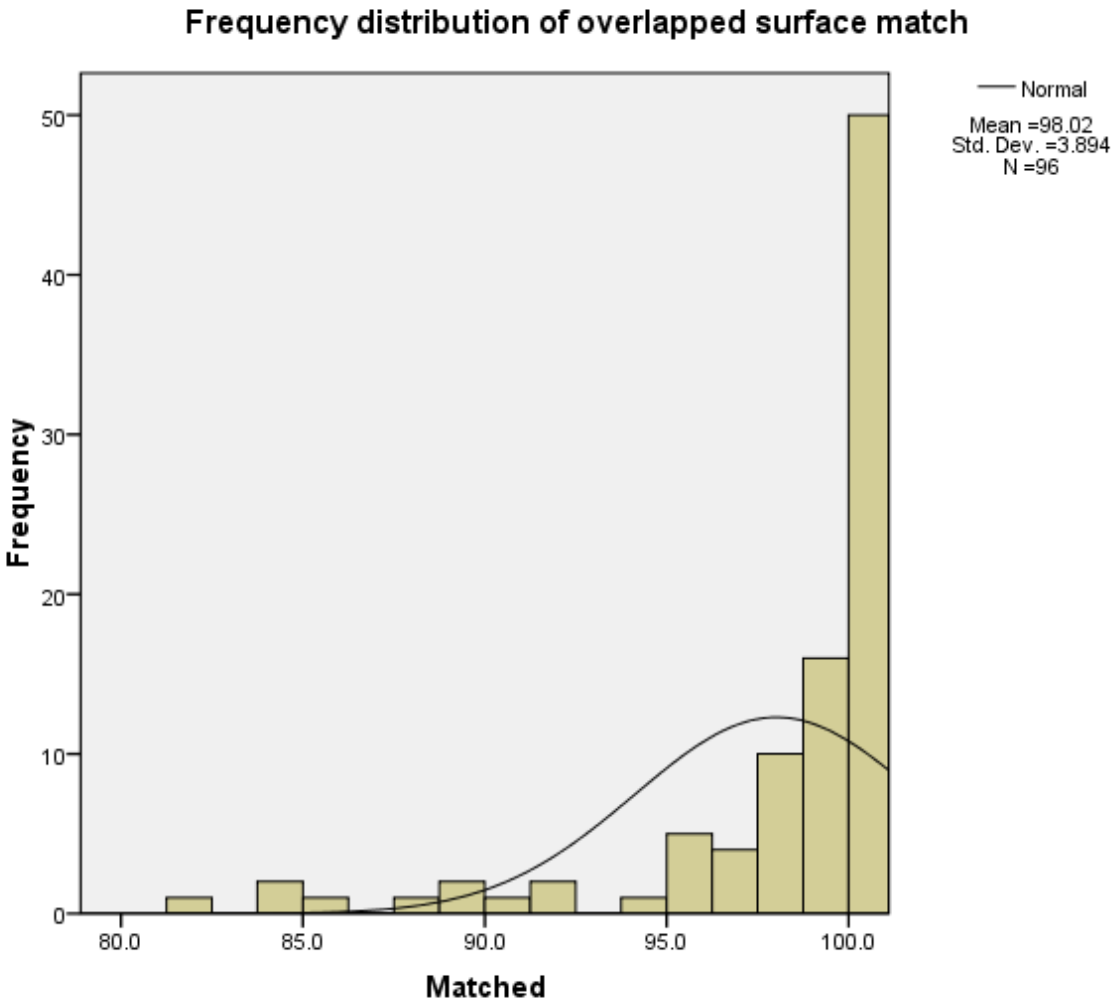


Figure III-5: Overlapped surface match distribution

Larger variation of non-identified surfaces occurred in 7 cases which were evaluated individually (Table III-2). As can be seen on the Figure III-6 non-identified surfaces are in larger bulks particularly in latero-dorsal portion of the superior facet joint and inferior portion of the inferior facet joint. After reviewing DICOM images in those locations we can conclude that the non-identified areas were produced by qualified decisions of each operator on presence or absence of osteophyte formation.

Table III-2: individual cases of non-identified surfaces

Subject	Symptom	Level	Position	Non-identified (%)
1	N	L2	sup	18.0
2	S	L3	inf	15.7
3	N	L4	inf	15.5
4	N	L4	sup	14.4
5	N	L5	sup	12.4
6	S	L3	sup	10.7
7	N	L5	sup	10.3

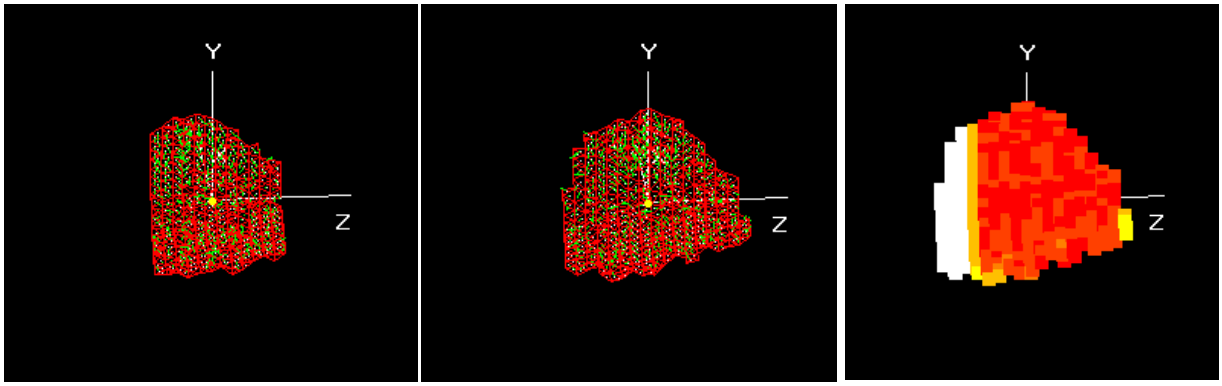


Figure III-6: An example of non-identified surface due to osteophyte formations

Age and symptom showed no significance in explaining an overall variance of the overlap (Figure III-7).

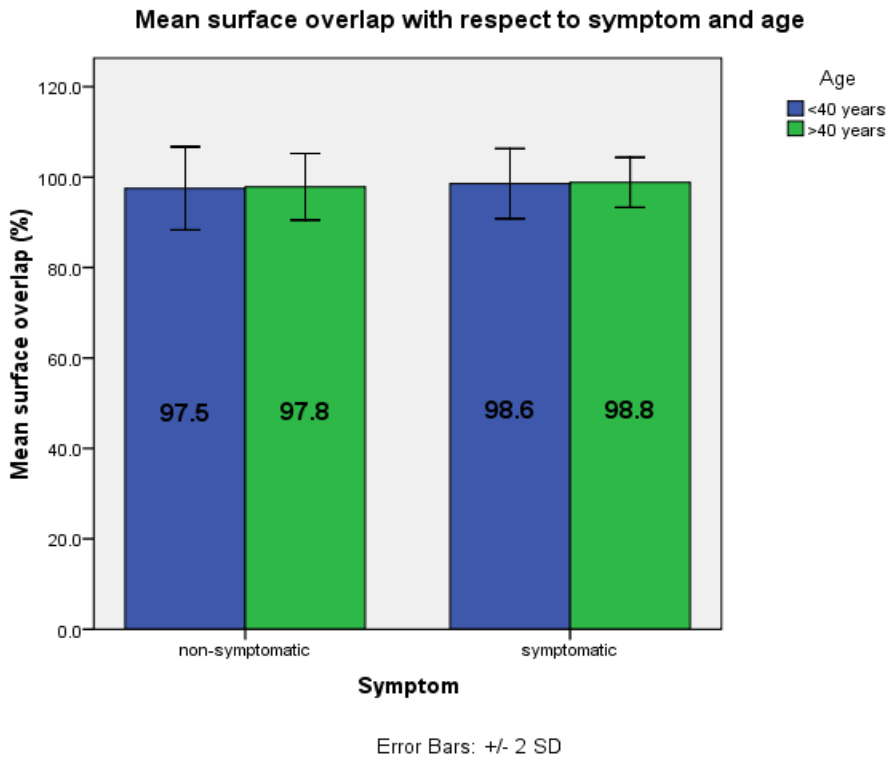


Figure III-7: Age and symptom effects on the surface identification

3.2. Precision of in-plane pixel selection

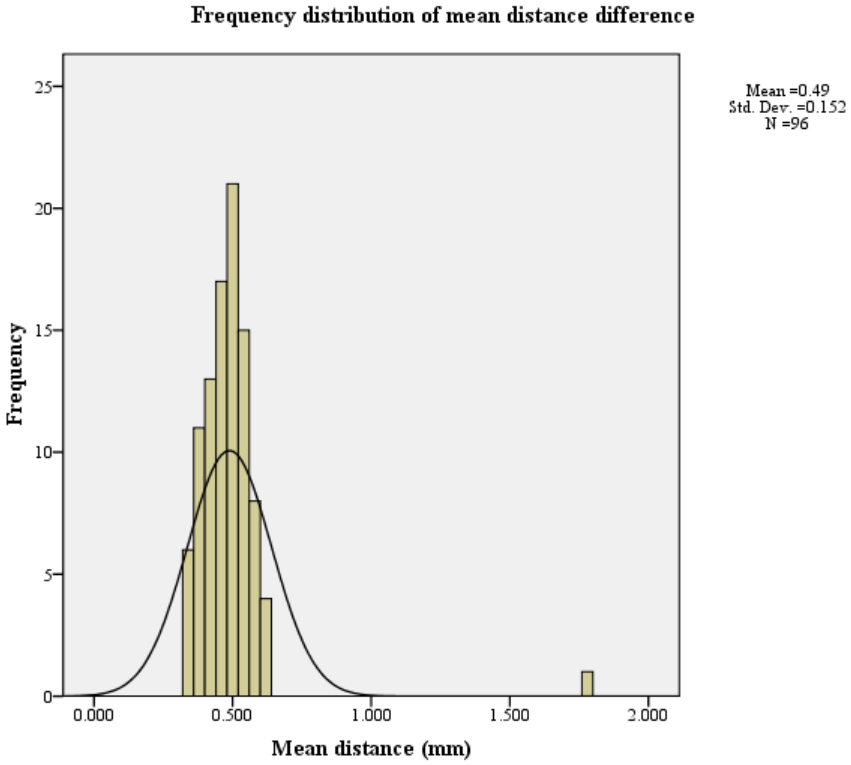


Figure III-8: Frequency distribution of the mean distance difference

Analysis of distance between two pixels selected independently by the two operators showed a normally distributed (Figure III-8) error of pixel selection with mean value of 0.49±0.15 mm. Percentage pixel match between two observers showed on average 59% of perfect match, 8% of one pixel error and 33% of two or more pixel error. There was no significant difference between studied groups with respect to age (Figure III-9) or symptom.

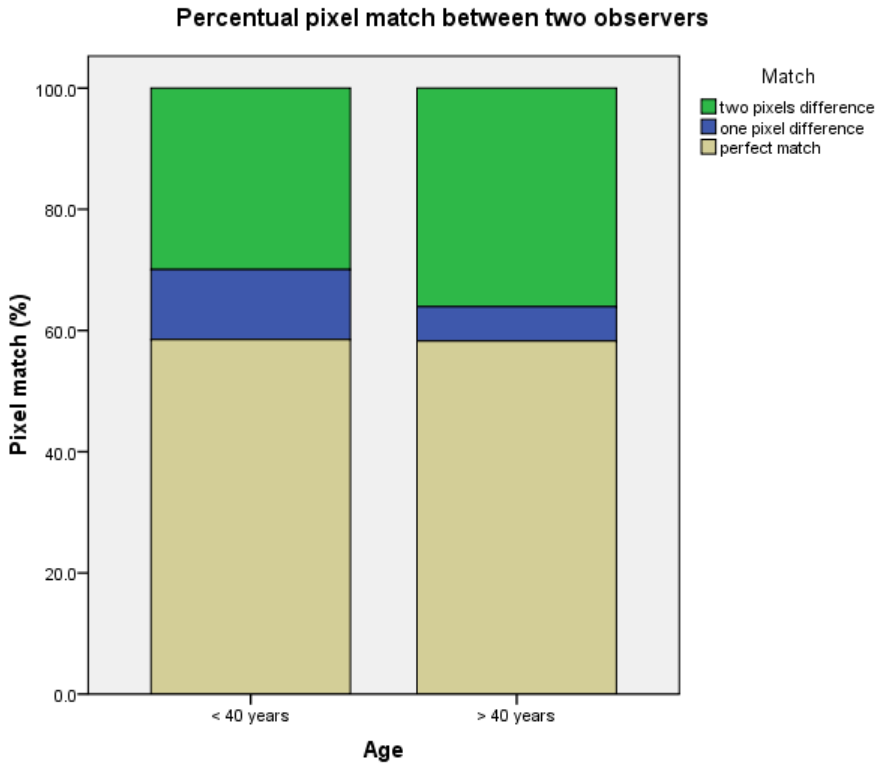


Figure III-9: Percentage pixel match between two observers

3.3. Facet joint surface area center error estimation

The difference between two surface area centers was calculated between each pair of studied surfaces. Distribution of error did not follow standard distribution (Figure III-10). Mean error of the facet joint surface area center was estimated at 0.69±0.5 mm with maximal value of 2.4 mm. In 56.3% of the cases distance was smaller than 0.625 mm (approximately two pixels).

3.4. Facet joint surface normal vector error estimation

The angular difference between two mean normal vectors was calculated between each pair of studied surfaces. Mean error of the facet joint surface normal was estimated at 1.9±0.9 degrees with maximal value of 3.8° (Figure III-11). In 51.3% of cases mean angle between two normal vectors was below 2°.

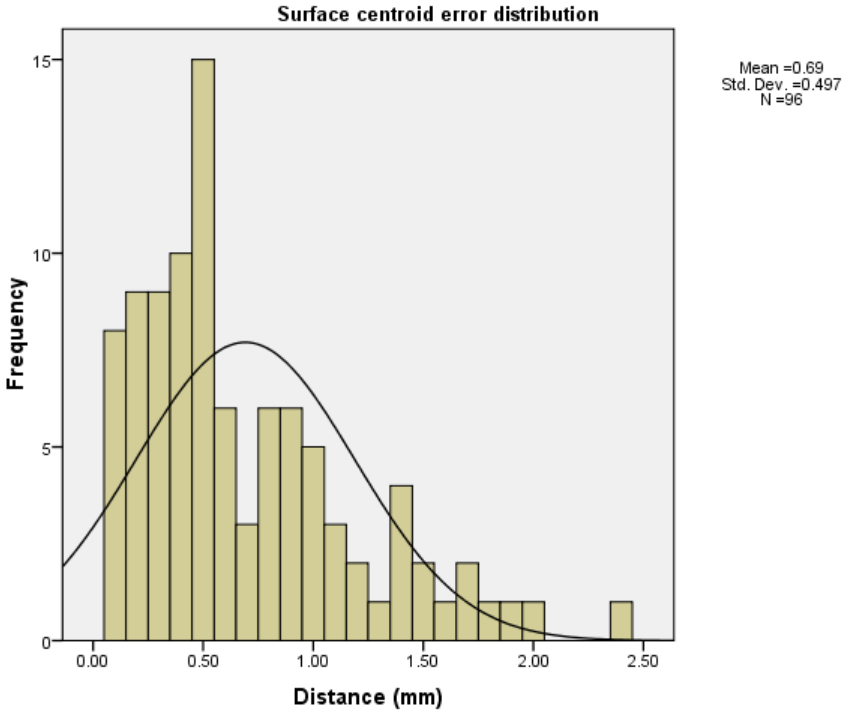


Figure III-10: Surface area center error distribution

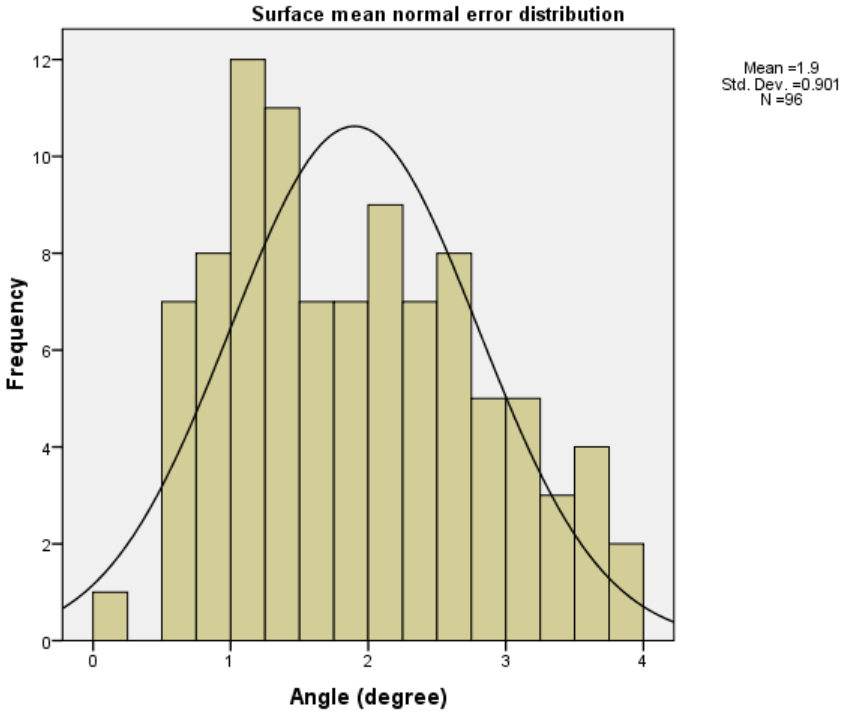


Figure III-11: Surface mean normal vector error distribution

4. Conclusion and Discussion

Kinematic parameters have value only if they are represented in an objective and repeatable manner. Geometry of the facet joint surface and posterior wall are the most sensitive inputs to the model. Accuracy of the dynamic CT geometrical method was previously validated with a mean absolute translation error of 0.1 mm and a mean absolute rotation error to be less than 0.2°[21, 22]. Though this validation can serve as assurance of the dynamic CT based three-dimensional models (vertebral bodies, posterior walls, intervertebral endplates), further validation of the precision was necessary for the facet joint surface geometry.

Validation of surface identification revealed that surfaces were correctly traced/identified in 98±3.9 % of cases. Validation concerning osteophyte exclusion revealed that only in 7 cases out of 96 a discrepancy on whether to include or exclude the osteophyte formation between the observers. Osteophyte identification is a very subjective procedure and may vary from observer to observer. However, the results indicate that rigorous rules concerning osteophyte identification applied in this study were sufficient in 92.87 % of studied cases.

Calculated precision of the facet joint segmentation technique was estimated at 0.49±0.15 mm. Repeatability of the meshing technique was estimated for surface area center 0.69±0.5 mm and for average normal vector of the facet joint 1.9±0.9 degree. Estimated precision for the facet joint surface area center is an important finding concerning the translational range of motions. When error of area center was taken into account, analysis revealed that on average, difference between original dataset and corrected for estimated error was 0.1 mm. This represents an influence of human factor on resultant translational ROM. Precision of the average normal vector is related to the rotational range of motion.

IV. Degeneration process in human lumbar spine

1. Background – degeneration of the human spine

Degeneration of the spine is a natural process that generally advances with age, although its occurrence is not restricted to the elderly. Degeneration has been linked to low back pain, however, the exact relationship between the two remains unknown[52]. Mechanical property changes resulting from degeneration are also likely contributors to lumbar spine segmental instability that lead to other pathologies and can be accelerated by injuries or deformities[7]. At each level of the spine, there are three joints forming the three-joint complex consisting of one intervertebral disc and two facet joints, with mutual load sharing between the three joints[4]. While intervertebral disc is a fibrocartilagenous joint, the facet joints are typical synovial joints. Degenerative changes of the spine can include disc degeneration, facet joint osteoarthritis, vertebral body degeneration and ligament degeneration[30]. The relationship between intervertebral disc and facet joints is very significant. Any change in one of them will influence the other two. Disc degeneration and facet joint osteoarthritis are usually concomitant, but it has been reported that disc degeneration generally precedes facet joint osteoarthritis[53, 54].

1.1. Intervertebral disc degeneration

The intervertebral disc has a composite structure consisting of nucleus pulposus and annulus fibrosus. The nucleus consists mainly of a proteoglycan-rich gelatinous matter that is surrounded by a collagen-rich annulus fibrous. The nucleus has high water content, which provides it with large resistance to the applied compression. Loads are transferred from nucleus to annulus through hydrostatic pressure. Degenerative changes in the biomechanical properties can take place in the nucleus pulposus and annulus fibrosus tissue individually. The most notable change is the reduction of water and proteoglycan content of the nucleus pulposus.

Intervertebral disc degeneration is evaluated radiographically, morphologically and using biochemical essays [55]. Clinically, there are two most commonly used classification schemes available:

Thompson scheme and Pfirrmann's [56]. Thompson et al evaluate disc degeneration by studying disc's gross morphology and categories are assigned based on its epidemiological changes. Thompson created five stages of disc degeneration (Figure IV-1). Figure IV-1 shows different stages of the human lumbar intervertebral discs (I being a healthy disc, and V being a severely degenerated intervertebral disc with a presence of the endplate collapse.

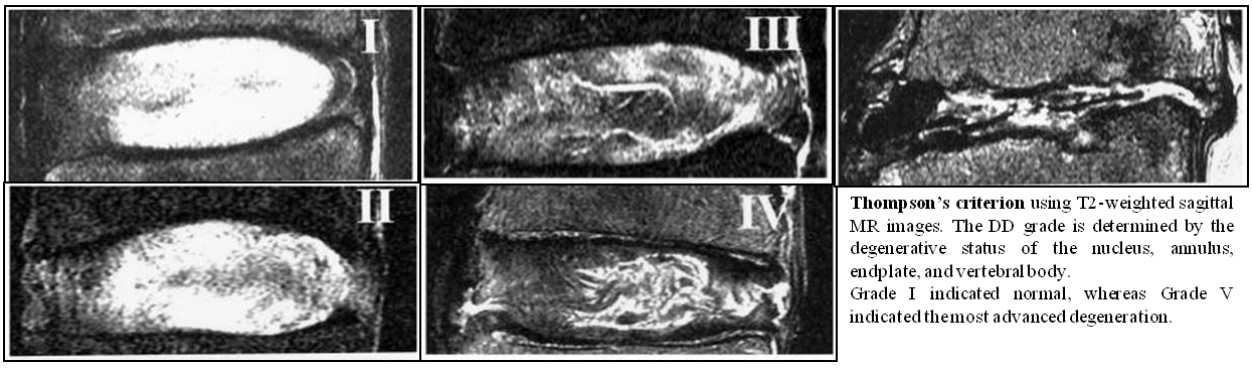


Figure IV-1: Disc degenration grade

1.2. Facet joint osteoarthritis

Facet joints are synovial joints in the spine which play an important role in controlling kinematics of the motion segment and load transmission in the spine[12, 20, 46]. The facet joints undergo degenerative and osteoarthritic changes similar to those of other weight-bearing joints[31]. Extensive motion and loading conditions can contribute to facet joint osteoarthritis development. Facet joint osteoarthritis has been considered as a potential source of low back pain and disability and contributes to 15-45% of chronic low back pain[9].

Osteoarthritis is, in general, characterized radiographically by joint space narrowing, subchondral bone sclerosis and osteophyte formation[57, 58]. Among these parameters, joint space narrowing has been considered to closely correlate to cartilage degeneration[48, 57]. For the facet joint, narrowing of the joint space, thinning of articular cartilage and subarticular cortical bone hypertrophy are frequently observed changes due to the aging process[48, 49].

In clinical practice, plain radiography remains the main screening technique to assess osteoarthritic changes; however, facet osteoarthritis evaluation by plain radiogram requires special techniques due to the three-dimensional orientation of the facet joint[48]. Ever since computed tomography (CT) made its appearance as a clinical diagnostic tool, it has been commonly used to provide a more accurate and anatomically correct evaluation of the facet joint geometry. Various parameters, such as facet joint orientation and joint area, have been previously reported based on CT methods[13, 25, 33, 59, 60]. The results of these studies indicated that variation of orientation of the facet joint is associated with age-related changes in load-bearing and development of lumbar facet joint osteoarthritis [25, 45, 6061]. Pathria *et al*, Weishaupt *et al*, and Kalichman *et al* used transverse CT as the diagnostic methods in the assessment of osteoarthritis of the lumbar facet joint[34, 48, 61] (Figure IV-2). Grading was based on four-point scale using the criteria listed in the Table IV-1. Using this approach, they were able to identify the abnormalities associated with facet joint osteoarthritis progression. However, these studies are qualitative only in nature, and facet joint space narrowing was evaluated within a limited number of transverse slices.

Macroscopic evaluation of the whole facet joint surface using mapping systems allowed detailed description of the extent and location of the cartilage degeneration[51, 62]. Analysis of the topographical patterns within anatomically-defined zones on the surface of the facet joint enables investigation of the effects of segmental lumbar motion on facet joint degeneration process.

We have developed a novel method of precise measurement of the three-dimensional space width distribution of lumbar facet joint using three-dimensional subject-based CT models[67]. This method allows measurement of facet joint space width distribution throughout the joint surface; however, a detailed mapping system has not been established to evaluate extent and location of the facet degeneration represented by narrowing of the facet joint space width. The aim of the present study was to determine lumbar facet joint space width within clinically relevant topographical zones *in-vivo* and its correlations with age, level and presence of low back pain.

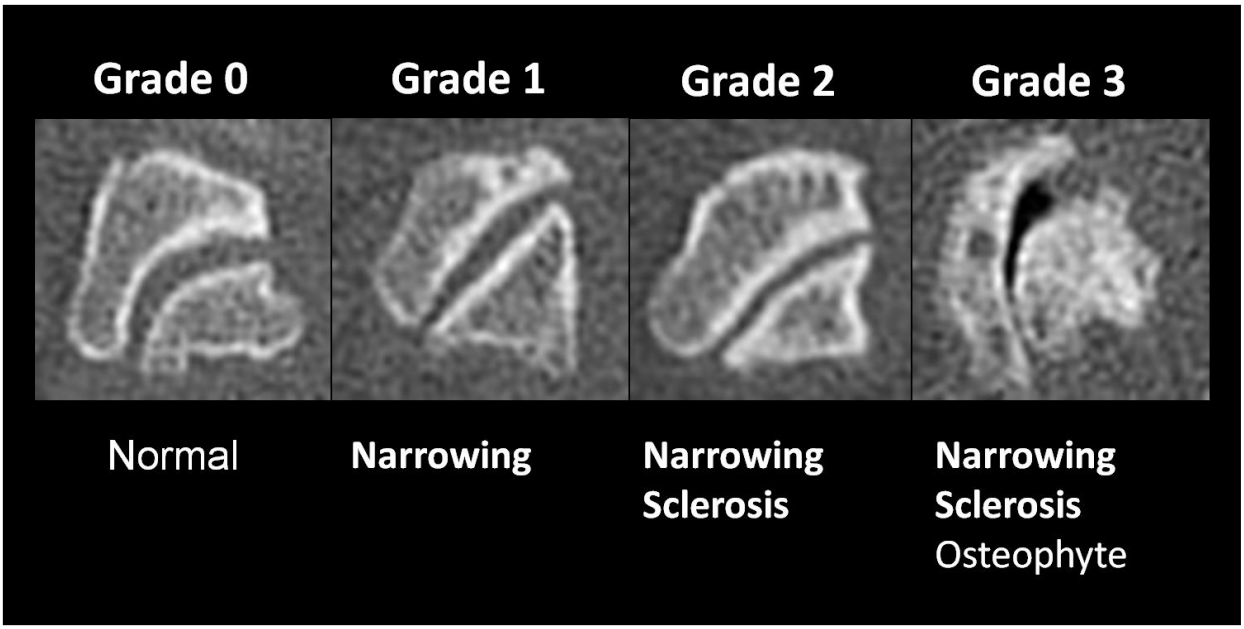


Figure IV-2: Facet joint osteoarthritis grade

2. Materials and Methods

2.1. Intervertebral disc degeneration evaluation

(a) Qualitative grading measures

Disc degeneration was evaluated by three experienced orthopedic surgeons. Image dataset was created in a blindly manner using T2 weighted sagittal MRI slices in the middle section of the intervertebral disc at each level. Lumbar intervertebral discs were graded on a four-point scale using criteria developed by Pfirrmann et al[64]. Individual grades were assigned to the intervertebral discs at all disc levels L1L2, L2L3, L3L4, and L4L5.

Grading was repeated during an identical second session scheduled two weeks later. In order to assess intraobserver variation, the same three graders independently evaluated blinded dataset of the study sample using the identical grading scheme. Each of the observers evaluated 356 individual intervertebral discs twice. To assure consistency, all assessment has been done on the same computer.

(1) Inter/intra observer evaluation

Using the above outlined grading scheme the inter-observer and intra-observer agreement has been calculated using Cohen's kappa method and reported together with percentage agreement[65]. This methodology was selected for evaluation because kappa, from definition, removes the proportion of agreement that could occur by chance. In order to address the seriousness of the disagreement between observers, quadratic weights were chosen, because difference by more than one category should be given more weight than the disagreement that differs by only one category.

Results were interpreted according to Landis and Koch guidelines for measurement of observer agreement for categorical data. Values of kappa between < 0.0 indicate poor agreement, 0.00-0.20 indicate slight agreement, 0.21-0.40 indicate fair agreement, 0.41-0.6 indicate moderate agreement, 0.61-0.8 indicate substantial agreement, and 0.81 and 1.00 indicate almost perfect agreement[66].

(b) Quantitative grading measures

Disc degeneration is clinically defined by the grade, which is based on the degenerative status of the nucleus, annulus, endplate, and vertebral body. In order to quantify the measure, the distance between intervertebral endplates was measured. Narrowing of the intervertebral disc, as a quantified measure can be useful in determining the occurrence and extent of disc degeneration. Although clinically disc height change occurs in the advanced stage of degeneration (grade III)[30], assessment of the localized changes in the disc height may be valuable.

(1) Disc height measurement

For analysis, the dataset of individual intervertebral disc surface models previously described in the first chapter was used. A total of 364 individual intervertebral disc models were created and exported as point-cloud data sets. Subsequently, triangular meshes were created from point-cloud data in the custom-written program (MV C++)[67].

(i) Local coordinate system of the intervertebral disc model

A local coordinate system was set in order to establish a mapping system on the surface of the intervertebral endplate. A normal vector was calculated for each mesh element and a mean normal vector of all normal vectors was calculated through the entire surface. The area center of the intervertebral endplate surface was calculated and the origin of the local coordinate system was set on that point. The mean normal vector was defined as one of the coordinate system axes. This axis and the CT coordinate system pointing towards the posterior direction formed a plane. The second coordinate was determined in this plane to be perpendicular to its mean normal vector and directed towards the posterior direction. The third coordinate was determined by the cross product between the first and the second vector[67].

(ii) Zoning algorithm

Five topographic zones consisting of central (nucleus), anterior, posterior, right and left zones were determined in three-dimensional space as described next. Cartesian coordinates for each point-cloud

data point were converted to a spherical coordinate system with the origin set at each intervertebral endplate surface model's center of area. The outer margin of the intervertebral endplate surface was defined by the points furthest from the origin within a virtual cone with a vertex angle of 30°. The margin of the central zone was defined so that its shape is analogue (concentric) to the outer margin of the intervertebral endplate surface and the area of the central zone is one-fifth of the whole intervertebral endplate surface area. The peripheral area was divided into four zones defined by an angular parameter in the spherical coordinate of each point (posterior zone; 315°±45°, left zone; 45°-135°, anterior zone; 135°-225°, right zone; 225°-315°) from the posterior axis (Figure IV-3). The angles represent projected angles on a plane perpendicular to the mean normal vector of the intervertebral endplate surface[26].

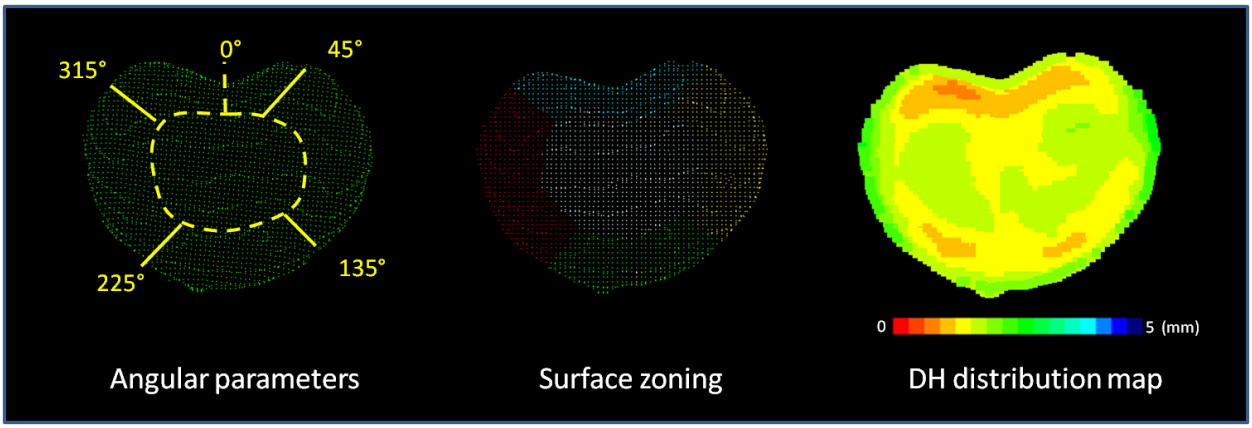


Figure IV-3: Intervertebral disc height measurement

(iii) Least distance measurement

Disc height was calculated as the least-distances between each pair of opposing surfaces (cranial endplate, caudal endplate) using a custom written least-distance algorithm[68]. The mean disc height for each zone was calculated by averaging the least disc height distances within each zone (Figure IV-3).

2.2. Facet joint degeneration evaluation

(a) Qualitative grading measures

Facet joint osteoarthritis evaluation was performed by three experienced orthopedic surgeons. Image dataset was created in a blind manner using axial CT slices in the middle section of the facet joints

at each level. Lumbar facet joints were graded on a four-point scale using criteria developed by Pathria et al[69](Table IV-1: Facet joint osteoarthritis grading scale). Individual grades were assigned to the facet joints on both the left and right side at all disc levels L1L2, L2L3, L3L4, and L4L5.

Table IV-1: Facet joint osteoarthritis grading scale

Grade 0	**Normal**	preserved joint space (2-4mm width)
Grade 1	**Mild**	narrowing of the facet joint space (< 2mm width) and/or small osteophytes and/or mild hypertrophy of the articular process
Grade 2	**Moderate**	narrowing of the facet joint space and/or moderate osteophytes and/or moderate hypertrophy of the articular process and/or mild subarticular bone erosions
Grade 3	**Severe**	narrowing of the facet joint space and/or large osteophytes and/or severe hypertrophy of the articular process and/or severe subarticular bone erosions and/or subchondral cyst

Grading was repeated during an identical second session scheduled two weeks later. In order to assess intraobserver variation, the same three graders independently evaluated the blinded dataset of the study sample using the identical grading scheme. Each of the observers evaluated 920 individual facet joints twice. To assure consistency, all assessment has been done on the same computer.

(1) Inter/intra- observer evaluation

Using an above outlined grading scheme the inter-observer and intra-observer agreement has been calculated using Cohen's kappa method reported together with percentage agreement[65]. This methodology was selected for evaluation because kappa, from definition, removes the proportion of agreement that could occur by chance. In order to address the seriousness of the disagreement between observers, quadratic weights were chosen, because difference by more than one category should be given more weight than the disagreement that differs by only one category.

Results were interpreted according to Landis and Koch guidelines for measurement of observer agreement for categorical data. Values of kappa between < 0.0 indicate poor agreement, 0.00-0.20

indicate slight agreement, 0.21-0.40 indicate fair agreement, 0.41-0.6 indicate moderate agreement, 0.61-0.8 indicate substantial agreement, and 0.81 and 1.00 indicate almost perfect agreement[66].

(b) Quantitative grading measures

Facet joint osteoarthritis progression is clinically defined by joint space narrowing, subchondral bone sclerosis and osteophyte formation[57]. In this study, facet joint osteoarthritis was evaluated in terms of facet joint space narrowing as it has been considered to closely correlate to cartilage degeneration[57].

(1) Facet joint space width measurement

For analysis, the dataset of individual facet joint surfaces, previously described was used. Particular care was taken to identify and exclude osteophyte formations from the joint surface. A total of 1912 individual facet joint surface models were created and exported as point-cloud data sets. Subsequently, triangular surface meshes were created from point-cloud data in the custom-written program[33].

(i) Local coordinate system evaluation

A local coordinate system was set in order to establish a mapping system on the facet joint. A normal vector was calculated for each mesh element and a mean normal vector of all normal vectors was calculated through the entire surface (Figure I-13). The gravity center of the facet joint surface was calculated and the origin of the local coordinate system was set on the gravity center. The mean normal vector was defined as one of the coordinate system axes. This axis and the CT coordinate system pointing towards the cranial direction formed a plane. The second coordinate was determined in this plane to be perpendicular to its mean normal vector and directed towards the cranial direction. The third coordinate was determined by the cross product between the first and the second vectors.

(ii) Zoning algorithm

Five topographic zones consisting of central, superior, inferior, medio-ventral and latero-dorsal zones were determined in three-dimensional space as described next. Cartesian coordinates for each

point-cloud data point were converted to a spherical coordinate system with the origin set at each facet joint surface model's center of area (Figure IV-4: Facet joint space width measurement). The outer margin of the facet joint surface was defined by the points which have the longest distance from the origin within a virtual cone with a vertex angle of 30° [70]. The margin of the central zone was defined so that its shape is analogue (concentric) to the outer margin of the facet joint surface and the area of the center zone is one-fifth of the whole facet joint surface area. The peripheral area, outside of the central zone, was divided into four zones defined by an angular parameter in the spherical coordinate of each point (superior zone; ±45°, medial zone; 45°-135°, inferior zone; 135°-225°, lateral zone; 225°-315°) from the cranial axis (Figure IV-2). The angles represent projected angles on a plane perpendicular to the mean normal vector of the facet joint surface.

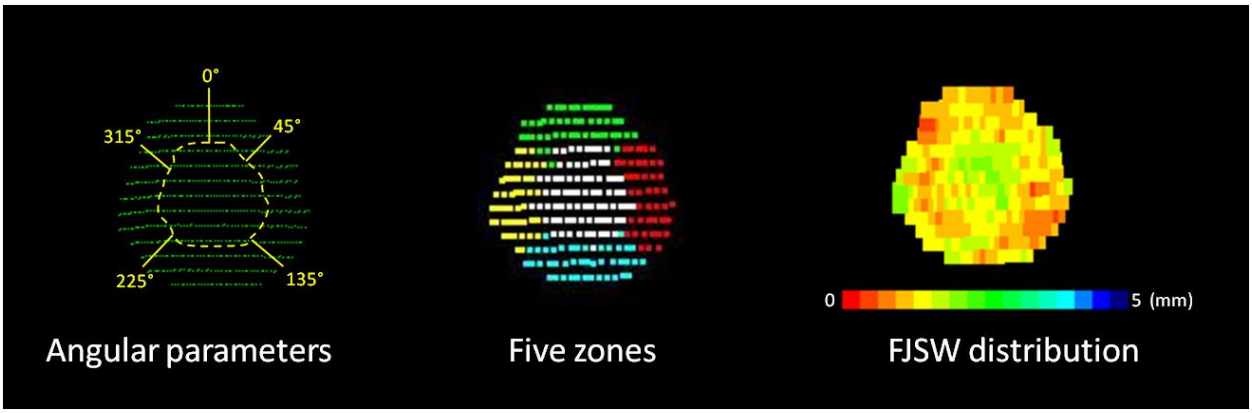


Figure IV-4: Facet joint space width measurement

(iii) Least distance measurement

Facet joint space width was calculated as the least-distances between each pair of opposing surfaces (inferior facet, superior facet) using a custom written least-distance algorithm[68]. The mean facet joint space width for each zone was calculated by averaging the least facet joint distances within each zone.

2.3. Statistical methods

Every dependent variable was tested for normality. Histograms were plotted and descriptive statistics reported to support the finding of normal distribution. Comparison of three or more independent groups was performed by one-way analysis of variance with a Fischer's post-hoc test to determine significant differences. Relationships between pairs of continuous, scale variables were investigated with Pearson correlation coefficients (one-tailed). Alpha value was set to 0.05. All results were reported with mean and standard deviations.

2.3.1 Inter/intra observer error estimation

For inter-observer and intra-observer agreement Cohen's kappa value method was used.

2.3.2 Correlation between a set of categorical variables

In order to quantify the association between intervertebral disc degeneration grade and facet joint osteoarthritis grade, it was necessary to define a new variable describing the relationship between them. Spinal degeneration ratio is the variable addressing this relationship. It is calculated as a ratio of disc degeneration grade and facet joint osteoarthritis grade. As disc degeneration is graded on scale 1-5 and facet joint osteoarthritis on scale 0-3 adjustments have been made in order to normalized the two. Facet joint osteoarthritis grade was adjusted by adding 1 to the every grade (making it 1-4). Disc degeneration grade was adjusted to four scale by merging grade 4 (severe degeneration) and grade 5 (very severe degeneration) into one grade. The advantage of the relatively young and healthy study population was taken in this step as there were only 14 cases (out of 364) that experienced grade 5 degeneration (3.8% of the study group). As there were no significant differences between right and left side, facet joint osteoarthritis grade was averaged per level. Spinal degeneration ratio was calculated per every level. Value of 1 indicates that disc degeneration was larger than degeneration of the facet joint. Ratio equal to 0 means that both intervertebral disc and facet joint degeneration grade was the same. Value of spinal degeneration ratio smaller than 1 means that facet degeneration grade was larger than disc degeneration grade.

3. Results

3.1. Qualitative measures

Qualitative measures are represented by qualitative variables that are not capable of being measured in a common way. Measurements made on qualitative variables convey information regarding attribute. In such cases measuring consists of categorizing and counting frequencies of occurrence of some attribute.

3.1.1 Disc degeneration:

356 individual intervertebral discs from 89 subjects were evaluated for disc degeneration (see Table IV-2: Mean values of disc degeneration grade with respect to gender, age, and level). Three observers evaluated disc degeneration grade on MRI images two times. Total of 6 observations were analyzed for each individual intervertebral disc. The mode value was calculated from all 6 observations. A perfect agreement (6/6) was observed in 43% of studied cases; a fair agreement (5/6) was observed in 19.2% cases; a good agreement (4/6) was observed in 27.2% cases; and a poor agreement (3/6) was observed in the remaining 10.6% of cases.

Table IV-2: Mean values of disc degeneration grade with respect to gender, age, and level

		Disc degeneration grade			
		Count	Percent	Mean	SD
Gender	Female	160	44.9	2.28	0.83
	Male	196	55.1	2.37	0.98
	Total	356	100		
Age	20	96	27.0	1.97	0.70
	30	136	38.2	2.24	0.95
	40	80	22.5	2.50	0.80
	50	44	12.4	3.09	0.91
	Total	356	100		
Level	L1L2	89	25	2.36	0.84
	L2L3	89	25	2.28	0.83
	L3L4	89	25	2.19	0.78
	L4L5	89	25	2.49	1.15
	Total	356	100		

(a) Inter/intra observer error estimation

Table IV-2: Mean values of disc degeneration grade with respect to gender, age, and level shows the degree of inter-observer and intra-observer agreement expressed as weighted kappa value (quadratic weights). As expected, intra-observer agreement (**bold**) was in general substantially higher than inter-observer agreement.

Table IV-3: Inter/Intra-observer evaluation of the intervertebral disc degeneration grading

	Observer 1 (first)	Observer 2 (first)	Observer 3 (first)
Observer 1 (second)	**0.821** 95% CI: 0.788 to 0.853	0.738 95% CI: 0.701 to 0.775	0.695 95% CI: 0.656 to 0.733
Observer 2 (second)	0.708 95% CI: 0.669 to 0.747	**0.794** 95% CI: 0.758 to 0.829	0.719 95% CI: 0.679 to 0.758
Observer 3 (second)	0.670 95% CI: 0.632 to 0.707	0.749 95% CI: 0.714 to 0.783	**0.885** 95% CI: 0.861 to 0.910

The validation of the grading system based on Thompson grading scale revealed substantial agreement between the observers and almost perfect agreement between two gradings of the same observer.

(a) Statistical evaluation with respect to AGE, GENDER and LEVEL

Statistical evaluation was performed in order to assess the role of independent covariates on explaining the overall variation of the dependent variable. The independent variables will be tested individually and in combination. The strength of the independent variable as predictor of the dependent variable (disc degeneration grade) was discussed. Statistical model was fitted with variables that explain variance the best in order to maximize the predictive ability of the model.

Histogram revealed approximately normally distributed sample population with the mean value of disc degeneration grade being 2.33±0.91 (Figure IV-5).

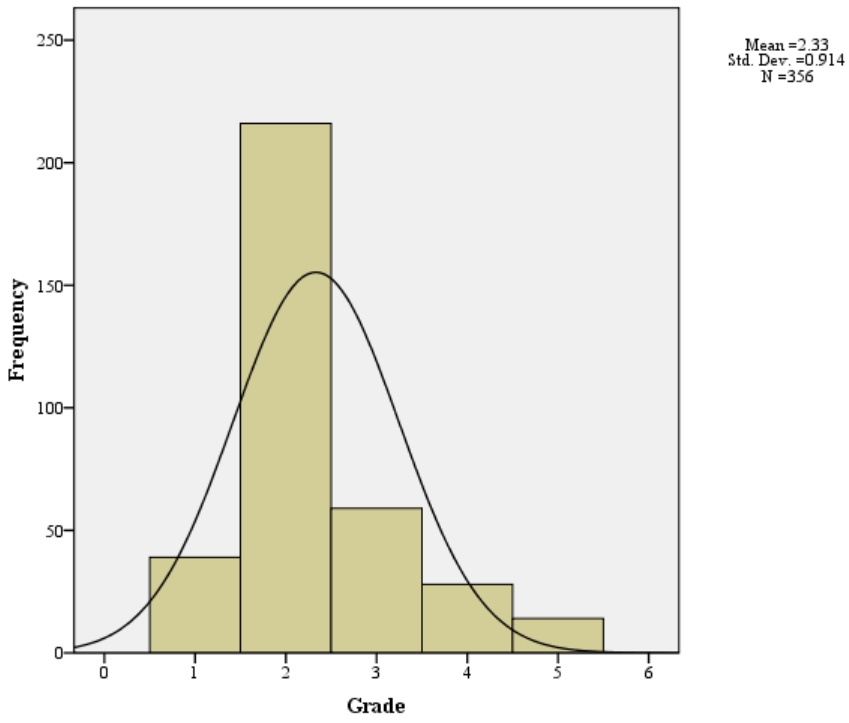


Figure IV-5: Distribution of disc degeneration grade

(1) Effect of AGE on disc degeneration grade

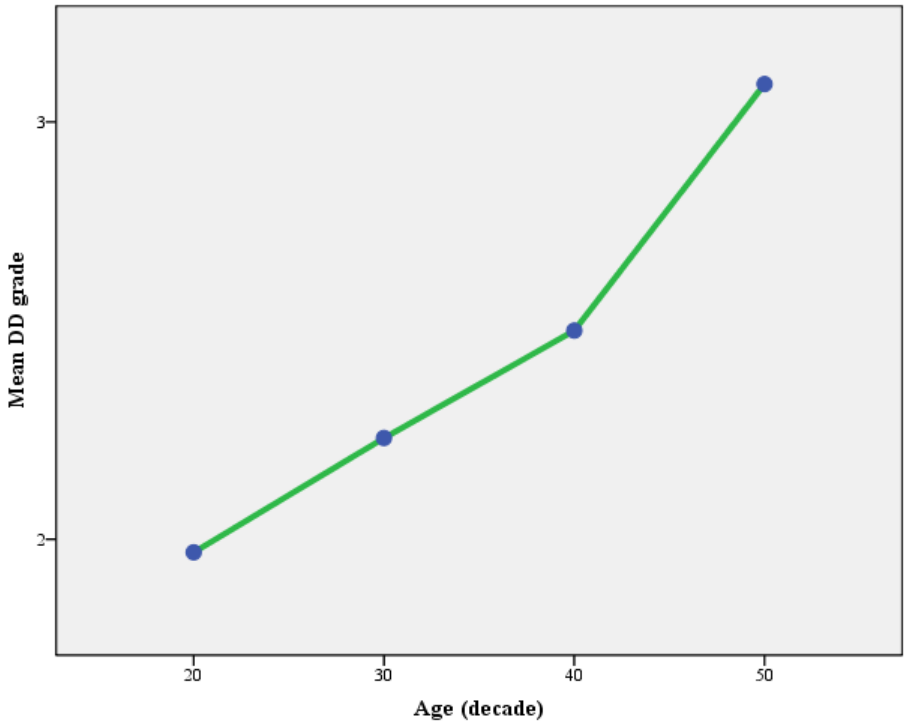


Figure IV-6: Effect of age on disc degeneration grade

Influence of age on disc degeneration when studied alone was strongly significant (Figure IV-6, Table IV-4). Disc degeneration increases as subject age and it follows linear trend in the first two decades. Trend increase ($p<0.0001$) in disc grade was observed in early forties and it seems intervertebral discs degenerate faster after the fourth decade.

Table IV-4: Effect of age on disc degeneration grade (LSD)

Fisher's Least Significant Difference (LSD) test **DD vs. AGE**

					95% Confidence Interval	
(I) Age	(J) Age	Mean Difference (I-J)	Std. Error	Sig.	Lower Bound	Upper Bound
20	30	**-0.27***	0.114	**0.016**	-0.50	-0.05
	40	**-0.53***	0.129	**< 0.0001**	-0.78	-0.28
	50	**-1.12***	0.155	**< 0.0001**	-1.43	-0.82
30	20	**0.27***	0.114	**0.016**	0.05	0.50
	40	**-0.26***	0.120	**0.033**	-0.49	-0.02
	50	**-0.85***	0.148	**< 0.0001**	-1.14	-0.56
40	20	**0.53***	0.129	**< 0.0001**	0.28	0.78
	30	**0.26***	0.120	**0.033**	0.02	0.49
	50	**-0.59***	0.160	**< 0.0001**	-0.91	-0.28
50	20	**1.12***	0.155	**< 0.0001**	0.82	1.43
	30	**0.85***	0.148	**< 0.0001**	0.56	1.14
	40	**0.59***	0.160	**< 0.0001**	0.28	0.91

***The mean difference is significant at the 0.05 level.**

(2) Effect of LEVEL on disc degeneration grade

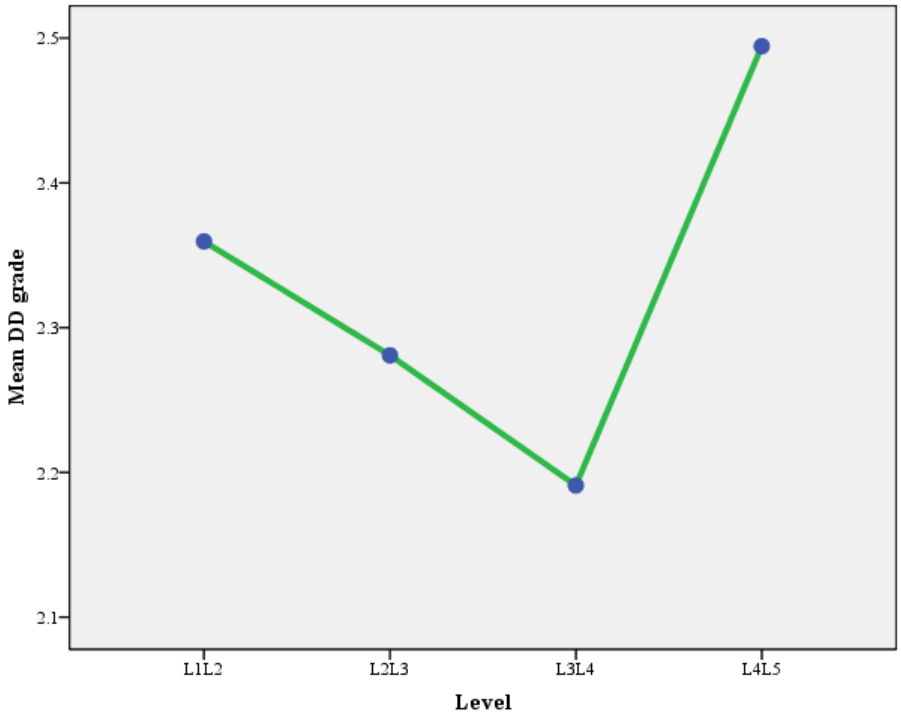


Figure IV-7: Effect of level on disc degeneration grade

Intervertebral disc demonstrated different distribution of degenerative changes throughout the lumbar levels. Higher grades of degeneration were observed in L1L2 and L4L5 (Figure IV-7). Power of level as a standalone predictor of disc degeneration was not proved as there was only one significant difference (L3L4 vs. L4L5, p=0.027). However, combined effect of level on disc degeneration will be further described.

(3) Effect of GENDER on disc degeneration grade

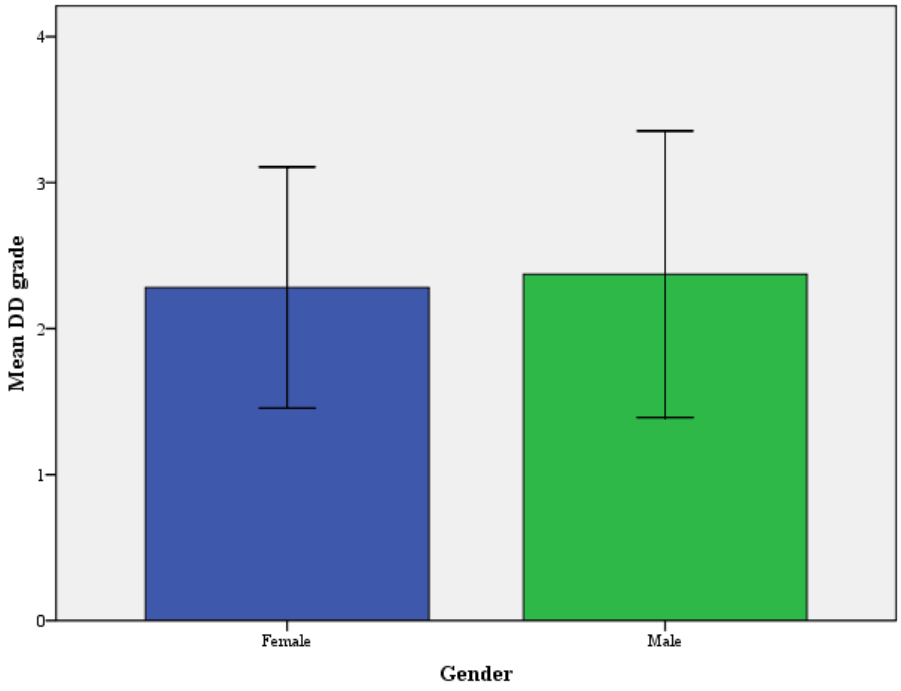


Figure IV-8: Effect of gender on disc degeneration grade

Influence of gender on disc degeneration was not proven in the statistical model where gender was the only independent variable (Figure IV-8). Possible effect of gender was further evaluated in the statistical models where the effect of independent variables was studied by their mutual combining.

(5) Influence of combined effects on disc degeneration grad

The effect of a combination of independent variables was evaluated in order to maximize the model's predictive ability by including more independent variables into the model. The combination of correctly selected variables might bring larger power in explaining the variation of the dependent variable into the model.

In the previous analysis, strong prediction power was found only in models with age variable; however some significance was also seen in the model with level variable. Thus, in the combined effects we will look at the age effect in dominance.

(i) AGE and LEVEL

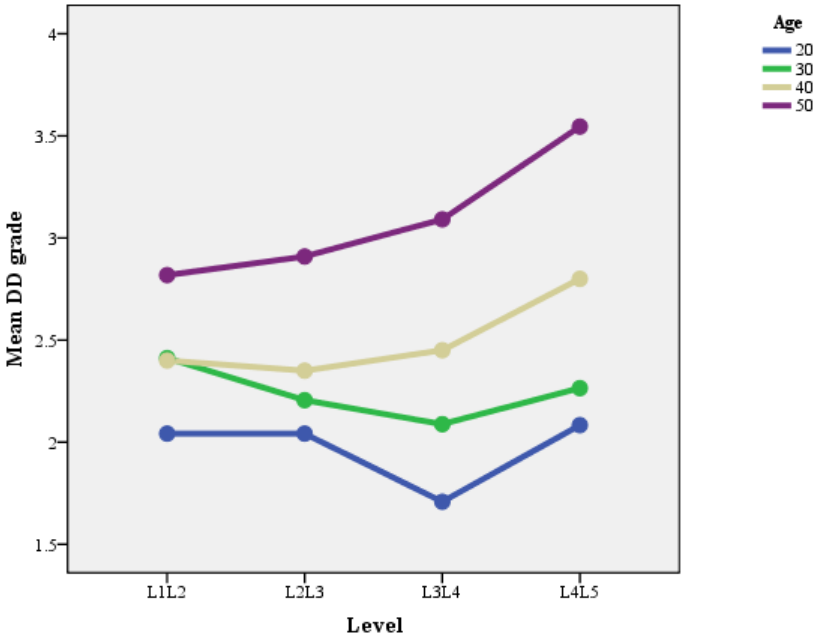


Figure IV-9: Combined effect of age and level on disc degeneration grade

Combined effect of age and level revealed no significant difference between mean values of disc degeneration between individual levels. As can be seen from Figure IV-9 above there are significant differences in mean disc degeneration grade between individual age groups by level. For instance,

amongst twenties there was significant difference between L3L4 and L4L5 (p=0.049) and among the fifties there was a significant difference between L1L2 and L4L5 (p=0.044).

(ii) AGE and GENDER

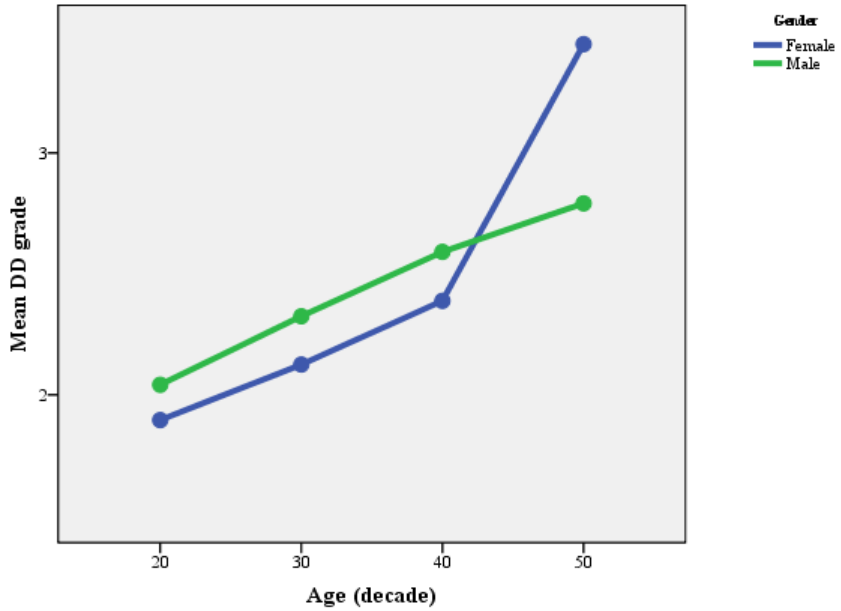


Figure IV-10: Combined effect of age and gender on disc degeneration grade

Combination of age and gender variables showed age related difference between genders during the aging process. Overall, a significant difference between both genders occurs in the fifth decade of life where female intervertebral disc tends to deviate from linear pace of degeneration in contrast with males. In females significance was observed between twenties and all other ages ($p<0.0001$), and at forties and fifties ($p<0.0001$) where degeneration significantly deviate from overall trend (Figure IV-10). Male subjects similarly showed significance between decades, having twenties different from forties and fifties at ($p=0.007$, $p=0.002$) and thirties different from fifties ($p=0.038$).

(iii) GENDER and LEVEL

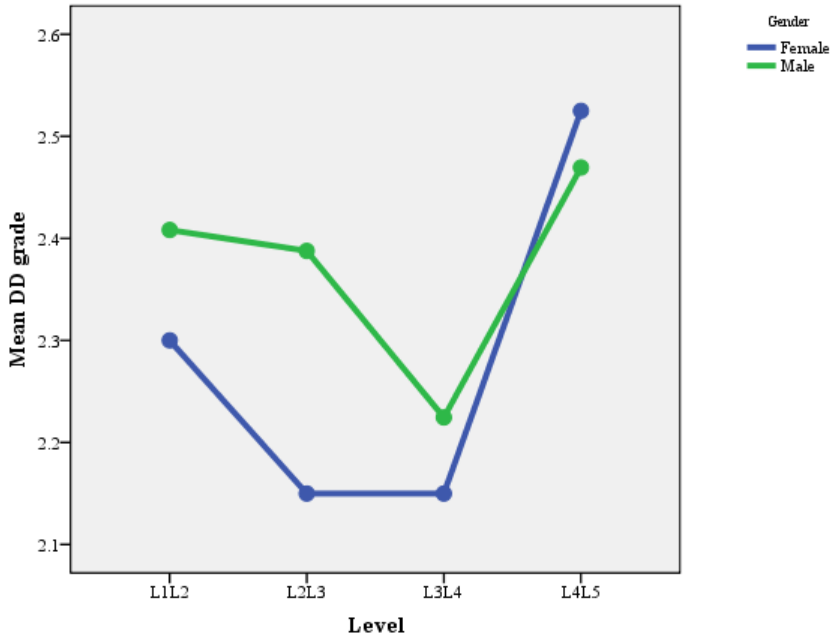


Figure IV-11: Combined effect of level and gender on disc degeneration grade

Distribution of mean values of disc degeneration with respect to combined effect of level and gender followed previously showed level dependent pattern. Gender difference showed no significant difference, however the Figure IV-11 demonstrates the difference in degeneration between male and female subjects at L4L5 level.

3.1.2 Facet joint osteoarthritis

728 individual facet joints from 91 subjects were evaluated for osteoarthritis (see Table IV-5). Three observers evaluated facet joint osteoarthritis grade on CT axial images two times. A total of 6 observations were analyzed for each individual facet joint. The mode value was calculated from all 6 observations. A perfect agreement (6/6) was observed in 32.1% of studied cases; a fair agreement (5/6) was observed in 28.8% cases; a good agreement (4/6) was observed in 26.3% cases; and a poor agreement (3/6) was observed in the remaining 12.8% of cases.

Table IV-5: Mean values of facet joint osteoarthritis grade with respect to gender, age, and level

		FJ OA grade – left side				**FJ OA grade – right side**			
		Count	Percent	Mean	SD	Count	Percent	Mean	SD
Gender	Female	164	45.1	2.23	0.47	164	45.1	2.15	0.42
	Male	200	54.9	2.06	0.40	200	54.9	2.04	0.44
	Total	364	100	2.11	0.44	364	100	2.11	0.44
Age	20	96	26.4	2.04	0.35	96	26.4	2.04	0.35
	30	140	38.5	2.08	0.42	140	38.5	2.01	0.42
	40	80	22.0	2.23	0.48	80	22.0	2.13	0.37
	50	48	13.2	2.31	0.55	48	13.2	2.33	0.60
	Total	364	100	2.11	0.44	364	100	2.11	0.44
Level	L1L2	91	25.0	2.03	0.23	91	25.0	1.98	0.33
	L2L3	91	25.0	2.07	0.36	91	25.0	2.02	0.36
	L3L4	91	25.0	2.13	0.50	91	25.0	2.10	0.37
	L4L5	91	25.0	2.30	0.57	91	25.0	2.25	0.57
	Total	364	100	2.11	0.44	364	100	2.11	0.44

(a) Inter/intra observer error estimation

Table IV-6,7 shows the degree of inter-observer and intra-observer agreement expressed as weighted kappa value (quadratic weights). As expected, intra-observer agreement (**bold**) was in general substantially higher than inter-observer agreement.

Table IV-6: Inter/Intra-observer evaluation for the facet joint osteoarthritis grading - left facet joint

left FJ	Observer 1 (first)	Observer 2 (first)	Observer 3 (first)
Observer 1 (second)	**0.727** 95% CI: 0.663 to 0.791	0.535 95% CI: 0.458 to 0.613	0.418 95% CI: 0.340 to 0.496
Observer 2 (second)	0.438 95% CI: 0.364 to 0.511	**0.738** 95% CI: 0.678 to 0.799	0.442 95% CI: 0.364 to 0.521
Observer 3 (second)	0.534 95% CI: 0.457 to 0.611	0.520 95% CI: 0.444 to 0.597	**0.619** 95% CI: 0.559 to 0.678

Table IV-7: Inter/Intra-observer evaluation for the facet joint osteoarthritis grading - right facet joint

right FJ	Observer 1 (first)	Observer 2 (first)	Observer 3 (first)
Observer 1 (second)	**0.693** 95% CI: 0.630 to 0.756	0.555 95% CI: 0.481 to 0.630	0.484 95% CI: 0.408 to 0.560
Observer 2 (second)	0.535 95% CI: 0.468 to 0.602	**0.738** 95% CI: 0.677 to 0.798	0.510 95% CI: 0.437 to 0.582
Observer 3 (second)	0.517 95% CI: 0.436 to 0.598	0.530 95% CI: 0.448 to 0.612	**0.599** 95% CI: 0.534 to 0.664

The validation of the grading system based on Pathria and Weishaupt grading scale revealed moderate agreement between the observers and substantial agreement between two gradings.

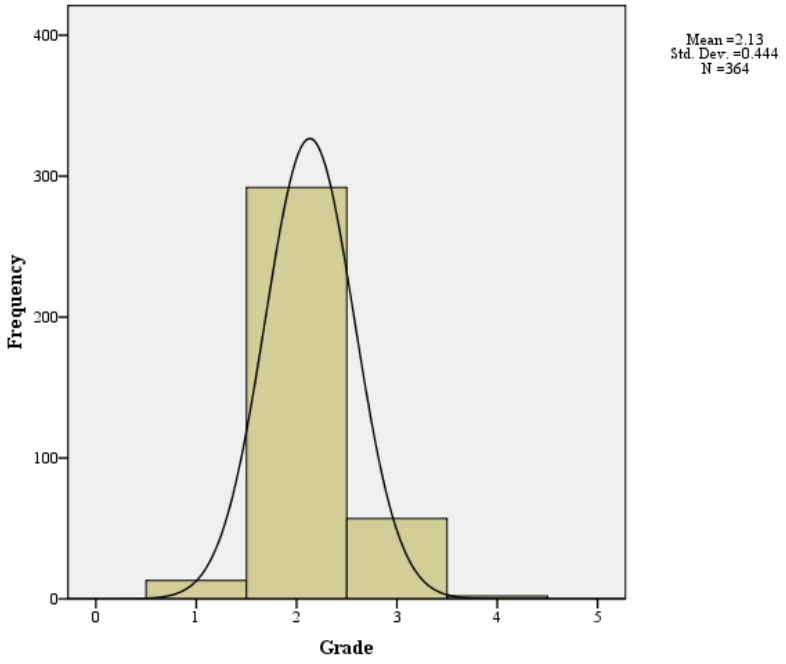


Figure IV-12: Distribution of facet joint osteoarthritis grade

(a) Statistical evaluation with respect to AGE, GENDER and LEVEL

The histogram revealed approximately a normally distributed sample population with the mean value of facet joint osteoarthritis grade being 2.13±0.44 (Figure IV-12: Distribution of facet joint osteoarthritis grade).

The facet joint is a paired type of a joint; therefore influence of side was evaluated first. There was no significant difference between osteoarthritis grade on the right and left side (p=0.1444). Therefore, in subsequent analysis both sides were independently introduced into the statistical model.

(1) Effect of AGE on the facet joint osteoarthritis grade

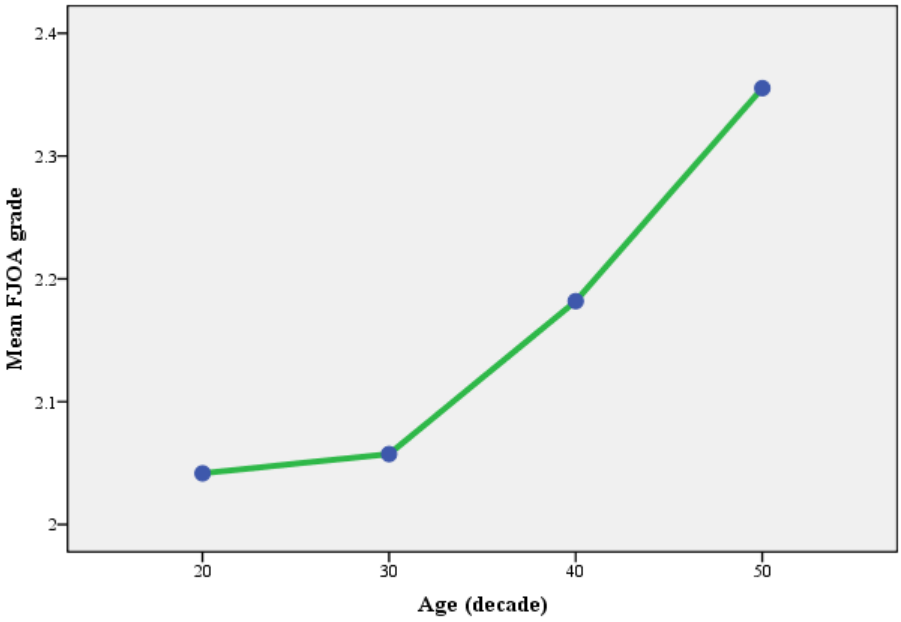


Figure IV-13: Effect of age on the facet joint osteoarthritis grade

Analysis showed a strong relationship between age and progression of osteoarthritis in the facet joint (Table IV-8). Increase with age is shown (Figure IV-13).

Table IV-8: Effect of age on the facet joint osteoarthritis grade (LSD)

Fisher's Least Significant Difference (LSD) test **FJOA grade vs AGE**

(I) Age	(J) Age	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
20	30	0.00	0.040	0.905	-.08	.07
	40	**-0.13***	0.046	**0.004**	-.22	-.04
	50	**-0.28***	0.053	**< 0.0001**	-.39	-.18
30	20	0.0001	0.040	0.905	-.07	.08
	40	**-0.13***	0.042	**0.002**	-.21	-.05
	50	**-0.28***	0.051	**< 0.0001**	-.38	-.18
40	20	**0.13***	0.046	**0.004**	.04	.22
	30	**0.13***	0.042	**0.002**	.05	.21
	50	**-0.15***	0.055	**0.007**	-.26	-.04
50	20	**0.28***	0.053	**< 0.0001**	.18	.39
	30	**0.28***	0.051	**< 0.0001**	.18	.38
	40	**0.15***	0.055	**0.007**	.04	.26

***. The mean difference is significant at the 0.05 level.**

(2) Effect of LEVEL on the facet joint osteoarthritis grade

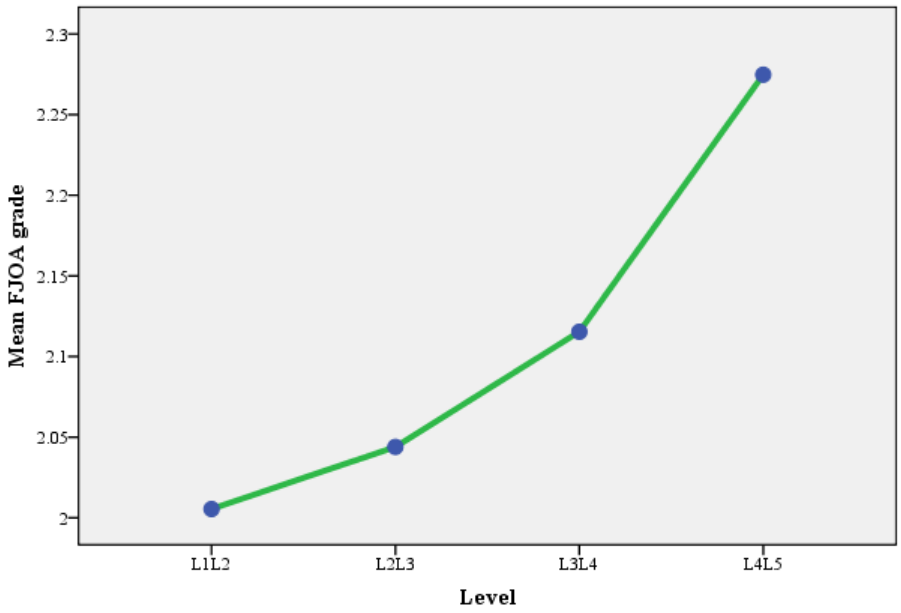


Figure IV-14: Effect of level on facet joint osteoarthritis grade

Effect of level on facet joint osteoarthritis grade was assessed with significance indicated in the Table IV-9. Caudal levels in general showed more significant difference than cranial levels (Figure IV-14).

Table IV-9: Effect of level on facet joint osteoarthritis grade (LSD)

Fisher's Least Significant Difference (LSD) test **FJOA grade vs. LEVEL**

(I) Level	(J) Level	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
L1L2	L2L3	-0.04	0.045	0.390	-.13	.05
	L3L4	**-0.11***	0.045	**0.014**	-.20	-.02
	L4L5	**-0.27***	0.045	**< 0.0001**	-.36	-.18
L2L3	L1L2	0.04	0.045	0.390	-.05	.13
	L3L4	-0.07	0.045	0.110	-.16	.02
	L4L5	**-0.23***	0.045	**< 0.0001**	-.32	-.14
L3L4	L1L2	**0.11***	0.045	**0.014**	.02	.20
	L2L3	0.07	0.045	0.110	-.02	.16
	L4L5	**-0.16***	0.045	**< 0.0001**	-.25	-.07
L4L5	L1L2	**0.27***	0.045	**0.0001**	.18	.36
	L2L3	**0.23***	0.045	**< 0.0001**	.14	.32
	L3L4	**0.16***	0.045	**< 0.0001**	.07	.25

***. The mean difference is significant at the 0.05 level.**

(3) Effect of GENDER on the facet joint osteoarthritis grade

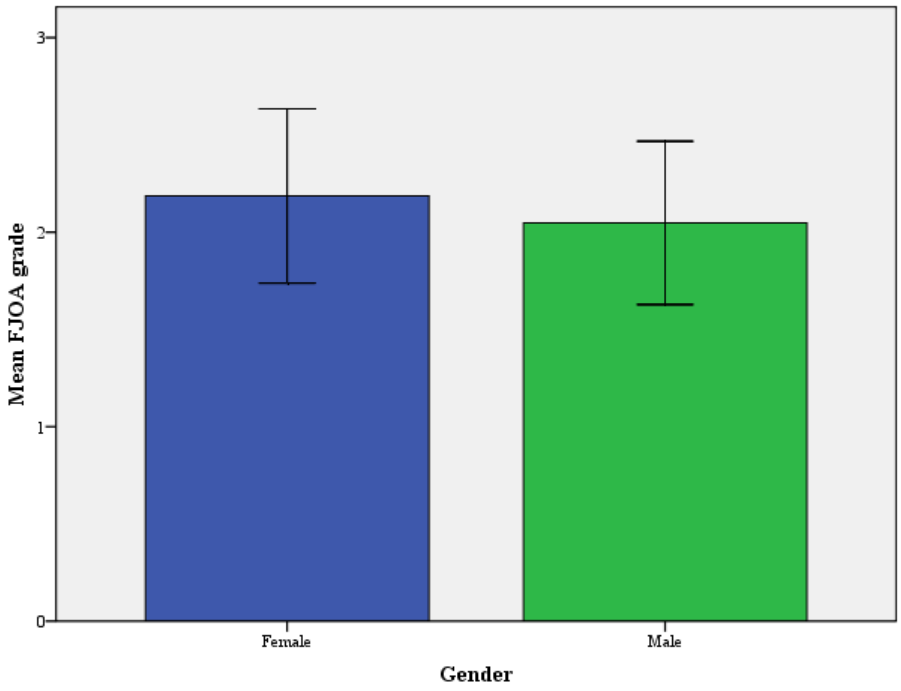


Figure IV-15: Effect of gender on the facet joint osteoarthritis grade

Effect of gender on the facet joint osteoarthritis grade was evaluated to be very significant ($p<0.0001$) (Figure IV-15).

(4) Influence of combined effects on osteoarthritis grade

In the previous analysis, significant effect on predictability was assessed for all three studied independent variables. Naturally, age was identified as an important factor influencing degeneration of the facet joint. In addition, level and gender of the study subject seem to play an important role in the degenerative process. As a consequence, all three variables were combined in the statistical model and their interactions were evaluated.

(i) AGE and LEVEL

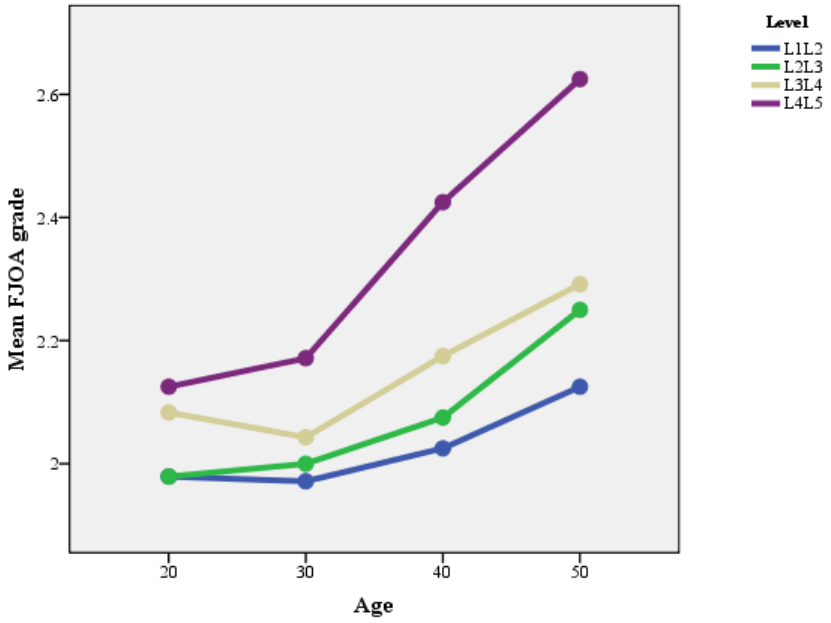


Figure IV-16: Combined effect of age and level on the facet joint osteoarthritis grade

Analysis revealed a significant difference of the facet joint osteoarthritis grade between individual levels during one's lifetime (Figure IV-16). Osteoarthritic changes are significantly more prevalent at the L4L5 level when compared to other levels at every age group, however significance was not shown. Remaining levels showed no difference. Age related changes within individual levels were more significant especially when comparing younger individuals (second, third decade) with older (forth, fifth

decade). There was significant difference between twenties and fifties at L1L2 (p=0.011), and L2L3 (p=0.004). A significant difference was also at L3L4 between twenties and all remaining levels (p<0.001); and fifties and all remaining levels (p<0.0001). At L4L5 significant increase of degeneration have been identified (Figure IV-16). Twenties significantly differed from forties and fifties (p=0.029 and p=<0.0001); thirties were different from forties (p=0.001) and fifties were different from twenties and thirties (p<0.0001, p=0.001).

(ii) AGE and GENDER

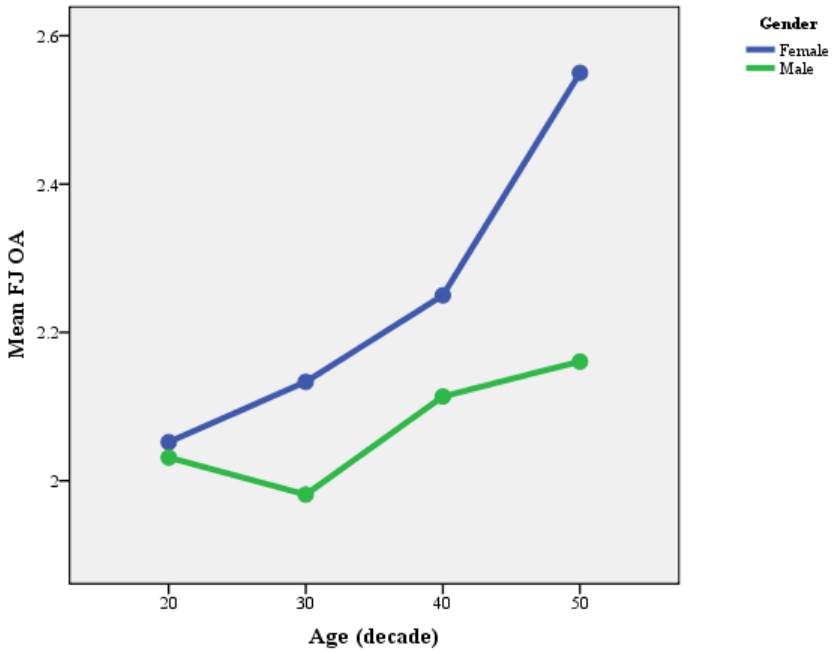


Figure IV-17: Combined effect of age and gender on the facet joint osteoarthritis grade

Gender of the study subjects is an important covariate to explain variation of the facet joint osteoarthritis grade. Significant changes were observed between the genders (p<0.0001) at every decade, except twenties (Figure IV-17). Female experienced more degenerative changes in the facet joint and degeneration process at fifth decade happened at a steeper pace (p<0.0001 for remaining age groups).

(iii) GENDER and LEVEL

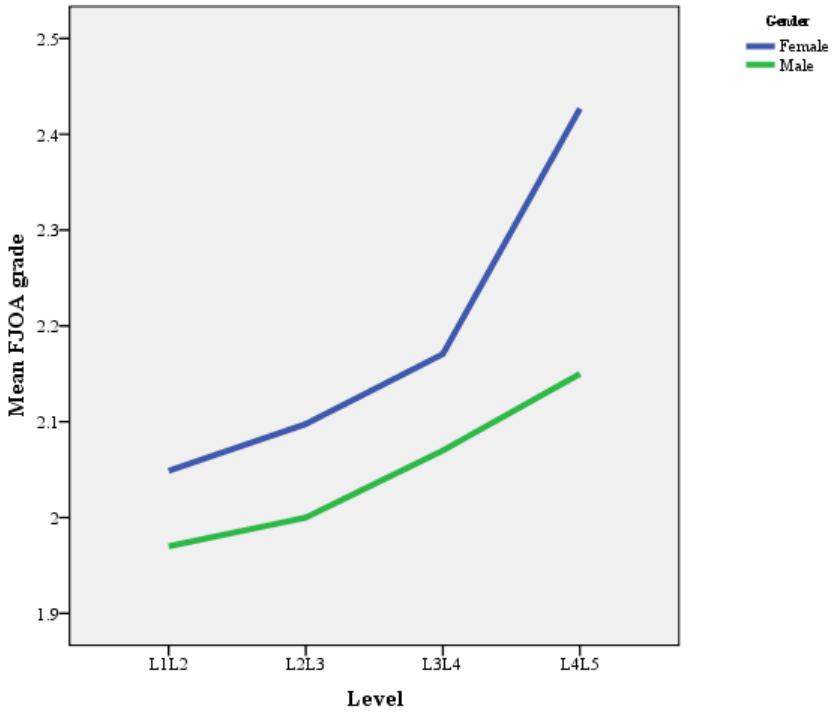


Figure IV-18: Combined effect of gender and level on the facet joint osteoarthritis grade

The average grade of the facet joint osteoarthritis was increasing with lowering the spinal level for both genders (Figure IV-18). The largest variation between genders was observed at L4L5 ($p<0.0001$).

3.1.3 Correlations between quantitative measures of spinal degeneration

The correlation between intervertebral disc degeneration grade and facet joint osteoarthritis grade has shown that facet joints degenerate faster than intervertebral disc. The grade of the facet joint osteoarthritis in females in their twenties was higher than disc degeneration grade at L2L3, L3L4 and L4L5 level, and in males at L3L4. Facet joint osteoarthritis grade was also higher than intervertebral disc in female subjects at L2L3 in the third decade (Figure IV-19).

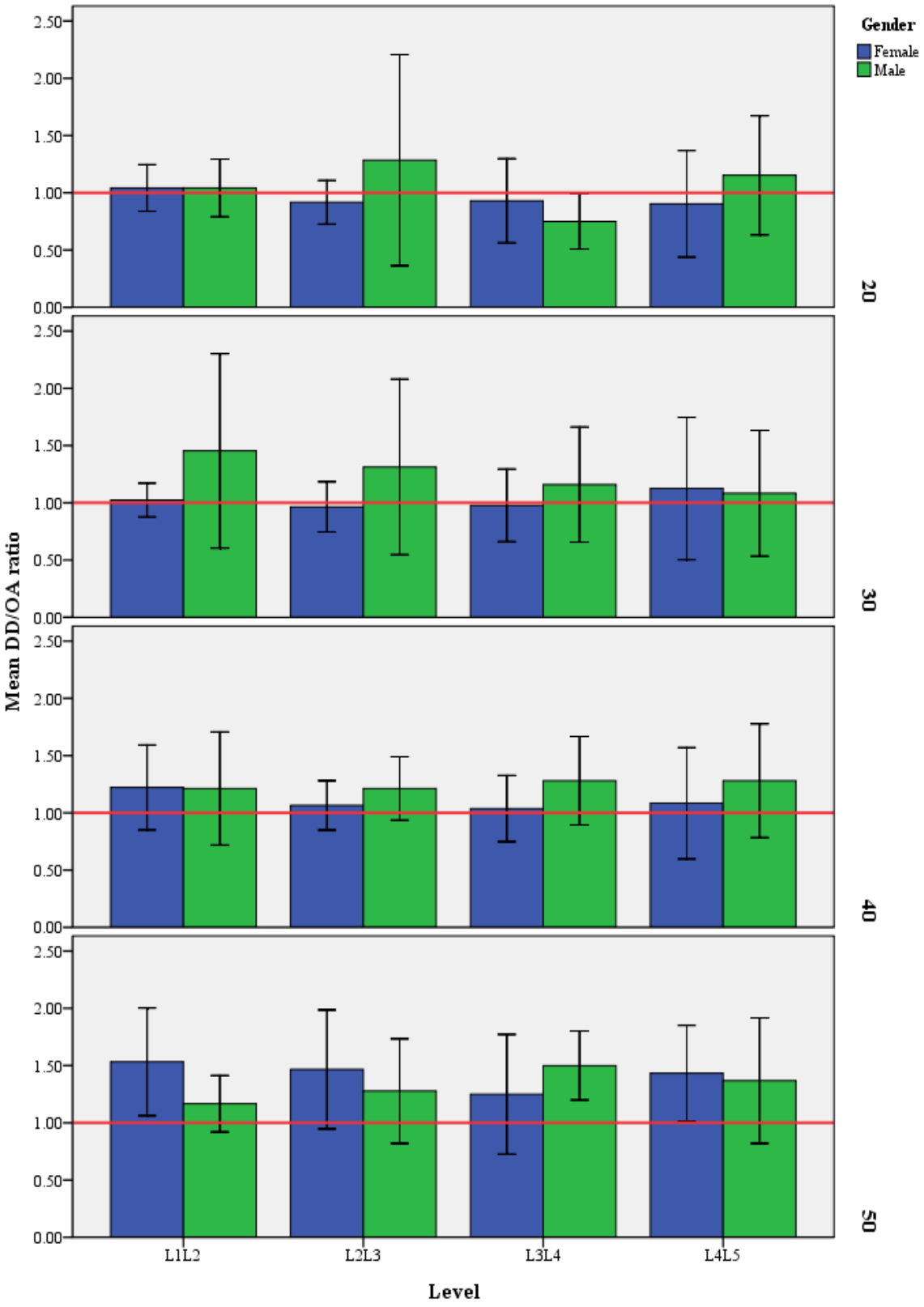


Figure IV-19: Effect of age, level and gender on the spinal degeneration index

3.2. Quantitative measures of spinal degeneration

Quantitative measures are represented by quantitative variables that can be measured in the usual sense. Measurements made on quantitative variables convey information regarding amount or scale.

3.2.1 Facet joint space width

728 individual facet joints from 91 subjects were evaluated for osteoarthritis (see Table IV-10: Mean values of facet joint space width with respect to gender, age, and level). Mean values and standard deviations were calculated with respect to age, gender, level and zone.

Table IV-10: Mean values of facet joint space width with respect to gender, age, and level

		FJSW – left side				FJSW – right side			
		Count	Percent	Mean	SD	Count	Percent	Mean	SD
Gender	Female	164	45.1	2.23	0.47	164	45.1	2.15	0.42
	Male	200	54.9	2.06	0.40	200	54.9	2.04	0.44
	Total	364	100	2.13	0.44	364	100	2.09	0.43
Age	20	96	26.4	2.04	0.35	96	26.4	2.04	0.35
	30	140	38.5	2.08	0.42	140	38.5	2.01	0.42
	40	80	22.0	2.22	0.48	80	22.0	2.12	0.37
	50	48	13.1	2.31	0.55	48	13.1	2.33	0.60
	Total	364	100	2.13	0.44	364	100	2.09	0.43
Level	L1L2	91	25.0	2.03	0.23	91	25.0	1.98	0.33
	L2L3	91	25.0	2.07	0.36	91	25.0	2.02	0.36
	L3L4	91	25.0	2.13	0.49	91	25.0	2.10	0.67
	L4L5	91	25.0	2.30	0.57	91	25.0	2.25	0.57
	Total	364	100	2.13	0.44	364	100	2.09	0.43

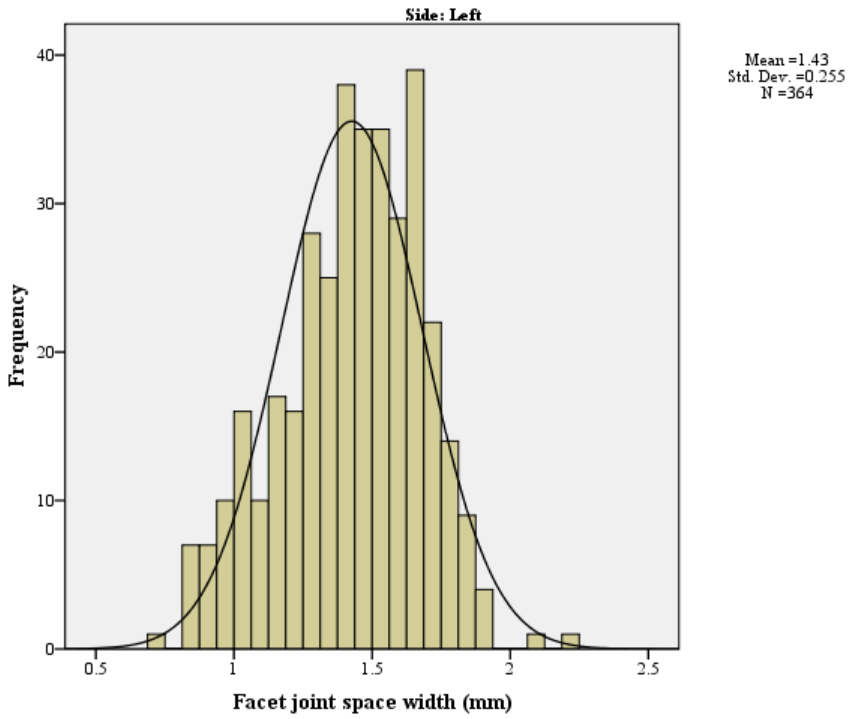


Figure IV-20: Distribution of the facet joint space width - left side

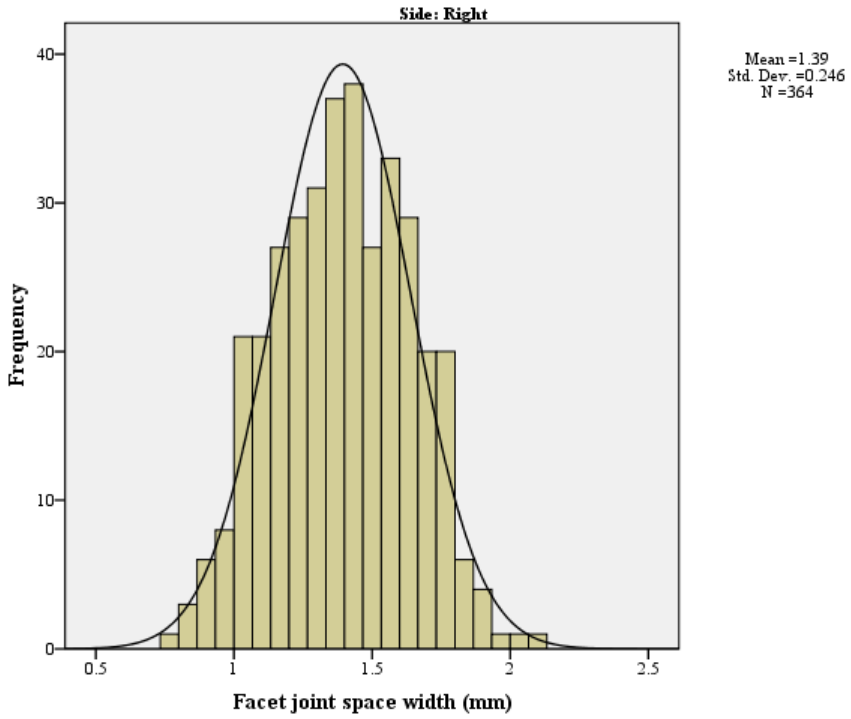


Figure IV-21: Distribution of the facet joint space width - right side

(a) Statistical evaluation with respect to AGE, GENDER, and LEVEL

Histograms proved normal distribution of the facet joint space width for both sides of the facet joints (Figure IV-20,21) with mean values of facet joint gap 1.43±0.26 mm for the left side and 1.39±0.25 for the right side. Parametric methods can be used for statistical analysis.

(1) Effect of AGE on facet joint space width

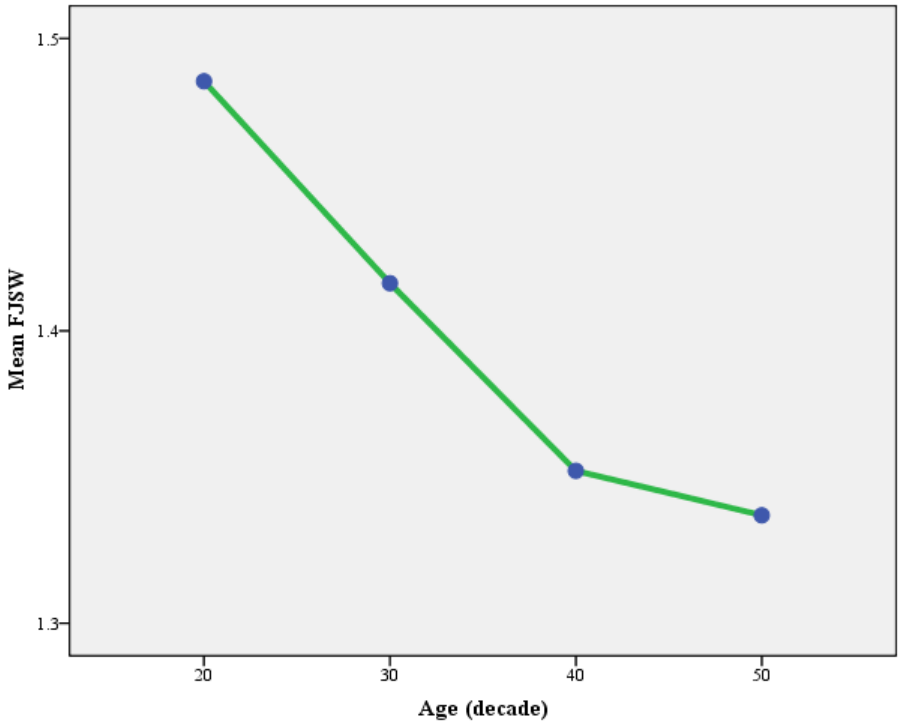


Figure IV-22: Effect of age on the facet joint space width

Influence of age on facet joint space width when studied alone was strongly significant (Figure IV-222, Table IV-11). Facet joint gap decreases as subject ages following a linear trend in the first three decades. Trend changes at forties when facet joint narrowing slows down.

Table IV-11: Effect of age on facet joint space width (LSD)

Facet joint space width (mm) LSD **FJSW vs. AGE**

(I) Age	(J) Age	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
20	30	**.07***	.013	**.000**	.04	.10
	40	**.13***	.015	**.000**	.10	.16
	50	**.15***	.018	**.000**	.11	.18
30	20	**-.07***	.013	**.000**	-.10	-.04
	40	**.06***	.014	**.000**	.04	.09
	50	**.08***	.017	**.000**	.05	.11
40	20	**-.13***	.015	**.000**	-.16	-.10
	30	**-.06***	.014	**.000**	-.09	-.04
	50	.02	.018	.405	-.02	.05
50	20	**-.15***	.018	**.000**	-.18	-.11
	30	**-.08***	.017	**.000**	-.11	-.05
	40	-.02	.018	.405	-.05	.02

***. The mean difference is significant at the 0.05 level.**

(2) Effect of LEVEL on facet joint space width

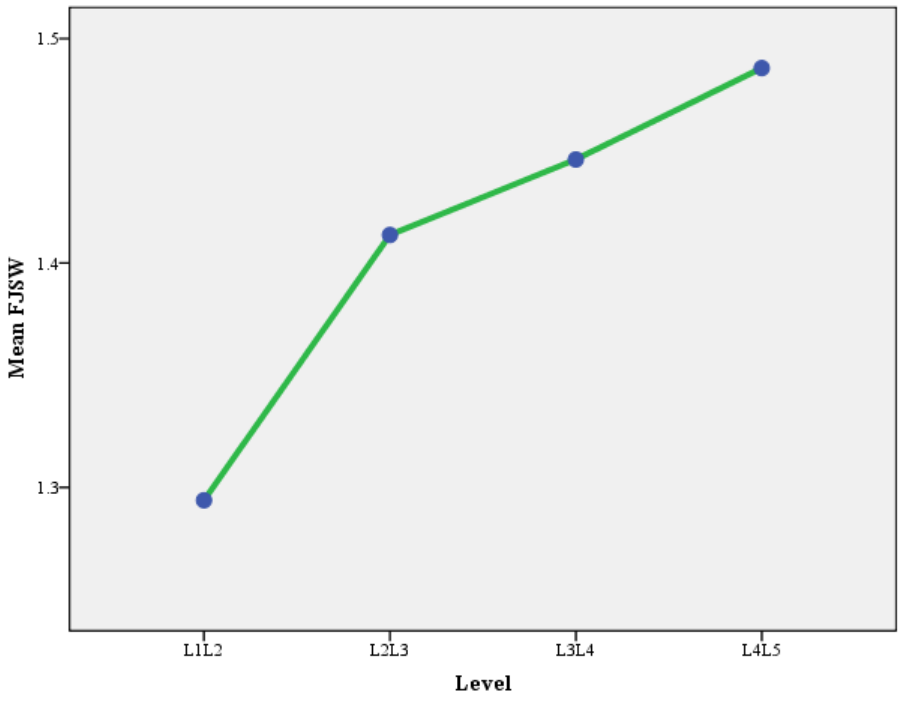


Figure IV-23: Effect of level on the facet joint space width

Effect of level on facet joint space width was assessed with significance indicated in the Table IV-12. Caudal levels in general showed more significant difference than cranial levels (Figure IV-233).

Table IV-12: Effect of level on facet joint space width (LSD)

Facet joint space width (mm) LSD **FJSW vs. LEVEL**

(I) Level	(J) Level	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
L1L2	L2L3	**-.12***	.036	**.001**	-.19	-.05
	L3L4	**-.18***	.036	**.000**	-.25	-.10
	L4L5	**-.22***	.036	**.000**	-.29	-.15
L2L3	L1L2	**.12***	.036	**.001**	.05	.19
	L3L4	-.06	.036	.116	-.13	.01
	L4L5	**-.10***	.036	**.004**	-.17	-.03
L3L4	L1L2	**.18***	.036	**.000**	.10	.25
	L2L3	.06	.036	.116	-.01	.13
	L4L5	-.05	.036	.196	-.12	.02
L4L5	L1L2	**.22***	.036	**.000**	.15	.29
	L2L3	**.10***	.036	**.004**	.03	.17
	L3L4	.05	.036	.196	-.02	.12

***. The mean difference is significant at the 0.05 level.**

(3) Effect of GENDER on facet joint space width

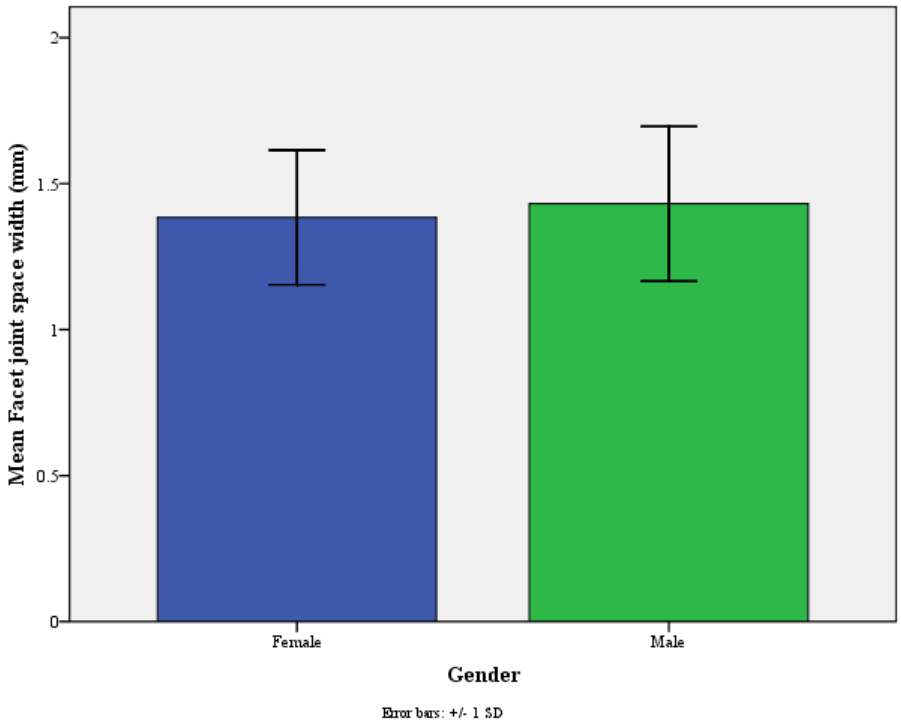


Figure IV-24: Effect of gender on the facet joint space width

Effect of gender on the facet joint space width was evaluated to be significant (p=0.0122) (Figure IV-24).

(4) Influence of combined effects on facet joint space width

In the previous analysis, significant effect on predictability was assessed for all three independent variables. Naturally, age was identified as an important factor influencing narrowing of the facet joint. In addition, level and gender of the study subject seem to play an important role in the explaining changes of the facet joint space width. As a consequence, all three variables were combined in the statistical model and their interactions were evaluated.

(i) AGE and LEVEL

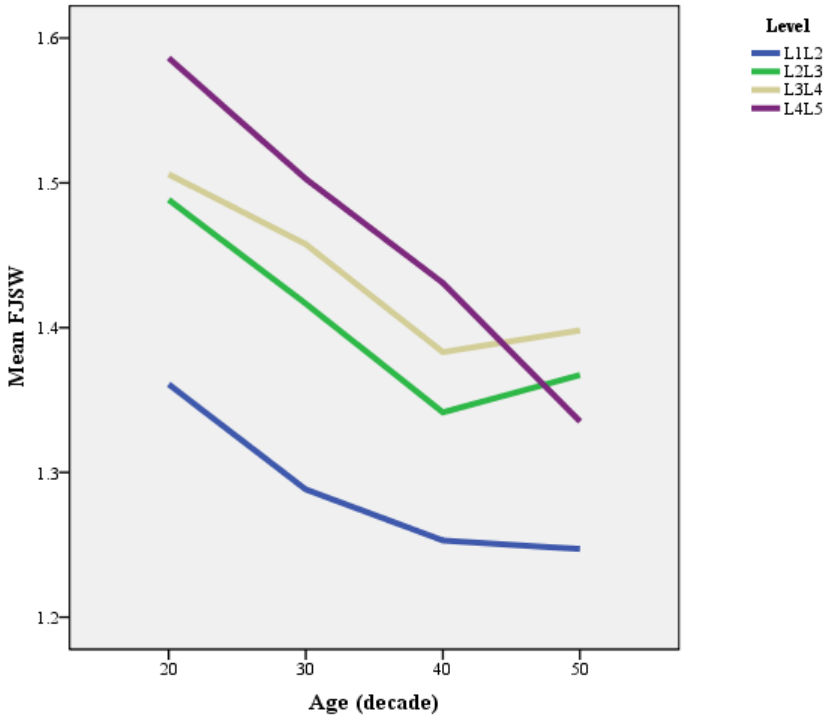


Figure IV-25: Combined effect of age and level on the facet joint space width

Facet joint space width changed significantly with age and level (Figure IV-25). When two factors are combined there is significant difference between L1L2 and all other levels at twenties and thirties ($p<0.0001$).

(ii) AGE and GENDER

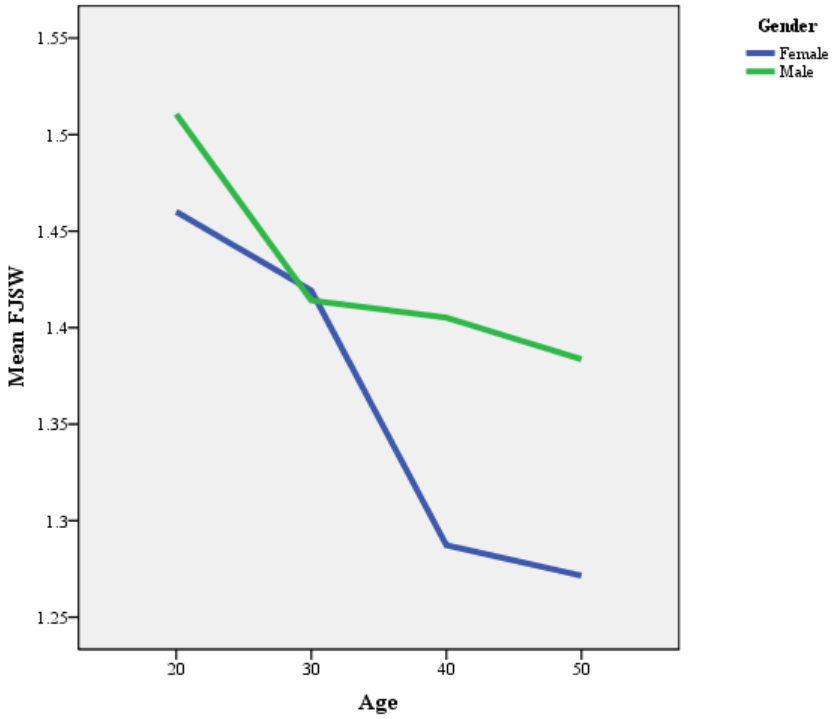


Figure IV-26: Combined effect of age and gender on facet joint space width

Both age and gender were highly significant when analyzed alone, however when combined only females showed significant differences with age. Particularly, twenties and thirties were significantly different from forties and fifties (Figure IV-266, Table IV-13).

Table IV-13: Effect of age and gender on facet joint space width (LSD)

Facet joint space width (mm) LSD **FJSW vs. AGE and GENDER - females**

(I) Age	(J) Age	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
20	30	.06	.045	.194	-.03	.15
	40	**.19***	.051	**.000**	.09	.29
	50	**.19***	.062	**.002**	.07	.32
30	20	-.06	.045	.194	-.15	.03
	40	**.13***	.049	**.010**	.03	.23
	50	**.13***	.060	**.027**	.02	.25
40	20	**-.19***	.051	**.000**	-.29	-.09
	30	**-.13***	.049	**.010**	-.23	-.03
	50	.01	.065	.932	-.12	.13
50	20	**-.19***	.062	**.002**	-.32	-.07
	30	**-.13***	.060	**.027**	-.25	-.02
	40	.00	.065	.932	-.13	.12

***. The mean difference is significant at the 0.05 level.**

(iii) GENDER and LEVEL

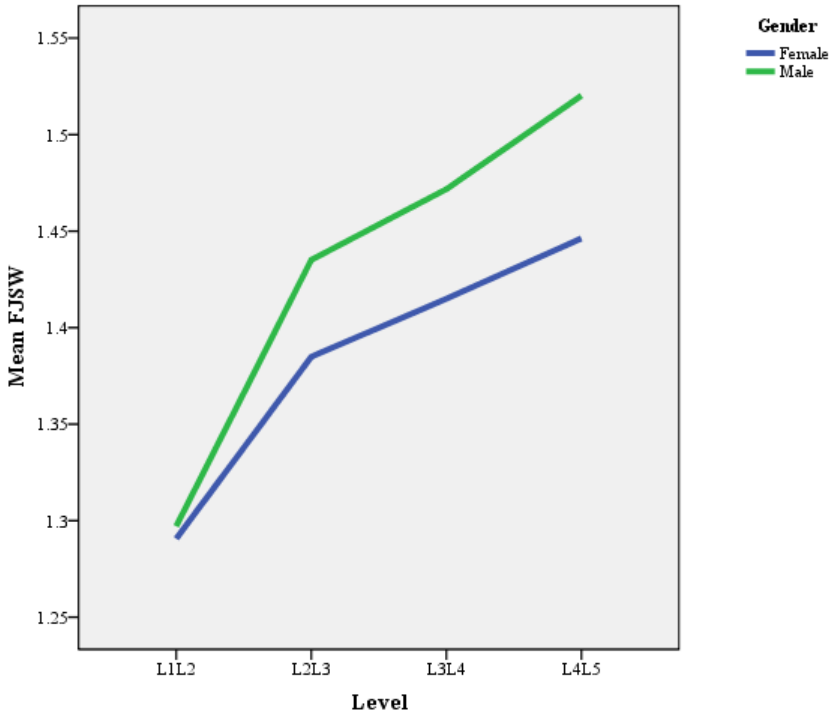


Figure IV-27: Combined effect of gender and level on facet joint space width

Model of combined effects of gender and level revealed significant difference between genders in the upper levels (Figure IV-277). Within the levels, for both genders there were significant differences between L1L2 and all remaining levels ($p<0.0001$).

(b) Zonal differences of facet joint space width

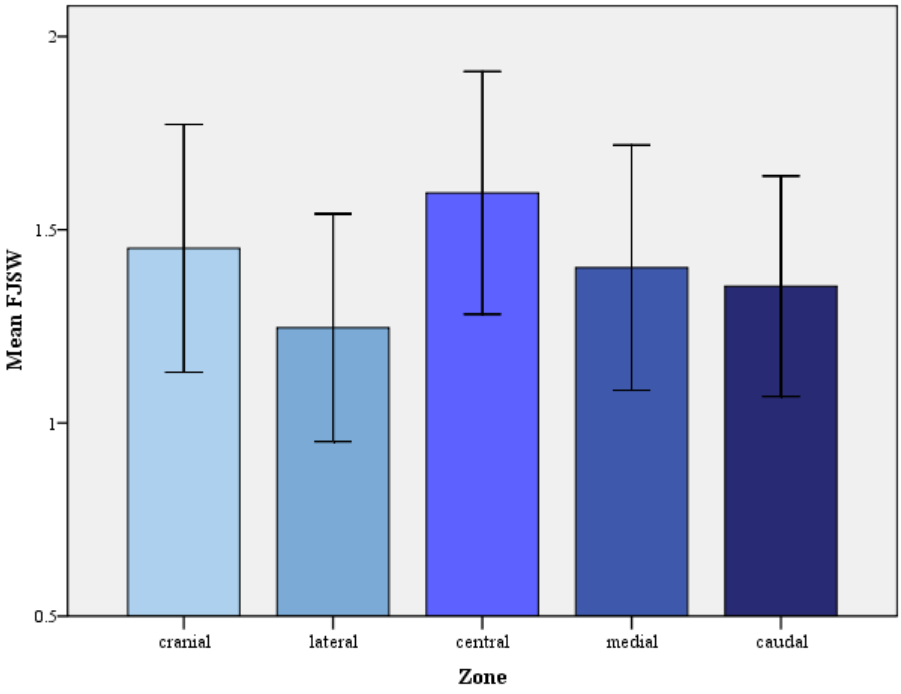


Figure IV-28: Zonal distribution of the facet joint space width

Influence of zone as a grouping variable revealed significant differences between them ($p<0.0001$). Facet joint space width was significantly different in every zone (Figure IV-288).

(1) Influence of combined effects on facet joint space width with respect to ZONE

In the previous analysis, facet joint surface zone was identified to have significant effects on predictability of the model. As a consequence, combined effects of zone and combination of level, age and gender were evaluated.

(i) ZONE and LEVEL

Analysis showed that there is a significant increase in facet joint space width with every decrease of the spinal level (Figure IV-299). Differences within the zone were significant for every zone except caudal. The effect of level will be further evaluated in combined model with age.

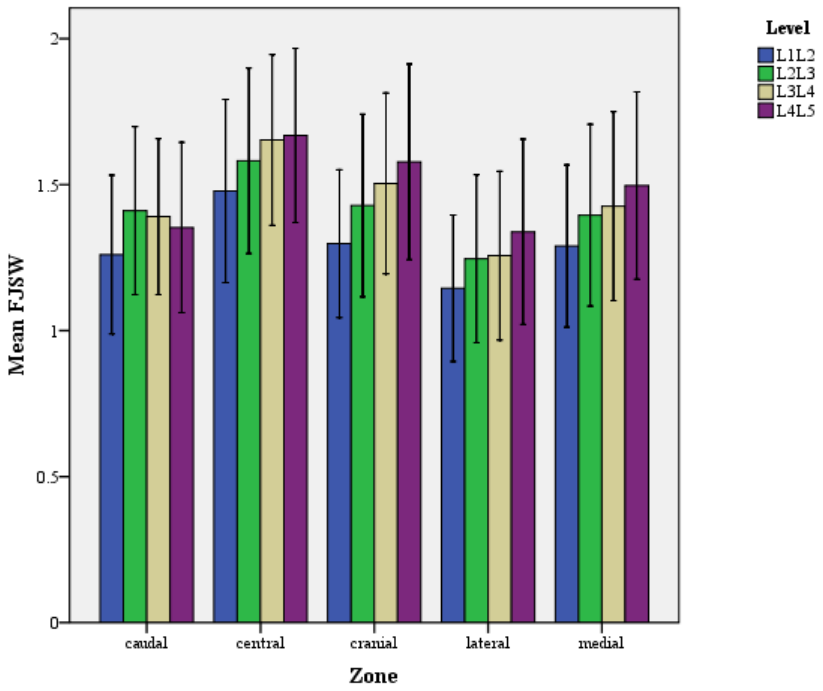


Figure IV-29: Combined effect of zone and level on facet joint space width

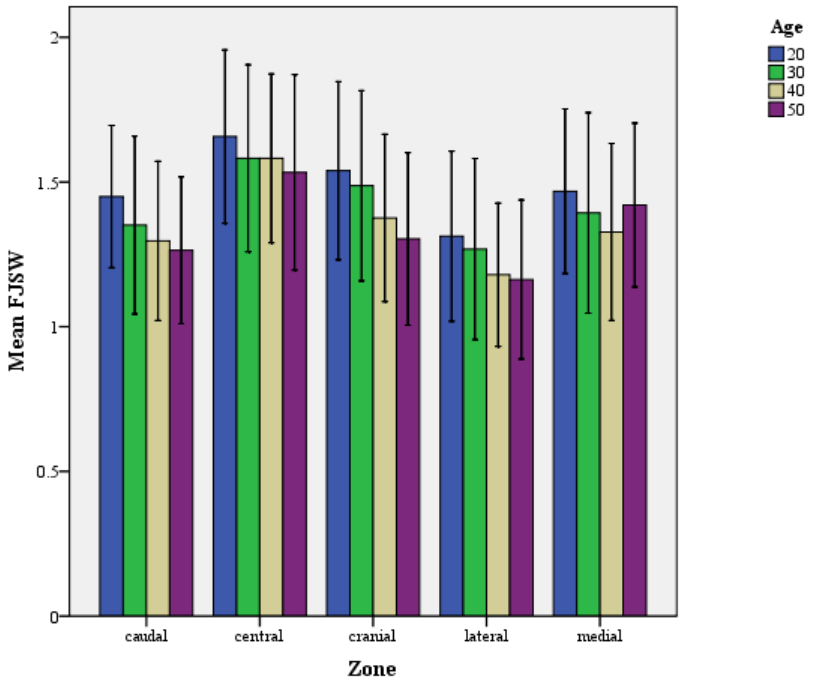


Figure IV-30: Combined effect of zone and age on facet joint space width

(ii) ZONE and AGE

Significant differences were observed when the combined factor of zone and age was evaluated. Differences between decades were significant at every zone (Figure IV-30). Facet joint space width was gradually decreasing with age at every zone (except fifth decade in the medial zone). Age, together with level, seems to explain variations in facet joint space width the best and will be further investigated in the combined model with reference to zone.

(iii) ZONE and GENDER

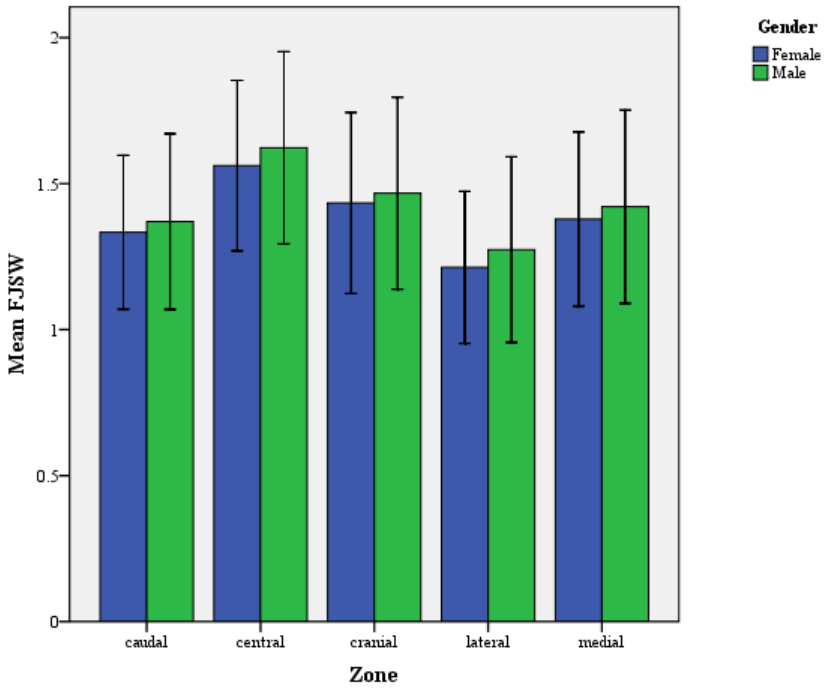


Figure IV-31: Combined effect of zone and gender on facet joint space width

In average, male subjects tend to have wider facet joint gap (Figure IV-31). Differences between the genders were significant at p=0.0122.

(iv) ZONE and AGE and LEVEL

The data presented in Figure IV-322 show zonal differences facet joint space width distribution at different levels with respect to age. Facet joint space width changes started in the fourth decade in the

peripheral zones for L1L2 and L2L3 and continued to fifth decade. In L3L4, only the superior and inferior zones shows significant changes in the forth and fifth decade. For L4L5, narrowing started as early as in the third decade in the inferior zones and implicates all remaining zones after the fourth decade.

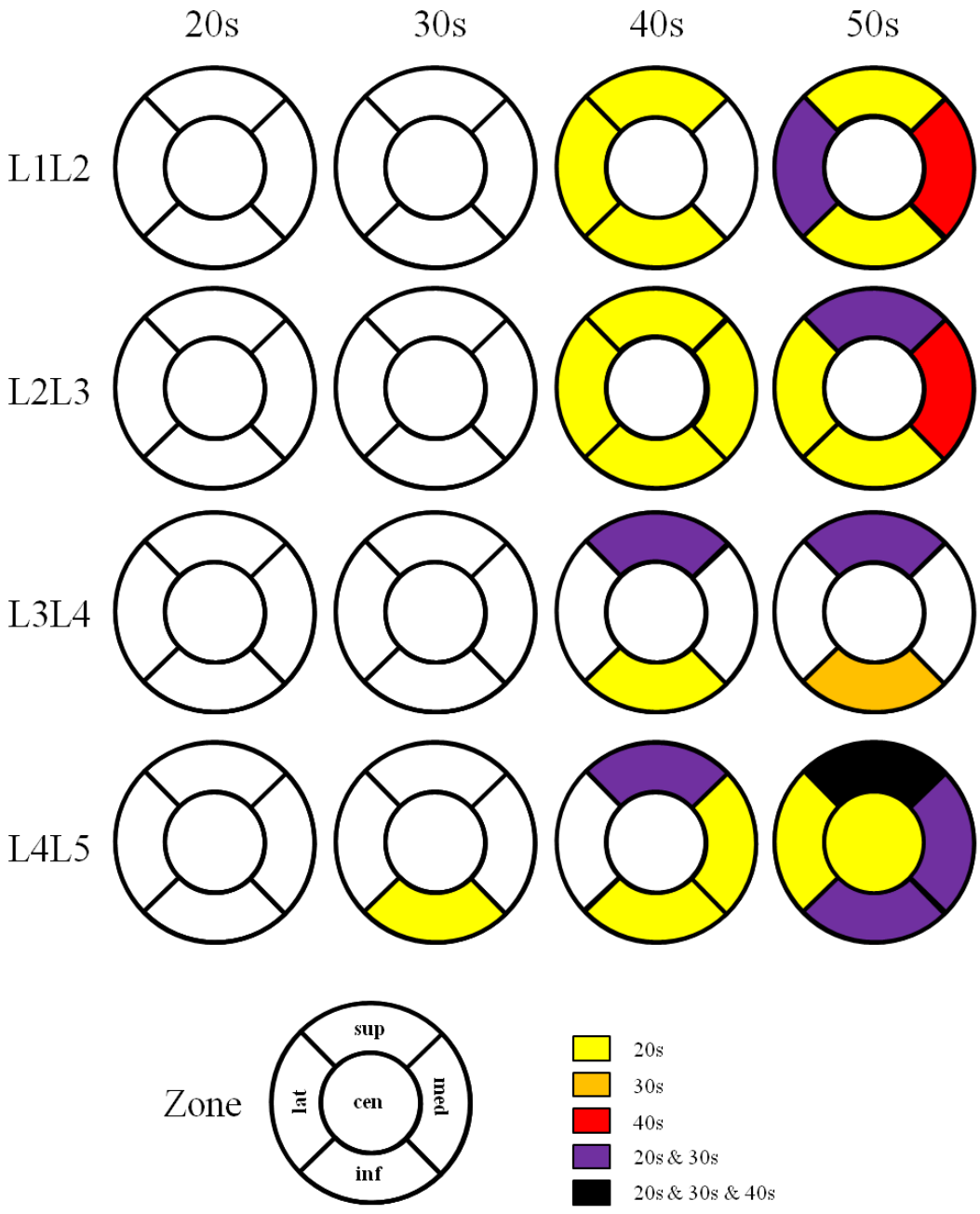


Figure IV-32: Combined effect of zone, age and level

3.2.2 Disc height measurement

Disc heights of 364 individual intervertebral disc models from 91 subjects were calculated (see Table IV-14). Mean values and standard deviations were reported with respect to age, gender, level and zone.

Table IV-14: Mean values of disc height with respect to gender, age and level

		DH			
		Count	Percent	Mean	SD
Gender	Female	164	45.1%	7.2	1.3
	Male	200	54.9%	7.7	1.3
	Total	364	100.0%	7.6	1.3
Age	20	96	26.4%	7.3	1.2
	30	140	38.5%	7.4	1.5
	40	80	22.0%	7.6	1.2
	50	48	13.2%	7.2	1.3
	Total	364	100.0%	7.4	1.3
Level	L1L2	91	26.4%	7.3	1.2
	L2L3	91	38.5%	7.4	1.5
	L3L4	91	22.0%	7.6	1.2
	L4L5	91	13.2%	7.2	1.34
	Total	364	100.0%	7.4	1.3

(a) Statistical evaluation with respect to AGE, GENDER, and LEVEL

Histograms showed that the sample is normally distribution with mean values of facet joint gap 7.45±1.39 mm (Figure IV-33). Statistical evaluation may use parametric methods.

Effects of independent variables were studied in order to identify covariates that explain the variation of dependent variable the best. Age, gender and level entered statistical model independently and in combination.

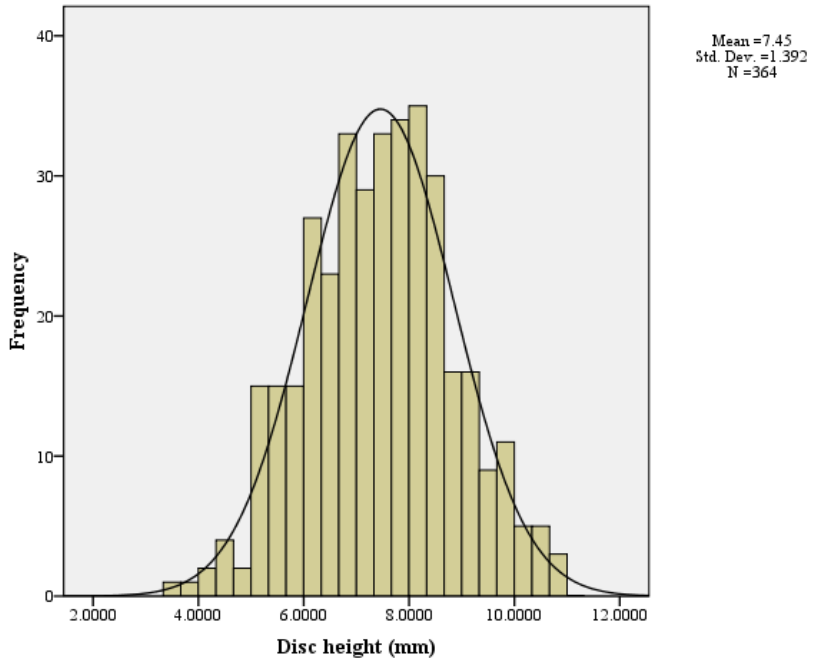


Figure IV-33: Distribution of disc height

(1) Effect of AGE on disc height

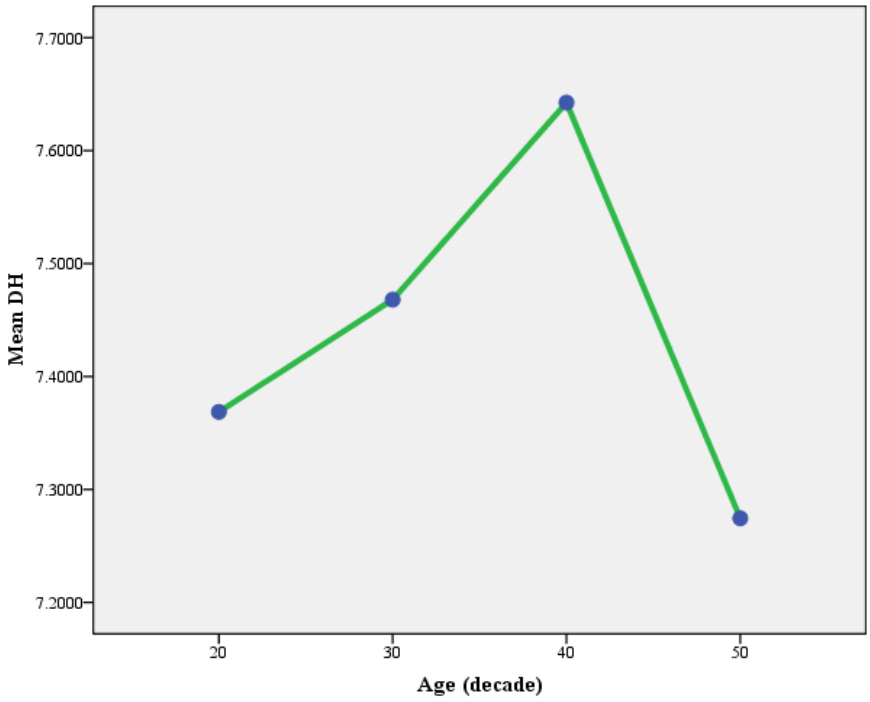


Figure IV-34: Effect of age on disc height

Age showed no significant difference (Figure IV-34).

(2) Effect of GENDER on disc height

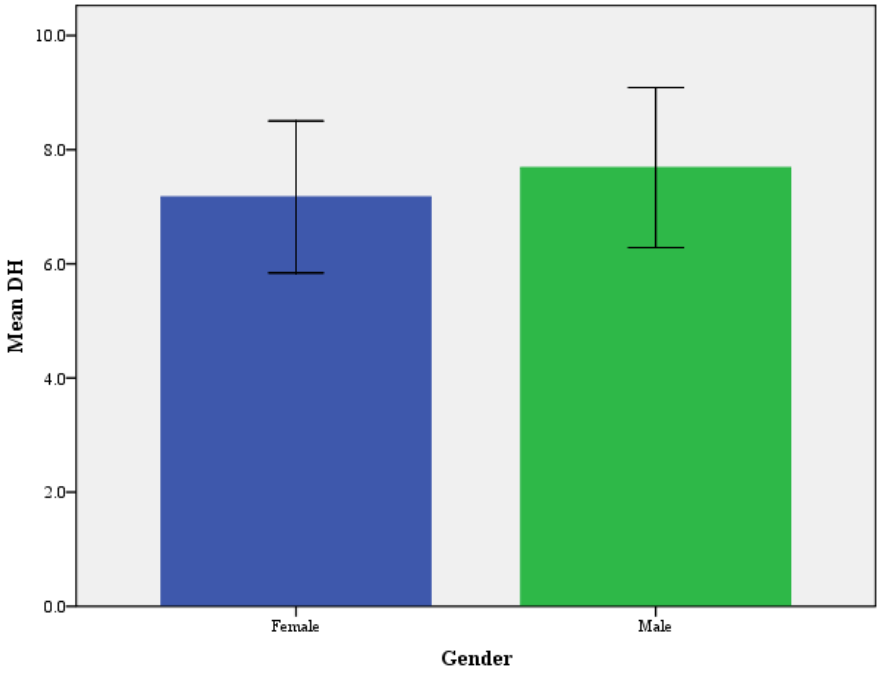


Figure IV-35: Effect of gender on disc height

There was a significant difference between genders (p=0.0004) (Figure IV-35).

(1) Effect of LEVEL on disc height

Effect of level on disc height was obtained with significance indicated in Table IV-15. In general, cranial levels showed larger disc height than caudal levels (Figure IV-36).

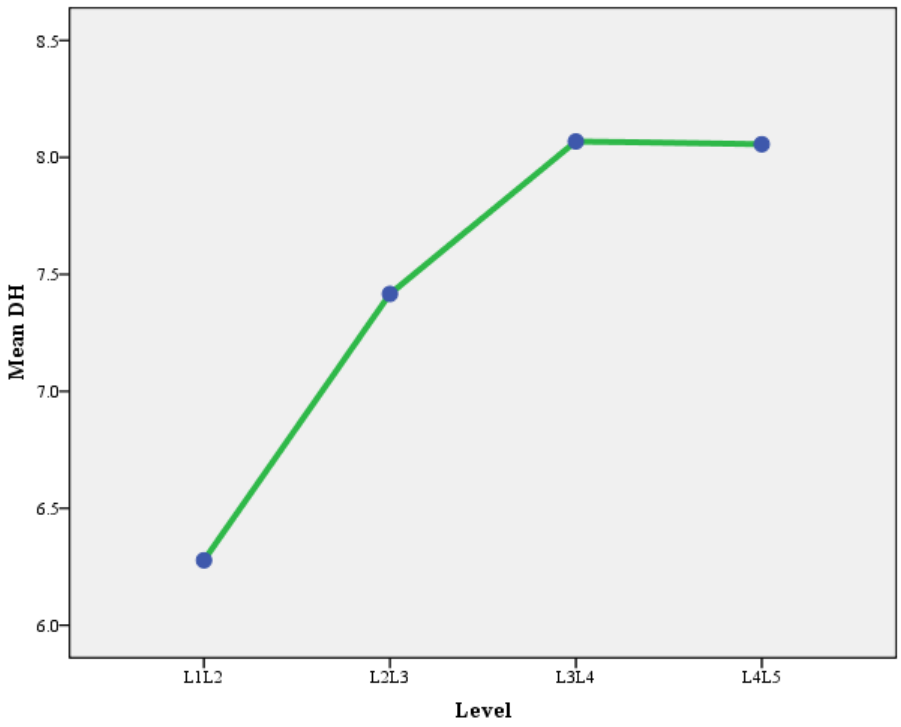


Figure IV-36: Effect of level on disc height

Table IV-15: Effect of level on disc height (LSD)

Disc height (mm) LSD **DH vs. LEVEL**

(I) Level	(J) Level	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
L1L2	L2L3	**-1.138***	.1765	**.000**	-1.485	-.791
	L3L4	**-1.790***	.1765	**.000**	-2.137	-1.443
	L4L5	**-1.778***	.1765	**.000**	-2.125	-1.431
L2L3	L1L2	**1.138***	.1765	**.000**	.791	1.485
	L3L4	**-.652***	.1765	**.000**	-.999	-.305
	L4L5	**-.640***	.1765	**.000**	-.987	-.293
L3L4	L1L2	**1.790***	.1765	**.000**	1.443	2.137
	L2L3	**.652***	.1765	**.000**	.305	.999
	L4L5	.012	.1765	.946	-.335	.359
L4L5	L1L2	**1.778***	.1765	**.000**	1.431	2.125
	L2L3	**.640***	.1765	**.000**	.293	.987
	L3L4	-.012	.1765	.946	-.359	.335

***. The mean difference is significant at the 0.05 level.**

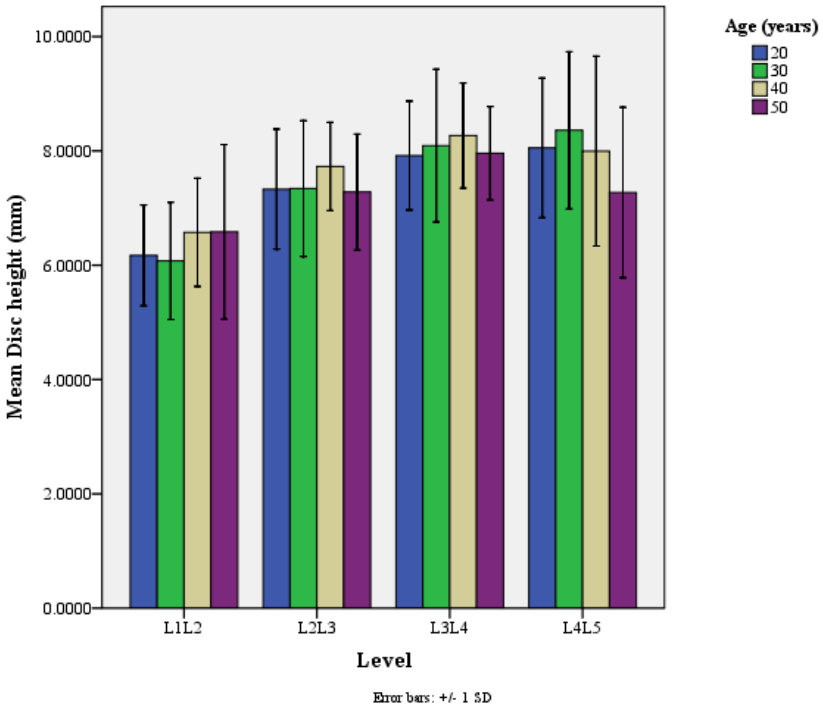


Figure IV-37: Combined effect of age and level on disc height

(2) Influence of combined factors on disc height

In previous analysis level and gender showed significance in explaining variability of the disc height. Further, interactions between age, gender and level will be evaluated.

(i) AGE and LEVEL

There were no significant age-related changes of the disc height at individual levels (Figure IV-37).

(ii) AGE and GENDER

Figure IV-388 presents age-related differences between both genders. Disc height in females tend to be significantly smaller than in males (p=0.0004).

(iii) GENDER and LEVEL

Analysis confirmed gender-related difference of disc height (Figure IV-39).

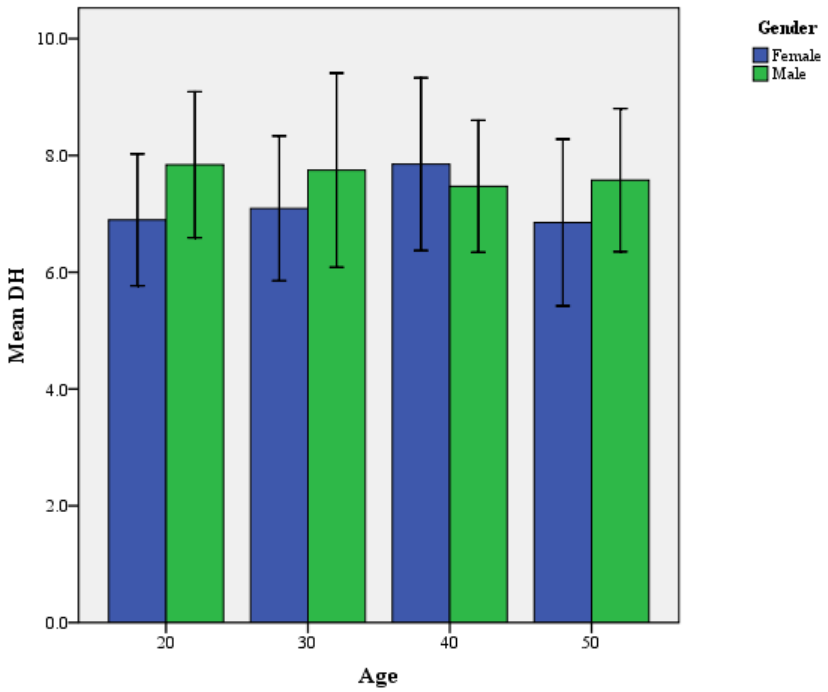


Figure IV-38: Combined effect of age and gender on disc height

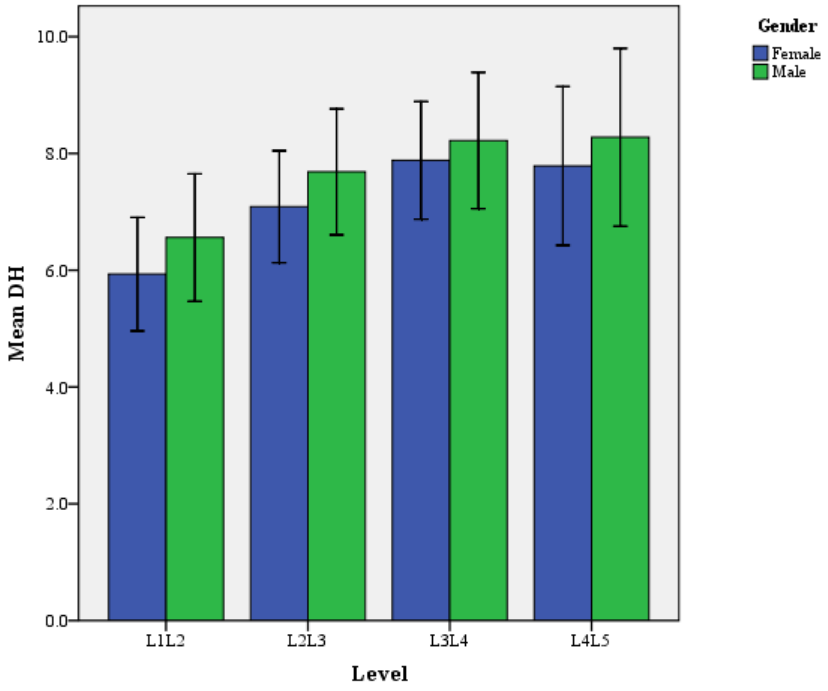


Figure IV-39: Combined effect of gender and level on disc height

(b) Zonal differences of disc height

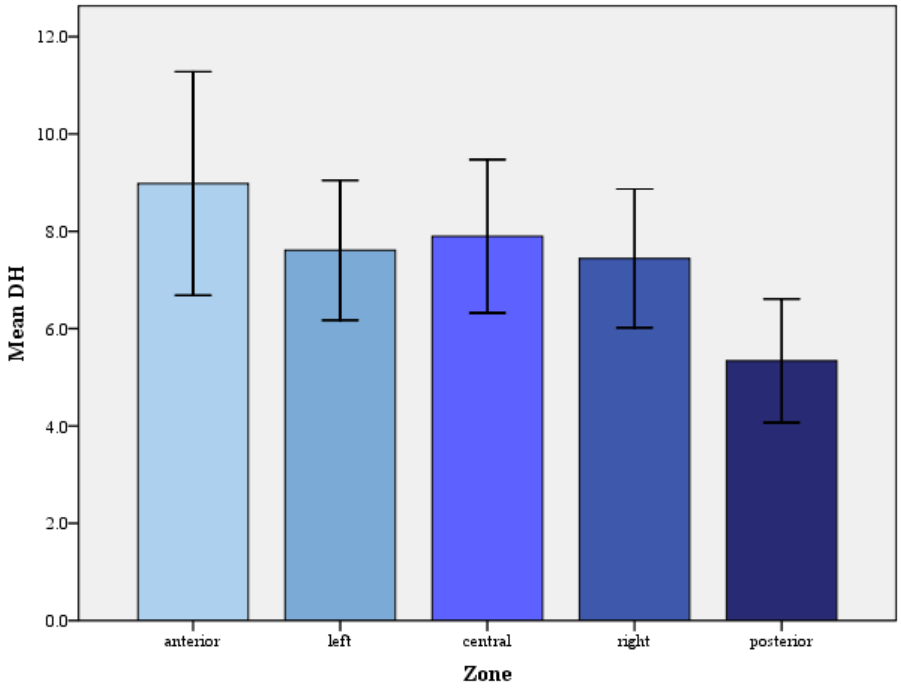


Figure IV-40: Zonal distribution of disc height

Influence of zone as a grouping variable revealed significant differences between individual zones ($p<0.0001$). Disc height was significantly different in every of them (Figure IV-40).

Influence of combined effects on disc height with respect to ZONE

Previous analysis showed relationships of average disc height with level, age and gender. Localized differences in disc height were also compared to above mentioned variables.

(i) ZONE and AGE and LEVEL

Figure IV-41 show zonal differences in disc height distribution at different levels with respect to age. Changes in disc height occurred as soon as in thirties in the posterior zones for L1L2. Significant changes in the disc height were later seen in forties in anterior and right zones of L1L2, and progressed into anterior and posterior zone in fifties. L2L3 showed significant change in disc height only in forties.

In L3L4, only the anterior zone shows significant changes in the forties. For L4L5, decrease in disc height started in the central zone and progressed in fifties to all remaining zones.

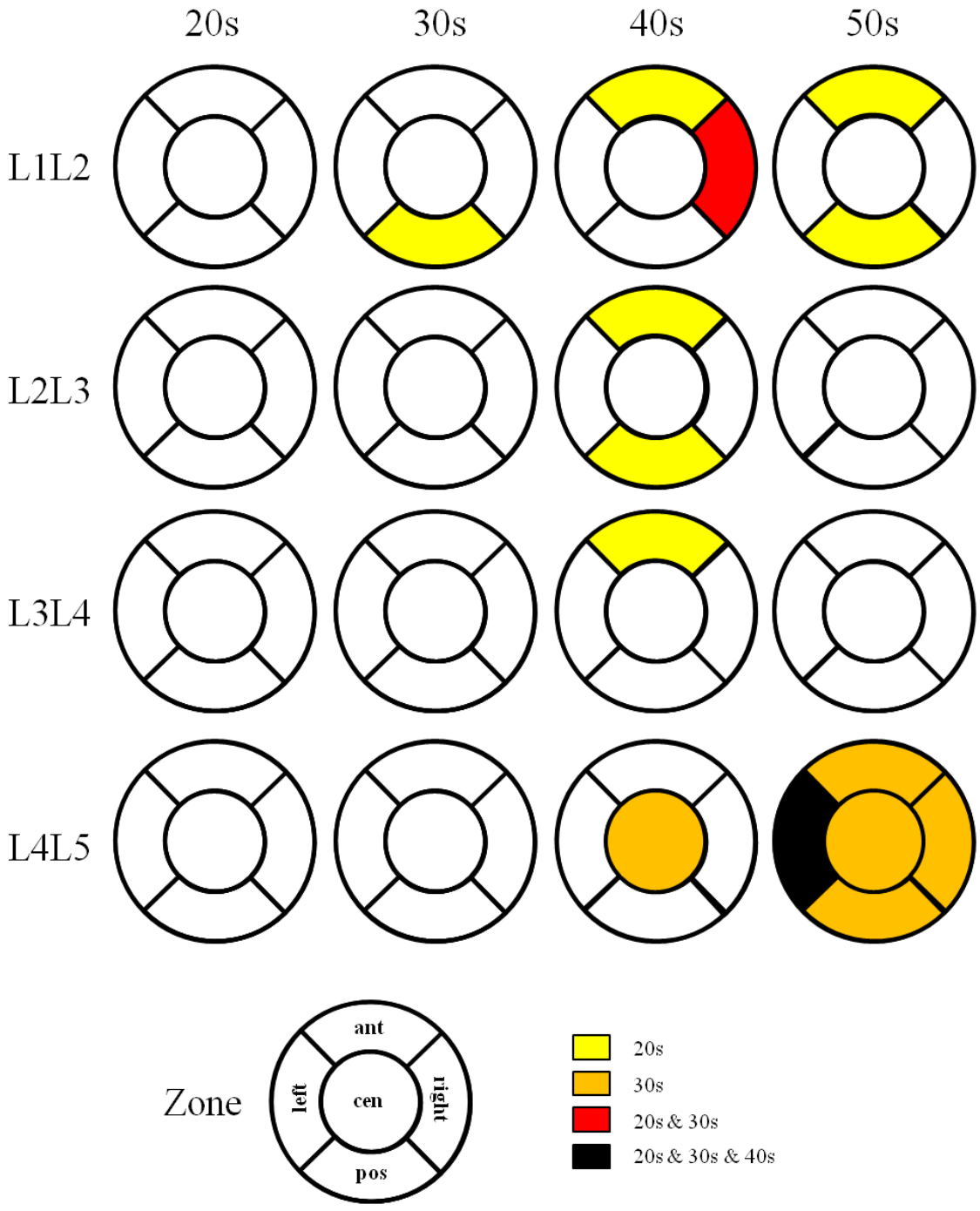


Figure IV-41: Combined effect of zone, age and level on disc height

3.2.3 Correlation between qualitative measures of spinal degeneration

(a) Facet joint space width and disc height correlation

Table IV-16: Facet joint space width and disc height correlation

		Left Side		Right Side	
		Sig. (one-tailed)	Pearson	Sig. (one-tailed)	Pearson
Level	L1L2	0.001	0.329	0.02	0.216
	L2L3	<0.0001	0.38	0.038	0.187
	L3L4	-	-	-	-
	L4L5	0.008	0.252	0.001	0.326

The result presented in the Table IV-16 shows very strong positive correlation of the facet joint space width and disc height at every level except L3L4.

3.3. Correlations between quantitative and qualitative measures of spinal degeneration

3.3.1 Disc degeneration grade and disc height

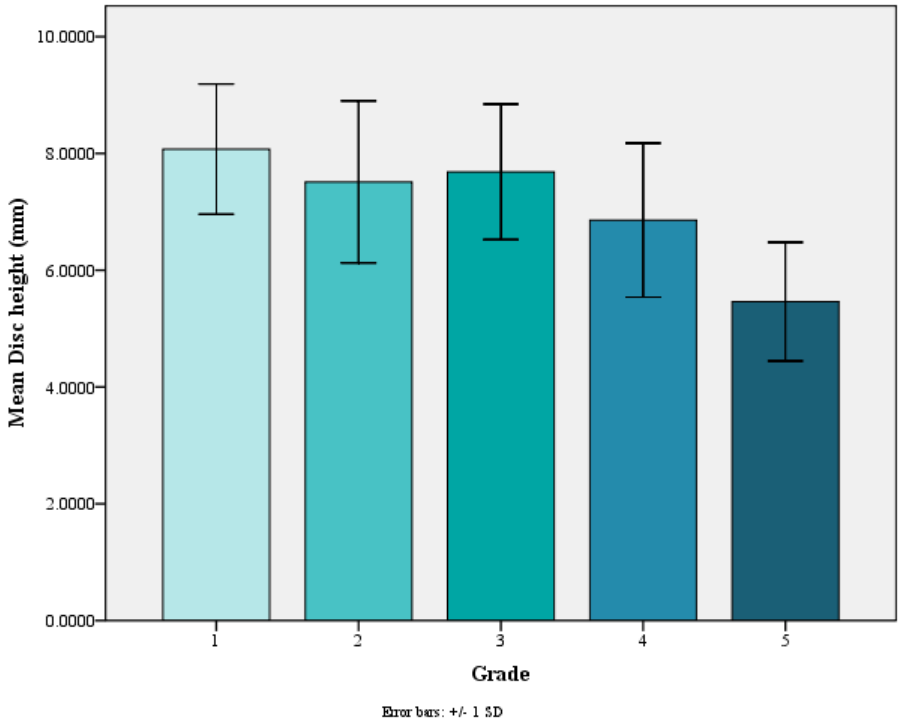


Figure IV-42: Correlation between disc degeneration and disc height

Using disc degeneration grade as a grouping variable results indicated a very strong relationship between quantitative measure of disc height and qualitative measure of disc degeneration grade (Figure IV-42, Table IV-17) exists.

Table IV-17: Effect of disc degeneration on disc height

Disc height (mm) LSD **DH and DD**

(I) Grade	(J) Grade	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1	2	**.563***	.0927	**.000**	.381	.745
	3	**.389***	.1100	**.000**	.173	.604
	4	**1.217***	.1320	**.000**	.958	1.476
	5	**2.612***	.1660	**.000**	2.287	2.938
2	1	**-.563***	.0927	**.000**	-.745	-.381
	3	**-.174***	.0783	**.026**	-.327	-.020
	4	**.654***	.1070	**.000**	.444	.864
	5	**2.050***	.1469	**.000**	1.761	2.338
3	1	**-.389***	.1100	**.000**	-.604	-.173
	2	**.174***	.0783	**.026**	.020	.327
	4	**.828***	.1223	**.000**	.588	1.068
	5	**2.223***	.1584	**.000**	1.913	2.534
4	1	**-1.217***	.1320	**.000**	-1.476	-.958
	2	**-.654***	.1070	**.000**	-.864	-.444
	3	**-.828***	.1223	**.000**	-1.068	-.588
	5	**1.395***	.1744	**.000**	1.053	1.737
5	1	**-2.612***	.1660	**.000**	-2.938	-2.287
	2	**-2.050***	.1469	**.000**	-2.338	-1.761
	3	**-2.223***	.1584	**.000**	-2.534	-1.913
	4	**-1.395***	.1744	**.000**	-1.737	-1.053

***. The mean difference is significant at the 0.05 level.**

3.3.2 Facet joint osteoarthritis grade and facet joint space width

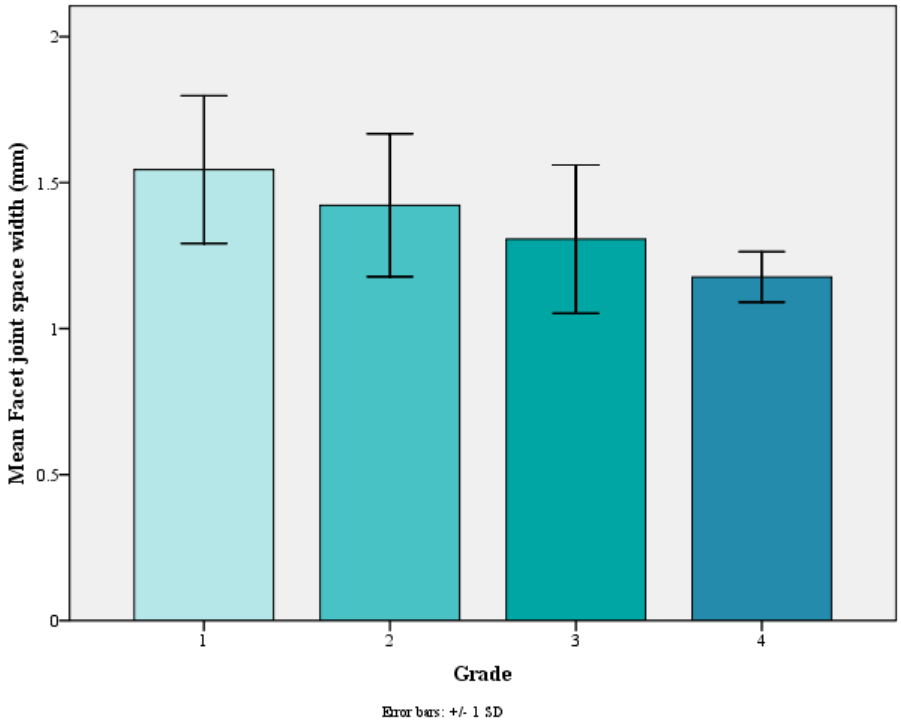


Figure IV-43: Correlation between facet joint OA grade and facet joint space width

Table IV-18: Effect of facet joint osteoarthritis grade on facet joint space width

Facet joint space width (mm) LSD **FJSW vs. FJOA**

(I) Grade	(J) Grade	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1	2	**.12***	.027	**.000**	.07	.18
	3	**.24***	.030	**.000**	.18	.30
	4	**.37***	.069	**.000**	.23	.50
2	1	**-.12***	.027	**.000**	-.18	-.07
	3	**.12***	.015	**.000**	.09	.15
	4	**.25***	.064	**.000**	.12	.37
3	1	**-.24***	.030	**.000**	-.30	-.18
	2	**-.12***	.015	**.000**	-.15	-.09
	4	**.13***	.065	**.046**	.00	.26
4	1	**-.37***	.069	**.000**	-.50	-.23
	2	**-.25***	.064	**.000**	-.37	-.12
	3	**-.13***	.065	**.046**	-.26	.00

***. The mean difference is significant at the 0.05 level.**

Results indicate very strong relationship between facet joint space width and facet joint osteoarthritis grade (Figure IV-43, Table IV-18).

4. Conclusion and Discussion

A statistical analysis of the spinal degeneration was successfully performed. A total of 91 subjects were included in this study. A combination of conventional, clinical methods and newly developed methods was used to quantify spinal degeneration.

In the past, there were numerous studies that focused on the degenerative process in the spine[32, 49, 71-74]. This study focused on quantification of degenerative changes *in-vivo*. In summary, the results showed that:

a) Disc degeneration:

Results from analysis indicate strong relationship of disc degeneration and age ($p<0.0001$). This finding was previously clearly demonstrated [75]. In contrast, evaluation of the disc height did not support the qualitative finding. There are multiple reasons that can explain this variation. Firstly, the grade of disc degeneration is assign based on multiple criteria. A decrease in disc height, being one of them, is not the most significant one in the earlier stages of degeneration. Analysis showed that disc height is a very good measure of degenerative change especially when it is presented within anatomical zones of the endplate. Subdividing disc height into zones made it a particularly useful method to identify zonal differences in disc height. Our analysis showed that there are early signs of the loss of the localized disc grade (posterior zone of L1L2 in thirties), which might not be detected when average value is used. Level dependency was not proven by disc degeneration grade, however significance of level in explaining the variation of the disc height was present ($p<0.0001$). The reason behind this discrepancy is again in the approach of both methods. Qualitative method evaluates disc height only visually in the single picture (sagittal MR) and only as one of the factors. Gender factor was non-significant in grading approach, however, became significant when gender was in combination with age or level. Gender variations are well known and studied. Fujiwara postulated that there are differences between genders when degeneration is concerned[30]. Different morphology (size) and biochemistry may also be of importance to explain the difference.

b) Facet joint osteoarthritis:

Osteoarthritis in the facet joint was evaluated without taking a side into consideration, as there was no significant difference between right and left facet joint. Age as an independent variable introduced into the model showed high significance in both approaches. An increase in facet joint grade was not significant between twenties and thirties in qualitative analysis. The result indicates that facet joint osteoarthritis occur later in the thirties. Evaluation of facet joint space width confirmed the indication, showing early occurrence of localized facet joint space narrowing. Level was also identified as a significant variable with incremental increase of facet joint grade from cranial towards caudal regions. Degeneration in lower lumbar levels has been previously reported[26]. The effect of gender was highly significant in both evaluations.

c) Qualitative vs. quantitative measures of spinal degeneration:

Conventional methods were evaluated for inter/intra observer agreement. Agreement obtained within and between observers, falls into acceptable range reported in the literature[76]. Quantitative measures of the spinal degeneration were identified as an excellent equivalent for conventionally used subjective methods. New methods for disc height measurement and facet joint space width evaluation offer three-dimensional, image-based assessment of the morphological changes in the lumbar spine. Disc height and facet joint space width showed highly significant power in predicting the grade of disc degeneration and facet joint osteoarthritis. Additionally, quantitative methods were able to identify early local changes in the intervertebral disc and facet joint. Implementation of those methods into clinical practice may have significant impact on diagnosis of low back pain.

d) Correlation between disc degeneration and facet degeneration:

Results showed that there is a strong correlation between facet joints space width and disc height. Except L3L4, positive correlation was shown for every level. This study showed the largest magnitude of the disc height at L3L4 (7.6±1.2 mm), what might be caused by spatial position of the level on the apex of

the lumbar lordosis. Analysis of qualitative parameters of spinal degeneration via spinal degeneration index showed the facet joint osteoarthritis at L2L3 and L3L4 in early twenties of higher grade than disc degeneration. Those results show the importance of the facet joint; as there is a possibility that facet does not degenerate secondarily. The normal sequence of degenerative events in the three-joint complex is that one joint is at first affected, and then because of the interplay, eventually changes occur in all three[18]. In light of this statement, facet may play more important role in etiology of degeneration than was assumed.

e) Facet joint osteoarthritis progression:

The present study measured facet joint space width distribution *in-vivo* to estimate extent and location of the facet joint degeneration using subject-based facet joint three-dimensional CT models. The zonal analysis in the present study demonstrated that facet joint space width was narrower in the inferior and medial regions of the facet joint. Furthermore, our data shows narrowing of the facet joint space width in the inferior region evident as early as in the third decade. Although previous cadaver-based studies demonstrated that the facet joint cartilage degeneration occurred in younger age population, the present study is the first to demonstrate early degenerative changes in the facet joint *in-vivo* using clinically-available CT by evaluating age-related changes in facet joint space width distribution in a quantitative manner. Topographic analysis of the whole facet joint area allows for a detailed description of extent and location of the joint degeneration. The analysis of the whole facet joint surface is beneficial for comparison between cartilage degeneration and three-dimensional characteristics of the structure and biomechanical functions of the facet joint such as restriction of the segmental motion and load transmission. The results of the present study showed smaller widths in the facet joint peripheral zones, consisting of superior, lateral, inferior and medial zones, when compared to the central zone. This finding is consistent with previous cadaveric studies which observed distribution of cartilage degeneration *in-vitro*[33,].

f) Disc degeneration progression:

Analysis of distribution of the disc height with respect to level and age showed significant disc narrowing in the fifties at L4L5. This finding corresponds to the reported studies on disc degeneration progression[50, 77, 78]. Disc height change is radiographically identified in the later stages of disc degeneration (grade 4 and 5). Also, narrowing in the central zone at L4L5 in forties and fifties indicated morphological changes in the endplate due to the loss of water content in the nucleus.

V. Segmental instability and low back pain

1. Background

Degenerative changes in the intervertebral disc and facet joints may have a significant influence on alteration of segmental motion characteristics. The effect of disc degeneration on kinematics has been previously reported [5-7, 47, 79, 80]. Although, facet joints play a major role in constraining motion in the segmental unit and morphological changes to the facet joint may cause decrease in their constraining function and subsequently lead to instability of the whole motion segment, there were, up to the best of author knowledge, no complex work published addressing this issue. Recently, facet joints have received attention as a potential cause of low back pain. Due to this fact, it has been postulated that facet joint osteoarthritis may act as a potential trigger of low back pain and subsequently cause disability.

There is a paucity of data in the published literature regarding the kinematics of the facet joint. First and foremost, the size of the facet joint and its complex three-dimensional geometry pose challenges for kinematic analysis. Recent advancements in medical imaging and its convenient accessibility allow researchers to study *in-vivo* three-dimensional characteristics of these smaller, complex structures. The aim of this study was to develop a three-dimensional *in-vivo* kinematic model in order to evaluate facet joint motion parameters, and correlate those parameters with degenerative changes in the lumbar spine and symptom of the low back pain. Results of such an approach should indicate whether segmental instability of the facet joint leads to the symptomatic pain.

2. Materials and methods

2.1. Statistical model

The relationship between spinal degeneration, kinematic parameters and low back pain were established using statistical model. Every variable was previously tested for normality, thus parametric statistical methods can be used. Effect of symptom on facet joint kinematics and degeneration was evaluated using one-way ANOVA with Fisher's post-hoc test.

Facet joint kinematic parameters are level dependent. As stated, effects of the symptom and degeneration will be evaluated with regards to level.

3. Results

3.1. Effect of symptom on facet joint kinematics

3.1.1 Rotational ROM

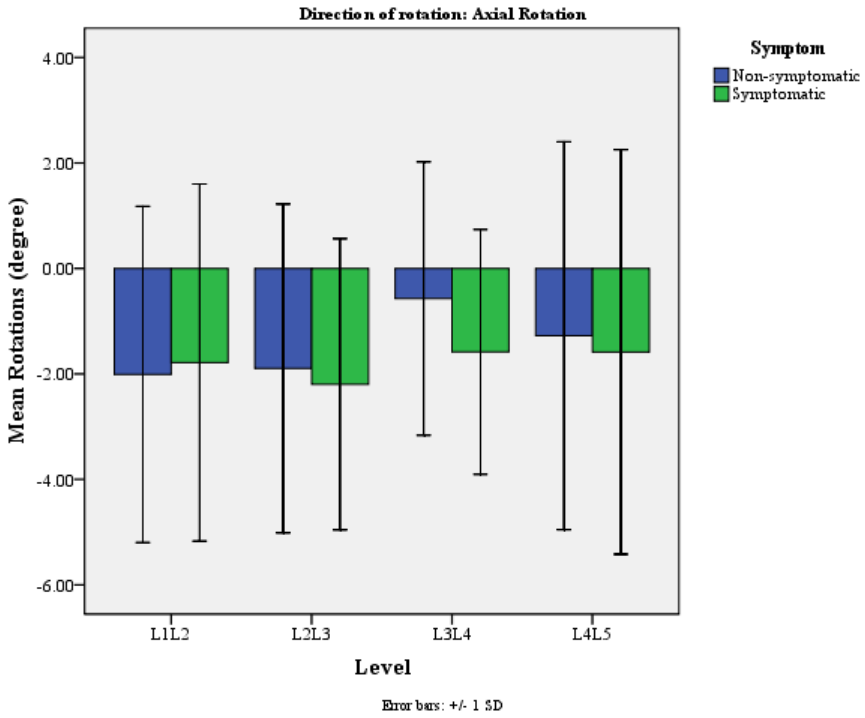


Figure V-1: Effect of symptom on rotational ROM – axial rotation

Comparison of rotational ROM was conducted taking into account coupled motions of the axial rotation and lateral bending. Flexion/extension motion was neglected, as it was of a small magnitude, when measured in torsion.

Axial rotation was evaluated with respect to presence or absence of the symptom and studied level. As can be seen in the Figure V-1, motion differs between symptomatic and non-symptomatic group when studied with respect to level. Significance between symptomatic and non-symptomatic group was seen at L3L4 ($p=0.0094$) where symptomatic subject had significantly larger rotational ROM. Lateral

bending showed significant difference in motion with respect to symptom at L1L2 (p=0.0252) (Figure V-2).

With respect to studied level, there were significant differences in both studied directions. Level has been previously proven to be a significant covariate in analysis of kinematic pattern. Results correlate with previously reported level dependency reported in the second chapter.

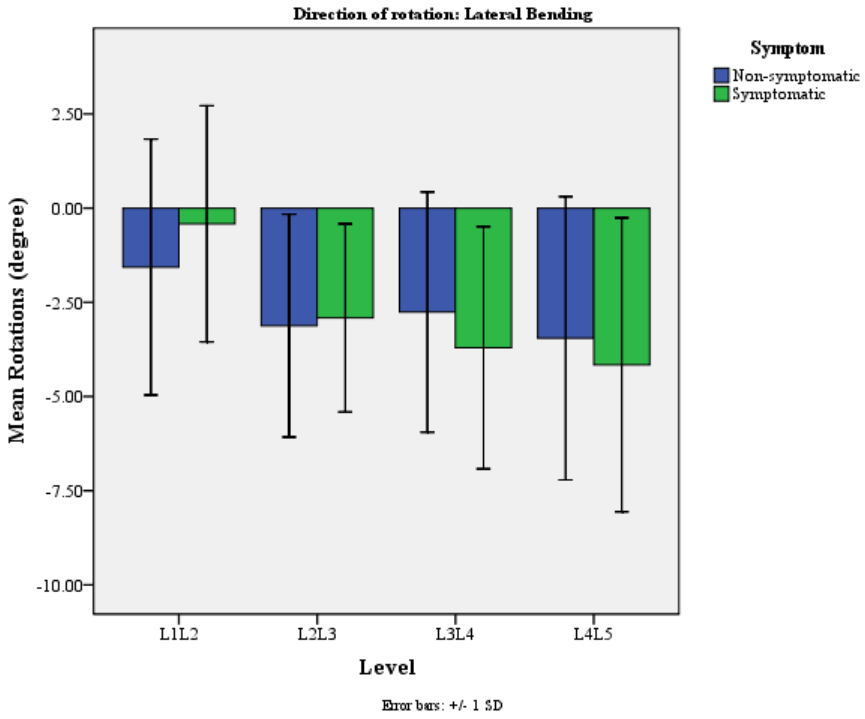


Figure V-2: Effect of symptom on rotational ROM – lateral bending

3.1.2 Translational ROM – left side

Translational ROM was evaluated with respect to side, as it was shown previously, that side is a significant factor in explaining translation of the facet joint.

Left side showed overall significance when symptom was evaluated as grouping variable. In anterior/posterior translation difference between symptomatic group of volunteers and non-symptomatic group of volunteers was highly significant ($p<0.0001$). Pattern of motion has changed with respect to level, having left facet joint translation to occur in anterior direction in symptomatic group (Figure V-3). Medial/lateral translation showed significant degrees in translation between groups with reference to symptom ($p=0.0002$) (Figure V-4). No difference was shown in cranial/caudal direction (Figure V-5).

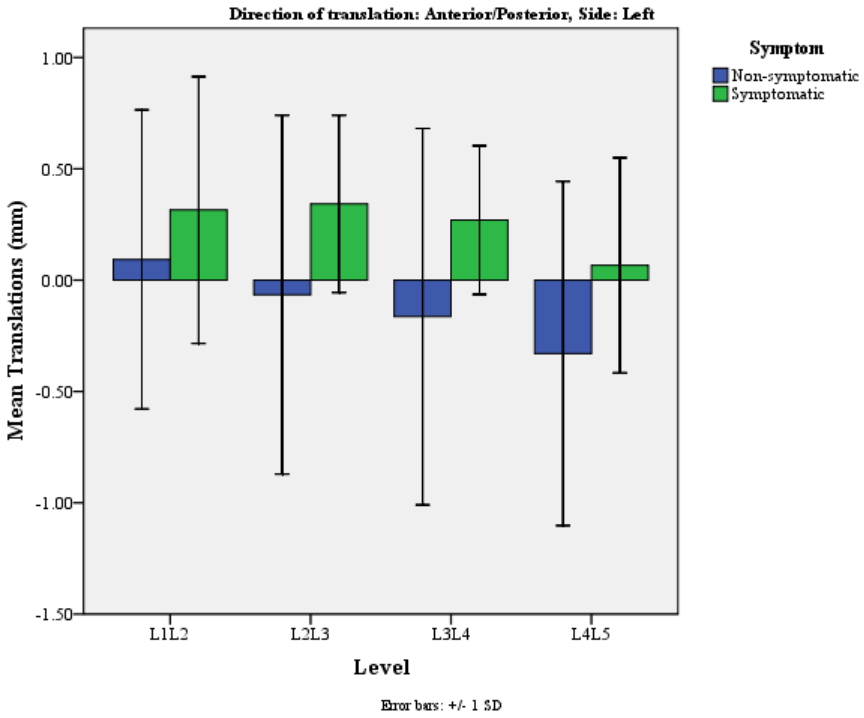


Figure V-3: Effect of symptom on translational ROM – anterior/posterior - left

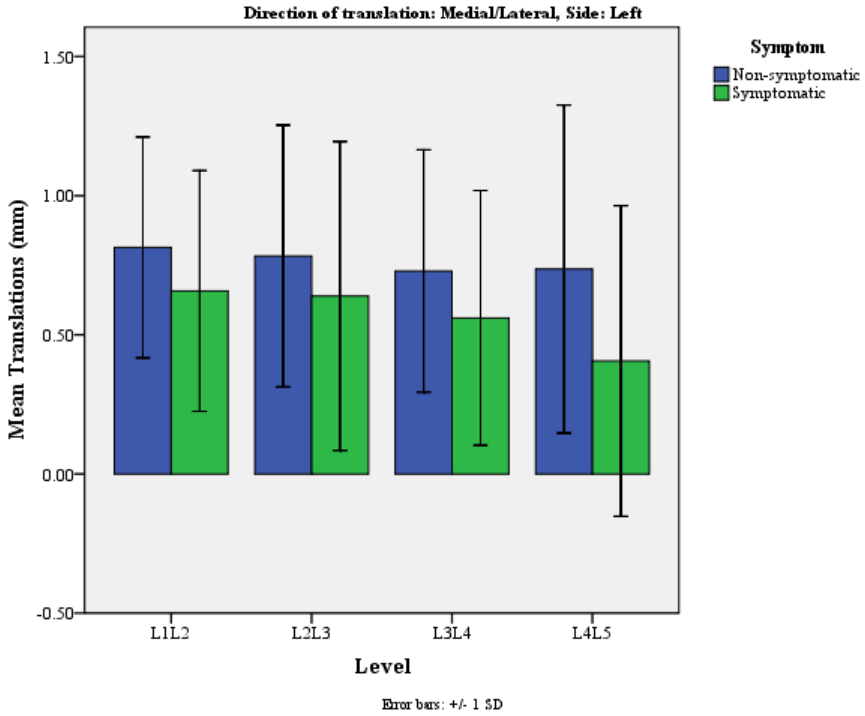


Figure V-4: Effect of symptom on translational ROM - medial/lateral - left

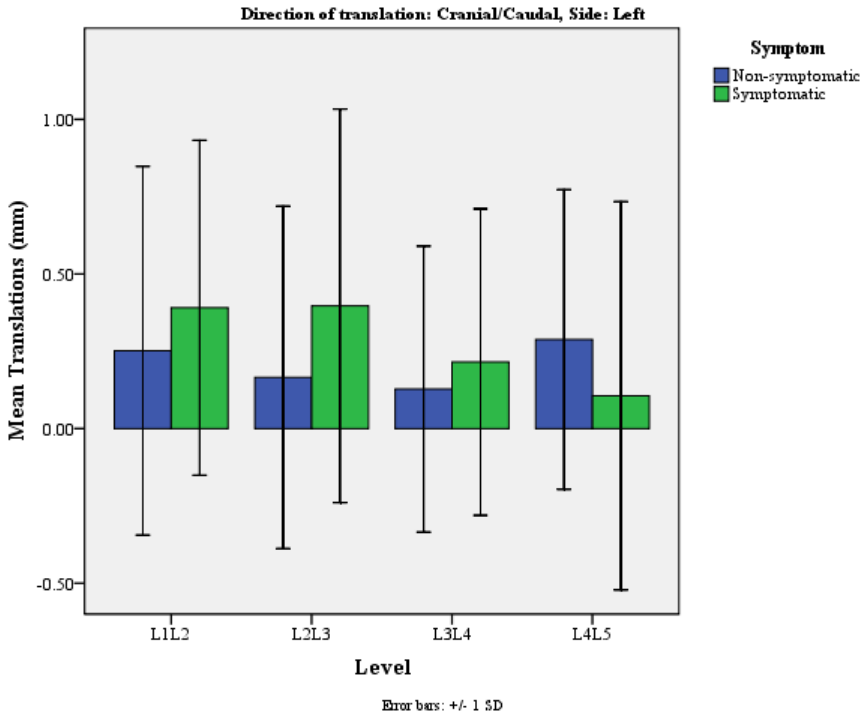


Figure V-5: Effect of symptom on translational ROM - cranial/caudal - left

Right side revealed substantial difference between studied groups. In all three directions an increase in translation was observed (Figure V-6, 7, 8). Significance was found for anterior/posterior translation and medial/lateral translation ($p<0.0001$).

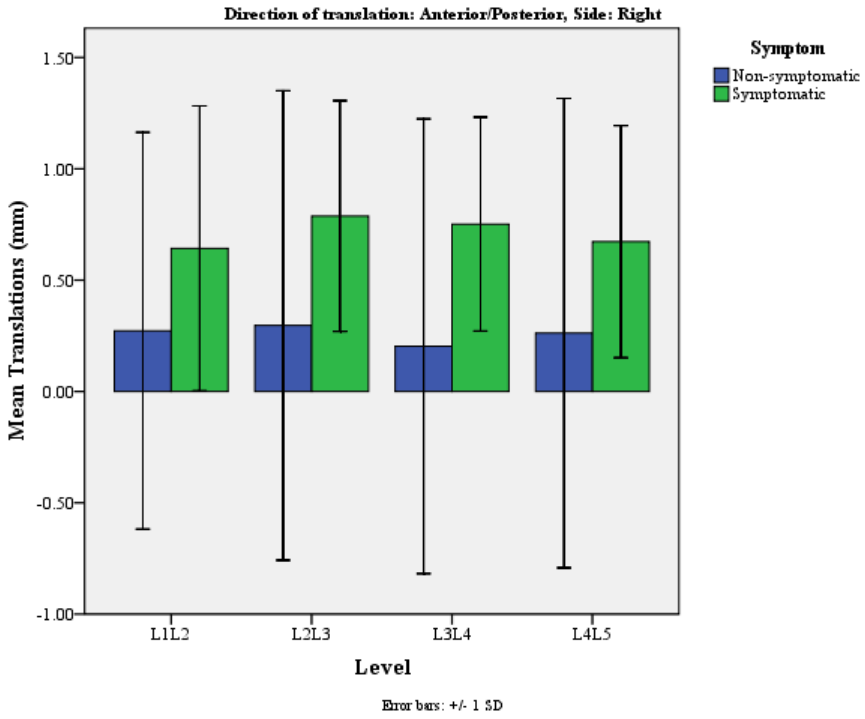


Figure V-6: Effect of symptom on translational ROM - anterior/posterior - right

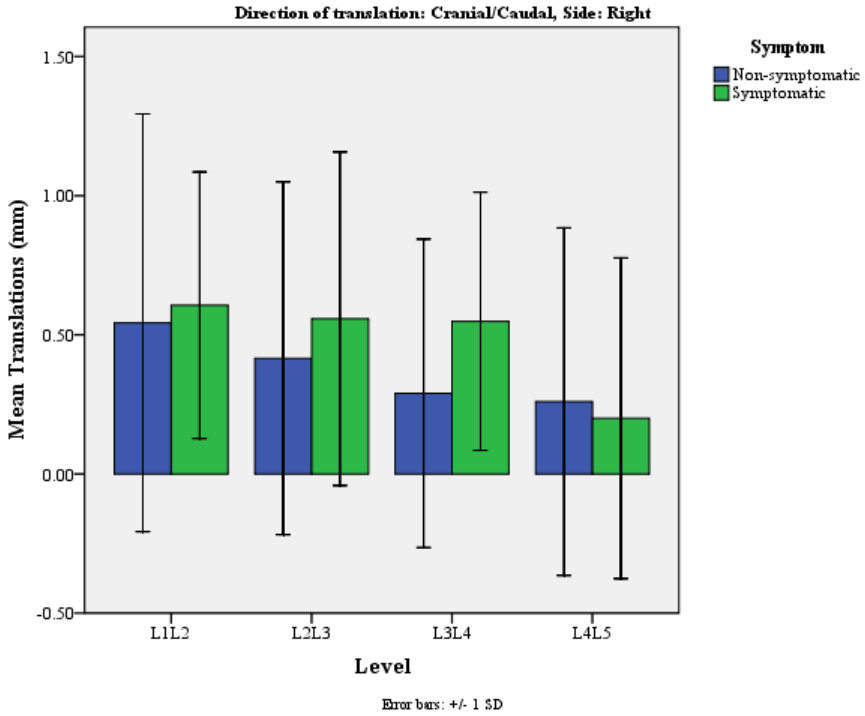


Figure V-7: Effect of symptom on translational ROM - cranial/caudal - right

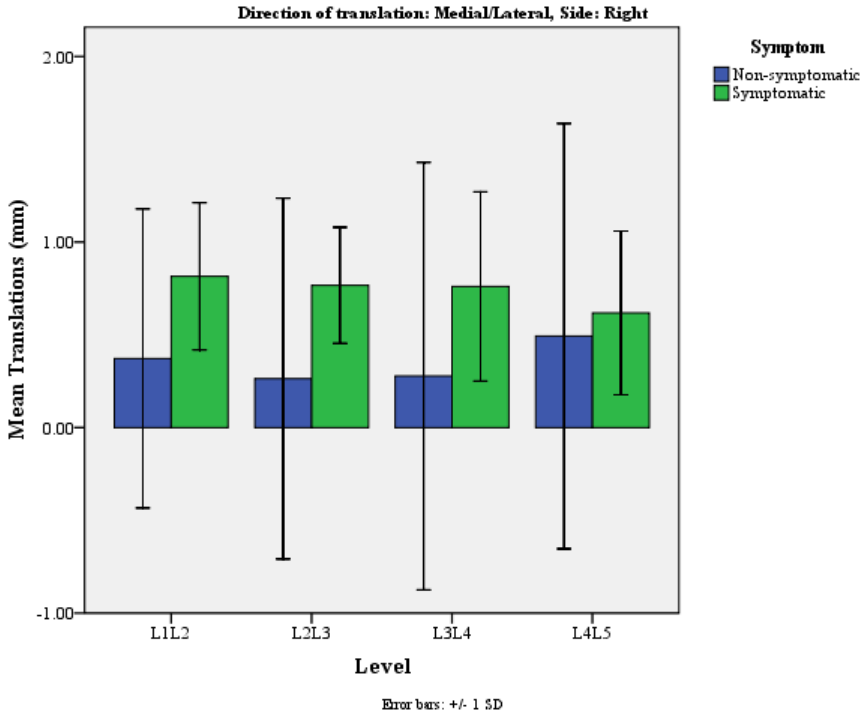


Figure V-8: Effect of symptom on translational ROM - medial/lateral - right

3.2. Effect of symptom on spinal degeneration progression

3.2.1 Disc degeneration

Relationship of disc degeneration grade and symptom of the low back pain was evaluated. Results showed significant differences in disc degeneration grade of symptomatic and non-symptomatic group ($p<0.0001$) (Figure V-9). When level was taken into the model, significance was observed at L1L2 ($p=0.0489$), L3L4 ($p=0.0112$), and L4L5 ($p<0.0001$).

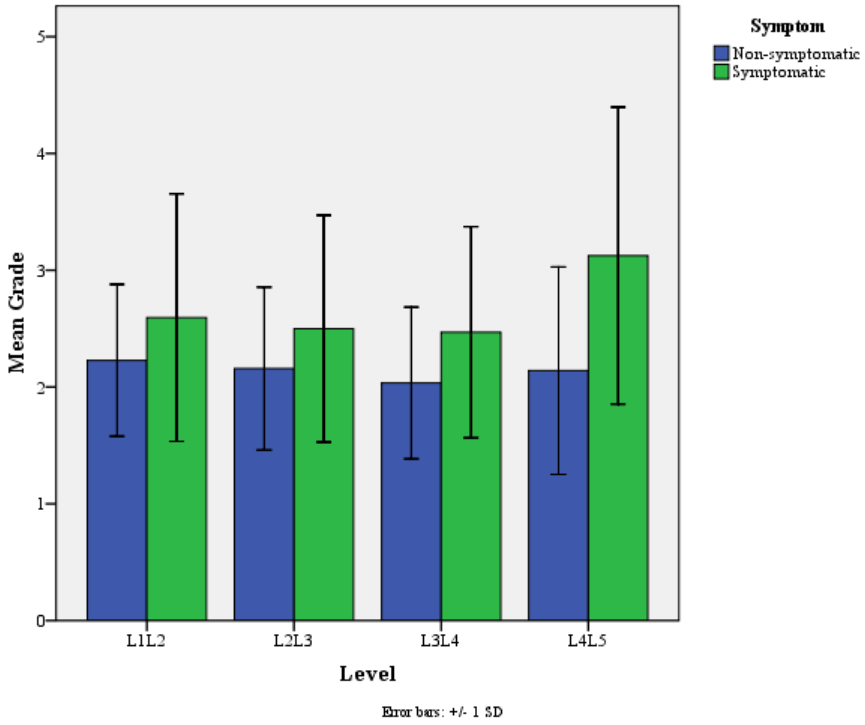


Figure V-9: Effect of symptom on disc degeneration grade

Disc height as an alternative measure of disc degeneration was evaluated for an influence of symptom. Result showed, that disc height of the symptomatic group significantly decreased ($p<0.0001$) when compared to non-symptomatic group (Figure V-10). Level dependency showed significant differences between groups based on the presence or absence of the symptom at L3L4 ($p=0.0255$) and L4L5 ($p<0.0001$).

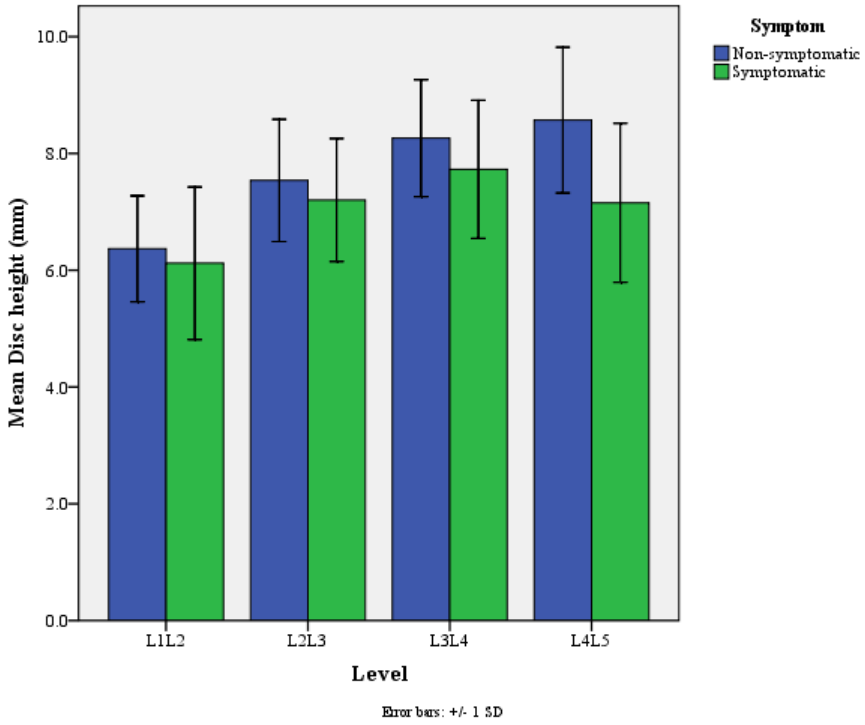


Figure V-10: Effect of symptom on disc height

3.2.2 Facet joint osteoarthritis

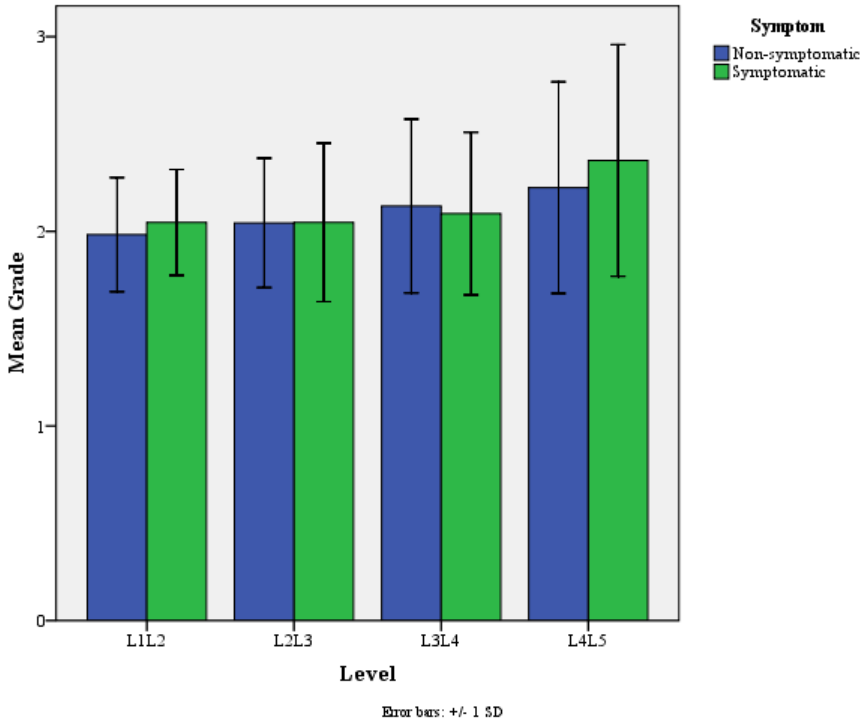


Figure V-11: Effect of symptom on facet joint osteoarthritis

There were no significant differences observed in facet joint osteoarthritis grade when symptom was in the model (Figure V-11).

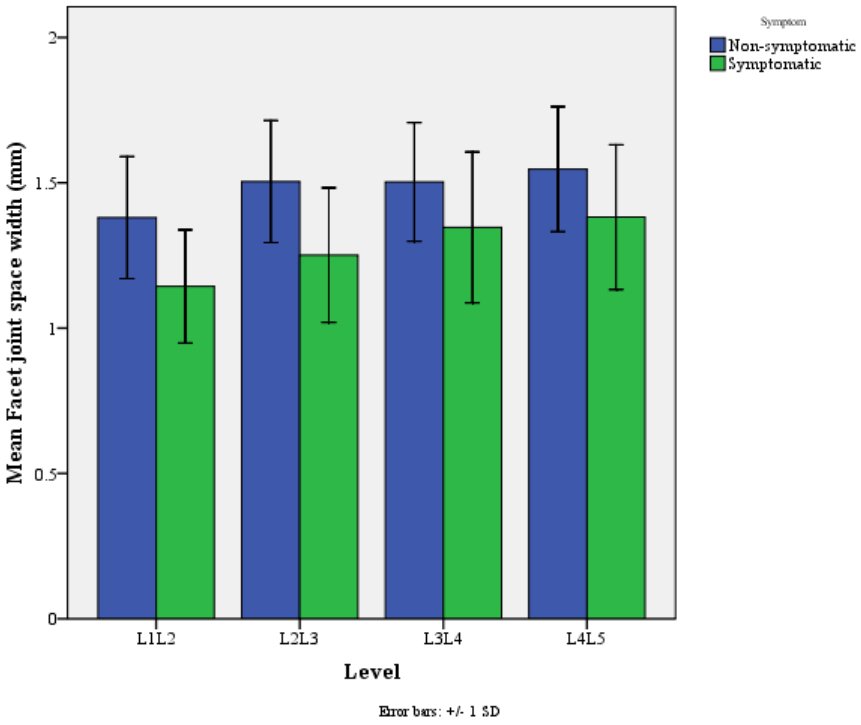


Figure V-12: Effect of symptom on facet joint space width

Although there were no difference measured in the statistical model between facet joint osteoarthritis grade and symptom, facet joint space width showed high significance between the groups ($p<0.0001$) when implemented into the model (Figure V-12). Within the group comparison maintained its high significance, when level was taken into consideration.

3.3. Correlation between kinematic parameters and degeneration parameters with reference to low back pain

In order to find the relationship between kinematic parameters of the lumbar facet joint, spinal degeneration and symptoms of low back pain, analysis was performed by comparing mean values of ROM between non-symptomatic and symptomatic subjects stratified by degeneration grade. Although the study group consists of 91 subjects, subdivision into groups defined by level, symptom and degeneration grade may result in decrease of statistical power. It was proven in the previous chapters that the level play an important role in explaining variation of facet ROM. Significance was studied for every group and corresponding p-value was reported for significant cases. It is important to note, that in some cases a p-value was observed for a comparison of the means that were calculated based on a statistically insignificant group; significance in such a case may be questionable. Although all variables were tested for normality, when stratified into smaller group, it is difficult to maintain the normal distribution. This is especially true in the case of degenerative changes, which are strongly dependent on age. The idea behind this comparison was to give an overall idea about the changes in facet ROM when symptom and degeneration are in question. Results are presented in tabular form with significance in bold.

Table V-1presents a comparison between rotational ROM and disc degeneration grade for symptomatic and non-symptomatic group. Significant differences between symptomatic and non-symptomatic groups were proved for the cases where comparison was done on larger groups.

Table V-2 lists the mean values of rotational ROM and facet joint osteoarthritis grade for symptomatic and non-symptomatic groups.

Table V-3 and 4 present comparisons between translational ROM measured on the left and right facet joint and disc degeneration grade with respect to symptom and level.

In Table V-5 and 6 shows a comparison between translational ROM measured on the left and right facet with respect to facet joint osteoarthritis grade, level and symptom.

Table V-1: Rotational ROM and Disc degeneration grade

Direction			Axial Rotation				Flexion/Extension				Lateral Bending			
Level	Grade	Symptom	Mean	N	SD	p-value	Mean	N	SD	p-value	Mean	N	SD	p-value
L1L2	1	N	-1.91	4	3.59		2.27	4	3.25		-0.43	4	4.21	
	2	N	-1.96	88	3.16		-0.03	88	3.19		-1.50	88	2.86	
		S	-1.41	46	3.01		-0.62	46	2.58		-0.61	46	2.94	
	3	N	-1.54	16	2.61		-0.47	16	2.63	0.0109	-2.23	16	1.37	0.015
		S	-3.12	6	4.73		3.18	6	2.96		0.59	6	3.73	
	4	N	-2.44	4	6.11		1.95	4	3.23		-0.06	4	3.25	
		S	-4.81	4	4.34		-2.23	4	1.98		-0.59	4	4.84	
	5	N	-4.56	2	2.02		-1.27	2	1.39		4.82	2	1.96	
		S	-1.94	8	3.89		0.78	8	2.67		1.12	8	2.55	
L2L3	1	N	-1.29	12	2.40		0.62	12	3.27		-4.23	12	2.58	
		S	-0.81	2	2.08		2.13	2	4.99		-5.85	2	2.87	
	2	N	-1.81	80	2.69		-0.71	80	3.79		-3.06	80	2.39	
		S	-2.33	42	2.83		-0.50	42	3.15		-3.02	42	2.22	
	3	N	-1.84	14	2.15		-0.64	14	3.12		-3.58	14	2.33	
		S	-2.00	12	2.99		-1.35	12	2.66		-2.15	12	2.67	
	4	N	-4.42	8	6.93		-1.25	8	3.16		-3.53	8	1.74	
		S	-2.38	2	3.75		-1.15	2	2.63		-3.25	2	4.69	
	5	S	-2.86	6	2.47		-1.16	6	1.42		-1.27	6	2.11	
L3L4	1	N	-1.35	18	2.55		0.50	18	3.32		-2.53	18	3.18	
		S	-0.44	6	2.14		1.38	6	2.18		-2.43	6	3.20	
	2	N	-0.47	78	2.62	**0.0302**	0.54	78	4.12		-2.78	78	3.06	**0.0338**
		S	-1.64	32	2.31		1.74	32	5.37		-4.19	32	3.24	
	3	N	0.45	14	2.25	**0.0327**	-0.92	14	2.92		-2.85	14	3.53	
		S	-1.27	18	2.06		-0.62	18	3.60		-4.35	18	2.38	
	4	N	-0.97	4	1.97		0.11	4	4.69		-1.29	4	5.20	
		S	-1.82	6	3.24		-0.28	6	2.44		-1.57	6	2.53	
	5	S	-3.74	2	2.40		-2.61	2	0.34		1.00	2	1.83	
L4L5	1	N	-1.21	28	3.64		-1.87	28	8.60		-2.82	28	3.89	
		S	-1.25	8	3.62		3.44	8	12.99		-5.36	8	4.02	
	2	N	-2.17	52	3.58		0.05	52	5.05		-3.29	52	3.60	
		S	-1.52	14	3.62		-1.33	14	3.53		-3.31	14	3.28	
	3	N	-0.21	24	2.97		-0.04	24	5.24	**0.0578**	-3.36	24	3.40	
		S	-0.43	14	3.13		-3.72	14	6.14		-4.92	14	3.72	
	4	N	0.19	10	5.18		-1.69	10	4.57		-6.17	10	4.70	
		S	-3.12	18	3.85		-2.61	18	5.38		-4.42	18	2.38	
	5	S	-0.61	10	5.03		0.24	10	10.31		-2.92	10	6.76	

Table V-2: Rotational ROM and facet joint osteoarthritis grade

			Axial Rotation				Flexion/Extension				Lateral Bending			
Level	Grade	Symptom	Mean	N	SD	p-value	Mean	N	SD	p-value	Mean	N	SD	p-value
L1L2	1	N	-1.70	6	2.79		-1.36	6	3.24		-2.51	6	4.18	
		S	4.95	1	n/a		1.55	1	n/a		4.50	1	n/a	
	2	N	-1.98	106	3.17		-0.02	106	3.13		-1.57	106	3.37	**0.035**
		S	-1.86	61	3.40		-0.31	61	2.93		-0.44	61	3.16	
	3	N	-3.42	4	4.78		1.72	4	2.88		-0.08	4	3.24	
		S	-2.26	4	1.44		-0.11	4	1.44		-1.24	4	2.00	
L2L3	1	N	-1.70	4	3.56		2.14	4	5.63		-4.79	4	3.14	
		S	-3.96	4	3.92		-3.16	4	1.65		-2.83	4	1.60	
	2	N	-1.89	103	3.09		-0.54	103	3.56		-2.91	103	2.99	
		S	-2.19	55	2.69		-0.48	55	3.18		-2.81	55	2.59	
	3	N	-2.03	9	3.63		-1.00	9	4.26		-4.73	9	1.81	
		S	-1.27	7	2.56		2.05	7	3.99		-3.73	7	2.26	
L3L4	1	N	-1.84	4	2.04		0.78	4	1.48		-3.58	4	1.12	
		S	-0.38	3	1.22		-0.06	3	4.14		-3.59	3	2.75	
	2	N	-0.63	94	2.56	**0.0042**	0.32	94	4.06		-2.87	94	3.22	
		S	-1.84	54	2.20		1.00	54	4.62		-3.72	54	3.15	
	3	N	-0.06	17	2.91		0.93	17	3.46	**0.049**	-1.99	17	3.43	
		S	-0.43	9	2.97		-1.91	9	3.66		-3.66	9	4.06	
	4	N	1.30	1	n/a		-2.40	1	n/a		-2.51	1	n/a	
L4L5	1	N	0.26	6	3.02		1.11	6	6.10		-1.08	6	2.41	
		S	-3.16	1	n/a		1.53	1	n/a		-0.58	1	n/a	
	2	N	-1.40	79	3.31		-0.75	79	5.87		-3.61	79	3.50	
		S	-1.23	43	3.45		-2.05	43	7.27		-4.60	43	3.57	
	3	N	-1.34	30	4.68		-0.61	30	6.65		-3.25	30	4.31	
		S	-1.55	19	4.57		-1.26	19	8.67		-3.89	19	4.04	
	4	N	0.99	1	n/a	0.05	-12.57	1	n/a	0.0024	-11.64	1	n/a	
		S	-6.35	3	1.49		3.05	3	0.66		-0.71	3	7.21	

Table V-3: Translational ROM - left side and disc degeneration grade

			Anterior/Posterior				Cranial/Caudal				Medial/Lateral			
Level	Grade	Symptom	Mean	N	SD	p-valu	Mean	N	SD	p-valu	Mean	N	SD	p-value
L1L2	1	N	0.15	2	0.21		0.70	2	0.14		1.20	2	0.28	
	2	N	0.14	44	0.49		0.26	44	0.46		0.82	44	0.42	**0.0131**
		S	0.35	23	0.62		0.39	23	0.46		0.56	23	0.36	
	3	N	0.21	8	0.41		0.29	8	0.71		0.68	8	0.35	
		S	0.43	3	0.15		0.27	3	0.45		0.77	3	0.67	
	4	N	0.25	2	0.35		0.55	2	0.21		0.70	2	0.00	
		S	0.30	2	1.41		0.05	2	1.48		1.50	2	0.42	
	5	N	-3.60	1	n/a	0.004	-2.40	1	n/a	0.0288	1.20	1	n/a	
		S	0.17	4	0.42		0.67	4	0.69		0.73	4	0.32	
L2L3	1	N	0.03	6	0.39		0.48	6	0.38		0.92	6	0.69	
		S	0.20	1	n/a		0.20	1	n/a		0.20	1	n/a	
	2	N	-0.02	40	0.62	0.**0319**	0.20	40	0.50		0.73	40	0.44	
		S	0.31	21	0.39		0.37	21	0.53		0.50	21	0.47	
	3	N	0.26	7	0.28		0.19	7	0.20		0.74	7	0.31	
		S	0.58	6	0.50		0.73	6	0.99		0.85	6	0.80	
	4	N	-1.32	4	2.11		-0.58	4	1.12		1.20	4	0.65	
		S	0.20	1	n/a		-0.20	1	n/a		1.60	1	n/a	
	5	S	0.23	3	0.38		0.50	3	0.30		0.83	3	0.25	
L3L4	1	N	0.06	9	0.25		0.24	9	0.39		0.84	9	0.35	
		S	0.10	3	0.10		0.20	3	0.10		0.70	3	0.52	
	2	N	-0.25	39	1.00		0.14	39	0.43	**0.0344**	0.74	39	0.48	
		S	0.21	16	0.35		0.43	16	0.52		0.58	16	0.44	
	3	N	0.03	7	0.31	0.0496	0.16	7	0.35		0.56	7	0.24	
		S	0.42	9	0.40		0.01	9	0.38		0.63	9	0.32	
	4	N	-0.15	2	0.49		-0.45	2	1.48		0.75	2	0.49	
		S	0.33	3	0.15		-0.17	3	0.67		-0.10	3	0.10	
	5	S	0.40	1	n/a		0.20	1	n/a		1.50	1	n/a	
L4L5	1	N	-0.46	14	0.79		0.21	14	0.50		1.04	14	0.85	
		S	0.25	4	0.24		0.40	4	0.38		0.32	4	0.26	
	2	N	-0.21	26	0.38		0.34	26	0.51		0.63	26	0.41	
		S	0.33	7	0.24		0.37	7	0.28		0.60	7	0.43	
	3	N	-0.54	12	1.35		0.20	12	0.47		0.66	12	0.33	
		S	0.16	7	0.40		-0.01	7	1.01		0.41	7	0.46	
	4	N	-0.16	5	0.48		0.36	5	0.42		0.64	5	0.92	
		S	-0.34	9	0.62		-0.16	9	0.39		0.31	9	0.92	
	5	S	0.04	5	0.28		0.38	5	0.49		0.32	5	0.19	

Table V-4: Translational ROM – right side and disc degeneration grade

Direction			Anterior/Posterior				Cranial/Caudal				Medial/Lateral			
Level	Grade	Symptom	Mean	N	SD	p-value	Mean	N	SD	p-value	Mean	N	SD	p-value
L1L2	1	N	0.10	2	0.00		0.50	2	0.71		0.15	2	0.35	
	2	N	0.40	44	0.79		0.59	44	0.73		0.39	44	0.72	**0.0192**
		S	0.52	23	0.51		0.58	23	0.33		0.76	23	0.26	
	3	N	0.16	8	0.66		0.76	8	0.52		0.60	8	0.40	
		S	0.87	3	0.32		0.80	3	0.40		0.50	3	0.61	
	4	N	0.05	2	0.21		-0.15	2	0.21		0.80	2	0.14	
		S	1.95	2	1.63		0.15	2	0.07		1.25	2	0.21	
	5	N	-3.50	1	n/a	0.0044	-1.80	1	n/a		-3.10	1	n/a	0.0005
		S	0.55	4	0.47		0.85	4	1.12		0.80	4	0.22	
L2L3	1	N	0.40	6	0.93		0.72	6	0.59		0.30	6	0.46	
		S	0.90	1	n/a		0.20	1	n/a		0.90	1	n/a	
	2	N	0.34	40	0.85		0.48	40	0.60		0.27	40	0.86	**0.0242**
		S	0.67	21	0.49		0.61	21	0.59		0.73	21	0.32	
	3	N	0.43	7	0.35	0.032	0.37	7	0.30		0.54	7	0.39	
		S	1.15	6	0.68		0.38	6	0.80		0.68	6	0.34	
	4	N	-0.43	4	3.05		-0.47	4	0.86		-0.47	4	2.58	
		S	1.00	1	n/a		1.10	1	n/a		1.20	1	n/a	
	5	S	0.90	3	0.30		0.70	3	0.26		0.93	3	0.21	
L3L4	1	N	-0.01	9	1.08		0.46	9	0.73		-0.41	9	1.74	
		S	0.40	3	0.50		0.60	3	0.35		1.00	3	0.46	
	2	N	0.19	39	1.11	**0.0179**	0.29	39	0.50	**0.0013**	0.31	39	1.07	
		S	0.89	16	0.39		0.79	16	0.45		0.81	16	0.46	
	3	N	0.29	7	0.54		0.24	7	0.33		0.79	7	0.41	
		S	0.61	9	0.52		0.33	9	0.41		0.76	9	0.58	
	4	N	0.80	2	0.00		-0.70	2	0.42	0.0338	1.00	2	0.14	
		S	0.77	3	0.70		0.23	3	0.15		0.37	3	0.12	
	5	S	1.30	1	n/a		0.10	1	n/a		-0.20	1	n/a	
L4L5	1	N	0.06	14	1.35		0.37	14	0.60		0.01	14	1.39	
		S	0.58	4	0.62		0.80	4	0.29		0.68	4	0.43	
	2	N	0.41	26	0.49		0.29	26	0.67		0.60	26	0.52	
		S	0.70	7	0.15		0.31	7	0.31		0.84	7	0.56	
	3	N	0.01	12	1.63		0.17	12	0.64		0.93	12	1.81	
		S	0.70	7	0.72		-0.19	7	0.87		0.57	7	0.33	
	4	N	0.72	5	0.57		0.08	5	0.53		0.16	5	0.29	0.0115
		S	0.61	9	0.63		0.38	9	0.37		0.54	9	0.55	
	5	S	0.84	5	0.46		-0.08	5	0.33		0.42	5	0.16	

Table V-5: Translational ROM – left side and facet joint osteoarthritis grade

Direction			Anterior/Posterior				Cranial/Caudal				Medial/Lateral			
Level	Grade	Symptom	Mean	N	SD	p-value	Mean	N	SD	p-value	Mean	N	SD	p-value
L1L2	1	N	1.10	1	n/a		0.10	1	n/a		1.00	1	n/a	
	2	N	0.07	55	0.67		0.24	55	0.61		0.81	55	0.41	
		S	0.31	31	0.61		0.39	31	0.54		0.67	31	0.44	
	3	N	0.25	2	0.35		0.55	2	0.21		0.70	2	0.00	
		S	0.45	2	0.35		0.40	2	0.71		0.50	2	0.14	
L2L3	1	N	-1.60	2	2.26		-0.10	2	0.14		1.65	2	0.92	
		S	0.70	1	n/a		0.90	1	n/a		1.50	1	n/a	
	2	N	-0.02	52	0.72	**0.016**	0.17	52	0.58		0.76	52	0.44	
		S	0.34	27	0.34		0.43	27	0.62		0.69	27	0.50	
	3	N	0.15	4	0.48		0.25	4	0.24		0.65	4	0.24	
		S	0.30	5	0.68		0.12	5	0.74		0.22	5	0.66	
L3L4	1	N	0.20	3	0.17		-0.03	3	0.51		0.57	3	0.32	
		S	0.35	2	0.35		0.20	2	0.28		0.40	2	0.14	
	2	N	-0.22	44	0.94	**0.0155**	0.10	44	0.46		0.78	44	0.45	
		S	0.25	26	0.31		0.28	26	0.46		0.63	26	0.46	
	3	N	-0.06	10	0.44		0.26	10	0.50		0.51	10	0.37	
		S	0.32	5	0.51		-0.14	5	0.65		0.28	5	0.45	
	4	N	0.20	1	n/a		0.60	1	n/a		1.10	1	n/a	
L4L5	1	N	-0.83	3	1.79		0.07	3	0.60		1.83	3	1.76	
		S	0.50	1	n/a		0.70	1	n/a		0.80	1	n/a	
	2	N	-0.36	37	0.82	**0.049**	0.39	37	0.43	**0.0382**	0.79	37	0.35	
		S	0.03	20	0.53		0.08	20	0.66		0.56	20	0.55	
	3	N	-0.18	18	0.37	**0.0487**	0.12	18	0.53		0.45	18	0.48	
		S	0.11	11	0.44		0.20	11	0.51		0.21	11	0.32	
	4	S	0.00	1	n/a		-1.00	1	n/a		-1.00	1	n/a	

Table V-6: Translational ROM – right side and facet joint osteoarthritis grade

Direction			Anterior/Posterior				Cranial/Caudal				Medial/Lateral			
Level	Grade	Symptom	Mean	N	SD	p-value	Mean	N	SD	p-value	Mean	N	SD	p-value
L1L2	1	N	-1.02	5	2.18		-0.42	5	1.21		-0.92	5	2.33	
		S	0.50	1	n/a		0.50	1	n/a		0.80	1	n/a	
	2	N	0.40	51	0.58		0.66	51	0.63		0.48	51	0.34	**<0.0001**
		S	0.67	30	0.67		0.63	30	0.49		0.83	30	0.41	
	3	N	0.15	2	0.07		-0.05	2	0.35		0.90	2	0.28	
		S	0.35	2	0.21		0.25	2	0.07		0.55	2	0.07	
L2L3	1	N	1.15	2	0.78		0.25	2	0.07		0.50	2	0.28	
		S	1.13	3	0.21		0.90	3	0.78		0.50	3	0.35	
	2	N	0.25	51	1.09	**0.0148**	0.44	51	0.67	**0.0066**	0.24	51	1.03	
		S	0.79	28	0.52		0.56	28	0.59		0.80	28	0.31	
	3	N	0.46	5	0.67		0.24	5	0.30		0.42	5	0.44	
		S	0.20	2	0.28		0.05	2	0.21		0.75	2	0.35	
L3L4	1	N	0.10	1	n/a		0.60	1	n/a		0.80	1	n/a	
		S	0.80	1	n/a		0.30	1	n/a		0.80	1	n/a	
	2	N	0.22	50	1.08	**0.012**	0.30	50	0.58	**0.0264**	0.25	50	1.23	**0.0493**
		S	0.78	28	0.48		0.59	28	0.48		0.72	28	0.50	
	3	N	0.10	7	0.60		0.16	7	0.40		0.37	7	0.35	0.0434
		S	0.57	4	0.59		0.30	4	0.32		1.03	4	0.64	
L4L5	1	N	-0.80	3	3.17		-0.23	3	0.47		-1.07	3	2.89	
	2	N	0.28	42	0.95		0.34	42	0.66		0.66	42	1.07	
		S	0.60	23	0.53		0.20	23	0.62		0.69	23	0.38	
	3	N	0.37	12	0.35	**0.032**	0.20	12	0.42		0.31	12	0.46	
		S	0.84	8	0.54		0.27	8	0.48		0.60	8	0.44	
	4	N	1.20	1	n/a		-0.70	1	n/a		0.40	1	n/a	
		S	0.90	2	0.00		-0.10	2	0.57		-0.15	2	0.64	

4. Discussion and Conclusions

A statistical analysis of spinal degeneration was successfully performed in order to assess whether there is a relationship between spinal degeneration, facet joint kinematic parameters and low back pain. To the best of the author's knowledge this is the first study to investigate this relationship *in-vivo*. A total of 91 subjects were included in this study.

In the past, there were numerous studies that focused on degenerative process in the intervertebral disc and facet joints and its influence on spinal segmental instability[6, 18, 22, 32, 42, 77, 77, 79, 81-84]. However, the effect of disc degeneration and facet osteoarthritis on the facet joint motion has not yet been investigated. Fujiwara et al showed that a correlation exists between facet joint osteoarthritis and segmental motion; and that segmental axial rotation increases with advanced osteoarthritis of the facet joint[30].

As hypothesized, segmental motions and spinal degeneration are significantly different between a symptomatic and a non-symptomatic group of volunteers. In summary, the results showed that:

a) Effect of symptom on facet joint kinematics

Results showed that there are significant differences in facet joint ROM between healthy subjects and subjects who experience low back pain. It has been previously identified that kinematic parameters are level dependent; the analysis took this fact into consideration. Results indicated an increase of rotational ROM for symptomatic group in axial rotation at every level except L1L2 with significance calculated for L3L4 ($p=0.0094$). In lateral bending rotation increased in lower lumbar spine and decreased in upper lumbar spine at L1L2 ($p=0.0252$). The effect of low back pain was also seen on the magnitude of translation. Anterior/posterior translation on the left side was highly significant for symptomatic group ($p<0.0001$) indicating the change of pattern of translation during torsion. Facets seem to translate posteriorly in the group of symptomatic subjects. However, relatively high values of standard deviation in the healthy subject group in this case might indicate that there may be other variables that better explain the variation. Decrease of translation in medial/lateral translation in the case of low back pain subjects

was expected as it has been shown in the previous chapter that facet joints are significantly narrower in this group, which may limit the segmental translation. An increase in segmental translation in cranial/caudal direction was obtained at every level except L4L5, but it was not significant. The right side experienced significant increase of translation in all three directions, however significance was calculated only for translation in anterior/posterior and medial/lateral translations ($p<0.0001$). Results indicate the increase in "sliding" of the facet joint on the right side at every level. An increase in medial/lateral direction may be due to partial opening of the facet joint (due to lateral bending) on the right side. Degeneration of the facet joint cartilage and laxity of the capsule may contribute to this opening. In conclusion, it can be speculated that the symptomatic group has larger segmental ROM (except medial/lateral translation in the left facet, reasoning of which was given). An increase in ROM, which can be considered a sign of clinical instability, may cause stretching of the ligamentous tissue in the area and produce pain. An increase in translation in combination with a decrease in facet joint space and the resultant laxity of the facet capsule may lead to localized events of facet capsule impingement.

b) Effect of symptom on spinal degeneration

This work proved the influence of spinal degeneration on symptoms of low back pain. Both qualitative and quantitative methods showed significant increase in degeneration with symptom. Intervertebral disc degeneration grade showed significance between two studied groups. Significant decrease in disc height was also detected in the analysis. Both parameters were significant at $p<0.0001$. This report showed the relationship between facet joint osteoarthritis and the presence of the low back pain. Although facet joint osteoarthritis grade was not significantly correlated with low back pain, the quantitative approach showed a very clear difference. Measuring the facet joint space width showed that narrowing of the facet joint gap was more prominent for symptomatic subjects. Since the average facet joint space width and disc height were found to be linearly-correlated in this study, low back pain symptoms should involve low back pain associated with intervertebral disc degeneration.

c) Effect of degeneration and low back pain on facet joint kinematics

The basic hypothesis states the common belief that spinal degeneration leads to segmental instability, which may lead to the low back pain. This work attempted to bring some understanding to this issue. Overall the results of the analysis of the influence of degeneration on segmental instability and low back pain showed a significant difference between the healthy group subjects and subjects experiencing low back pain. To assess the analysis with such complexity, it is necessary to have a study group large enough to form individual sub-groups with an equal number of the members. This work was based on the study group formed by randomly selected individuals from the general population. Occurrence of degenerative changes is age related and thus it is very difficult if not impossible to find young individuals with severe degeneration without any spinal pathology. Similarly, it is difficult to find individuals in their late age without visible degenerative changes. The results of this work were influenced by the above mentioned limitations; however research work still showed the influence of spinal degeneration on segmental instability and low back pain. Results showed that when study groups were large enough for statistical comparison significance was found.

The statistical model in this chapter was based on the assumptions that need to be taken into consideration for selected methods. It is believed, that the results presented in this work will act as a valuable source of basic information concerning lumbar facet joint.

VI. Overall study Summary and Conclusion

1. Summary and conclusion

This study addressed the effect of spinal degeneration (disc degeneration and facet joint osteoarthritis) on facet joint kinematics with reference to low back pain. It was hypothesized that the presence of spinal degenerative changes causes spinal instability that is believed to be associated with low back pain. The effect of individual variables has been evaluated. This study was designed in a way to be easily applicable to clinical settings, using conventional CT scanner. The main idea behind the study was to develop a set of the quantitative methods which would be capable of evaluating factors that may lead to the development of low back pain.

In order to evaluate various parameters of the facet joint, such as facet-specific *in-vivo* kinematics and facet joint osteoarthritis, innovative techniques able to analyze complex surfaces were developed. Three-dimensional definition of the spatial position and orientation of individual parts of the motion segment were defined based on geometric surface models. The precise definition of the surface was obtained with an in-plane pixel selection method, which was validated to have a precision of 0.49±0.15 mm. The position and orientation definition of the vertebral bodies and individual facet joint surfaces was achieved by defining local coordinate systems based solely on precisely obtained geometrical parameters of individual parts of the lumbar spine. Progression of spinal degeneration was estimated by utilizing conventional clinical grading methods. Additionally, degeneration was quantified by means of selected, measurable parameters of degeneration.

The main findings for the study with their implications to the field of facet joint kinematics were:

- Facet joint under torsion experience coupled motion. Axial rotation is supplemented by lateral bending. Shape and orientation of the facet joint play an important role in this process.

- Age and gender are significant factors in predicting motion pattern of the lumbar facet joint. Alterations of facet joint kinematics are age-dependent, which is closely related to the degenerative changes. Degeneration in the female tends to deviate from male after fourth decade.
- Conventional method to study degenerative changes in the human spine correlated with quantitative methods. However, quantitative methods were able to detect early changes in morphology of the intervertebral disc and facet joint better. Quantification of degenerative changes may be a valuable tool in explaining the origin and causes of degenerative process, and also can significantly contribute to the development of new diagnostic and treating strategies for spinal care.
- Facet joint degeneration may not be secondary to the disc degeneration. The rule defined by Kirkaldy-Willis can be fully implemented. The normal sequence of degenerative events in the three-joint complex is that one joint is at first affected, and then because of the interplay, eventually changes occur in all three[18]. This finding has a significant clinical application. It can help to develop new diagnostic methods, change existing ones, and in general contribute to development of new treatments in the spinal care.
- Both, facet joint kinematic parameters and degeneration in the intervertebral disc and facet joint are significantly different in the study group of symptomatic subjects. Results suggest that degeneration initiate spinal instability and as a combined factor may lead to the low back pain. Further investigation need to be done, particularly correlation of motion patterns in intervertebral disc and facet joint can help to understand etiology of low back pain.

Based on these findings, concept of segmental instability can be better understood and results can be valuable in design of new diagnostic methods and treatments, or alternating existing ones, designing spinal implants, finite element modeling, spinal manipulation, etc. Study has also significant value in the

basic understanding of the motion and degeneration of the human lumbar spine and methods developed in this work should be openly accessible to enhance research. These results can serve as a base reference for the further study of the “mysterious” facet joint.

2. Study limitations

This study was not without limitations. Particularly, the age of our subjects ranging from 20-60 years (mean ± SD: 36.5 ± 10.0 years) may not be sufficient for evaluation of advanced degenerative changes. Also, the study subjects were not perfectly matched with respect to symptom and age. This fact is due to difficulties in gathering subjects with low back pain in the second decade and subjects with no symptoms in the fifth decade.

Additionally, the slice thickness of the clinical CT used in this study (1 mm) may limit surface geometry precision. However, in order to establish a clinically relevant methodology in diagnosis spinal segmental instability, it was necessary to work within the frame of conventional clinical methods.

In this study, the subjects were scanned in the supine position in neutral and rotated position. As a limitation, it is important to note, that torsion applied in the supine position might not represent true, native motion pattern in the facet joint and intervertebral disc. Perhaps advancements in vertical imaging modalities will validate this approach one day.

3. Future work

The methods developed in this work should be applied further into the analysis of the facet joint, and other complex joints. Local coordinate system definition with reference to the natural spinal lordosis can be a very powerful concept on which many new quantitative parameters can be defined, and old one re-defined.

Position and orientation of the facet joint significantly contributes to the articulation pattern. Facet tropism has been defined in the literature as degenerative deviation from the orientation between right and left side. Using methods developed in this study, particularly the local coordinate system definition can be very useful in quantifying tropism and defining its contribution to kinematic alterations and progression of degenerative changes.

Facet joint osteoarthritis was evaluated in this study using only one, however very significant parameter – facet joint space width. In order to get broader picture of the facet joint osteoarthritis, it is necessary to evaluate other parameters as well. Space width narrowing is closely correlated with cartilage thinning. There were numerous studies evaluating facet joint cartilage gross morphology *in-vitro*[51,62]. However, data on facet joint cartilage thickness are missing. The result of this study showed that the facet joint gap ranges from 0.6-2.3 mm measured in the different zones. To measure such a delicate surface, it is necessary to develop a method that is able to scan the surface of the cartilage with a high precision in minimal time (cartilage looses water when exposed to air, what results in cartilage spontaneous thinning). Data on cartilage thickness will make it possible to precisely evaluate facet joint contact and to get a closer look at facet joint load shearing and pressure distribution. Another parameter, correlated to facet joint osteoarthritis, subchondral plate thickness nees to be evaluated. It reflects the loading pattern and it is believed that in contrast with cartilage thinning, subchondral bone sclerosis cause a decrease in motion[30]. Three-dimensional evaluation of subchondral bone thickness distribution will significantly contribute to the understanding of segmental instability in the older population.

Future attempts in explaining the complexity of facet joint motion should also include *in-vitro* measurements of facet joint motion in all three principal directions (flexion/extension, lateral bending, axial rotation). If such a method is developed, change of segmental motion due to spinal implants or fusion can be better understood.

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APPENDIX A

Dynamic CT scan Protocol

Procedure:

1. Remove padding used with patients from the CT scanner bed
2. Place plastic backboard on CT bed with metal pieces up and 'head' facing away from scanner.
3. Make sure that the 'grey' line of the CT scanner bed is located superior of the ROI (higher than T12 on subject).
    a. This line is the furthest in the bed will go into the scanner.
4. Connect both parts of Torsion system to backboard
    a. Both sections are initially placed between scanner and appropriate metal pieces on backboard
        i. For the upper section, the ring is furthest from scanner coil
        ii. For the lower section, the posts are furthest from scanner coil
    b. Slide system sections onto metal backboard pieces (away from scanner coil).
        i. The system sections will slide smoothly if parallel to metal pieces of backboard.
        ii. Align lower section with black lines on backboard
        iii. Tighten lower section of Torsion system
        iv. Make sure the upper section is set at 0°
        v. Adjust upper section of Torsion system as needed to accommodate the height of the subject.
        vi. Place pillows between both sections of torsion system
5. Ask subject if he/she wishes to have a lead apron around his/her hips
6. Lower CT bed so that subject can easily sit on lower section
    a. Have subject sit as close to the top of the lower Torsion section (the post end) as possible.
    b. The lower section posts should be positioned around the greater trochanters of the subject
    c. Place a clean pillow case on the head form of the upper Torsion section
    d. The subject should lay down onto the upper section
    e. Adjust upper section so that the subject can comfortably lay in system.
    f. Tighten bolts of upper section
7. Tighten straps around subject
    a. Across thighs, hips, chest and shoulders
8. Lift scanner bed and slide bed into CT scanner coil with subject
    a. Use the directional arrows on sides of scanner coil
    b. When the directional arrows for moving the bed in or out of the scanner are lit, then you can move the bed into the coil
    c. Make sure the bed is as low as possible in the coil so that nothing will hit the scanner coil
9. Check alignment of backboard on scanner
    a. The backboard should be centered on CT bed
    b. The subject should be lined up perpendicular to scanner coil
        i. Use laser cross hairs to align subject
        ii. Tell subject not to look into the laser source!
        iii. Adjust subject as needed
    c. Secure the backboard to the CT bed using the white tape
        i. Don't put tape on vinyl foot rest of bed
10. Slide bed into scanner coil until second (caudal) laser line is above T12 level

11. Once subject is aligned, hit the ‘zero’ button on key pad of scanner
12. Remove metal wrenches from around the subject
13. Close CT room doors
14. View CT scout images
    a. Tell Edwin (pager x5650) subject number, age and birthdate
    b. Give blank CDs to Edwin for copying CT (and MRI) images
    c. We don’t need any hard copy films, except for scout images
    d. Make sure CT forms are filled in appropriately
    e. The CT scout should be lateral and AP
        i. From the AP scout
            1. Make sure you can see T12 to sacrum
            2. Is the torsion system in the ROI? Yes - Move subject
            3. Is the spine straight? No- Adjust subject
        ii. From the lateral scout
            1. Does the spine have a ‘normal’ lordosis? No- Adjust pillows (or add more)
            2. Make sure you can see T12 to Sacrum
15. Get 0° scans
16. Make sure subject is doing ok
17. Place head strap across temples of subject
    a. If uncomfortable for subject, place pillow case between strap and forehead
18. Loosen bolt holding upper section ring and turn slowly to 50° (right).
    a. Tell subject to relax and not perform motions on their own
19. Tighten upper section ring
20. Make sure subject is ok
21. Get 50° to the right scans
22. Make sure subject is ok
23. Loosen bolt holding upper section ring and turn slowly to 0°
    a. Let subject rest for a moment
24. Unstrap the subject from torsion system and help him/her exit scanner bed
25. Tell subject directions for water or restroom as needed
26. Break down torsion system and return CT room to original set up

APPENDIX A

Three-dimensional CT model segmentation protocol

Program: Materialise

MIMICS 14.2

Procedure:

1. To convert CT scans from CD
    a. Go to Mimic 14.12
    b. File: Import images (filename.pat)
    c. Select all files
    d. Add Auto
    e. Unselect Compression
    f. Select desired target directory to create a new project
    g. Convert
2. File: Open CT scans
3. Set Threshold levels (icon)
4. Record selected threshold for the rotated position (in the same subject)
5. Select Edit (icon)
    a. Erase unwanted pixels
    b. Set color for Masks. Use a different mask color for each vertebrae
        i. Need to color each slice of a vertebrae
        ii. Color vertebrae perimeter (make sure the perimeter is closed)
        iii. 'Fill' the area outside your selected perimeter with a random color
        iv. 'Fill' the area inside your selected perimeter with the desired color
        v. Turn off the random color
6. Go to Project Manager
    a. Select desired mask
    b. Use Calculate 3D to get pixel coordinates. This option splices all slices together to form a solid 3D model.
    c. Check that model looks ok by selecting View 3D (icon)
    d. Repeat for each vertebral mask
    e. Create point-cloud for each mask (button)

APPENDIX A

Posterior wall model segmentation protocol

Program: Inoue

Eraser MicroCT

Procedure:

1. open Eraser MicroCT program
2. click open file button
3. select folder containing desired subject vertebral body surface point-clouds
4. select vertebral body of the desired level
5. click X button
6. adjust orientation using RX-, RX+, RY-, RY+ RZ-, RZ+ button such that vertebral body is oriented in a top view with posterior wall portion in line
7. click draw button
8. draw portion of posterior wall in between the pedicles
9. click draw save button and enter the FILENAME
10. open file and select drown surface
11. adjust orientation using RX-, RX+, RY-, RY+ RZ-, RZ+ button such that posterior wall is oriented in a front view
12. click erase button and remove unnecessary points if needed
13. click erase save and enter the FILENAME

APPENDIX A

Endplate model segmentation protocol

Program: Inoue

Eraser MicroCT

Procedure:

14. open Eraser MicroCT program
15. click open file button
16. select folder containing desired subject vertebral body surface point-clouds
17. select vertebral body of the desired level
18. click X button
19. adjust orientation using RX-, RX+, RY-, RY+ RZ-, RZ+ button such that vertebral body is oriented in a sagittal view with endplate of interest aligned horizontally
20. click draw button
21. draw portion of an endplate, be careful to not include unnecessary sides of the vertebral body, always do check!!!
22. click draw save button and enter the FILENAME
23. open file and select drown surface
24. adjust orientation using RX-, RX+, RY-, RY+ RZ-, RZ+ button such that posterior wall is oriented in a front view
25. click erase button and remove unnecessary points if needed
26. click erase save and enter the FILENAME

APPENDIX A

Facet joint surface tracing protocol

Program: Inoue

Ryota v2

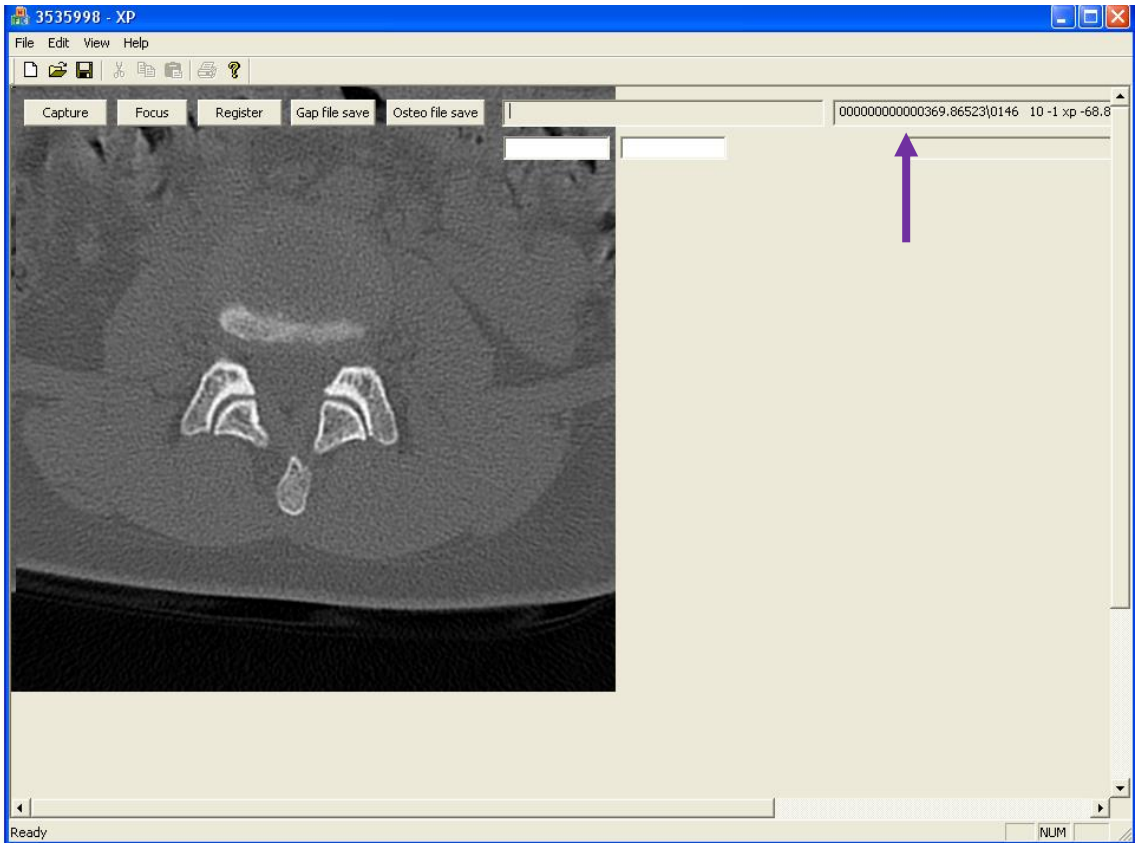
Procedure:

A. Prepare data and rename image files

1. Import CT data from CD to computer. There are two sets of images, B10 and B60. Select the B60 series, NOT the B10 series.

B. Rename the DICOM image file according to the Z-coordinate

1. The original image file name is not in sequential. For easier utilization, it's better to rename the DICOM image according to the Z coordinates by using Ryota v2.
2. Run Ryota v2, and open the DICOM image. The original file name (red arrow) is shown on the left upper corner. The Z-coordinate is shown on the right upper part (purple arrow). See the following example. The original file name is 3535998. The Z-coordinate is 0146. Change the file name from 3535998 to 0146.



C. <u>Trace the subchondral bone of the facet joint</u>

1. Run “Ryota v2”
2. Open the most distal image of one facet joint.
3. Select the facet surface which you want to trace (for example, left anterior facet surface). Right click around the facet (A yellow dot will show up on the screen where you dotted) and then click the “Capture” button.
4. Left click a point, which is on the selected facet surface side and is distant away from the facet joint surface, and then click the “Focus” button.
5. Trace the facet joint surface from lateral side to medial side. Beware not to include the osteophytes or laminae.
6. If you make any wrong tracing, click “Capture” button and trace again.
7. Click “Register” button.
8. Open the next image and repeat step 3 to step 6 until you finish tracing the most proximal image of the facet joint.
9. Click the “Gap save file” button to save point-cloud data of the facet joint surface.
10. Click the “Osteo save file” button to save SBD data of the facet joint surface.
11. Close “Ryota v2”.
12. Run “Ryota v2” again, trace the other joint surface of the facet joint (left posterior, right anterior, and right posterior facet surfaces).

APPENDIX A

Facet joint normal vector calculation protocol

Program: Inoue

Facet 5 zones box v2-1

Procedure:

1. open Facet 5 zones box v2-1 program
2. click left mouse button
3. select folder containing desired subject FJ surface pointclouds
4. select superior (inferior) surface of the desired level (L1L2 etc.)
5. click L button
6. adjust orientation using B button such that mean normal vector has positive (negative if inferior) y coordinate
7. click H button
8. click right mouse button
9. save as FILENAME
10. repeat step 1-12 for another FJ surface pair
11. save using append function in the same folder
12. update excel file

APPENDIX A

Posterior wall LCS calculation protocol

Program: Inoue

Eigen New v3

Procedure:

1. open Eigen New v3 program
2. click Open file button
3. select folder containing desired subject PW surface point-clouds
4. select posterior wall surface of the desired level (L1L2 etc.)
5. click power method button
6. check if results give sense (orientation is with reference to rectangular shape of the posterior wall, etc.)
7. click Save file button
8. save as FILENAME
9. save using append function in the same folder
10. update excel file

APPENDIX A

Disc degeneration grading protocol

Procedure:

1. Images:
   a. Use the mid-sagittal DICOM images of MRI. The contrast and brightness should be standardized on each image. Make these images to a PowerPoint file.
2. In the PowerPoint file, the arrangement of the image sequence should be randomized by the coordinator. The raters should be blinded to the image sequence.
3. Ideally, there should be at least two raters to grade the discs. With the interval of 2 weeks, each rater makes the 2nd-time grading. For the 2nd-time grading, the coordinator should re-arrange the image sequence and make a new PowerPoint file.
4. The raters should thoroughly discuss details of illustrative images and grading procedure to make sure they grade images under the same standard.
5. Raters must grade images on the same computer with the same setting.
6. References for disc grading:
   - Thompson JP et al: Preliminary evaluation of a scheme for grading the gross morphology of the human intervertebral disc. Spine 5(5): 411-415, 1990.
   - Fujiwara A et at: The Effect of Disc Degeneration and Facet Joint Osteoarthritis on the Segmental Flexibility of the Lumbar Spine. Spine 25(23), p3036-3044, 2000. (Figure 1)

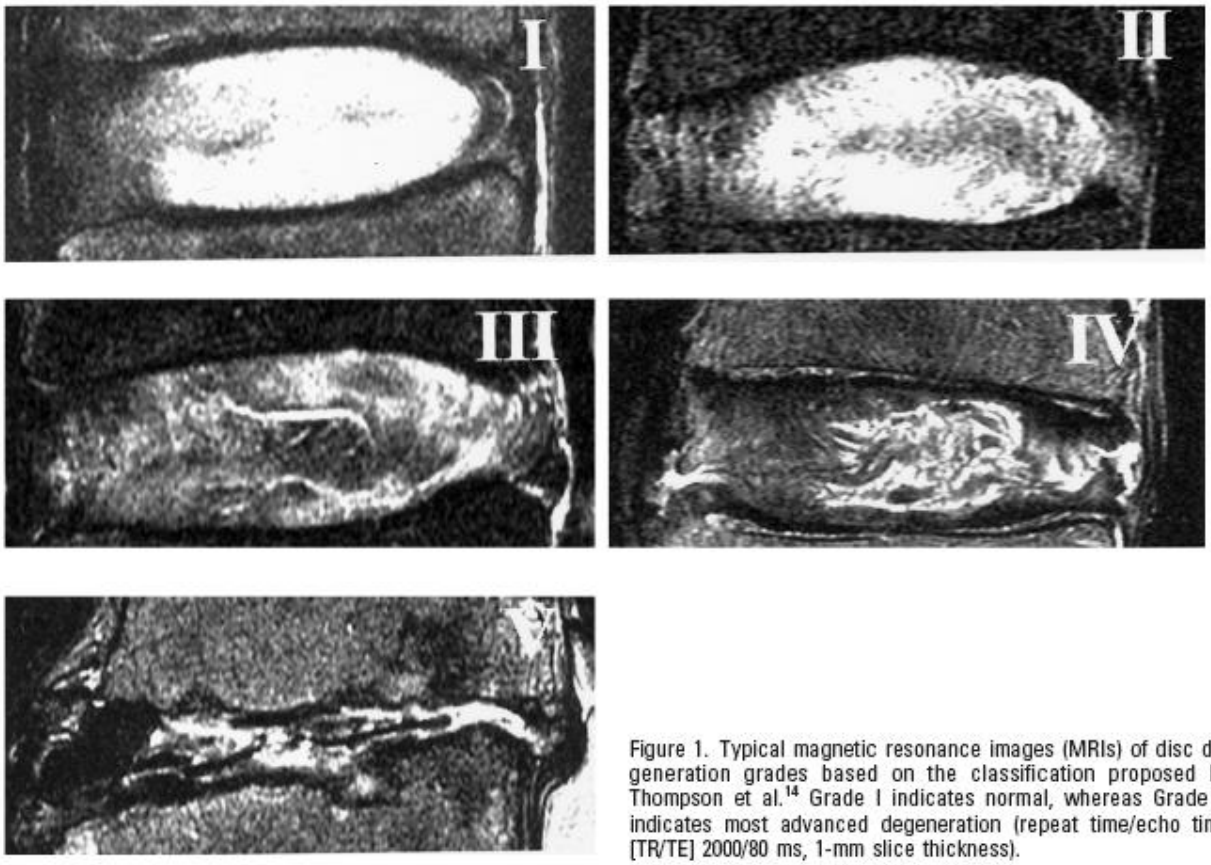


Figure 1. Typical magnetic resonance images (MRIs) of disc degeneration grades based on the classification proposed by Thompson et al.[14] Grade I indicates normal, whereas Grade V indicates most advanced degeneration (repeat time/echo time [TR/TE] 2000/80 ms, 1-mm slice thickness).

APPENDIX A

Facet Joint Space Osteoarthritis Grading

Procedure:

1. Images:
   a. Use the mid-axial DICOM images of CT (B60 series, NOT B10). The contrast and brightness should be standardized on each image. Make these images to a PowerPoint file.
2. In the PowerPoint file, the arrangement of the image sequence should be randomized by the coordinator. The raters should be blinded to the image sequence.
3. Ideally, there should be at least two raters to grade the discs. With the interval of 2 weeks, each rater makes the 2nd-time grading. For the 2nd-time grading, the coordinator should re-arrange the image sequence and make a new PowerPoint file.
4. The raters should thoroughly discuss details of illustrative images and grading procedure to make sure they grade images under the same standard.
5. Raters must grade images on the same computer with the same setting.
6. References for facet grading:
   - Weishaupt D et. al. MR Imaging and CT in Osteoarthritis of the Lumbar Facet Joints. Skeletal Radiology 1999; 28:215-219. (Figure 2)

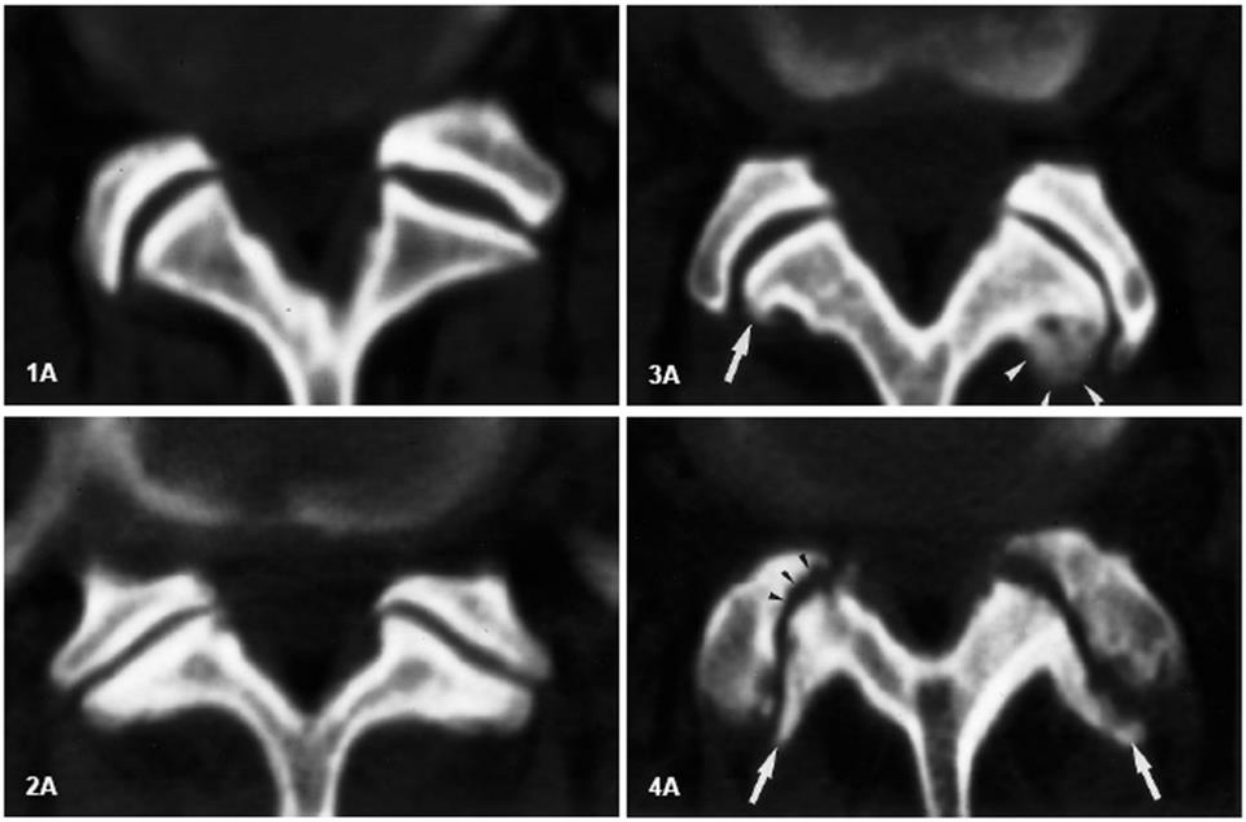


Table 1 Criteria for grading osteoarthritis of the facet joints (adapted from [9])

Grade	Criteria
0	Normal facet joint space (2–4 mm width)
1	Narrowing of the facet joint space (< 2 mm) and/or small osteophytes and/or mild hypertrophy of the articular process
2	Narrowing of the facet joint space and/or moderate osteophytes and/or moderate hypertrophy of the articular process and/or mild subarticular bone erosions
3	Narrowing of the facet joint space and/or large osteophytes and/or severe hypertrophy of the articular process and/or severe subarticular bone erosions and/or subchondral cysts

APPENDIX A

Facet Joint Space Width measurement

Program: Inoue

Facet 5 zones box v2-1

Procedure:

1. open Facet 5 zones box v2-1 program
2. click left mouse button
3. select folder containing desired subject FJ surface pointclouds
4. select superior surface of the desired level (L1L2 etc.)
5. select inferior surface of the desired level (L1L2 etc.)
6. click L button
7. adjust orientation using B button such that mean normal vector has negative y coordinate
8. click H button
9. click 9 button – switch to zone mode
10. adjust zone 5 point count to average point count
11. click right mouse button
12. save as FILENAME
13. repeat step 1-12 for another FJ surface pair
14. save using append function in the same folder
15. update excel file

APPENDIX A

Disc Height measurement

Program: Inoue

Disc height 5 zones v1

Procedure:

1. open Disc height 5 zones v1 program
2. click left mouse button
3. select folder containing desired subject FJ surface pointclouds
4. select inferior endplate of desired level as first (L1L2 etc.)
5. select superior endplate of the desired level as second (L1L2 etc.)
6. click J button
7. orientation of normal vector should be towards z direciton
8. click H button
9. click 9 button – switch to zone mode
10. check the presentation of zone if correct not missing, no holes
11. click right mouse button
12. save as FILENAME
13. repeat step 1-12 for another IVD surface pair

APPENDIX B

National Spine Network outcome questionnaire

IRB # ORA 0509080 1

SUBJECT # _____

from Michelangelo

Health Status Survey

Long-Term Follow-Up

NSN

NATIONAL SPINE NETWORK, INC.

When completing this health status survey, please:

Marking Example

Correct Mark

Incorrect Marks

- Use a soft lead pencil (No. 2)
- Make dark marks that fill the response circle completely
- Erase changes completely
- Make no stray marks near the response circles

Please [illegible] the [illegible] to begin

Office Use Only

NSN Site ID | NSN Clinician ID | NSN Patient ID | Today's Date

Please use a pencil

Medical Care Contacts

1. In the past 6 months, have you been seen at this clinic for your spine condition?

① Yes → If Yes (answer questions a and b below):

a. How many times have you been seen ?

① 1 time ②2 times ③3 times ④4 or more times

b. Of these visits, how many were **unscheduled** - that is, due to some sudden or unexpected change in your condition?

①None, all visits were planned in advance

② 1 visit ③2 visits ④3 visits ⑤4 or more unscheduled visits

② No

2. In the past 6 months, have you been to see any **other health care professional** for any reason (including emergencies, check-ups, or other medical problems)?

① Yes → If Yes (answer questions a and b below):

a. How many times were you seen **for your spine condition**?

①None ②1 time ③2 times ④3 times ⑤4 or more times

b. How many times were you seen **for any other reason**?

①None ②1 time ③2 times ④3 times ⑤4 or more times

② No

Compensation

1. Have you applied for, or are you receiving, compensation (such as worker's compensation or disability insurance) as a result of your spine-related problems?

① Yes → If yes, what is the current status ?

①My application is in process ②I am receiving compensation

②My application was turned down (not eligible) ③I received but am no longer receiving compensation

② No

2. Have you engaged an attorney to aid you with your spine-related condition?

① Yes → If yes, what is the current status of your legal action?

①My legal action or lawsuit is pending or in process.

②My legal action has been resolved, but not in my favor.

③My legal action has been resolved in my favor.

② No → If No, are you considering the need for an attorney? ① Yes ② No

Surgical Summary

INDICATIONS

Mark all indications that apply.

- ◯ Axial Pain
- ◯ Radicular Pain
- ◯ Sensory Deficit
- ◯ Weakness
- ◯ Radiculopathy
- ◯ Myelopathy
- ◯ Neurogenic Claudication
- ◯ Spinal Instability
- ◯ Cord Compression
- ◯ Spinal Stenosis
- ◯ Cauda Equina Syndrome
- ◯ Other ________

Revision surgery
- ◯ Symptomatic non-union
- ◯ Instrumentation failure

Deformity
- ◯ Cosmesis
- ◯ Curve Magnitude
- ◯ Progression of Curve
- ◯ Pulmonary Function
- ◯ Cardio Pulmonary Compromise

SURGICAL FACTORS

Total Operation Time (Incision to Close)	Blood Loss	Total Blood Replacement
MINUTES	CC	CC

ANTERIOR PROCEDURE

Mark all ANTERIOR procedures performed

- ◯ Fusion
- ◯ Decompression
  - ◯ Cord
  - ◯ Nerve Root
  - ◯ Cauda Equina
  - ◯ Canal
- ◯ Pseudarthrosis
  - ◯ Exploration
  - ◯ Repair
- ◯ Removal of Instrumentation
  - ◯ Partial ◯ Complete
- ◯ Thoracoplasty
- ◯ Osteotomy
- ◯ Discectomy
- ◯ Vertebrectomy or Corpectomy
- ◯ Other anterior procedure ▼ ________

Approach
- ◯ Thoracotomy
- ◯ Thoraco-abdom.
- ◯ Retro-peritoneal
  - ◯ paramedian
- ◯ Laproscopic
- ◯ Transperitoneal

Procedure Type ◯ Initial ◯ Revision ◯ Planned Staged

Levels Decompressed ◯ NA

Levels Fused ◯ NA

Levels Instrumented ◯ NA ◯ Same

Type of Ant. Fusion
- ◯ None
- ◯ Interbody
- ◯ Strut
- ◯ Morselized
- ◯ Vascularized
- ◯ Other fusion ▼ ________

Type of Instrumentation ◯ None

Manufacturer: ________

Components:
- ◯ Ant. Plate(s)
- ◯ Cage(s)
  - ◯ Threaded type
  - ◯ Strut type
- ◯ Hook(s)
- ◯ Rod(s)
- ◯ Screw(s)
- ◯ Wire(s)
- ◯ Other Instr. ▼ ________

Graft (mark all that apply) ◯ None

Autograft
- ◯ Structural ◯ Non-Structural

Source
- ◯ Ilium ◯ Cortical
- ◯ Ribs ◯ Cancellous
- ◯ Fibula ◯ Local
- ◯ Other Source ________

Allograft
- ◯ Structural ◯ Non-Structural

Source
- ◯ Ilium ◯ Cortical
- ◯ Ribs ◯ Cancellous
- ◯ Fibula ◯ Femoral Hd.
- ◯ DBM
- ◯ Other Source ________

POSTERIOR PROCEDURE

Mark all POSTERIOR procedures performed

- ◯ Fusion
- ◯ Decompression
  - ◯ Cord
  - ◯ Nerve Root
  - ◯ Cauda Equina
  - ◯ Canal
- ◯ Pseudarthrosis
  - ◯ Exploration
  - ◯ Repair
- ◯ Removal of Instrumentation
  - ◯ Partial ◯ Complete
- ◯ Discectomy
- ◯ Facetectomy
- ◯ Foraminotomy
- ◯ Laminectomy
- ◯ Laminotomy
- ◯ Osteotomy
- ◯ Vertebrectomy or corpectomy

Approach
- ◯ Costotrans-versectomy
- ◯ Transpedicular
- ◯ Posterolateral
- ◯ Percutaneous
- ◯ Other posterior procedure ▼ ________

Procedure Type ◯ Initial ◯ Revision ◯ Planned Staged

Levels Decompressed ◯ NA

Levels Fused ◯ NA

Levels Instrumented ◯ NA ◯ Same

Type of Post. Fusion
- ◯ None
- ◯ Interbody
- ◯ Intratransverse
- ◯ Strut
- ◯ Morselized
- ◯ Other fusion ▼ ________

Type of Instrumentation ◯ None

Manufacturer: ________

Components:
- ◯ Band(s)
- ◯ Cage(s)
  - ◯ Threaded type
  - ◯ Strut type
- ◯ Hook(s)
- ◯ Rod(s)
- ◯ Screw(s) - pedicle
- ◯ Screw(s) - other
- ◯ Wire(s)
- ◯ Other Instr. ▼ ________

Graft (mark all that apply) ◯ None

Autograft
- ◯ Structural ◯ Non-Structural

Source
- ◯ Ilium ◯ Cortical
- ◯ Ribs ◯ Cancellous
- ◯ Fibula ◯ Local
- ◯ Other Source ________

Allograft
- ◯ Structural ◯ Non-Structural

Source
- ◯ Ilium ◯ Cortical
- ◯ Ribs ◯ Cancellous
- ◯ Fibula ◯ Femoral Hd.
- ◯ DBM
- ◯ Other Source ________

INTRAOPERATIVE COMPLICATIONS

Instrumentation Complications
- ◯ Screw breakout
- ◯ Loss of purchase
- ◯ Implant breakage

Other Complications
- ◯ Dural laceration / tear
- ◯ Excessive Bleeding
- ◯ Esophageal injury
- ◯ Nerve root injury
- ◯ Spinal cord injury
- ◯ Urologic injury
- ◯ Vascular injury
- ◯ Anesthesia Complications
- ◯ CSF Leak

◯ Other complication(s) ________

COMMENTS

____

NSN Health Status Survey – Initial Visit / Follow-up Visit (NSN2.0)

The NSN 2.0 instrument is the current outcomes instrument of the NSN and has been in use since February 1997. There are 27,853 patients in the database with data from these forms. To access this data set, select "NSN 2.0" from the study selection list on the main Cohort Builder Screen. Additionally, selecting "NSN 1.0 and 2.0" from this study selection list will give you a database composed of the variables that are common between the two major revisions of this instrument.

Health Status Questionnaire 2.0 (cont.)

These questions are about how you feel and how things have been with you during the **past 4 weeks**. For each question, please give the one answer that comes closest to the way you have been feeling.

How much of the time during the **past 4 weeks**...

(Fill in only **one circle on each line**)	**All of the time**	**Most of the time**	**A good bit of the time**	**Some of the time**	**A little of the time**	**None of the time**
23. Did you feel full of pep?	①	②	③	④	⑤	⑥
24. Have you been a very nervous person?	①	②	③	④	⑤	⑥
25. Have you felt so down in the dumps that nothing could cheer you up?	①	②	③	④	⑤	⑥
26. Have you felt calm and peaceful?	①	②	③	④	⑤	⑥
27. Did you have a lot of energy?	①	②	③	④	⑤	⑥
28. Have you felt downhearted and blue?	①	②	③	④	⑤	⑥
29. Did you feel worn out?	①	②	③	④	⑤	⑥
30. Have you been a happy person?	①	②	③	④	⑤	⑥
31. Did you feel tired?	①	②	③	④	⑤	⑥

32. During the **past 4 weeks,** how much of the time has your **physical health or emotional problems** interfered with you social activities (like visiting with friends, relatives, etc.)? (Fill in only **one circle**)

① All of the time ② Some of the time ③ A little of the time
④ Most of the time ⑤ None of the time

How TRUE or FALSE is each of the following statements for you?

(Fill in only **one circle on each line**)	**Definitely True**	**Mostly True**	**Don't Know**	**Mostly False**	**Definitely False**
33. I seem to get sick a little easier than other people	①	②	③	④	⑤
34. I am as healthy as anybody I know	①	②	③	④	⑤
35. I expect my health to get worse	①	②	③	④	⑤
36. My health is excellent	①	②	③	④	⑤

MARK NO MARKS BELOW THIS LINE

Health Status Questionnaire 2.0

Instructions:

The survey on the following pages asks for your views about your health. This information will help your doctors keep track of how you feel and how well you are able to do your usual activities. Answer every question by completely filling in the correct circle. If you are unsure about how to answer a question, please give the best answer you can.

1. In general would you say your health is: (Fill in only one circle)
   ① Excellent ② Very good ③ Good ④ Fair ⑤ Poor

2. **Compared to one year ago**, how would you rate your health in general now? (Fill in only **one circle**)
   ① Much better than 1 year ago
   ② Somewhat better than 1 year ago
   ③ About the same
   ④ Somewhat worse than 1 year ago
   ⑤ Much worse than 1 year ago

The following items are about activities you might do during a typical day. Does **your health now limit** you in these activities? If so how much? If your activities are limited because of your health, is this due to your spine related problems? (Answer for each activity)

	Yes, limited a lot	**Yes, limited a little**	**No, not limited at all**	**If Limited, due to spine related problems?**
3. **Vigorous activities**, such as running, lifting heavy objects, participating in strenuous sports.	①	②	③	① Yes ② No
4. **Moderate activities**, such as moving a table, pushing a vacuum cleaner, bowling, or playing golf.	①	②	③	① Yes ② No
5. Lifting or carrying groceries.	①	②	③	① Yes ② No
6. Climbing **several** flights of stairs.	①	②	③	① Yes ② No
7. Climbing **one** flight of stairs.	①	②	③	① Yes ② No
8. Bending, kneeling, or stooping.	①	②	③	① Yes ② No
9. Walking **more than a mile**.	①	②	③	① Yes ② No
10. Walking **several blocks**.	①	②	③	① Yes ② No
11. Walking **one block**.	①	②	③	① Yes ② No
12. Bathing or dressing yourself.	①	②	③	① Yes ② No

MAKE NO MARKS BELOW THIS LINE

Work

1. Were you working for wages prior to your current spine-related symptoms?

○1 Yes → If Yes, on average how many hours a week did you work?
- ○1 40 or more hours per week
- ○2 20 – 29 hours per week
- ○3 30 – 39 hours per week
- ○4 Less than 20 hours per week

○2 No

2. Are you working for wages now?

○1 Yes → If Yes (answer questions a, b, c and d below):

a. On average how many hours a week do you work?
- ○1 40 or more hours per week
- ○2 20 – 29 hours per week
- ○3 30 – 39 hours per week
- ○4 Less than 20 hours per week

b. Is this the same job you had before your symptoms? ....○1 Yes ○2 No

c. Have the physical requirements of your work been reduced as a result of your symptoms? .....○1 Yes ○2 No

d. Since you began receiving treatment at this spine center, how much work have you missed due to your spine-related symptoms?
mark one answer each for months and weeks (or partial weeks)

Months	○0	○1	○2	○3	○4	○5	○6	○7	○8	○9	○10	○11	○12 or more
Weeks	○0	○1	○2	○3									

○2 No → If No (answer questions e and f below):

e. Why aren't you working? (Mark all that apply.)
- ○1 I choose not to work outside of the home (housewife/househusband)
- ○2 I am a student
- ○3 I am unable to work because of my spine-related problems
- ○4 I am unable to work because of another disability
- ○5 I am on leave from work
- ○6 I have retired by my choice
- ○7 I have retired involuntarily (employer's choice)
- ○8 I am a seasonal employee
- ○9 I can't find work
- ○10 Other reason _____

f. Are you currently looking for work? .....○1 Yes ○2 No

3. Whether you are working for wages or not, how would you describe the physical requirements of your usual daily responsibilities?

○1 Extremely strenuous ○2 Moderately strenuous ○3 Not very strenuous at all

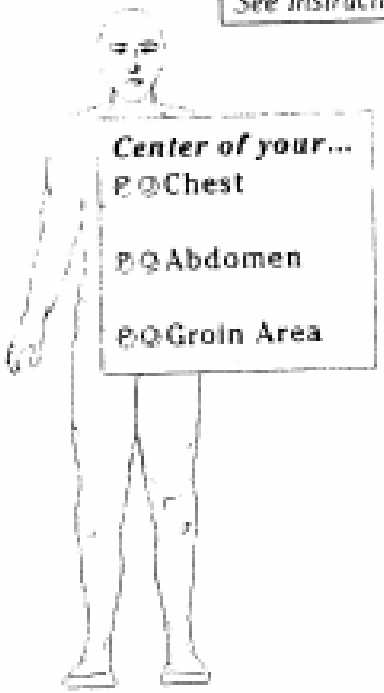
MAKE NO MARKS BELOW THIS LINE

Current Symptoms

Fill in **P** *for* ***pain****, or* **O** *for* ***other spine-related symptoms****.*
See Instructions next page

Your Right FRONT...

Head P O
Neck P O
Shoulder P O
Chest P O
Upper Arm P O
Lower Arm P O
Hand / Fingers P O
Abdomen P O
Hip - front P O
Hip - outside P O
Thigh - front P O
Thigh - outside P O
Knee P O
Shin P O
Ankle P O
Foot P O



Center of your...

P O Chest
P O Abdomen
P O Groin Area

Your Left FRONT...

P O Head
P O Neck
P O Shoulder
P O Chest
P O Upper Arm
P O Lower Arm
P O Hand / Fingers
P O Abdomen
P O Hip - front
P O Hip - outside
P O Thigh - front
P O Thigh - outside
P O Knee
P O Shin
P O Ankle
P O Foot

Your Left BACK...

Head P O
Neck / Upper Back P O
Shoulder P O
Upper Arm P O
Lower Arm P O
Hand / Fingers P O
Middle Back P O
Lower Back P O
Buttocks P O
Hip P O
Thigh P O
Knee P O
Calf P O
Ankle P O
Foot P O

Center of your...

P O Neck/Upper Back
P O Middle back
P O Lower Back
P O Tailbone

Your Right BACK...

P O Head
P O Neck / Upper Back
P O Shoulder
P O Upper Arm
P O Lower Arm
P O Hand / Fingers
P O Middle Back
P O Lower Back
P O Buttocks
P O Hip
P O Thigh
P O Knee
P O Calf
P O Ankle
P O Foot

MAKE NO MARKS BELOW THIS LINE

Satisfaction

1. If you had to spend the rest of your life as you are right now, how would you feel about it? (Mark one answer only.)

① Extremely satisfied ② Very satisfied ③ Somewhat satisfied ④ Mixed, about equally satisfied and dissatisfied ⑤ Somewhat dissatisfied ⑥ Very dissatisfied ⑦ Extremely dissatisfied

2. How would you rate your satisfaction with the treatments you have been given for your spine condition? (Mark one answer only.)

① Satisfied ② Somewhat Satisfied ③ Somewhat Dissatisfied ④ Dissatisfied

Spine-Related Pain and Interference

Answer questions 1-6 below on a scale of 0 to 10 where 0 is least (or best) and 10 is most (or worst). Fill in only one circle for each question.

1. How would you describe your spine-related **pain** at the **present time**?	No pain ◄►	Worst Possible Pain
2. In the past 6 months, how intense was your **worst pain**?	No pain ◄►	Worst Possible Pain
3. In the past 6 months, how intense was your **pain** on the **average**?	No Pain ◄►	Worst Possible Pain
4. In the past 6 months, how much has your spine-related **pain interfered** with your daily activities?	No Interference ◄►	Unable to do Any Activities
5. In the past 6 months, how much has your spine-related **pain changed your ability** to take part in recreational, social and family activities?	No Change ◄►	Extreme Change
6. In the past 6 months, how much has your spine-related **pain changed your ability to work** (including household chores)?	No Change ◄►	Extreme Change

7. In the past 6 months, about **how many days** have you been kept from your usual daily activities (for example, work, school, housework) **because of pain** associated with your spine-related problems?

① 0-6 days ② 7-14 days ③ 15-30 days ④ 31 or more days

Instructions for marking current symptoms:

Indicate the **spine-related symptoms** you have been feeling **in the past 4 weeks**. Mark the "**P**" circle in those areas where you have been experiencing **Pain** and the "**O**" circle in those areas where you have been experiencing **Other Spine-Related Symptoms** (such as numbness, weakness or stiffness.)

Mark all that apply.

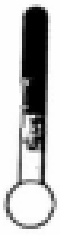
Symptoms Intensity

Rate the **intensity** of your **spine related symptoms** (such as pain, numbness, weakness or stiffness) **in the past 4 weeks.**

1. How bad are your symptoms **when they are at their worst**?

- ⑤ Very Severe
- ④ Severe
- ③ Moderate
- ② Mild
- ① Very Mild
- ⓪ None

2. How bad are your symptoms **when they are at their least**?



- ⑤ Very Severe
- ④ Severe
- ③ Moderate
- ② Mild
- ① Very Mild
- ⓪ None

3. How bad are your symptoms **on an "average" day?**

- ⑤ Very Severe
- ④ Severe
- ③ Moderate
- ② Mild
- ① Very Mild
- ⓪ None

4. How much of the time are your symptoms at their **worst**?
   - ① Rarely
   - ② Less than half the time
   - ③ About half the time
   - ④ More than half the time
   - ⑤ Almost all the time
   - ⑥ All of the time (symptoms never let up)

5. Generally speaking, are your symptoms getting **better or worse**?
   - ① Getting better
   - ② Staying about the same
   - ③ Getting worse

6. Are your symptoms (mark one):
   - ① Spreading (affecting more areas)?
   - ② Receding (affecting fewer areas)?
   - ③ Neither spreading or receding?

MARK NO MARKS BELOW THIS LINE

Medications

1. Are you currently taking any medications **for your spine-related problem**?

○ Yes → If Yes (answer questions a, b, c, and d below):

a. How many of these medications are prescription medications?

○ None ○ 1 ○ 2 ○ 3 or more

b. How many of these medications are over-the-counter medications?

○ None ○ 1 ○ 2 ○ 3 or more

c. How often do you need to take this medication?

○ It varies (sometimes a lot, sometimes little or none)
○ Rarely
○ Less than once a day
○ Daily or several times a day

d. What effect does medication have on your symptoms?

○ Medication relieves symptoms a great deal
○ Medication relieves symptoms somewhat
○ Symptoms do not seem to be affected by medication
○ Symptoms are somewhat worse with medication
○ Symptoms are much worse with medication

○ No

2. Are you currently taking any medications **for other conditions**?

○ Yes → a. How many different medications, besides any you may be taking for your spine related problem, are you now taking?

○ None ○ 1 ○ 2 ○ 3 ○ 4 ○ 5 ○ 6 or more

○ No

3. What side effects do you have from your medications? (Mark all that apply.)

○ Doesn't apply to me, I am not taking any medications
○ I have not noticed any side effects

○ Bloating	○ Fatigue or loss of energy	○ Ringing ears
○ Constipation	○ Frequent urination	○ Shaking
○ Diarrhea	○ Headache	○ Stomach upset
○ Difficulty urinating	○ Insomnia, sleep problems	○ Sweating or hot sensation
○ Dizziness	○ Jitters	○ Unable to concentrate
○ Drowsiness	○ Light headedness	○ Vision problems
○ Dryness of mouth	○ Mood swings, irritability	○ Other(indicate below)
○ Emotional problems	○ Nervousness	

MAKE NO MARKS BELOW THIS LINE

Health Status Questionnaire 2.0 (cont.)

During the **past 4 weeks**, have you had any of the following problems with your work or other regular daily activities **as a result of your physical health**? (Fill in only **one circle on each line**)

13. Cut down the **amount of time** you spent on work or other activities? ① Yes ② No
14. **Accomplished less** than you would like? ① Yes ② No
15. Were limited in the **kind** of work or other activities? ① Yes ② No
16. Had **difficulty** performing the work or other activities (for example, it took extra effort)? ① Yes ② No

During the **past 4 weeks**, have you had any of the following problems with your work or other regular daily activities **as a result of any emotional problems** (such as feeling depressed or anxious)? (Fill in only **one circle on each line**)

17. Cut down the **amount of time** you spent on work or other activities? ① Yes ② No
18. **Accomplished less** than you would like? ① Yes ② No
19. Didn't do work or other activities as **carefully** as usual? ① Yes ② No

20. During the **past 4 weeks**, to what extent has your physical health or emotional problems interfered with your normal social activities with family, friends, neighbors, or groups? (Fill in only **one circle**)

① Not at all ② Slightly ③ Moderately ④ Quite a bit ⑤ Extremely

21. How much **bodily pain** have you had during the **past 4 weeks**? (Fill in only **one circle**)

① None ② Very mild ③ Mild ④ Moderate ⑤ Severe ⑥ Very Severe

22. During the **past 4 weeks**, how much did **pain** interfere with your normal work (including both work outside the home and house work)? (Fill in only **one circle**)

① Not at all ② A little bit ③ Moderately ④ Quite a bit ⑤ Extremely

MAKE NO MARKS BELOW THIS LINE

Health Status Questionnaire 2.0 (cont.)

Please answer YES or NO for each of the following questions.
(Fill in only **one circle on each line**)

37. In the past year, have you had 2 weeks or more during which you felt sad, blue, depressed or when you lost all interest in things that you usually cared about or enjoyed? ○ Yes ○ No

38. Have you had 2 years or more in your life when you felt depressed or sad most days, even if you felt okay sometimes? ○ Yes ○ No

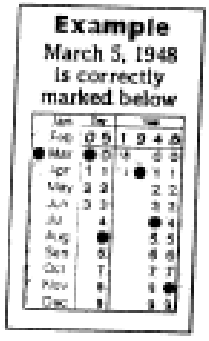
39. Have you felt depressed or sad much of the time in the past year? ○ Yes ○ No

About You:

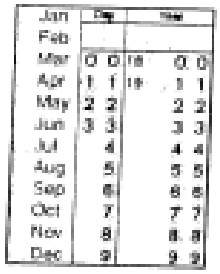
1. Are you male or female? ○ Male ○ Female

To indicate dates, *write in the numbers, then fill in the circles that match the numbers you have written.*

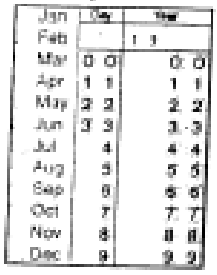
Include zeroes *(such as 02 or 03) in the day and year.*



2. What is your date of birth?



3. What is today's date?



About this Survey:

1. How long did it take to complete this survey?
   - ① Less than 10 minutes
   - ② 10 – 19 minutes
   - ③ 20 – 29 minutes
   - ④ 30 – 39 minutes
   - ⑤ 40 minutes or more

2. How was this survey to complete?
   - ① Very easy
   - ② Somewhat easy
   - ③ Somewhat difficult
   - ④ Very difficult
   - ⑤ Too difficult to complete

3. Who completed the survey?
   - ① Myself (the patient)
   - ② Parent, Spouse, or Caregiver
   - ③ Clinic personnel

Stop Here. We appreciate the time you have taken to complete this survey.

Thank you!

MARK NO MARKS BELOW THIS LINE

ATIONAL SPINE NETWORK

Surgical Summary
and
Discharge Summary

Patient Identification

The following information must be complete, or this form cannot be processed!

NSN Site ID

NSN Clinician ID

NSN Patient ID

Patient Date of Birth

Patient Gender
- ○ Male
- ○ Female

Previous Back Surgeries?
- ○ No
- ○ Yes, for this problem
- ○ Yes, for another problem

Discharge Summary (Surgical Summary on back)

Postoperative Factors

Postop Complications
- ○ None

Neuro Complications
- ○ Spinal cord injury
- ○ Nerve root injury

Fusion-Related Complications
- ○ Pseudarthrosis
- ○ Implant failure
- ○ Implant loosening
- ○ Loss of fixation
- ○ Loss of reduction
- ○ Other fusion-related compl

Infection
- ○ Deep wound
- ○ Superficial wound
- ○ Urinary tract
- ○ Pneumonia
- ○ Other infection

Other Medical Complications
- ○ Decubitus
- ○ DVT
- ○ GI bleed
- ○ Hyperkalemia
- ○ Hypovolemia
- ○ Myocardial infarction
- ○ Pulmonary embolism
- ○ Stroke
- ○ Urinary retention
- ○ Wound hematoma
- ○ Wound dehiscence
- ○ Other (specify)

_____

_____

Post-op Ambulation
- ○ Not assessed

DAYS

Immobilization
- ○ None
- ○ Collar
- ○ Milwaukee brace
- ○ Corset
- ○ LSO/TLSO
- ○ Leg extension
- ○ Halo
- Soft collar
  - ○ Foam
  - ○ Philadelphia
- ○ Rigid cervical brace
- ○ Other (specify) _____

Discharge Medications
- ○ None
- ○ Non-narcotic
- ○ Mild narcotic
- ○ Strong narcotic

Other Modalities
- ○ Bone Growth Stimulator
- ○ Bone Growth Factor

Follow-up
- ○ 2 weeks ○ 6 weeks ○ PRN
- ○ 4 weeks ○ 3 months ○ 6 months
- ○ Other (specify) _____ ○ 1 year

Length of Stay

Admission Date

Date of Surgery
- ○ Same as Admission Date

Discharge Date
- ○ Same as Surgery Date

Comments

_____

_____

_____

_____

_____

_____

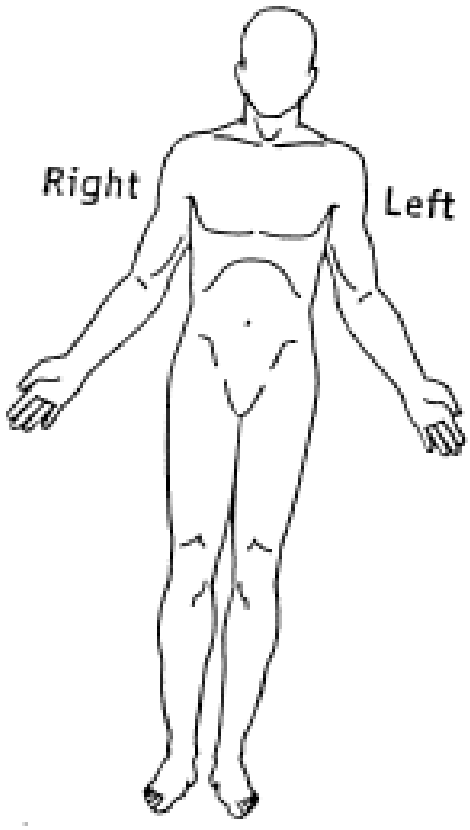
_____

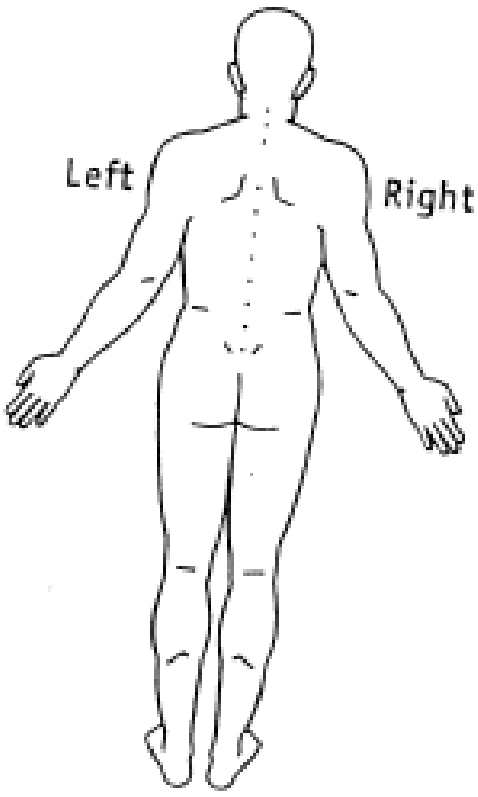
Name _____ Date _____

WHERE IS YOUR PAIN NOW?

Mark the areas on your body where you feel the described sensations. Use the appropriate symbols. Mark the areas of radiation. Include all affected areas.
Just to complete the picture, please draw in your face.

ACHE ^^^^ NUMBNESS ≈≈≈≈ PINS & NEEDLES ═══ BURNING xxxx STABBING ////





.EASE MARK ON THE LINE:

w bad is your BACK PAIN now?

No Pain _____ Worst Possible Pain

bad is your LEG PAIN now?

No Pain _____ Worst Possible Pain

VITA

PETER SIMON, M.Sc.

EDUCATION

2007 – 2012 (spring) **Ph.D.** in Biomechanics. Department of Bioengineering, UIC, Chicago, IL.

Expected spring 2012. Doctoral studies with a concentration in Spinal Biomechanics and image-based evaluation of degenerative changes.

GPA 3.6/4.0. Relevant coursework: Computational Biomechanics, Implant Design, Mechanics of the Human Spine, Biomechanics, Bioinstrumentation, Biostatistics, Applied regression analysis.

Dissertation: "*The relationship between facet joint kinematic parameters and progression of degenerative changes in the human lumbar spine measured in-vivo*".

2002 – 2007 **M.Sc.** Biomedical engineering (minor in mechanical engineering). Department of Mechanical Engineering, Technical University of Kosice, Slovakia.

92/100%. Relevant coursework: Medical Imaging, Biomeasurements, Clinical Orthopeadics, Biophysics, Biomaterials, Kinematic, Multibody dynamic analysis.

Thesis: "*Services and technologies in home ambient intelligence*" under MonAMI – 6th framework program of European Commission.

Spring 2006 **EU Student Mobility**. Department of Biomedical engineering. Gent Universiteit, Gent, Belgium.

TEACHING/ADMINISTRATION EXPERIENCE

2007 – 2010 **Teaching Assistant**. Department of Bioengineering. UIC, Chicago, IL.
Senior Design – Prof. Terry Layton. Teaching assistant in charge of student team's progress, training undergraduate in mechanical engineer skills (drawings, CAD, manufacturing operation in UIC manufacturing lab), participated in individual experiment design, reporting and grading. In charge of Senior Design budget.

RELEVANT WORK EXPERIENCE

2008 – Present **Research Assistant**.
Department of Orthopedic Surgery. Rush University Medical Center, Chicago, IL.
My duties include:

Biomechanical testing:

- experiment design
- sample preparation: dissection, potting, instrumentation
- load/displacement control of experiment using servohydraulic system INSTRON
- kinematic measurement – 3D passive optical motion capture
- intervertebral disc pressure measurement
- intervertebral disc bulging measurement
- soft tissue testing using MTS
- lumbar facet joint capsule strain measurement
- lumbar facet joint contact pressure measurement (Tekscan)

3D image-based morphology of cervical and lumbar spine:

- spatial position and orientation of vertebral bodies
- facet join surface curvature measurement
- facet joint space width measurement
- facet joint subchondral bone density measurement
- disc height measurement
- vertebral endplate subchondral bone density measurement

Clinical research:

- dynamic/clinical CT
- dynamic/clinical X-ray
- clinical MRI (sequence selection)
- 3D to 3D image registration – volume merge
- real-kinematic modeling *in-vivo*
- MRI based intervertebral disc degeneration *in-vivo*/*in-vitro* evaluation
- CT based facet joint OA *in-vivo*/*in-vitro* evaluation

Statistical evaluation.

RESEARCH PROJECTS

Ph.D. Dissertation Degenerative changes in human lumbar spine and 3D facet joint kinematics evaluation measured on cohort of healthy and low-back pain subjects –*in-vivo* experiment validated *in-vitro*.

Expandable Cage Stabilizing potential of expandable cage vs. strut graft following two-level cervical corpectomy – *in-vitro* biomechanical evaluation.

Facet Joint Cartilage 3D analysis of lumbar facet joint cartilage thickness distribution – *in-vitro* method development and validation.

Facet Joint Capsule Lumbar facet joint capsule strain measurement – *in-vitro* method development.

Hip Stability Effect of surgical techniques on hip stability – *in-vitro* measurement.

Glenoid Resurfacing 3D Topographic Modelling for Glenohumeral Osteoarthritis: Digital Recreation of Glenoid Articular Surface to the Medial Tibial Plateau – *in-vitro* method development and validation.

Cervical Laminoplasty Biomechanical Evaluation of Basket-Shaped Titanium Implant for Cervical Laminoplasty – evaluation using sawbone.

Cervical Fusion Different cervical fixation techniques evaluation – *in-vitro* evaluation of Oc-C2, C2-C6 types of fusion.

Shoulder Remplissage To evaluate biomechanically, the efficacy of a remplissage procedure with multiple levels of glenoid and humeral head bone loss.

PROFESSIONAL MEMBERSHIP

IEEE Institute of Electrical and Electronics Engineers – *member*

ASME American Society of Mechanical Engineers - *member*

PUBLICATIONS

Simon P, Espinoza Orías AA, Andersson GBJ, An HS, Inoue N. *In-vivo* topographic analysis of lumbar facet joint space width distribution in healthy and symptomatic subjects. *Spine* (published ahead of print), March 16, 2012. PubMed PMID: 22433501.

Takigawa T, **Simon P**, Espinoza Orías AA, Hong JT, Inoue N, An HS. Biomechanical Comparison of Occiput-C1-C2 Fixation Techniques: Occiput C1 transarticular screw and Direct Occiput Condyle screw. In Press, *Spine,* November 22, 2011. PubMed PMID: 22158063

Espinoza Orías AA, **Simon P**, Tani S, Inoue N, Mizuno J. Biomechanical Evaluation of Basket-Shaped Titanium Implant for Cervical Laminoplasty. Submitted to *Bio-Medical Materials and Engineering*. April 2011 (In review).

Hong JT, Takigawa T, Udayakunmar R, Shin HK, **Simon P**, Espinoza Orías AA, Inoue N, An HS. Biomechanical effect of the C2 laminar decortication on the stability of C2 intralaminar screw construct and biomechanical comparison of C2 23 intralaminar screw and C2 pars screw. Neurosurgery. 2011 Sep; 69 Suppl Operative: ons1-7. PubMed PMID: 21415794.

CONFERENCES

American Society of Mechanical Engineers, 2012 Summer Bioengineering Conference, Fajardo, Puerto Rico, June 20-23, 2012 (accepted)

Kim L**, Simon P,** Andersson GBJ, An HS, Inoue N., Espinoza Orías AA**.** Non-contact experimental Assessment of Spinal Facet Joint Cartilage Dehydration.

International Society for the Study of the Lumbar Spine 38th Annual Meeting, SpineWeek Amsterdam May 28-June 1st, 2012 (accepted)

Ishihara Y, **Simon P**, Espinoza Orías AA, Andersson GBJ, An HS, Inoue N. Lumbar Facet Joint Centroids as a Function of Spinal Level and Age.

Ishihara Y, Espinoza Orías AA, **Simon P**, An HS, Andersson GBJ, Sugisaki K, Inoue N. *In-vivo* Measurement of Morphological Changes in the Human Lumbar Spine Pedicle.

AOSSM Annual Meeting, Baltimore, MD July 12-15, 2012 (accepted)

Bayne C, Stanley RA, **Simon P**, Espinoza Orías AA, Inoue N, Nho SJ. The Effect of Capsulotomy on Hip Stability.

ORS 2012 Annual Meeting, San Francisco February 4-7, 2012

Simon P, Espinoza Orías AA, An HS, Andersson GBJ, Inoue N. 3D Facet Joint Space Width Distribution: Comparison with Age, Level and Lower Back Pain Symptoms. *Accepted as a Poster*.

Ishihara Y, Espinoza Orías AA, An HS, Andersson GBJ, Sugisaki K, **Simon P**, Inoue N. Age-related Changes in Pedicle Morphology: Correlation with Lumbar Canal Diameter. *Accepted as a Poster.*

American Academy of Orthopaedic Surgeons - Annual Meeting, Feb. 7-11, 2012 San Francisco, CA

Bayne C, **Simon Peter**, Espinoza Orías AA, Nho SJ. The Effect of Capsulotomy and Capsulectomy on Hip Stability. Paper. No. 668 (accepted)

Intl. Society for Hip Arthroscopy Annual Scientific Meeting, Paris, France, October 14-15, 2011

Bayne C, Stanley RA, **Simon P**, Espinoza Orías AA, Inoue N, Nho SJ. The Effect of Capsulotomy and Capsulectomy On Hip Stability. *Accepted for podium presentation. Paper No. 532.*

North American Spine Society Annual Meeting, Chicago, IL November 2-5, 2011

Simon P, Espinoza Orías AA, An HS, Andersson GBJ, Inoue N. 3D Facet Joint Gap Decrease in Distribution Patterns is Age-Dependent. *Accepted as an Electronic Poster (ePoster) with Best Poster Presentation time.*

Philadelphia Society for Spine Research, Spine Research Symposium 2011, Philadelphia, PA November 16-18, 2011

Simon P, Espinoza Orías AA, An HS**,** Andersson GBJ, Inoue N. 3D Facet Joint Gap Decrease in Distribution Patterns is Age-Dependent. *Accepted as a Podium Presentation.*

American Society of Mechanical Engineers, 2011 Summer Bioengineering Conference, Nemacolin Woodlands Resort, Farmington, Pennsylvania, USA, June 22-25, 2011

Ishihara Y, Espinoza Orías AA, **Simon P**, An HS, Andersson GBJ, Inoue N. In- Vivo Three-Demensional Analysis of the Facet Joint Surface Center SBC2011- 53659. *Trans. ASME Summer Bioengineering Conference.*

Simon P, Espinoza Orías AA, Kotwal N, Parrish T, An HS, Andersson GBJ, Sumner DR, Inoue N. 3D Analysis of Lumbar Spine Facet Joint Cartilage Thickness Distribution SBC2011-53894. *Trans. ASME Summer Bioengineering Conference*.

International Society for the Study of the Lumbar Spine 37th Annual Meeting, Gothenburg, Sweden. June 14-18, 2011

Simon P, Espinoza Orías AA, An HS, Andersson GBJ, Inoue N. *In-vivo* Topographic Analysis of Lumbar Facet Joint Space Width Distribution in Healthy and Symptomatic Subjects. *Proceedings from the ISSLS 2011 Annual Meeting*.

Orthopaedic Research Society 57th Annual Meeting, Long Beach, CA, Jan 13-16, 2011

Takigawa T, **Simon P**, Espinoza Orías AA, Hong JT, Ito Y, Inoue N, An HS. Biomechanical Analysis of Novel Occiput-C1-C2 Fixation Techniques. *Transactions Vol. 36, Long Beach, CA, 2011:745*

2010 Cervical Spine Society Annual Meeting. Charlotte, NC, December 2-4, 2010.

Takigawa T, **Simon P**, Espinoza Orias AA, Hong JT, Ito Y, Inoue N, An HS. Biomechanical Comparison of Occiput-C1-C2 Fixation Techniques: C0-C1 Transarticular Screw and Direct Occipital Condyle Screw. Winner of the 2nd place in the Resident/Fellow Award Competition. *Proceedings of the 38th Annual Meeting of the CSRS.*

American Society of Mechanical Engineers, 2010 Summer Bioengineering Conference, Grande Beach Resort, Naples, FL, June 16-19, 2010

Takigawa T, Espinoza Orias AA, An HS, **Simon P**, Sugisaki K, Natarajan RN, Wimmer MA, Andersson GBJ, Inoue N. Lumbar Spine Capsule Strain After Total Disc Replacement. SBC2010-19023. *Trans ASME Summer Bioengineering Conference.*

AWARDS AND HONORS

November 2011 — **Best Poster Presentation Time** at NASS 26th Annual meeting, Chicago, IL

June 2011 — **Outstanding paper**. International Society for the Study of the Lumbar Spine (ISSLS), Gothenburg, Sweden. Accepted abstract invited to the manuscript submission and further publication in June, 2012 ISSLS special societal issue.

June 2011 — **Graduate Student Council Travel Award.** ASME Summer Bioengineering Conference. Farmington, PA

July 2007 — **Dean Award for Outstanding Graduate Student**. Department of Mechanical Engineering. Technical University of Kosice, Slovakia.