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A Comprehensive Assessment of Clinical, Radiological, and Histopathological Parameters in Lumbar Disc Herniation Using Correlation Matrices Analysis

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ABSTRACT

AIM: To provide deeper insights into the biological mechanisms underlying disc degeneration and recurrence by studying histopathological features of excised disc tissue. Moreover, due to limited predictive role of radiological grading systems like Pfirrmann and Modic classifications in understanding postoperative outcomes and recurrence mechanisms, to perform holistic analysis on clinical, patient specific factors, radiological and histological findings on matrix correlation statistics.

MATERIAL and METHODS: We conducted a retrospective study including 87 patients who underwent lumbar discectomy between 2019 and 2024. Detailed preoperative magnetic resonance imaging (MRI) evaluations using Pfirrmann grading, along with semi-quantitative histopathological analysis, were performed. Statistical analyses included Spearman correlation and ANOVA to explore relationships between clinical, radiological, and histopathological parameters.

RESULTS: Higher Pfirrmann grades were significantly associated with radiological instability ($p<0.001$). Histopathological analysis revealed that matrix disorganization was the only parameter significantly associated with clinical recurrence: all patients with recurrent disc herniation exhibited Grade 3 matrix disorganization ($p<0.001$), while only 40.5% of non-recurrent cases showed this pattern. Spearman correlation matrices further confirmed the absence of strong linear relationships among most individual clinical, radiological, and histological variables.

CONCLUSION: Our integrated approach underscores the importance of matrix disorganization as a biomarker for recurrence risk in lumbar disc herniation. Our integrated approach underscores the importance of matrix disorganization as a histopathological hallmark and potential biomarker for recurrence risk in lumbar disc herniation. In contrast, other histological features—such as chondrocyte grouping and cellularity—did not demonstrate consistent associations with clinical or radiological parameters. Radiological instability was reliably associated with advanced disc degeneration (higher Pfirrmann grades), but did not correlate with histopathological severity. This study advocates for personalized risk stratification tools integrating multi-dimensional data.

KEYWORDS: Lumbar disc herniation, Lumbar discectomy, Predictive biomarkers, Recurrent lumbar disc herniation

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INTRODUCTION

Lumbar disc herniation is a leading cause of pain and disability worldwide. Although surgical intervention often provides symptomatic relief, recurrence rates remain considerable, and the underlying biological mechanisms remain unclear (12,13,16,17). Magnetic resonance imaging (MRI) has enabled the development of grading systems such as the Pfirrmann classification; however, the predictive value of radiological findings alone for postoperative outcomes is limited (1,3,8,11). Furthermore, studies report complex and often inconsistent associations between clinical risk factors and disease progression (6,17).

Histopathological changes in disc degeneration have been increasingly investigated, but most studies address only a single dimension of the disease, involve small cohorts or apply overly simplistic analyses (2,8,9,13,16). Consequently, the integration of clinical, radiological, and histopathological data to identify robust biomarkers for recurrence remains uncommon, limiting advances in surgical decision-making (10,11). There is a clear need for comprehensive studies that systematically evaluate relationships between tissue-level features and patient outcomes (12,13,14,17).

The present study addresses these gaps through a retrospective, integrative analysis of patients undergoing lumbar discectomy, we combined detailed MRI grading with semi-quantitative histopathological scoring (15), hypothesizing that multi-dimensional integration would reveal novel associations, clarify the biological determinants of recurrence, and improve prognostic accuracy in lumbar disc disease (16).

MATERIAL and METHODS

Study Design and Ethics

This retrospective observational study was approved by the Institutional Review Board (IRB: 2024-068, decision no. 6/28-09.05.2024) and conducted in accordance with the Declaration of Helsinki. Written informed consent was obtained from all patients. The study adhered to the Strengthening the Reporting of Observational Studies in Epidemiology guidelines.

Power Analysis

An a priori power analysis determined the minimum required sample size for correlation analyses. Using an alpha level of 0.05 and a statistical power of 0.90, the required sample size was calculated to be 86 patients. The final cohort included 87 participants.

Patient Population and Follow-Up

Eighty-seven consecutive adults who underwent primary lumbar discectomy for symptomatic intervertebral disc herniation between 2019 and 2024 were retrospectively reviewed. The inclusion criteria were: age > 18 years, availability of complete clinical records, preoperative lumbar MRI, and adequate excised disc material for histopathological analysis. Patients were excluded if they had a history of spinal tumor, infection, or trauma; prior lumbar instrumentation; or incomplete clinical or imaging data. The mean follow-up duration was 17 months (range, 12–60 months).

Clinical and Demographic Data

Demographic variables included age, sex, and body mass index. Smoking status, and comorbidities—hypertension, diabetes mellitus, hypothyroidism, chronic obstructive pulmonary disease, coronary artery disease, and rheumatologic diseases—were extracted from electronic medical records. Surgical details, including operated spinal levels, recurrence status (defined as symptomatic herniation at the same level requiring reoperation), and follow-up duration, were recorded. In patients with multilevel discectomy, all excised disc materials were pooled and analyzed as a single specimen per patient.

Radiological Assessment

Preoperative lumbar MRI was performed on a 1.5 T system (Achieva, Philips) using sagittal T1-weighted, sagittal T2-weighted, and axial T2-weighted sequences (slice thickness 4 mm). Two neurosurgeons, blinded to other data, independently assessed the images for Pfirrmann grade and herniation type. Discrepancies were resolved by consensus, and interobserver agreement was calculated using Cronbach's alpha. The following MRI parameters were assessed: 1) disc degeneration, graded using the Pfirrmann classification on T2-weighted images (Figure 1); 2) disc morphology, defined as protrusion (base wider than any other dimension) or extrusion (maximum diameter greater than the base), according to the criteria of Fardon et al. (4); 3) annulus–nucleus distinction, scored as clear or indistinct; 4) signal intensity, classified as homogeneous, heterogeneous, or black disc; 5) disc height, categorized as normal, decreased, or collapsed; 6) facet joint effusion, noted as absent, unilateral, or bilateral, defined as > 1 mm fluid signal within the facet joint space on axial T2-weighted images; and 7) radiological instability, defined as the presence of segmental translation > 3 mm or angulation > 10° between adjacent vertebrae on dynamic lateral flexion-extension radiographs, or the presence of a pars interarticularis defect.

Discrepancies between observers were resolved by consensus. Interobserver reliability was assessed using Cronbach's alpha.

Histopathological Analysis

Excised intervertebral disc specimens were fixed in 10% buffered formalin, paraffin-embedded, and stained with hematoxylin and eosin (H&E). Two pathologists, blinded to all clinical and radiological data, independently evaluated the specimens, resolving differences by consensus. Four histopathological parameters were assessed using a semi-quantitative system adapted from previously published criteria (2,9,14) and modified for practical applicability and internal consistency: 1) matrix organization (Grades 1–3), 2) chondrocyte grouping (Grades 1–3), 3) group cellularity (Grades 1–3), and 4) overall cellularity (excluding cartilaginous endplate areas).

Matrix organization

- Grade 1: Mild or minimal changes not meeting criteria for Grade 2 or 3

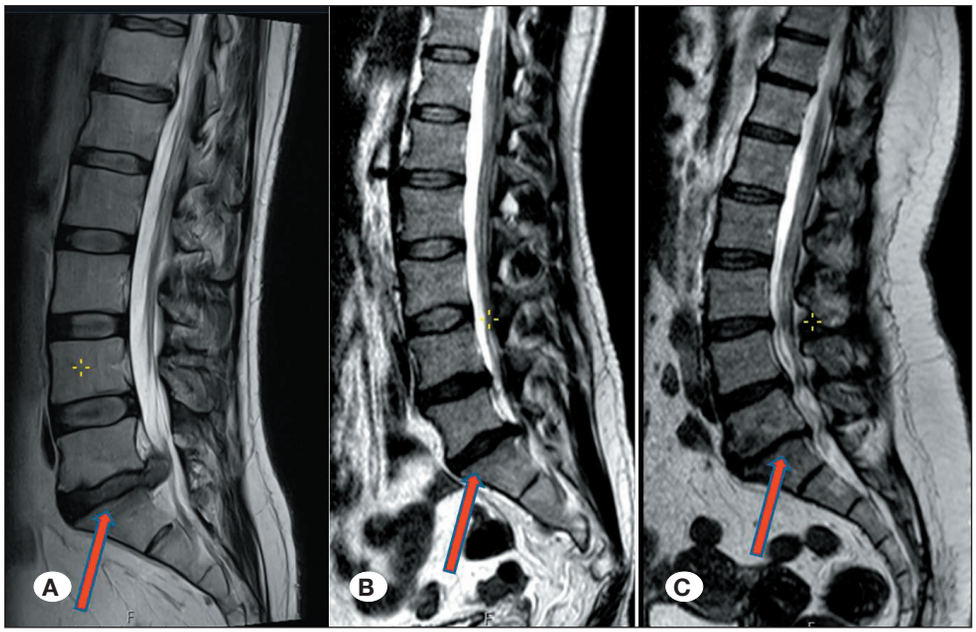

Figure 1: Representative sagittal T2-weighted magnetic resonance imaging (MRI) scans illustrating the Pfirrmann classification of lumbar disc degeneration. **A)** A Grade 2 herniated disc with mild degeneration is observed at the L5-S1 level (red arrow). Adjacent disc structures at the superior levels show minimal degeneration (Grade 1). **B)** A Grade 4 herniated disc is shown at the L5-S1 level (red arrow), with an adjacent Grade 3 disc at the L4-5 level. **C)** A severely degenerated Grade 5 herniated disc is visible at L5-S1 (red arrow), characterized by complete structural disorganization and a significant loss of signal. An adjacent Grade 3 disc is seen at the L4-5 level. The Pfirrmann grading was specifically performed on the surgically treated disc level from which the histopathological specimen was obtained.

- Grade 2: Marked myxoid changes visible at low magnification (H&E, ×40)
- Grade 3: Marked myxoid change with clear matrix separation visible at low magnification (H&E, ×40)

Chondrocyte grouping

- Grade 1: Scattered, non-grouping chondrocytes
- Grade 2: Occasional groups apparent at higher magnification (H&E, ×40)
- Grade 3: Numerous groups readily observed at low magnification (H&E, ×40)

Group cellularity

- Score 1: No grouping (as in chondrocyte grouping Grade 1)
- Score 2: Groups with ≤ 5 chondrocytes
- Score 3: Groups with > 5 chondrocytes

Overall cellularity

The total number of chondrocytes was counted in the most cellular field, excluding cartilaginous endplate areas for standardization, using a ×100 objective.

Statistical Analysis

Statistical analyses were conducted using SPSS version 27 (IBM Corp., Armonk, NY, USA). Categorical variables are presented as counts and percentages; continuous variables as mean ± standard deviation or median (interquartile range), as appropriate, normality was assessed with the Kolmogorov–Smirnov test and Q–Q plots. Categorical variables were compared using the chi-square test; continuous variables were compared using the independent-samples t-test or analysis of variance (ANOVA) for normally distributed data; Mann–Whitney U test or Kruskal–Wallis test for non-normally distributed data.

Correlations among clinical, radiological, and histopathological variables were examined using Spearman's rank correlation coefficient, and correlation matrices were generated for comprehensive visualization. Interobserver reliability was assessed with Cronbach's alpha. Statistical significance was set at $p<0.05$.

RESULTS

A total of 87 patients (mean age, 58.6 ± 11.4 years; range, 31–77 years) who underwent lumbar discectomy were included in the analysis. Females comprised 63.2% (n=55) of the cohort. The mean body weight was 78.7 ± 13.7 kg, mean height 1.64 ± 0.10 m. The mean body mass index (BMI) was 29.0 ± 4.5 kg/m^2. A history of smoking was reported in 23% (n=20) of patients, hypertension in 43.7% (n=38), and diabetes mellitus in 31% (n=27) of patients. The prevalence of hypothyroidism, chronic obstructive pulmonary disease, coronary artery disease, and rheumatologic disorders was 8.0%, 6.9%, 12.6%, and 4.6%, respectively (Table I).

Table I: General Characteristics and Clinical Features of the Study Cohort

Descriptives	Mean values
Age (mean±SD) (years)	58.63±11.36
Gender, Female, n (%)	55 (63.2)
Weight (mean±SD) (kg)	78.65±13.67
Height (mean±SD) (m)	1.64±0.10
BMI (mean±SD)	29.02±4.46
Smoking, n (%)	20 (23.0)
Hypertension, n (%)	38 (43.7)
Diabetes, n (%)	27 (31.0)
Hypotyroid, n (%)	7 (8.0)
COPD, n (%)	6 (6.9)
Coronary Heart Disease, n (%)	11 (12.6)
Rheumatological, n (%)	4 (4.6)
Level of discectomy, n (%)	
L5-S1	11 (12.7)
L4-5	42 (48.3)
L3-4	12 (13.8)
L2-3	2 (2.3)
L1-2	1 (1.1)
Multiple levels	19 (21.8)
Recurrence in patients, n (%)	13 (14.9)
Extrude Disk apperance on MRI (78 pt), n (%)	40 (51.3)
Radiological instability, n (%)	31 (35.6)

BMI:* *Body Mass Index,* ***COPD:* *Chronic Obstructive Pulmonary Disease*

The most frequently operated levels were L4–L5 (48.3%) and L5–S1 (12.6%); 21.8% of patients underwent multilevel discectomy. During a mean follow-up of 17 months (range, 12–60 months), 13 patients (14.9%) experienced recurrent disc herniation requiring reoperation.

Preoperative MRI revealed an extruded disc in 51.3% of patients and a protrusion in 48.7%. Radiological instability was observed in 35.6% (n=31). The distribution of Pfirrmann grades was as follows: Grade 2 (7.6%), Grade 3 (20.3%), Grade 4 (37.9%), and Grade 5 (34.2%); no patients had Grade 1 degeneration. A "black disc" appearance on T2-weighted MRI was seen in 32.9% of patients. The annulus fibrosus–nucleus pulposus distinction was clear in only 23.1% of cases, indistinct in 50%, and unreported in the remainder. Disc height was preserved in 24.1% of patients and collapsed in 19%. Facet effusion was absent in 61.2% of cases, unilateral in 25%, and bilateral in 13.8%.

Radiological instability was significantly associated with higher mean Pfirrmann grades (4.39 ± 0.47 vs. 3.78 ± 0.75 in stable patients, $p<0.001$; Figure 2). No significant association was found between facet effusion and radiological instability ($p>0.05$). Interobserver reliability was excellent for overall MRI assessment (Cronbach's alpha = 0.784) and substantial for Pfirrmann grading (Cronbach's alpha = 0.709).

Histopathological Findings

Matrix organization was graded as follows: Grade 1 in 16.1%, Grade 2 in 34.5%, and Grade 3 in 49.4% of cases (Figure 3). Chondrocyte grouping was Grade 1 in 6.9%, Grade 2 in 23%, and Grade 3 in 70.1% of cases (Figure 4). Group cellularity was Grade 1 in 6.9%, Grade 2 in 36.8%, and Grade 3 in 56.3% of cases (Figure 5). The mean chondrocyte count (overall cellularity) was 81.2 ± 41.9 (range, 18–252).

Correlation of Radiological and Histopathological Parameters

When radiological and histopathological variables were compared using ANOVA and chi-square tests, no statistically significant associations were found between chondrocyte grouping or group cellularity and any of the following MRI parameters: disc appearance, radiological instability, Pfirrmann grade, disc structure, annulus–nucleus distinction, signal intensity, disc height, or facet effusion (all $p > 0.05$; Tables II-IV).

Matrix organization was significantly associated only with the annulus–nucleus distinction on MRI ($p=0.034$) but not with other radiological features. Patients with radiological instability exhibited higher Pfirrmann grades, but no significant differences in histopathological parameters were observed between instability groups.

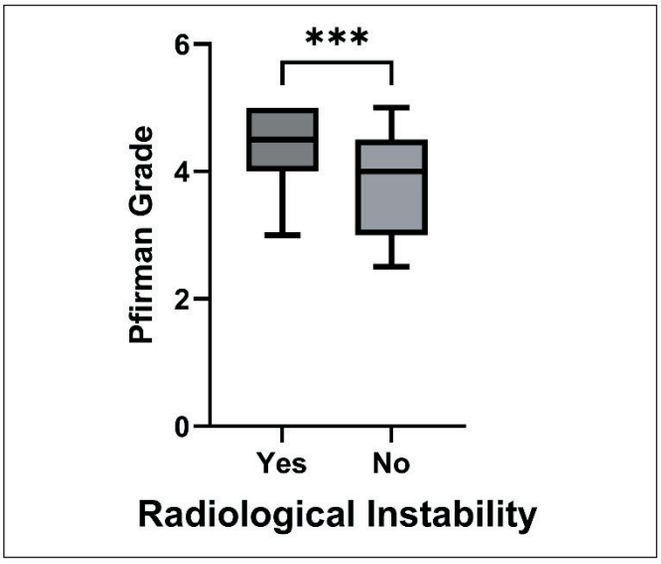

Figure 2: Box-and-whisker plot illustrating the distribution of Pfirrmann grades according to the presence or absence of radiological instability. Patients with radiological instability demonstrated significantly higher Pfirrmann grades compared to those without instability (***$p<0.001$). Statistical comparison was performed using the Mann–Whitney U test.

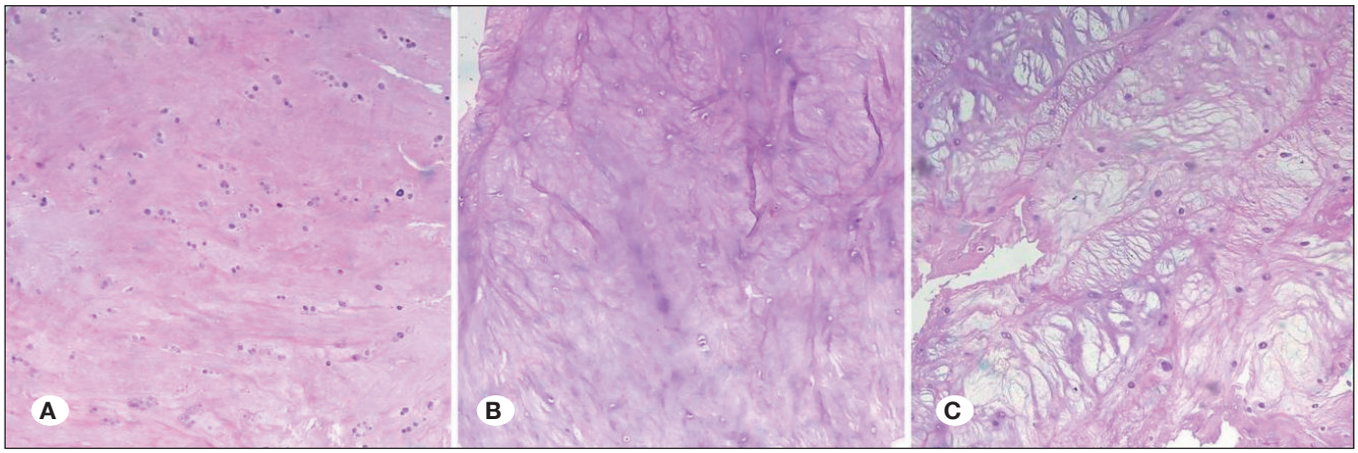

Figure 3: Representative histopathological images demonstrating the grading of matrix organization in intervertebral disc specimens. **A)** Grade 1 – Cases not meeting the criteria for grade 2 or grade 3. **B)** Grade 2 – Marked myxoid changes readily apparent at low magnification (H&E, ×40). **C)** Grade 3 – Marked myxoid change with prominent areas of matrix separation easily visible at low magnification (H&E, ×40). (H&E: hematoxylin and eosin).

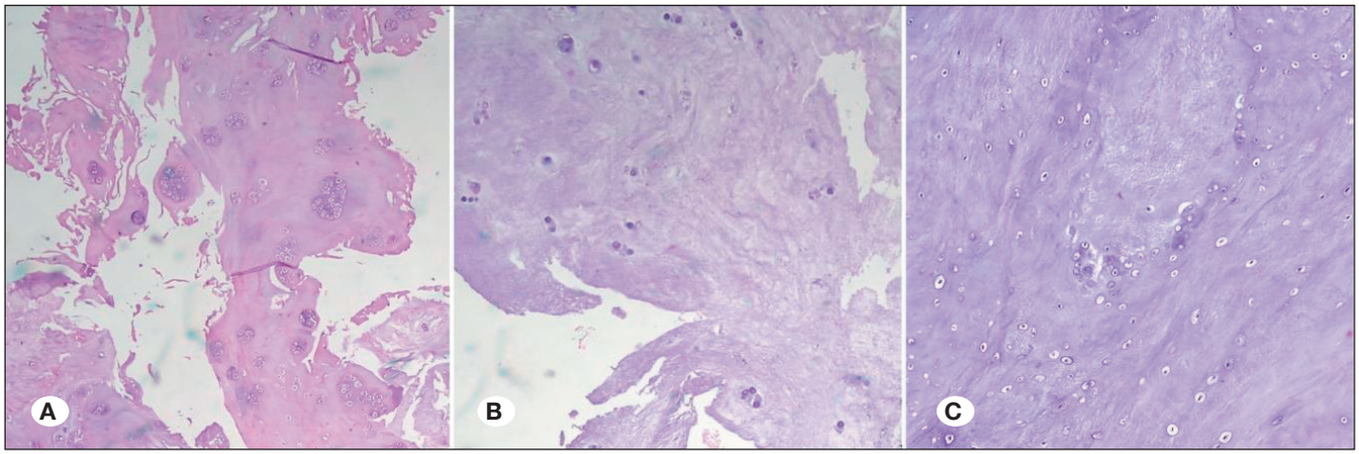

Figure 4: Representative histopathological images illustrating the grading of chondrocyte clustering in intervertebral disc specimens. **A)** Grade 1 – Isolated chondrocytes observed singly without forming clusters. **B)** Grade 2 – Occasional chondrocyte clusters detected either sporadically or on closer inspection (H&E, ×40). **C)** Grade 3 – Numerous chondrocyte clusters easily identified at low magnification (H&E, ×40). (H&E: hematoxylin and eosin).

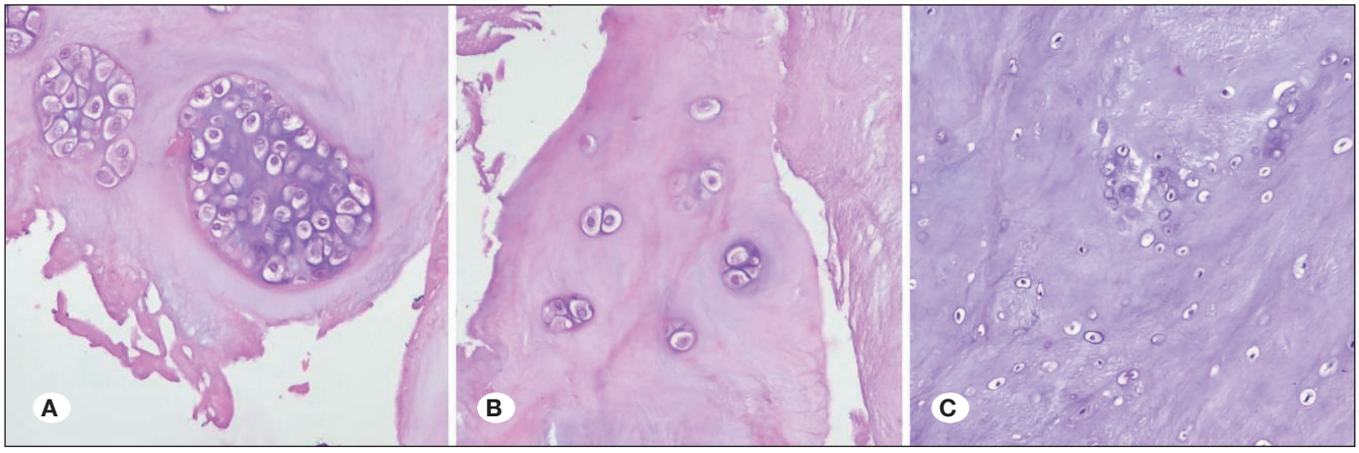

Figure 5: Representative histopathological images showing the grading of group cellularity in chondrocyte clusters within intervertebral disc specimens. **A)** Grade 2 – Chondrocyte clusters containing ≤5 cells per group. **B)** Grade 3 – Chondrocyte clusters containing >5 cells per group. **C)** Grade 1 – cases in which there is no intercellular clustering and chondrocytes are distributed individually (as single cells) (H&E, ×40). (H&E: hematoxylin and eosin).

Table II: Comparison of Histopathological Parameters Between Patients with and without Recurrent Lumbar Disc Herniation

	Recurrence (n=13)	No recurrence (n=74)	p-value
Histopathological Cellularity	99.84±57.86	77.91±37.96	0.148
Grouping Grade, n (%)			
Gr 1	1 (7.7)	5 (6.8)	0.992
Gr 2	3 (23.1)	17 (23)	
Gr 3	9 (69.2)	52 (70.2)	
Group Cellularity Grade, n (%)			
Gr 1	1 (7.7)	5 (6.8)	0.888
Gr 2	4 (30.8)	28 (37.8)	
Gr 3	8 (61.5)	41 (55.4)	
Matrix Organisation, n (%)			
Gr 1	0	14 (18.9)	**<0.001**
Gr 2	0	30 (40.5)	
Gr 3	13 (100)	30 (40.6)	

Table III: Histopathological Findings Stratified by the Presence and Laterality of Facet Joint Effusions

	Facet Effusions			
	No (n=49)	One facet (n=20)	Two facet (n=11)	p-value
Histopathological Cellularity	84.38±42.56	71.80±40.16	77.45±35.68	0.502
Grouping Grade, n (%)				
Gr 1	5 (10.2)	1 (5)	0	0.760
Gr 2	10 (20.4)	5 (25)	2 (18.2)	
Gr 3	34 (69.4)	14 (70)	9 (81.8)	
Group Cellularity Grade, n (%)				
Gr 1	5 (10.2)	1 (5)	0	0.447
Gr 2	17 (34.7)	10 (50.0)	3 (27.3)	
Gr 3	27 (55.1)	9 (45.0)	8 (72.7)	
Matrix Organisation, n (%)				
Gr 1	7 (14.3)	5 (25)	2 (18.2)	0.670
Gr 2	15 (30.6)	6 (30)	5 (45.5)	
Gr 3	27 (55.1)	9 (45)	4 (36.4)	

Recurrent Versus Non-Recurrent Cases

Mean chondrocyte cellularity was higher in recurrent cases compared with non-recurrent cases (99.8 ± 57.9 vs. 77.9 ± 38.0), although the difference did not reach statistical significance (p=0.148). The distributions of chondrocyte grouping, group cellularity, and overall cellularity grades did not differ significantly between recurrent and non-recurrent patients (all p>0.05). Notably, all recurrent cases demonstrated Grade 3 matrix organization, compared with 40.5% of non-recurrent cases (p<0.001), indicating a strong association between advanced matrix disorganization and recurrence (Table II).

Subgroup Analyses

No significant differences in histopathological cellularity, chondrocyte grouping, group cellularity, or matrix organization

Table IV: Comparison of Histopathological Features between Patients with and Without MRI-Detected Disc Extrusion

	Extrude dis apperance on MRI		
	Yes	**No**	**p-value**
Histopathological Cellularity	80.25±47.92	79.21±33.67	0.146
Grouping Grade, n (%)			
Gr 1	3 (7.5)	3 (7.9)	0.627
Gr 2	7 (17.5)	10 (26.3)	
Gr 3	30 (75)	25 (65.8)	
Group Cellularity Grade, n (%)			
Gr 1	3 (7.5)	3 (7.9)	0.908
Gr 2	14 (35.0)	15 (39.5)	
Gr 3	23 (57.5)	20 (52.6)	
Matrix Organisation, n (%)			
Gr 1	5 (12.5)	9 (23.7)	0.347
Gr 2	15 (37.5)	10 (26.3)	
Gr 3	20 (50.0)	19 (50.0)	

were observed when patients were stratified by the presence or absence of facet effusion or by disc extrusion versus protrusion on MRI (all p>0.05; Tables III-IV).

Correlation Matrix Findings

Comprehensive Spearman correlation matrices were constructed to evaluate relationships among clinical, radiological, and histopathological parameters. No strong or statistically significant correlations ($r > 0.5$, $p<0.05$) were found between individual demographic, clinical (Figure 6), or radiological variables (Figure 7) and histopathological parameters (Figure 8). The most notable correlation was between radiological instability and higher Pfirrmann grade. Heatmaps illustrated a general absence of robust linear relationships between most individual parameters.

DISCUSSION

This study provides a comprehensive evaluation of the interplay between demographic, clinical, radiological, and histopathological parameters in patients undergoing lumbar discectomy. By combining detailed MRI grading, objective assessments of radiological instability, and a semi-quantitative histopathological scoring system, we identified predictors of disc recurrence and examined the relationships between tissue-level changes and clinical–radiological findings. Notably, severe matrix disorganization on histopathology emerged as the most consistent correlate of recurrence, whereas common patient-specific factors—such as BMI, smoking, and comorbidities—did not independently predict recurrence or advanced degeneration. Additionally, higher Pfirrmann grades were strongly associated with radiological instability, underscoring the prognostic value of MRI grading in risk stratification.

Unlike most previous studies, which have examined binary relationships between either radiological and histopathological features or clinical risk factors and outcomes, our study employed an integrated, multi-modal approach. Earlier reports have primarily focused on MRI-based grading systems, such as the Pfirrmann classification (7,11) or Modic changes (3,5), in relation to gross disc pathology or symptoms, with relatively few systematically linking histopathology, imaging, and clinical data within a single cohort. Boos et al. and Rutges et al. described cellularity and matrix changes in disc degeneration, but without connecting these features to recurrence or instability in a unified framework (2,14). Our simultaneous assessment of four histopathological variables—matrix organization, chondrocyte grouping, group cellularity, and overall cellularity—alongside MRI parameters and recurrence outcomes offers new insights into the tissue-level mechanisms influencing surgical prognosis.

Consistent with earlier reports, higher Pfirrmann grades were prevalent among patients with radiological instability, with more than 70% of cases graded 4 or 5. This may reflect our institution's role as a tertiary referral center. Although advanced imaging has been proposed as a surrogate for degeneration severity (10), our study uniquely linked radiological findings with prospectively scored histopathological changes. Matrix disorganization was the only histological feature significantly associated with both radiological and clinical endpoints, being present in all recurrent cases—a relationship not previously described in detail (2,14).

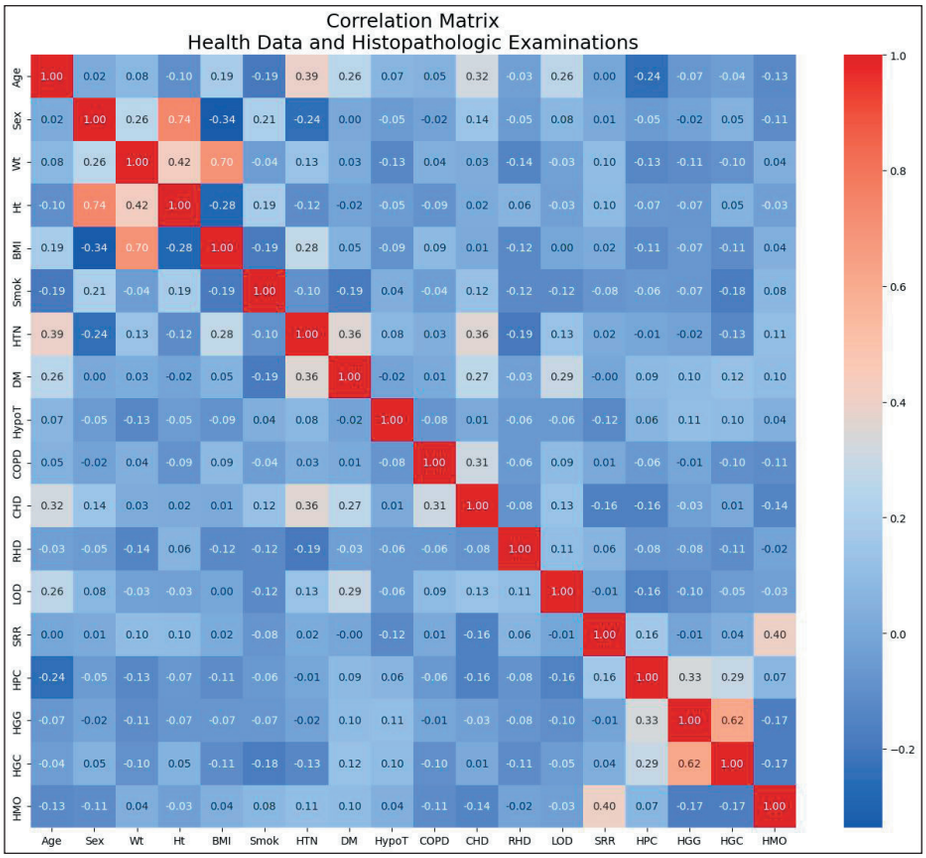

Figure 6: Correlation matrix heatmap demonstrating the relationships between clinical and demographic parameters (e.g., age, sex, BMI, smoking, comorbidities) and radiological findings in the patient cohort. The color scale indicates the strength and direction of Spearman correlation coefficients.

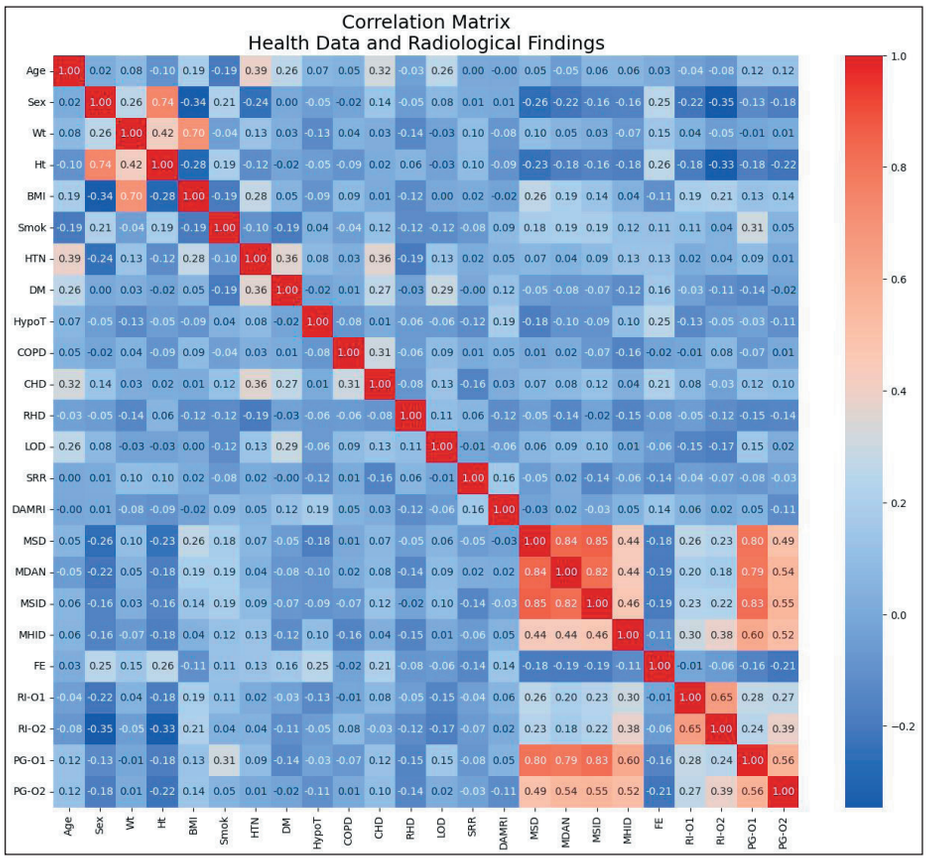

Figure 7: Correlation matrix heatmap illustrating the associations between clinical and demographic features (health data) and histopathological parameters in excised disc specimens. The color scale indicates the Spearman correlation coefficients between each pair of variables.

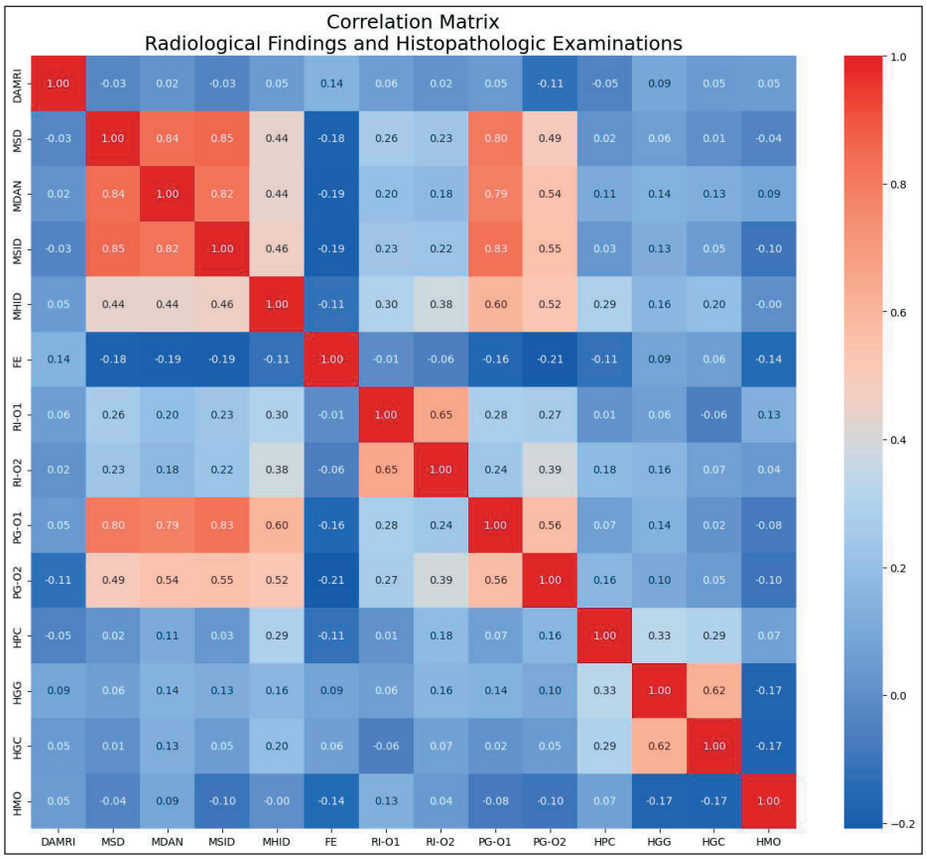

Figure 8: Correlation matrix heatmap visualizing the relationships between radiological findings and histopathological parameters in lumbar disc specimens. The color scale indicates the degree of correlation (Spearman's coefficient) between each radiological and histopathological variable.

Contrary to reports emphasizing patient-specific risk factors (6,16,17), we found no significant association between demographic variables, BMI, smoking, diabetes, or hypertension and either histopathological severity or recurrence risk. These findings suggest that the intrinsic biological state of the intervertebral disc—particularly extracellular matrix integrity—may outweigh traditional risk factors in determining prognosis. Furthermore, while MRI-based features such as facet effusion, disc extrusion, and annulus–nucleus distinction are frequently incorporated into assessment algorithms (15), they showed no consistent or statistically significant correlation with histopathological scores other than matrix organization. This discrepancy highlights the complexity of lumbar disc disease and underscores the need for integrated, multi-parameter evaluation in both research and clinical practice.

Clinically, our findings have two key implications. First, the strong association between matrix disorganization and recurrence suggests that histopathological assessment may be more prognostically relevant than many conventional risk factors, particularly in the presence of advanced radiological degeneration or instability. While MRI remains valuable for surgical planning, reliance on imaging features alone may lead to inaccurate recurrence risk estimation (7,17). Second, correlation matrix analysis across clinical, radiological, and histopathological variables—revealed a general absence of strong linear associations, except for the relationships between Pfirrmann grade and instability, and between matrix disorganization and recurrence. This multidimensionality highlights the potential utility of multi-modal, data-driven approaches—such as machine learning—for refining prognostication and enabling personalized management (18).

Strengths of our study include a large, prospectively characterized single-center cohort; standardized MRI interpretation; blinded, semi-quantitative histopathology; and systematic interobserver reliability assessment. To the best of our knowledge, few studies have conducted correlation matrix analyses across these domains. The identification of matrix disorganization as a recurrence predictor—independent of conventional clinical and radiological factors—represents a novel and clinically relevant finding.

However, several limitations should be noted. The retrospective, single-center design may limit generalizability, and although our sample size was determined by a priori power analysis, multi-center prospective validation is needed. Our histopathological scoring system, while refined for clarity and reproducibility, relied exclusively on H&E staining, limiting molecular-level insights.

Future research should validate these findings in larger, multi-institutional cohorts, extend follow-up to capture long-term outcomes such as pain and disability, and incorporate advanced techniques—including immunohistochemistry, proteomics, and gene expression profiling—to elucidate mechanisms underlying matrix disorganization. The dataset gen-

erated here could inform machine learning–based predictive models for individualized risk stratification. Prospective integration of multi-modal assessment, potentially including preoperative biopsy or non-invasive biomarkers, may bridge the current gap between imaging, tissue pathology, and clinical decision-making.

CONCLUSION

Severe matrix disorganization on histopathology emerged as the strongest tissue-level predictor of recurrence in lumbar disc herniation, underscoring the limitations of relying solely on patient demographics or conventional radiological parameters. Through the integration of standardized histopathological scoring, detailed MRI evaluation, and comprehensive statistical correlation, this study offers new insights into the multidimensional nature of lumbar disc disease. These findings support a more integrated, biologically informed approach to patient assessment and highlight the need for future research incorporating advanced analytical and molecular techniques to refine prognostication, optimize surgical decision-making, and reduce recurrence risk.

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Declarations

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Availability of data and materials: The datasets generated and/or analyzed during the current study are available from the corresponding author by reasonable request.

Disclosure: The authors declare no competing interests.

AUTHORSHIP CONTRIBUTION

Study conception and design: CCT, DS
Data collection: EST, OE, GA, KY
Analysis and interpretation of results: UOM, OE, GA, OE
Draft manuscript preparation: CCT, EST, UOM, KY
Critical revision of the article: CCT, DS
Other (study supervision, fundings, materials, etc...): n/a
All authors (CCT, EST, UOM, OE, GA, KY, OE, DS) reviewed the results and approved the final version of the manuscript.

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Supplementary Table I: Comparison of Radiological Parameters according to Histopathological Chondrocyte Grouping Grades in Intervertebral Disc Specimens

Descriptive	Histopathological Grouping Grade			p-value*
	Grade 1	Grade 2	Grade 3	
Extrude Disc appearance on MRI	3 pt	7 pt	30 pt	0.637
Radiological instability	2 pt	6 pt	23 pt	0.669
Pfirrman grade 2-3	2 pt	6 pt	14 pt	0.315
Pfirrman grade 4-5	4 pt	11 pt	42 pt	0.573
MR structure of disc- Black disc	2 pt	5 pt	19 pt	0.666
MR distinction of annulus nuscleus- No	2 pt	6 pt	31 pt	0.471
MR signal intensity of disc- Hypointensity	1 pt	5 pt	21 pt	0.490
MR height of intervertebral disc- collapsed	1 pt	3 pt	11 pt	0.318
Facet effusion- no effusion	5 pt	10 pt	34 pt	0.456

**Representative subgroups (e.g., "black disc", "hypointensity") are shown as examples. The p values reflect the comparison of all categories within each radiological feature against grouping grades using Pearson's chi-square test.*

Supplementary Table II: Association Between Radiological Features and Group Cellularity Grades in Excised Disc Tissue

Descriptive	Histopathological Group Cellularity			p-value*
	Grade 1	Grade 2	Grade 3	
Extrude Disc appearance on MRI	3 pt	14 pt	23 pt	0.911
Radiological instability	2 pt	13 pt	16 pt	0.988
Pfirrman grade 2-3	2 pt	7 pt	13 pt	0.353
Pfirrman grade 4-5	4 pt	23 pt	30 pt	0.608
MR structure of disc- Black disc	2 pt	9 pt	15 pt	0.954
MR distinction of annulus nuscleus- No	2 pt	12 pt	25 pt	0.64
MR signal intensity of disc- Hypointensity	1 pt	10 pt	16 pt	0.626
MR height of intervertebral disc- collapsed	1 pt	5 pt	9 pt	0.216
Facet effusion- no effusion	5 pt	17 pt	27 pt	0.453

**Representative subgroups (e.g., "black disc", "hypointensity") are shown as examples. The p values reflect the comparison of all categories within each radiological feature against group cellularity grades using Pearson's chi-square test.*

Supplementary Table III: Radiological Features according to Matrix Organization Grades in Histopathological Analysis

Descriptive	Histopathological Matrix Organization			p-value*
	Grade 1	Grade 2	Grade 3	
Extrude Disc appearance on MRI	5 pt	15 pt	20 pt	0.356
Radiological instability	2 pt	12 pt	17 pt	0.589
Pfirrman grade 2-3	1 pt	11 pt	10 pt	0.095
Pfirrman grade 4-5	13 pt	14 pt	30 pt	0.106
MR structure of disc- Black disc	7 pt	6 pt	24 pt	0.106
MR distinction of annulus nuscleus- No	9 pt	6 pt	24 pt	**0.034**
MR signal intensity of disc- Hypointensity	7 pt	6 pt	14 pt	0.127
MR height of intervertebral disc- collapsed	4 pt	3 pt	8 pt	0.076
Facet effusion- no effusion	7 pt	15 pt	27 pt	0.473

***Representative subgroups (e.g., "black disc", "hypointensity") are shown as examples. The p values reflect the comparison of all categories within each radiological feature against matrix organization grades using Pearson's chi-square test.*