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Level-Dependent Alterations in Human Facet Cartilage Mechanics and Bone Morphometry with Spine Degeneration

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Abstract

The zygapophyseal joints of the spine, also known as the facet joints, are paired diarthrodial joints posterior to the intervertebral disc and neural elements. The pathophysiology of facet osteoarthritis, as well as crosstalk between the disc and facets, remains largely understudied compared to disc degeneration. The purpose of this study was to characterize alterations to human facet cartilage and subchondral bone across a spectrum of degeneration and to investigate correlations between disc and facet degeneration. Human lumbar facet articular surfaces from 6 independent donors were subject to creep indentation mechanical testing to quantify cartilage mechanical properties, followed by μ CT analyses for subchondral bone morphometry. The degenerative state of each articular surface was assessed via macroscopic scoring and via OARSI histopathology scoring. Our data suggest reduced facet cartilage compressive and tensile moduli and increased permeability with increasing degenerative grade, particularly at the lower levels of the spine. μ CT analyses revealed spinal level-dependent alterations to the subchondral bone, with an increase in trabecular bone at the L4-L5 level, but a decrease at the upper levels of the lumbar spine with increasing degenerative grade. Cortical bone volume fraction was generally decreased with increasing degenerative grade across spinal levels. Correlation analysis revealed several associations between quantitative measures of disc degeneration and facet osteoarthritis. This work showed that alterations in the mechanical properties of facet cartilage and in the structural properties of facet subchondral bone correlated with aspects of disc degeneration and were highly dependent on spinal level.

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Author Contributions Statement

Study conception and design (SEG, RLM, HES), acquisition of data (SG, MF, SEG), analysis and interpretation of the data (all authors), statistical expertise (RX), obtaining of funding (SEG, RLM, HES), drafting the article (SEG, SG), revising the article critically for important intellectual content (all authors), final approval of the version to be submitted (all authors).

Conflict of Interest

Robert L. Mauck is a Co-Editor in Chief of JOR Spine.

Keywords

zygapophyseal joint; intervertebral disc degeneration; biomechanics; osteoarthritis; indentation

Introduction

Back pain is one of the most common causes of disability worldwide, resulting in more than 200 billion dollars in yearly healthcare costs in the US alone¹. The causes of back pain are complex and multifactorial, and degeneration of the musculoskeletal components of the spine can be a frequent source of pain. The anterior column of the spine is composed of bony vertebral bodies with intervening intervertebral discs. Each intervertebral disc forms a fibrocartilaginous joint (or symphysis) and consists of a central nucleus pulposus, composed primarily of proteoglycans, surrounded by the lamellar annulus fibrosus, which consists mainly of type I collagen². These elements interact to provide the disc with tension-resisting properties similar to a ligament and compression-resisting properties as seen in articular cartilage³. Posterior to each intervertebral disc are paired diarthrodial facet joints, also known as zygapophyseal joints. Each facet consists of a superior articular process (SAP) of the inferior vertebra, which faces dorsomedially and articulates with the inferior articular process (IAP) of the superior vertebra, which faces ventrolaterally³. The facet joint shares features that are characteristic of other synovial joints in the body, such that cartilage covers each articular surface atop a layer of subchondral bone, with the entire articulation immersed in synovial fluid and surrounded by a joint capsule.

The spinal motion segment is often referred to as a three-joint complex, with the intervertebral discs anteriorly bearing about 75% of the axial loads through the spine and the facets bearing the remaining 25% of axial loads⁴. In addition, facets play a role in providing torsional stiffness, resistance to shear, lateral and antero-posterior vertebral translation, and joint distraction^{5,6}. Thus, both the anterior and posterior column are integral to the stability of the motion segment. With aging or following spinal trauma, degeneration of both the discs and facets can occur, the downstream consequences of which can include spinal instability, nerve compression, pain, and motor deficits. Disc degeneration and concomitant facet osteoarthritis are frequently observed in humans; however, the temporal relationship between the two processes is not well defined^{7,8}.

In an effort to further understand spinal pathologies contributing to back pain, many have focused on studying disc degeneration itself⁹. Compared to the numerous studies on the pathophysiology of disc degeneration reported in the literature, the structure-function relationships associated with facet degeneration are largely understudied. Research suggests that facet degeneration develops in patients as young as 15 years old, with almost two-thirds of individuals affected by facet arthritis by 30 years of age¹⁰. Facet degeneration has been most commonly reported at L4-L5, with no detectable difference between right versus left facet joints¹¹. Pathology of the facet cartilage during OA is characterized by progressive cartilage fibrillation, thinning and loss of proteoglycan content^{8,12}. The effect of these structural alterations on the mechanical properties of the facet cartilage has not been studied, but in other synovial joints OA is associated with dramatic alterations in poroviscoelastic

mechanical properties of the articular cartilage¹³. In other synovial joints such as the knee, it is also accepted that degeneration is not only associated with compromised cartilage structure and mechanics but also with changes in the underlying subchondral bone^{14–16}. Previous work comparing human osteoarthritic and healthy facets suggests that subchondral cortical plate thickness is reduced while trabecular bone volume fraction is increased.¹⁷ It has also been shown that patients with back pain have higher facet subchondral bone mineral density¹⁸.

The morphological, biomechanical and histological changes across facet bone and cartilage with degeneration as well as across levels of the human lumbar spine remain poorly understood. Therefore, the goal of this study was to not only examine the facet joint cartilage and subchondral bone structure-function properties with advanced degeneration but also to further elucidate correlations between facet and disc degeneration in human spines across a range of degenerative states. We hypothesized that alterations in facet cartilage biomechanical properties and subchondral bone morphometry with increasing OA severity would be most evident at the lower levels of the spine, and that structure-function metrics of facet OA and disc degeneration would correlate.

Methods

Donor Demographics and Specimen Isolation

Six human donor lumbar spines were purchased fresh-frozen from the National Disease Research Interchange and Science Care, yielding 24 total spinal motion segments for analysis. Donor demographics included 4 male donors (54yo, 65yo, 67yo, 69yo) and 2 female donors (54yo, 66yo). Deidentified patient demographics and the spinal levels utilized from each donor are summarized in Figure 1A and 1B. When requesting donor tissue, a history of spine surgery or implants was an exclusion criterion; however, any clinical history of back pain in the donors is unknown. Spines were stored at -20°C until dissection.

Each spine was carefully dissected to isolate anterior bone—intervertebral disc—bone motion segments as well as the posterior elements at each level. For the posterior elements, the facet articulation was carefully disrupted by dissection through the facet joint capsule, and 4 facet articular surfaces were isolated from each level. Following dissection, each facet or articular process was photographed and macroscopically scored on a scale of 0 (healthy) to 4 (most degenerative) by 2 blinded, independent graders according to established methods¹⁹ (Figure 2A). In instances where graders did not agree, the reasoning behind each score was discussed and a consensus score was determined.

Intervertebral Disc Motion Segment Analyses

The compressive mechanical properties, NP T2 relaxation times, and disc height of the anterior portion of the motion segments were analyzed as described in our prior work, which characterized changes in these parameters over a spectrum of degeneration²⁰. Briefly, after thawing, each donor spine underwent MRI scanning at 3T to acquire mid-sagittal T2-weighted images to measure disc height and for Pfirrmann grading²¹, as well as a sequence of images for quantitative T2 mapping. Isolated motion segments were then subject to

a compressive mechanical testing protocol consisting of 20 cycles of compression (0 to -750N) at 0.05 Hz in a bath of phosphate buffered saline (PBS) with protease inhibitors. Mechanical properties (toe and linear region moduli and transition and maximal strains) normalized to disc area and height obtained from the MR images were calculated from the 20th cycle of compression, as previously described^{20,22}.

Facet Articular Cartilage Mechanical Testing

Following dissection, to quantify changes in facet articular cartilage properties with degeneration, each articular surface was subjected to a biomechanical indentation testing protocol. Facets were potted using a low melting temperature indium casting alloy. Next, a custom indentation testing rig coupled with an Instron 5948 electromechanical test frame was used to apply a creep load of -0.1N for 15 minutes through a 1mm diameter spherical indenter while simultaneously measuring deformation (Figure 4A)²³. Indentation testing was conducted in a PBS bath with protease inhibitors at room temperature. Four points on each facet surface, each 3mm apart in a “diamond” configuration (Figure 4B), were tested. Mechanical properties of the facet cartilage including the hydraulic permeability (k_0), nonlinear strain-dependent flow-limited constant (M), the tensile modulus (E_{Y+}), and the compressive modulus (E_{Y-}) were then calculated by fitting the displacement vs. time curves to a Hertzian biphasic creep model²⁴ (Figure 4D). Data from each of the four indentation locations were averaged for each facet. Indentation tests that resulted in an R^2 value of less than 0.95 in the creep model fit, and had a total deformation less than 0.02 mm, were excluded from the above analysis. These samples did not exhibit the characteristic viscoelastic creep behavior of cartilage and likely represented regions of severe cartilage erosion where the indentation queried the underlying bone, as only macroscopic grades 3 (two samples) and 4 (five samples) facets were excluded from the creep analysis.

Assessment of Facet Subchondral Bone via Microcomputed Tomography (μ CT)

Following cartilage indentation testing, all samples were fixed in 10% neutral buffered formalin and imaged using μ CT (Scanco μ CT50) at an isotropic 10.3 μ m resolution to characterize the underlying cortical and trabecular subchondral bone as in our previous studies^{25,26}. For each articular surface, the cortical bone was manually contoured and the bone volume fraction (BV/TV) within the central 4 mm of the joint quantified (Figure 5A). Additional bone morphometry parameters (BV/TV, trabecular number, trabecular thickness, and trabecular spacing) were determined in the adjacent trabecular bone within a rectangular region of interest for each sample (superior facet: 8mm x 1.5mm, inferior facet: 3.5mm x 1.5mm) using Scanco software. Different sized regions of interest were utilized due to the smaller size of the inferior facet.

Facet Histology and OARSI Scoring

To examine the facet cartilage at a microscopic scale, each articular process was decalcified and processed through paraffin for histology. A single 10 μ m thick mid-sagittal section for each facet was stained with Safranin-O and Fast Green, and slides were imaged at 20x using an Aperio Slide Scanner. Each sample was scored according to the OARSI (Osteoarthritis Research Society International) Cartilage OA (osteoarthritis) histopathology grading system

previously developed for human knee cartilage²⁷. OARSI scoring was conducted by 3 independent graders, and the scores were averaged for each sample.

Statistical Analysis

Statistical analyses were conducted using GraphPad Prism 9 and R ([R-project.org](https://www.R-project.org)). The two-sided p value of 0.05 was used as the statistical significance cutoff. Standard descriptive statistics were used to summarize the patient characteristics and the macroscopic and histology scores, e.g., mean and standard deviation (SD) for continuous variables, and count and percent for categorical variables. A paired t-test was applied to compare the within-subject quantitative outcomes (cartilage mechanics and subchondral bone morphometry) between superior and inferior across all levels. In addition, linear regression was used to test whether the difference between superior and inferior macroscopic scores depended on level or grade. Linear regressions were also used to evaluate any correlation between the macroscopic and corresponding histology scores. Generalized estimating equations (GEE) were used to assess the effect of the interaction between spinal level and grade (macroscopic or OARSI) on all quantitative outcome metrics of facet cartilage mechanics or subchondral bone morphometry. GEE accounts for the within-subject correlation due to multiple measures taken on the same subject by using a sandwich estimator of the standard error of the regression coefficients. For OARSI scoring, the intraclass correlation coefficient (ICC) was calculated to assess inter-rater reliability. To assess relationships between disc and facet degeneration, Pearson correlation coefficients were calculated for all combinations of measured variables from disc and facet pairs. To generate the Pearson correlation matrix, quantitative data were averaged across all facets at each spinal level such that each disc was paired with a single value for each facet outcome.

Results

For each level of the lumbar spine, four facets were dissected (the SAP and IAP from each laterality), and 96 articular surfaces isolated from 24 spinal levels (Figure 1A and 1B). One of the 96 samples was incidentally damaged during dissection. The remaining 95 were scored macroscopically using the above mentioned criteria revealing: 6 grade 1, 36 grade 2, 29 grade 3, and 24 grade 4 facets¹⁹. Combining this analysis with previous MRI grading of discs from these motion segments revealed no strong association between facet macroscopic grade and disc Pfirrmann grade (linear regression $r^2 = 0.06$, $p=0.01$). In addition, there was no clear qualitative association between spinal level and macroscopic grade (Figure 2B and 2C).

OARSI histopathology scoring of a single mid-sagittal section from all facets revealed 26 grade 2, 23 grade 3, 21 grade 4, and 26 Grade 5 facets. There was very good agreement between the three independent graders, with an ICC of 0.89 (95% CI: 0.85, 0.92). Examples of each grade from different donors are represented in Figure 3A, demonstrating the structural variability between facets within the same grade. With regard to spinal level, the distribution of facet OARSI score was relatively even (Figure 3B). There also were no obvious associations between disc Pfirrmann grade and facet OARSI score (Figures 3C)—

severely degenerative facets (OARSI scores of 4 and 5) were found adjacent to discs of all Pfirrmann grades.

For quantitative outcomes inclusive of facet cartilage mechanical properties and subchondral bone morphometry, paired t-tests revealed no statistically significant differences between superior and inferior facet joints. Due to the sample size limitations of the data set, we therefore did not include superior/inferior as a factor in the GEE model. OARSI grades 2-3, and 4-5 were combined for this statistical analysis, as were macroscopic grades 1-2 and 3-4. The GEE model identified significant interactions between spinal level and OARSI score only for cartilage mechanical testing outcomes, and between spinal level and macroscopic grade only for subchondral bone morphometry variables. Cartilage mechanical properties stratified by level and macroscopic score and subchondral bone morphometric parameters stratified by level and OARSI score are shown in Supplemental Figures 1 and 2.

Facet cartilage creep indentation testing demonstrated increasing heterogeneity in the creep deformation curves with increasing OARSI score (Figure 4C). Facet cartilage compressive modulus decreased with increasing OARSI score by 33% and 26% at L3-L4 and L5-S1, respectively (Figure 4E). Facet cartilage tensile modulus was also significantly reduced by 44% in OARSI scores 4-5 at the L3-L4 spinal level (Figure 4F). There was a concomitant 293% increase in facet cartilage permeability at the L5-S1 spinal level with increasing OARSI scores (Figure 4G).

Facet subchondral cortical bone volume fraction was significantly reduced by 8% and 10% at L3-L4 and L4-L5, respectively, with more severe facet OA characterized by higher macroscopic degeneration grades (Figure 5A–B). Facet trabecular bone volume fraction was also reduced by 38% at L2-L3, driven primarily by reductions in trabecular number and thickness and increases in trabecular spacing at L2-L3 and other upper spinal levels. Interestingly, a significant 27% increase in trabecular bone volume fraction was observed at L4-L5 with increasing macroscopic grade, driven by increases in trabecular thickness and reductions in trabecular spacing (Figure 5 C–F).

To elucidate any associations between disc and facet degeneration in our paired sample set, a Pearson correlation coefficient matrix of all combinations of facet mechanical properties, μ CT parameters, facet OARSI and macroscopic scores, disc mechanical properties, disc height, and disc NP T2 relaxation times was calculated (Table 1). Facet trabecular thickness negatively correlated with disc compressive modulus ($r = -0.34$, $p = 0.021$), while facet trabecular number positively correlated with disc transition and maximum strains ($r = 0.35$, $p = 0.018$; $r = 0.34$, $p = 0.020$ respectively). Facet macroscopic grade correlated with several parameters, including positive correlations with disc compressive modulus and negative correlations with disc transition and maximum strains. With regards to OARSI score, there was a trending negative correlation with disc height ($r = -0.31$, $p = 0.071$) and a positive correlation with disc compressive modulus ($r = 0.25$, $p = 0.039$).

Discussion

This study sought to evaluate facet joint cartilage and subchondral bone structure-function properties across a spectrum of spine degeneration and to investigate their correlations with adjacent disc degeneration in the human lumbar spine. Our results suggest that with advancing stages of degeneration, alterations to facet cartilage mechanics and subchondral bone structure occur in a highly level dependent manner. These spinal level dependent changes were not immediately apparent when simply identifying the number of facets of higher macroscopic/OARSI scores at each spinal level but became evident when stratifying structure-function properties by spinal level. Significant differences in facet cartilage mechanics or subchondral bone morphometry were most frequently observed at the lower levels of the spine (L3 to S1), in agreement with prior studies that have demonstrated higher rates of degeneration at L4-L5¹⁹. This may be related to the increased mechanical stress and contact loads at lower regions of the spine leading to more advanced degeneration in these areas²⁸.

Facet cartilage biomechanical properties measured by creep indentation testing were significantly impacted by degeneration and generally included reductions in compressive and tensile modulus and increases in cartilage permeability (Figure 4). These observed alterations in facet cartilage mechanics demonstrate a loss of integrity of the articular cartilage, which is to be expected with advanced degeneration¹³. This is consistent with previous work in other human synovial joints, where permeability is increased and compressive modulus is decreased with higher OARSI scores^{13,29}. We also noted increased variability in the creep deformation response (Figure 4C) with increasing severity of degeneration, likely related to heterogeneity of human samples especially with more severe stages of cartilage wear⁴. The average values for facet cartilage compressive modulus quantified in this study ranged from 0.87 MPa (OARSI grades 2-3) to 0.68 MPa (OARSI grades 4-5). This is within the range aggregate moduli previously reported from creep testing of healthy human knee cartilage (0.6-0.7 MPa), and human knee cartilage from OARSI grades 2 through 5 (0.25-1MPa)^{29,30}, suggesting that facet and knee cartilage in humans have roughly similar mechanical properties. This is in contrast with quadrupedal species, in which facet cartilage aggregate modulus is approximately four times lower than knee cartilage in the same species³¹.

Substantial alterations to the facet subchondral bone across spinal levels and with increasing degree of macroscopic degeneration were also observed in this study (Figure 5). Generally cortical and trabecular bone volume fraction were reduced with increasing degree of degeneration, particularly in the mid-lumbar spine. Interestingly, an increase in trabecular bone volume fraction was observed only at the L4-L5 spinal level, driven by increases in trabecular thickness and reductions in trabecular spacing. These overall trends, with exception to those at L4-L5, are consistent with prior studies involving knee OA models that showed greater subchondral and cortical bone resorption with increased porosity and a concurrent loss of bone mineral density with advancing stages of degeneration³²⁻³⁶. A previous study of subchondral bone changes in human osteoarthritic and healthy facets demonstrated increases in both cortical and trabecular bone in osteoarthritic facets, but the study did not account for level dependent differences and examined a broader age range

of donors than the current study includes¹⁷. Our findings at L4-L5 could be related to bony changes specific to that level and may require further study with greater sample sizes. Osteoporosis could be a confounding factor which may account for the loss of cortical bone, especially with advanced age³⁷. Finally, previous work has suggested overall facet bone density is higher in patients with back pain versus asymptomatic individuals¹⁸. Future work should aim to expand characterization of these facet cartilage and bone structure-function relationships to patient populations with back pain. Nevertheless, our study demonstrates that, similar to the knee and other joints of the body, facet osteoarthritis is a degenerative disease of both bone and cartilage^{16,38}.

The correlation analysis between quantitative metrics of facet and disc health and mechanical function revealed statistically significant correlations between these two spinal tissues, similar to prior studies¹¹. Our data suggests that facet bony sclerosis (increased trabecular thickness and number) is associated with increased adjacent disc strains and reduced disc compressive moduli, which are mechanical changes characteristic of disc degeneration. Facet macroscopic grade and OARSI score correlated with different parameters. Our statistical analysis matched these correlations, showing significant differences by level for cartilage mechanics only for OARSI score and for subchondral bone morphometry only for macroscopic grade. This is likely due to heterogeneity in cartilage erosion patterns across the facet articular surface (as captured in macroscopic scoring) that may not be well represented by a single 10-micron histological section in the mid-plane of the facet. Additionally, facet cartilage mechanical properties and disc mechanical properties were not correlated, in agreement with a recent *in vivo* study which found no association between disc and facet biomechanics under diurnal loading³⁹. Future studies may need to quantify whole facet cartilage volumes (using contrast enhanced μ CT⁴⁰) to improve such correlations.

Due to the cross-sectional nature of this study in cadaveric human tissues, any causal relationships between disc and facet degeneration cannot be determined. Prior studies, including those by Butler, Vernon-Roberts, and Bywaters have postulated that disc degeneration occurs before facet OA, given their observation of preserved facet joints in degenerated discs, as assessed by MRI^{28,41,42}. However, cadaveric studies have noted significant facet degeneration in the absence of disc degeneration, and other work has proposed that disc and facet degeneration occur concurrently^{43,19}. Many of these prior studies rely solely on clinically available imaging, such as MRI or CT to detect facet degeneration, methods that may be less sensitive in detecting the early stages of OA. Further work will be necessary to elucidate temporal relationships between disc and facet degeneration, potentially in animal models where degeneration of each spinal substructure can be induced independent of one another^{44,45}.

Limitations to this study include the number of donors, especially given the variability and heterogeneity in some outcomes, particularly indentation testing of the cartilage. A priori data were not available for human facet cartilage mechanical properties. However a power analysis was conducted using previously published data from Netzer et al.¹⁷ on subchondral bone morphometry in healthy and osteoarthritic facets. Assuming a conservative 18.4% standard deviation in trabecular bone volume fraction at our sample size (approximately 6

vs. 18 facets at each grade strata), we can detect a difference of 19.2% using GEE with an intraclass correlation of 0.5, 80% power, and a significance level of 0.05. This detectable difference is smaller than we have observed in our study for trabecular bone parameters (where percent changes in trabecular bone morphometry range from 27-38%), suggesting that our study is adequately powered at least with respect to bone morphometry.

In the current study, it is also difficult to discern any effect of sex on facet degeneration, due to the limited number of female donors. Future studies should involve a greater number of donors with more balanced age and sex distributions. We were also unable to measure lumbar lordosis or facet alignment, which can contribute to facet OA and should be investigated in future work⁴⁶. Overall, this study characterized alterations in the mechanical properties of facet cartilage and structural properties of facet subchondral bone over a spectrum of spine degeneration which were highly dependent on spinal level. We found facet OA to be characterized by heterogeneous and progressive cartilage erosion, which culminated in reduced cartilage mechanical properties. Our results suggest an overall loss of subchondral bone with increasing degeneration, except at the L4-L5 level where bony sclerosis was observed in the trabecular compartment. Facet bony sclerosis, macroscopic grade and OARSI score were significantly correlated with disc mechanical properties, suggesting a significant interrelationship between these adjacent tissues and highlighting the importance of considering the contribution of the facet joints in the study of disc degeneration and repair.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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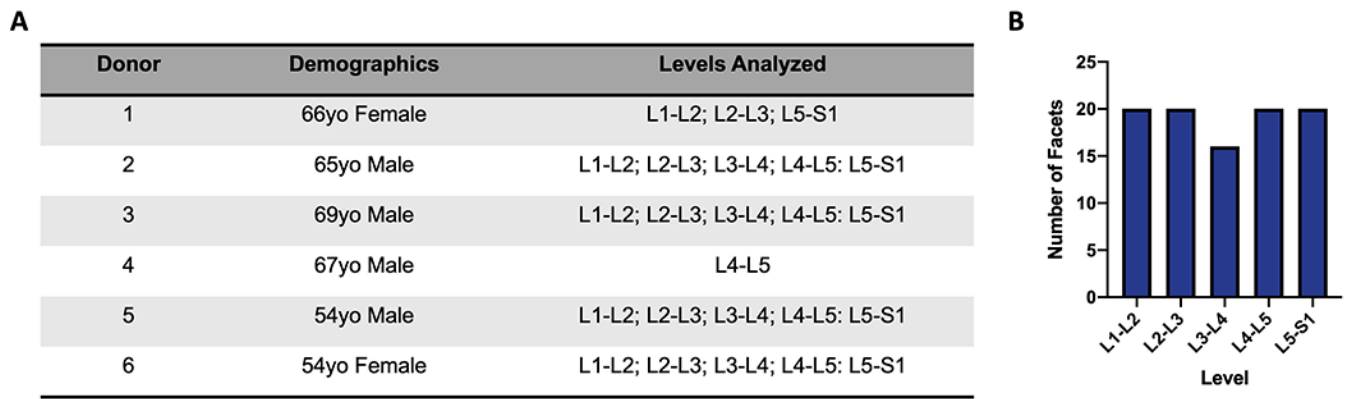


Figure 1.

A). Donor Demographics and levels analyzed per donor. B). Number of facets evaluated corresponding to each lumbar spine level.

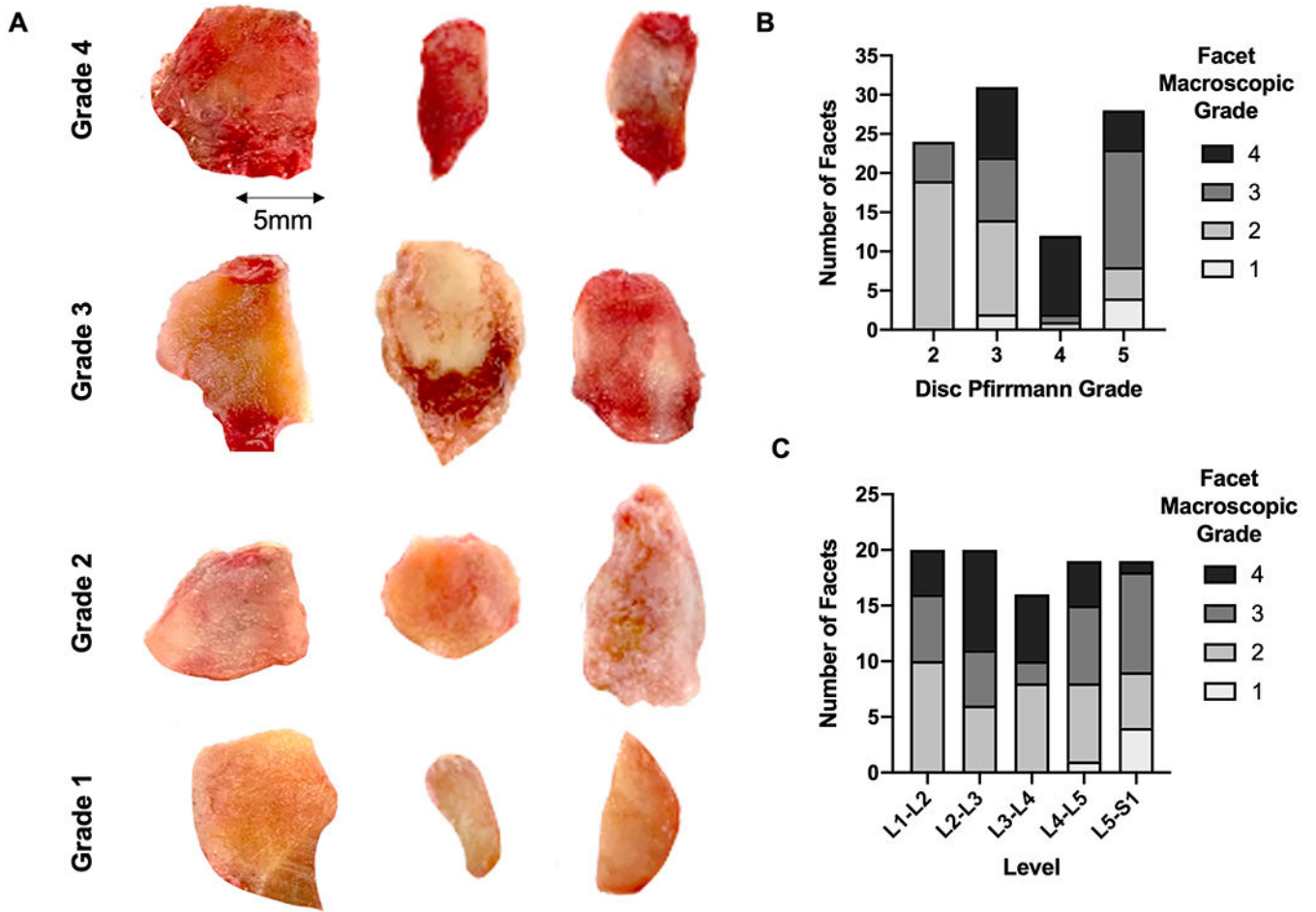


Figure 2.
 A). Sample macroscopic images of individual facets for each grade from different donors. Graded according to prior study by Li et al; (Grade 1: surface fibrillation; Grade 2: fissuring; Grade 3: erosion of 30% or less of the articular surface; Grade 4: erosion of more than 30% of the articular surface). B). Distribution of number of facets from each macroscopic grade stratified by disc Pfirrmann grade. C). Distribution of number of facets from each macroscopic grade stratified by spinal level.

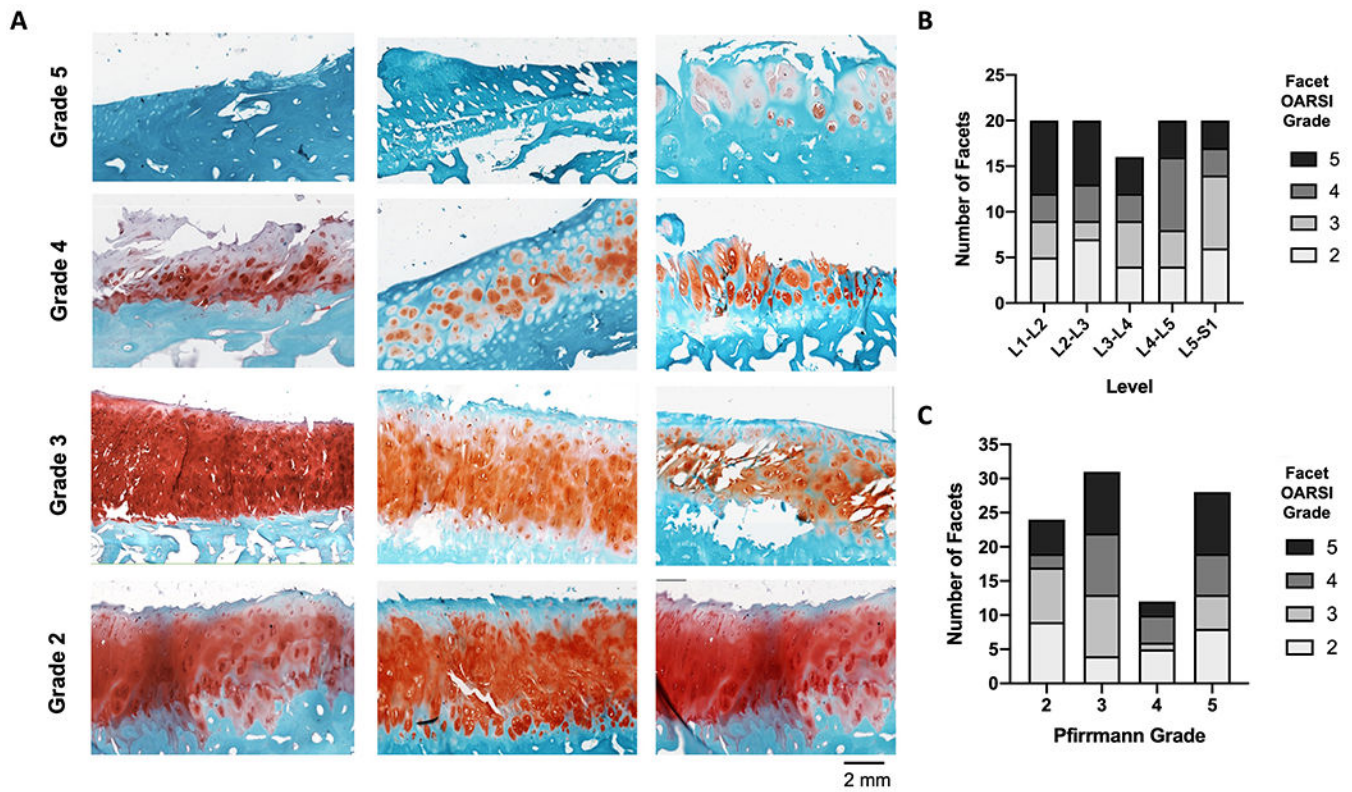


Figure 3.

A). Safranin-O and Fast Green-stained histological sections of human facets demonstrating the sample variation from different donors within the same OARSIS score (Scale = 2 mm).

The number of facets from each OARSIS score was stratified by B). spinal level and C). disc Pfirrmann grade.

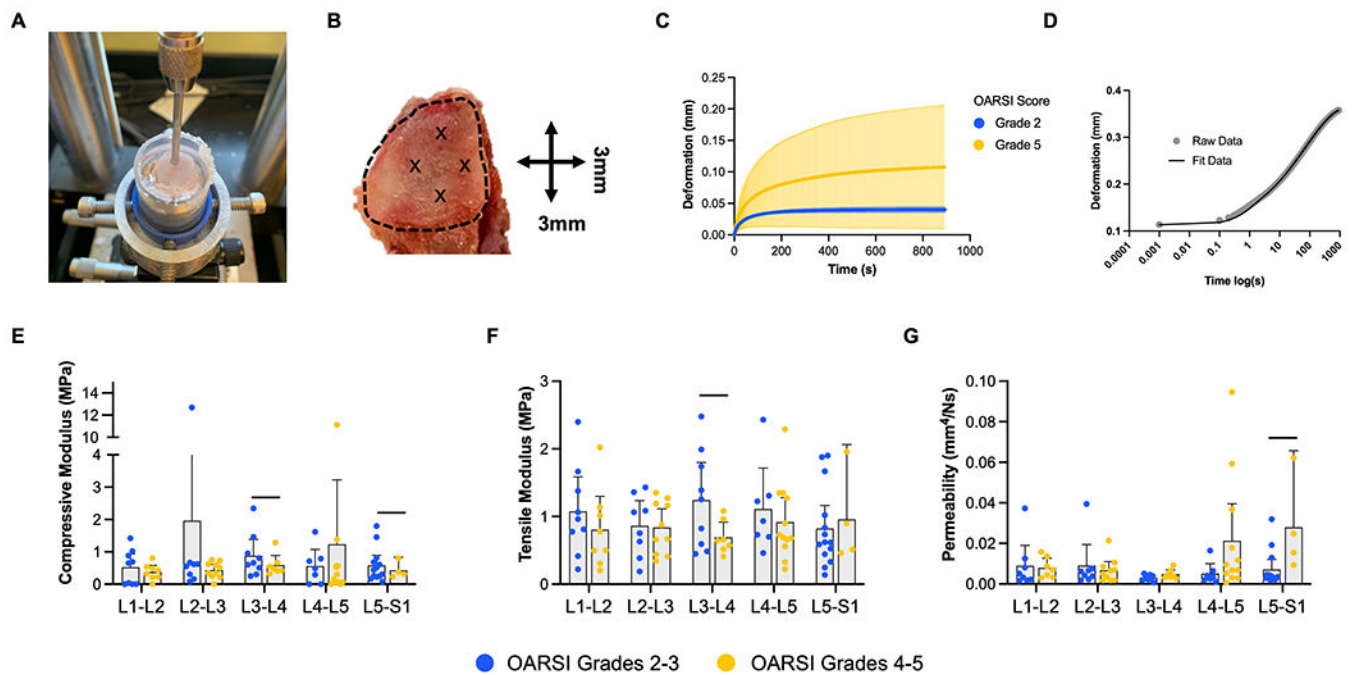


Figure 4.

A). Photograph of cartilage indentation testing setup with 1mm indenter and potted facet sample. B). "Diamond" configuration demonstrating the 4 individual points, each 3mm apart, where cartilage creep testing was performed. The dashed line delineates the articular surface. C). Mean (dark colored line) and standard deviation (shaded area) deformation versus time curves from the creep indentation testing for OARSIS grade 2 and 5 facets. D). Individual sample deformation versus time (on a logarithmic scale) showing the Hertzian biphasic theory model fit to the raw data from indentation testing to determine compressive modulus, tensile modulus, K_0 , and M of the facet cartilage²⁴. E). Compressive modulus, F). tensile modulus and G). permeability stratified by OARSIS grade and spinal level. Graphs depict mean plus the 95% confidence interval, and bars denote significant differences between groups.

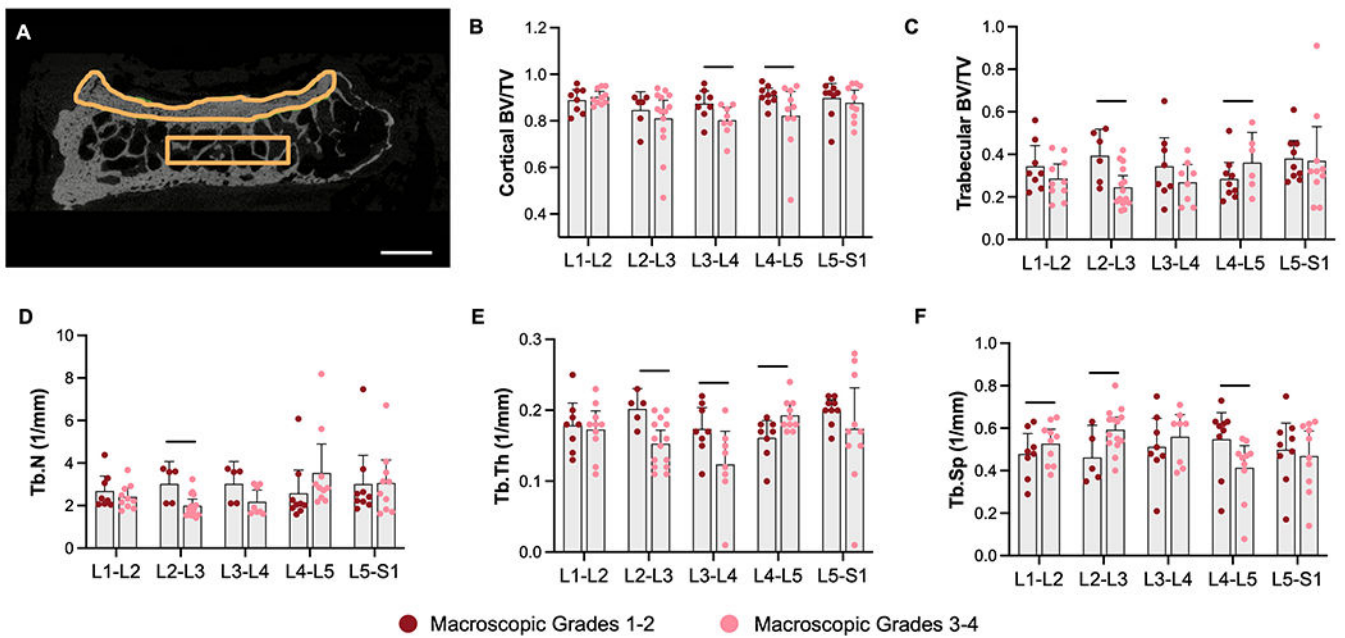


Figure 5.

A). Example contours of facet cortical and trabecular bone for μ CT analysis (scale = 3mm) of B). cortical bone volume fraction (BV/TV), C). trabecular bone volume fraction (BV/TV), D). trabecular number, E). trabecular thickness, and F). trabecular spacing, stratified by spinal level and macroscopic grade. Graphs depict mean plus the 95% confidence interval, and bars denote significant differences between groups.

Table 1.

Results from the Pearson correlation matrix between quantitative facet and disc outcome metrics.

Parameter 1	Parameter 2	Pearson Correlation Coefficient (r)	P Value
Facet Tb.Th	Disc Compressive Modulus	-0.34	0.021
Facet Tb. N	Disc Transition Strain	0.35	0.018
	Disc Max Strain	0.34	0.020
Facet Macroscopic Grade	Disc Transition Strain	-0.45	0.002
	Disc Max Strain	-0.43	0.003
	Disc Compressive Modulus	0.30	0.043
Facet OARSI Score	Disc Height	-0.31	0.071
	Disc Compressive Modulus	0.26	0.039