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***In vivo* topographic analysis of lumbar facet joint space width distribution in healthy and symptomatic subjects**

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Abstract

Study Design—*In vivo* three-dimensional facet joint space width measurement.

Objective—To determine lumbar facet joint space width within clinically relevant topographical zones *in vivo* and its correlations with age, level and presence of lower back pain symptoms.

Summary of Background Data—Narrowing of the facet joint gap, articular cartilage thinning, and subarticular cortical bone hypertrophy are frequently observed age-related changes. Facet joint space width is a well-defined parameter to evaluate osteoarthritis. To the best of our knowledge, there is no other study that quantifies three-dimensional facet joint space width distribution *in vivo*.

Methods—Three-dimensional measurement to quantify facet joint space width distribution based on five clinically relevant topographic zones in a cohort of healthy and symptomatic low-back-pain volunteers using subject-based three-dimensional CT models with respect to spinal level, subject age, gender and presence/absence of lower back pain.

Results—Facet joint space width was 1.93 ± 0.51 (mean \pm standard deviation) mm for the central zone, 1.75 ± 0.48 mm for the superior zone, 1.63 ± 0.49 mm for the inferior zone, 1.48 ± 0.44 mm for the medial and 1.65 ± 0.48 mm for the lateral zone, respectively. There were no significant differences between right and left facet joints. Males showed larger space width than females. Overall, space width of symptomatic subjects was significantly narrower when compared against the asymptomatic group. Facet joints in the peripheral zones were narrower than in the central zone. Age-group comparisons showed local narrowing occurring as early as in the third decade at the inferior zone of L5/S1 with all the remaining zones implicated after the fourth decade.

Conclusions—This *in vivo* study shows variations in facet joint space width narrowing with spinal level and region within the facet joint and *in vivo* evidence of localized, age-influenced facet cartilage thinning. Techniques developed in this study may be applied in the detection of early osteoarthritis-related changes in the facet joints.

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IRB-approved study (IRB Approval No. 00042801)

Keywords

lumbar spine; facet joint; facet joint space width; facet joint degeneration; osteoarthritis; three-dimensional space width distribution

Introduction

Facet joints are synovial joints in the spine which play an important role in controlling kinematics of the motion segment and transmitting loading in the spine¹⁻³. The facet joints undergo degenerative and osteoarthritic changes similar to those of other weight-bearing joints⁴. Extensive motion and loading conditions can contribute to facet joint osteoarthritis (OA) development. Facet joint OA has been considered as a potential source of low back pain and disability and contributes to 15-45% of chronic low back pain⁵.

Osteoarthritis is, in general, characterized radiographically by joint space narrowing, subchondral bone sclerosis and osteophyte formation^{6,7}. Among these parameters, joint space narrowing has been considered to closely correlate to cartilage degeneration^{6,8}. 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^{8,9}.

In clinical practice, plain radiography remains the main screening technique to assess OA changes; however, facet OA evaluation by plain radiogram requires special techniques due to three-dimensional (3D) orientation of the facet joint⁸. 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^{3,10-13}. 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 OA¹¹⁻¹³. Pathria *et al*, Weishaupt *et al*, and Kalichman *et al* used transverse CT as the diagnostic methods in the assessment of OA of the lumbar facet joint^{8,14,15}. Using this approach, they were able to identify the abnormalities associated with facet joint OA 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 extent and location of the cartilage degeneration^{16,17}. 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 3D space width distribution of lumbar facet joint using 3D subject-based CT models^{18,19}. 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 lower back pain.

Materials and Methods

Subjects

A total of 96 volunteers participated in this IRB-approved study (IRB Approval No. 00042801): Forty-five female and fifty-one males, average age 37.6 years (range; 22-59 years), average weight 75.4 kg (range; 45-129 kg), average height 168.6 cm (range; 145-188 cm). All subjects were screened for presence of lower back pain and preexisting lumbar spine pathology. Subjects with lower back pain were categorized as symptomatic subjects (Table 1) with inclusion criteria defined as recurrent low back pain with at least two episodes of at least 6 weeks. Exclusion criteria for the symptomatic group were prior surgery for back pain, age over 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 asymptomatic subjects with exclusion criteria for the asymptomatic group defined by the presence of the low back pain, previous spinal surgery, history of low back pain, age over 60 years, obesity, and claustrophobia or other contraindication to MR and CT imaging.

Creation of facet joint surface model

Each subject underwent lumbar CT (Volume Zoom, Siemens, Malvern, PA) scans in supine position. Raw imaging data were post-processed in axial plane at 1.0 mm slice thickness and exported in DICOM format. The facet joint surfaces were traced from axial DICOM images in custom-written program (Microsoft Visual C++ 2003 under Microsoft Foundation Class programming environment) using a tablet digitizer (Wacom Intuos 3; Wacom, Saitama, Japan). Particular care was taken to identify and exclude osteophyte formations from the joint surface. Tracing methodology was previously described by Otsuka *et al*¹³. A total of 1,920 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.

Definition of a local coordinate system

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 1). The facet joint surface area center was calculated and the origin of the local coordinate system was set on said surface area 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 (Figure 2).

Determination of five topographic zones

Five topographic zones consisting of central, superior, inferior, medial and lateral zones were determined in 3D 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 area center (Figure 2). 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°²⁰. 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 central 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; $\pm 45^\circ$, medial zone; 45° - 135° , inferior zone; 135° - 225° , lateral zone; 225° - 315°) from the cranial axis (Figure 3a). The angles represent projected angles on a plane perpendicular to the mean normal vector of the facet joint surface.

Facet joint space width calculation

Facet joint space width was calculated as the least-distances between each pair of opposing surfaces (inferior facet, superior facet). Distances between one point in the point-cloud model of the inferior facet surface and all points in the superior facet surface were calculated in 3D space using a custom-written program^{21,22}. The algorithm computes the distance between the point in question and each of its neighbors. Then it records the shortest distance, which will be eventually termed “the least distance”. The inferior facet surface under analysis was set as the reference frame for a least-distance search directed towards the opposing point-cloud data representing the superior facet surface. This least-distance at the point in question on the inferior facet surface was defined as the least-distance at the point in the inferior facet surface. This procedure was repeated for all points in the inferior facet surface. The mean facet joint space width for each zone was calculated by averaging the least facet joint distances within each zone.

Statistical analysis

ANOVA and Fisher *post hoc* tests were used to evaluate differences between zones, levels, age and symptoms. Differences between right and left sides and gender comparison were carried out with an unpaired *t*-test. Results were reported as mean and standard deviation. Significance was set to $\alpha = 0.05$.

Results

The average facet joint space width (\pm SD) was 1.93 ± 0.51 mm for the central zone, 1.75 ± 0.48 mm for the superior zone, 1.63 ± 0.49 mm for the inferior zone, 1.48 ± 0.44 mm for the medial zone and 1.65 ± 0.48 mm for the lateral zone.

Statistical correlation between facet joint space width distribution in right and left facet joints showed no side preference; therefore we used all facet joints individually in the analysis of level, gender, age, and symptoms. Gender comparison showed greater width distribution in males in all zones ($p < 0.0001$). Overall space width was significantly lower in symptomatic subjects ($p < 0.0001$).

Level comparison showed significant differences. The average facet joint space width for asymptomatic group (Figure 4) was 1.58 ± 0.36 mm at L1/L2; 1.84 ± 0.42 mm at L2/L3; 1.88 ± 0.41 mm at L3/L4; 1.95 ± 0.43 mm at L4/L5 and 1.63 ± 0.41 mm at L5/S1. The facet joint space width at L4/L5 was significantly greater than all levels ($p < 0.0001$) except L3/L4 ($p < 0.003$). The narrowest facet joint space width was measured at L1/L2 and L5/S1 levels with mutual significant difference ($p < 0.02$). When compared with other levels, L1/L2 and L5/S1 were significantly smaller ($p < 0.0001$). The average facet joint space width for symptomatic group was 1.24 ± 0.36 mm at L1/L2; 1.51 ± 0.53 mm at L2/L3; 1.7 ± 0.59 mm at L3/L4; 1.76 ± 0.59 mm at L4/L5; and 1.38 ± 0.56 mm at L5/S1. Similar to the asymptomatic group (Figure 5), facet joint space width at L4/L5 was significantly larger than that at the other levels ($p < 0.0001$) except L3/L4 ($p = 0.1$). The smallest facet joint space widths were again measured at L1/L2 and L5/S1, however there were significant differences between them ($p < 0.001$). L1/L2 was different than every other level ($p < 0.0001$), while L5/S1 was different than L3/L4, L4/L5 level ($p < 0.0001$), and L2/L3 ($p < 0.003$).

The facet joint space width was always larger in the central zone than in the peripheral zones ($p < 0.0001$) for both symptomatic and asymptomatic group. Inferior zone space width was significantly narrower in the asymptomatic group ($p < 0.0001$), and in the symptomatic group ($p < 0.04$) when compared to the superior zone. Space width within the medial zone was the smallest for both groups ($p < 0.0001$).

The data presented in Figure 6 show changes in 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 L1/L2. For L2/L3, narrowing occurred only at the lateral zone in the fifth decade. At L3/L4, narrowing occurred during the fourth decade in lateral and superior zones and facet joint space width increased in the fifth decade. Changes in the L4/L5 level involved all lateral zones in the fourth and fifth decade and central zone in the fifth decade. For L5/S1, narrowing started as early as in the third decade in the inferior zones and implicates all remaining zones after the fourth decade.

Discussion

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 3D CT models. The results of the present study showed that overall facet joint space width at L5/S1 was narrower than that in L3/4 and L4/5. This finding is consistent with a previous study which evaluated facet degeneration using CT grading²³. 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. Macroscopic studies of the whole cartilage surface have been conducted using human cadaveric lumbar spines^{16, 17}. Although microscopic histological studies evaluate early changes in cartilage degeneration, this analysis is usually performed in arbitrarily-selected slices taken from the specimens. The analysis of the whole facet joint surface is beneficial for comparisons between cartilage degeneration and three-dimensional characteristics of facet joint structure and its biomechanical functions, such as restriction of the segmental motion and load transmission as described later.

In order to describe extent and location of the cartilage lesions in the facet joint, it is crucial to define a mapping system specific to the facet joint. Swanepoel *et al* defined the central and peripheral regions in the facet joint surface based on the distance of the center of the damaged area from the center of the whole facet joint surface in a quantitative manner¹⁶. Tischer *et al* further divided the facet joint surface into five topographic zones including the central, superior, medial, inferior and lateral regions; in spite of this, a detailed mapping method was not described¹⁷. In a cadaveric study, the exposed facet joint surface can be rotated manually so that the joint surface becomes parallel to a graphical image plane for analysis. However, the facet joint surface orientation must be defined in space for 3D *in vivo* analyses. In the present study, joint surface 3D orientation was defined by the mean normal vector calculated by averaging all normal vectors from the elements comprising the surface joint mesh¹³. A local coordinate system was determined by using the mean normal vector as one axis of the coordinate. The second coordinate was determined in the anatomical cranio-caudal direction in the present study. A vector product between these two perpendicular

directions provides the third axis and completes the coordinate system. The geometry of the facet joint is often assumed as an ellipse and a local facet joint coordinate system can be set to coincide with the axes of such ellipse^{3, 24}. Under the elliptical shape assumption, eigenvectors can be used to determine the local coordinates in 3D²⁰; however, the shape of the facet joint is not always elliptical and the directions of the axes other than the normal direction of the facet surface cannot be determined if the shape of the facet is close to a circle. Furthermore, the orientation of the axis of the ellipse declines from the anatomical axis²⁴, which may obscure the interpretation of the topographic differences in relation to the lumbar spine segmental motion.

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*^{16, 17}. Tischer *et al* observed that most cartilage defects are located in the superior region of the superior facet and in the inferior region of the inferior facet¹⁷. The authors postulated that cartilage degeneration in the superior portion of the superior facet was caused by more cartilage contact with the opposing inferior facet in this region during full flexion, whereas the cartilage degeneration in the inferior portion of the inferior facet with pressure accumulation originated from bone-to-bone contact of inferior portion of inferior facet with superior facet during full extension^{1, 17}. Increased load transmission through the inferior portion of the inferior facet is also postulated in lordotic posture and erect posture with heavy loads¹. Since segmental lordosis is reported to be higher at L5/S1²⁵, early onset of the facet joint space narrowing in the inferior region at L5/S1 measured in the present study may be explained by the higher lordosis in this level in addition to the higher load transmission in the lower lumbar levels. This study has shown lateral region facet joint narrowing at L3/L4, L4/L5 and L5/S1 in the fourth decade. Segmental lumbar axial rotation movement is mainly restricted by the facet joint¹ and high contact pressures in the lateral region of the facet joint have been estimated during axial rotation²⁶. This loading pattern during axial rotation may cause relatively early onset of facet joint space narrowing in the lateral region of the facet joint.

Fibrillation of the joint cartilage has been considered as an early sign of joint degeneration^{4, 16, 27}. Previous macroscopic studies using cadaveric lumbar spines have made possible early detection of facet joint degeneration by visualizing cartilage fibrillation and demonstrated that facet joint degeneration is initiated at an earlier age than that postulated by studies using clinical CT and MR imaging^{8, 14, 15, 28}. While fibrillation of the joint cartilage surface can be observed *in vivo* via arthroscopic images for the synovial joints in the extremities, such technique is not feasible for the facet joint in the present clinical setting. Although joint space narrowing corresponds to a more advanced stage than the cartilage fibrillation in the cartilage degeneration cascade, the zonal analysis of the facet joint space width used in the present study may be useful for early detection of the facet cartilage degeneration using currently available imaging modalities.

This report shows that narrowing of the facet joint width was more prominent for symptomatic subjects. Since average facet joint space width and disc height were found to be linearly-correlated in this study¹⁹, low back pain symptoms should involve low back pain associated with intervertebral disc degeneration. It is believed that facet joint degeneration is secondary to intervertebral disc degeneration and several studies have supported this theory^{4, 29}. However, 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^{16, 30}. Adams and Hutton addressed different mechanisms of facet joint regional damages and causes for pain under different motion segment movement¹. Future studies are required to clarify

relationships between extent and location of facet degeneration and facet joint kinematics *in vivo* and to identify possible causes for low back pain associated with facet joint degeneration.

This study is not without limitations. Particularly, the small sample sizes on some age groups can lead to less than ideal statistical power. This can happen when too many subgroups are used in the data analysis. Secondly, joint space width was measured by the least distances between the superior and inferior facet joint surfaces in the present study; therefore, thinning of cartilage at individual facet joint could not be estimated in this technique.

Although normal vectors for all polygons were calculated throughout each facet joint surface, only the mean normal vector was used to determine the facet-based local coordinate system in the present study. Regional variation of the normal vector orientation could be used for analyses of curvature of the facet surface, which may be an important factor causing regional differences in cartilage degeneration via different loading conditions within a facet joint surface. Future studies will address contribution of the regional curvature variations to regional differences in facet joint degeneration.

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Key Points

1. Facet joint space width is an important parameter in evaluating facet joint osteoarthritis.
2. Facet joint space width is larger in males than females; and it is also larger in asymptomatic subjects than symptomatic subjects.
3. First signs of facet joint narrowing occur as early as in the third decade.
4. Significant changes of facet joint space width occur in the joint periphery rather than in the joint center.

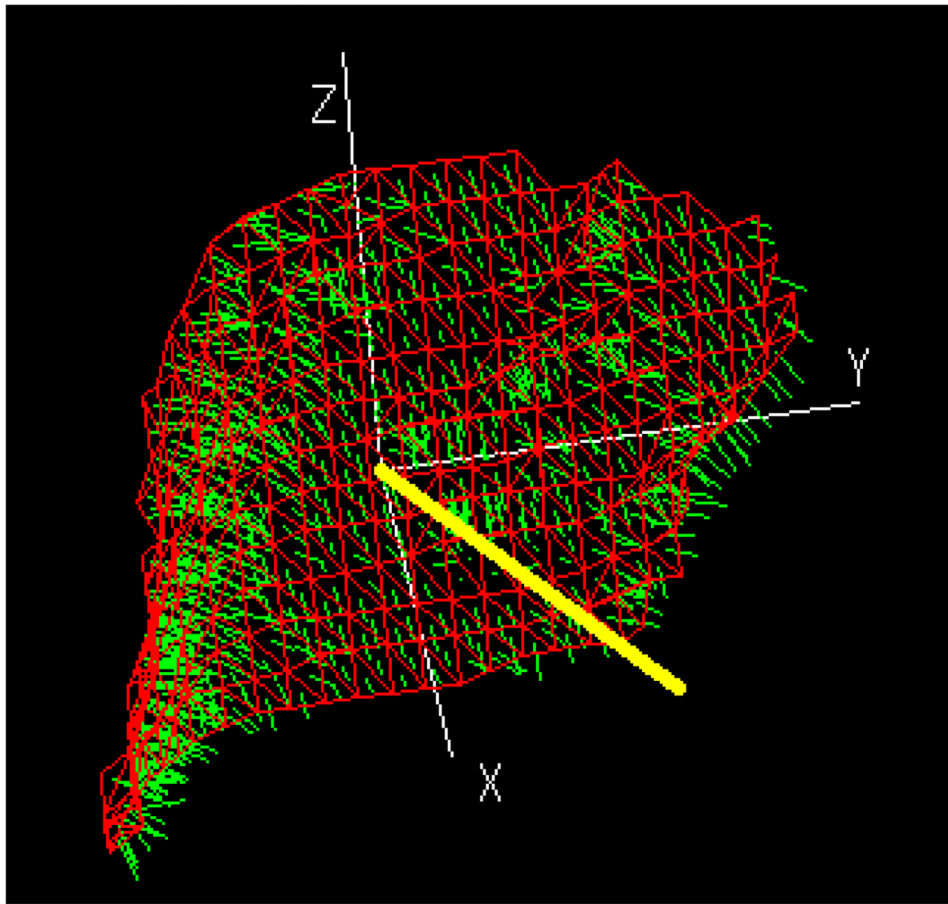


Figure 1. Polygon mesh (red lines) of the facet surface, normal vectors of each polygon (green lines) and average surface normal vector (yellow line). Coordinates represent CT coordinate system.

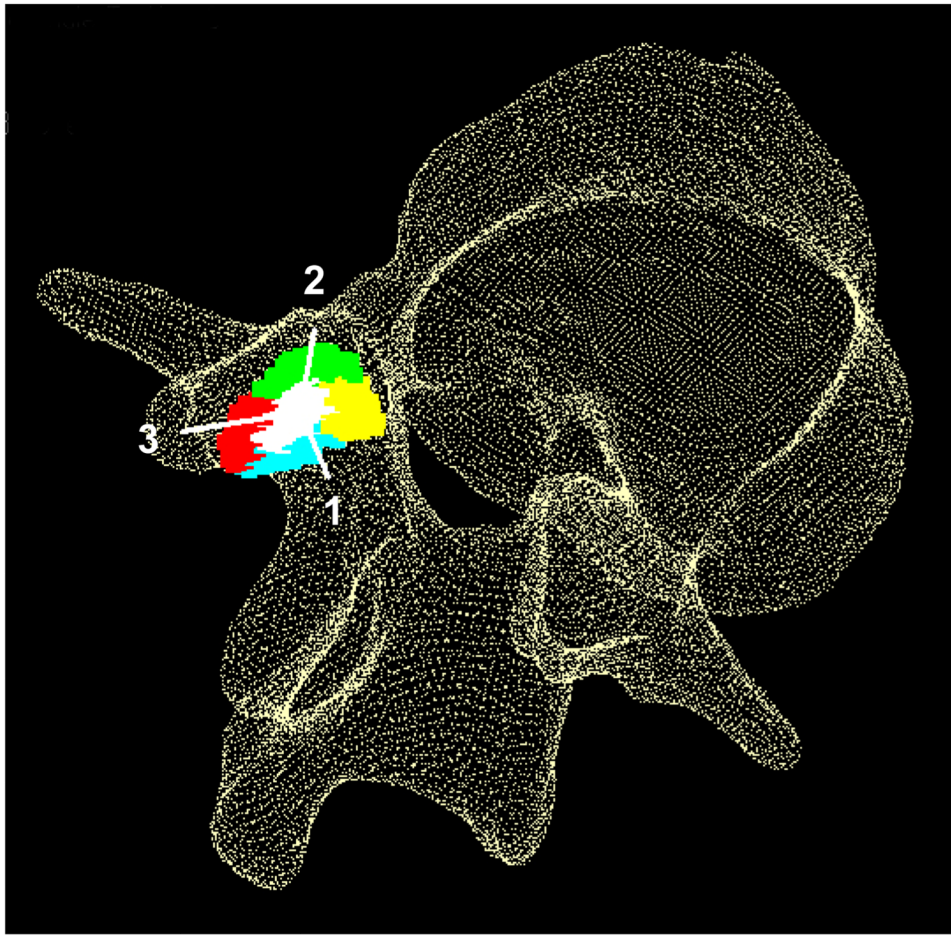


Figure 2. Local coordinate system and five zones on facet joint surface. 1: direction of mean surface normal vector, 2: cranial direction, 3: direction orthogonal to Axis 1 and Axis 2. Green: superior zone, Red: lateral zone, Cyan: inferior zone, Yellow: medial zone, White: central zone.

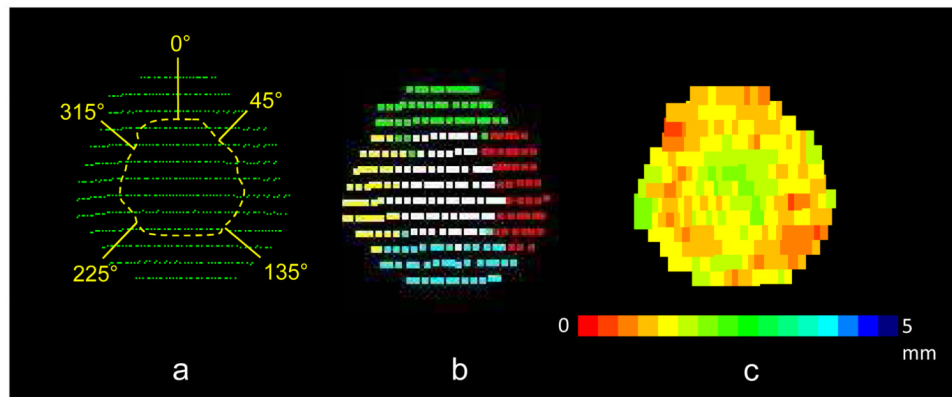


Figure 3. Facet joint surface zoning. **a:** Definition of peripheral zones based on angular parameters. The 0° direction corresponds to Axis 2's (cranial) direction in Figure 2. **b:** The five zones based on the facet-based coordinate system. **c:** Facet joint space width distribution map.

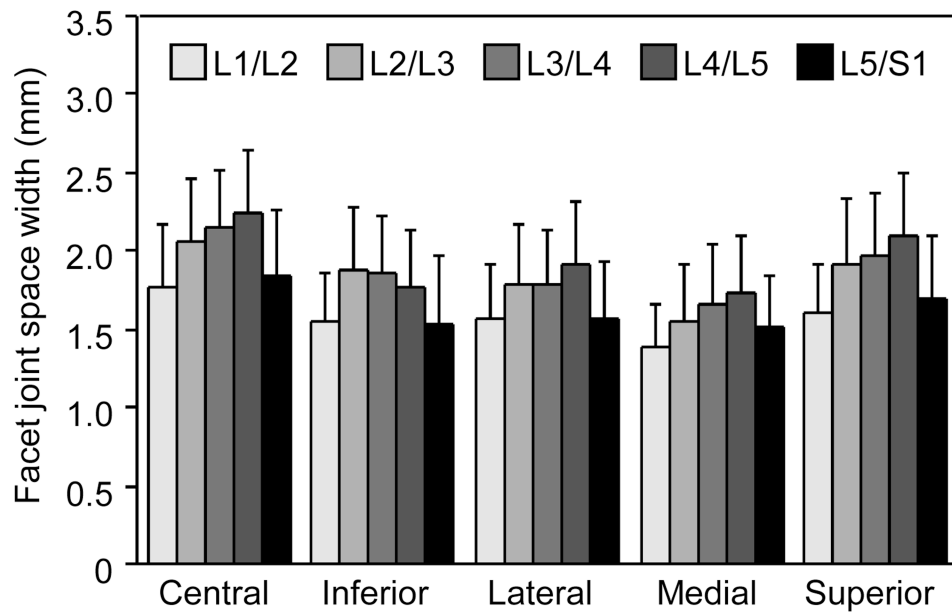


Figure 4.
Facet joint space width for asymptomatic subjects.

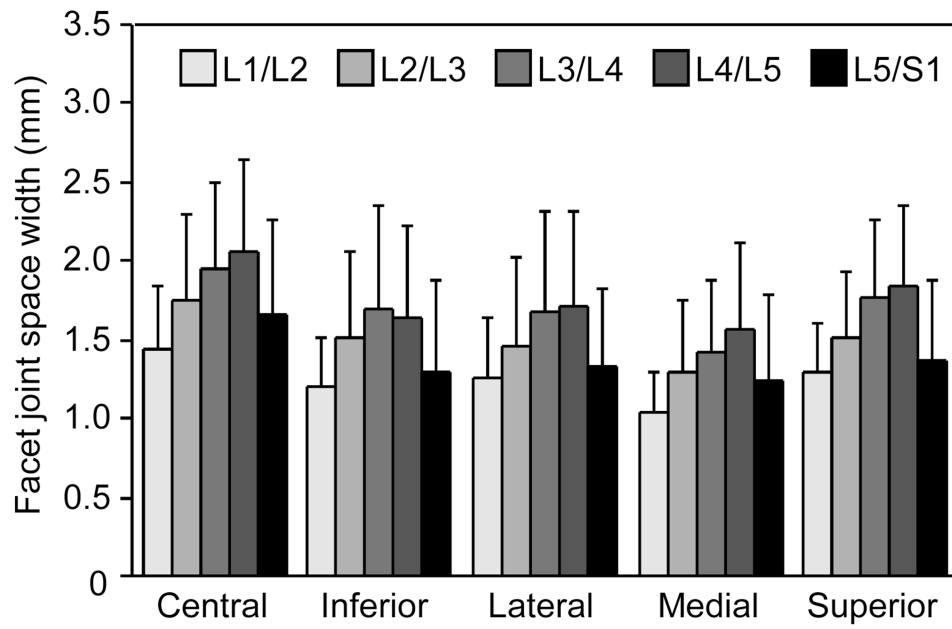


Figure 5.
Facet joint space width for symptomatic subjects.

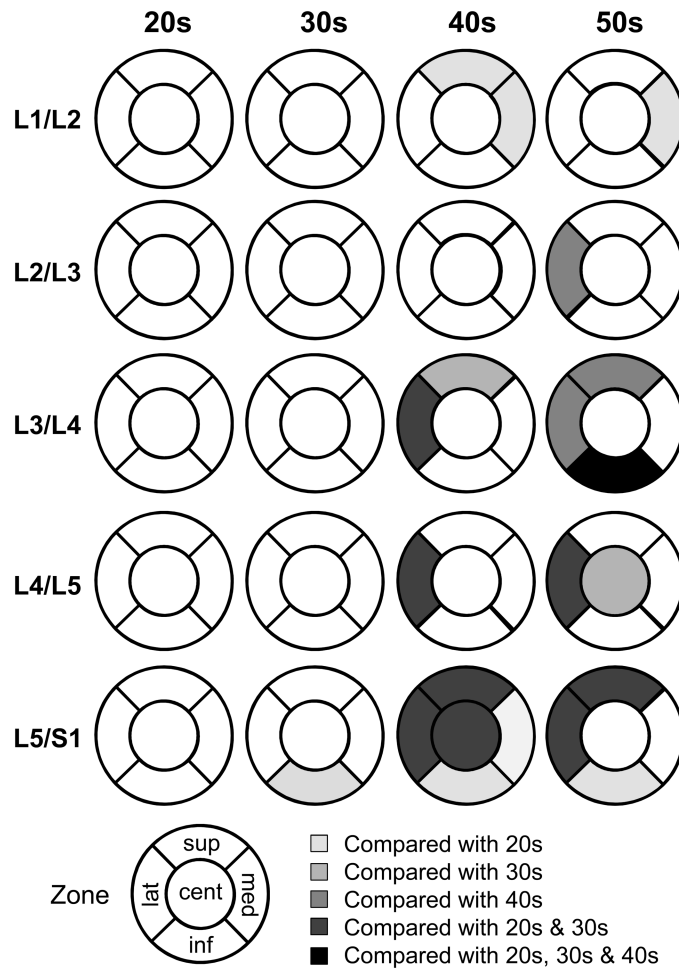


Figure 6. Changes in facet space width with age. Color code indicates significant differences ($p < 0.05$) among different age groups within each spinal level and each zone.

Table 1

Study population categorized by gender, symptoms and age.

	Male (n = 51)		Female (n = 45)	
	Asymptomatic (n = 33)	Symptomatic (n = 18)	Asymptomatic (n = 29)	Symptomatic (n = 16)
20s	10	3	9	2
30s	11	9	11	5
40s	9	3	7	4
50s	3	3	2	5