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A QUANTITATIVE IMAGING AND FUNCTIONAL ASSESSMENT FRAMEWORK FOR EARLY DETECTION AND MANAGEMENT OF DEGENERATIVE SPINE CONDITIONS

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ABSTRACT

Degenerative spine conditions involve progressive structural deterioration that may substantially affect pain, mobility, and functional capacity. This study evaluated a quantitative framework integrating imaging-derived characteristics with functional measures for early detection and severity assessment of spinal degeneration. A quantitative observational analysis included 320 participants categorized into minimal/no, early, and moderate-to-advanced degeneration groups. Imaging assessment incorporated normalized disc height, spinal canal area, foraminal area, endplate irregularity, and degeneration score, while functional assessment included pain, disability, and mobility. Increasing degeneration severity was associated with reduced disc height, spinal canal area, and foraminal area and with greater endplate irregularity and functional impairment. Degeneration score correlated positively with disability ($r = 0.71$) and pain ($r = 0.64$), whereas disc height was inversely associated with disability ($r = -0.62$). The integrated imaging–functional model achieved an AUC of 0.92, with 88.1% sensitivity, 84.7% specificity, and 86.6% accuracy, exceeding the discriminatory performance of imaging-only and functional-only models. Integration of quantitative structural and functional indicators therefore provides a potentially useful approach for early identification and stratification of degenerative spine conditions.

KEYWORDS: quantitative imaging, spinal degeneration, functional assessment, early detection, risk stratification

1. INTRODUCTION

Degenerative spine disease encompasses a wide spectrum of progressive, degenerative structural disease of the intervertebral disc, vertebral endplates, facet joints and associated tissues. These changes can lead to pain, limited mobility, neurological dysfunction and loss of functional independence. The intervertebral disc exists in a specialised state, and is loaded in a particular way that is critical for maintaining the stability and flexibility of the spine and is vulnerable to ageing and biomechanical changes (Frost et al., 2019). Modern understanding of intervertebral disc degeneration also considers it a multifactorial process with regards to involvement of structural, cellular, biochemical, mechanical and systemic factors, and not just an anatomical abnormality (Hammoor et al., 2026).

Even though the degenerative changes may be early, it is still important to identify them, since structural changes may occur before significant functional changes occur. Imaging can be used to quantify anatomical and tissue level attributes that may not be fully captured by symptoms alone. Quantitative imaging has been shown to be useful in other clinical applications such as cardiovascular magnetic resonance assessment (Gao et al., 2024), retinal vascular characterization (Alam et al., 2021) and functional imaging of liver reserve (Sun et al., 2023). Cardiomyopathy and fibrosis have also been characterized through imaging based measurements in complex cardiovascular disease (Pan et al., 2026). The examples are representative of the more general promise quantitative imaging can bring to the clinical assessment, that of breaking away from subjective visual interpretation.

Imaging is especially important in the detection of disease when the changes are subtle and are the progression of disease over time. In neurodegenerative disorders, imaging is now playing a crucial role in the early diagnosis and to monitor disease progression over time (van Oostveen & de Lange, 2021). Recent evidence regarding cholinergic degeneration in PD prodromal and early stages of the disease also highlights the importance of the detection of measurable biological changes in early disease stages (Eisenstein et al., 2026). When applied to degenerative spine diseases, this concept can be used to assess quantitative parameters like disc height, canal size, foraminal stenosis, endplate changes and combined degeneration scores prior to significant structural changes.

There is not a one-to-one relationship between structural abnormalities and clinical burden experienced by an individual, however. Functional assessment is used to complement information on pain, disability, mobility and restriction of daily

activities. More generally, assessment science also highlights the complementary and mutually reinforcing nature of the different types of assessment and the value of using a variety of complementary assessment measurements to provide a more complete picture than using any single assessment approach (Meylani, 2024). As a consequence, a spine assessment framework should be integrated, by linking the measurable anatomical changes to the resulting functional consequences, rather than separate assessment of radiology and function.

The need to such integration is accentuated by limitations that are experienced throughout traditional diagnostic pathways. Although there are developments in diagnostic technologies that increase the precision in diagnosis, each diagnostic technology has limitations regarding sensitivity, specificity, interpretation, accessibility, and clinical applicability (Pulumati et al., 2023). These same problems have been reported in other diagnostic areas such as endometriosis (Pascoal et al., 2022), schistosomiasis (Fasogbon et al., 2024), syphilis (Cao et al., 2023) and Helicobacter pylori infection (Mărginean et al., 2022). These conditions are very distinct from spinal degeneration but all illustrate methodological constraint of using a single diagnostic modality in the context of a heterogeneous expression of disease.

Such quantitative imaging paradigms that incorporate imaging biomarkers with functional measurements might then offer a more informative framework for the detection and stratification of degenerative spine conditions. The multidimensional data can also be analyzed with traditional statistical modelling and prediction methods, which are complementary in diagnosis and clinical decision-making in medicine (Rajula et al., 2020). Defining the relationships between these measures of structural degeneration, pain, disability, and mobility can help identify abnormality at an early stage and provide clinically relevant information to assess severity and plan for management. Therefore, it was decided to aim for the following:

Quantify imaging and functional changes across degeneration severity levels.

Determine associations between structural abnormalities and functional impairment.

Evaluate an integrated framework for early detection and severity classification.

2. MATERIALS AND METHODS

2.1 Study Design and Population

A quantitative observational framework was used with 320 participants that were classified as minimal/no degeneration, early degeneration, and moderate to advanced degeneration. There were 112, 118 and 90 subjects in the groups, respectively. Demographic and functional variables such as age, body mass index (BMI), pain intensity, disability and mobility scores allowed for comparison between the different levels of progressive degeneration.

2.2 Quantitative Imaging Assessment

Normalised intervertebral disc height, spinal canal area, foraminal area, endplate irregularity and quantitative degeneration score were used to characterize structural degeneration. Canal and foraminal areas were reported in mm^2 and normalized disc height was used to compare structures between participants. These measurements showed a progressive change in disc morphology and narrowing of the discs in relation to increasing severity of degeneration.

2.3 Functional Assessment

Pain intensity, disability and mobility scores were used to assess functional status. Symptomatic burden, disability and physical performance were captured by pain, disability and mobility, respectively. These measures were contrasted between degeneration categories, and were then combined with imaging characteristics to assess the association between structural degeneration and functional impairment.

2.4 Integrated Imaging–Functional Framework

Imaging and functional variables were first assessed separately and then were integrated with an assessment framework. The degeneration score, the normalized disc height, the foraminal area, the disability, the pain intensity and the age were used as candidate predictors of the severity of degeneration. Imaging-only, functional-only and integrated models were compared to see how much discriminatory value was added by combining both assessment domains.

2.5 Statistical Analysis

Data analysis was conducted in python using the libraries pandas, NumPy, SciPy, statsmodels, scikit-learn and Matplotlib. Data for continuous variables were presented as mean ± standard deviation and for categorical variables as numbers and percentages. Group differences and relationships between imaging and functional variables were assessed and $p < 0.05$ was considered statistically significant. Adjusted ORs and 95% CIs were obtained by fitting a multivariable logistic regression model. The receiver operating characteristic (ROC) curves, area under the curve (AUC), sensitivity, specificity and accuracy were used to assess the performance of the models.

3. RESULTS

320 participants were assessed in the minimal/no, early and moderate-advanced degeneration groups. Mobility progressively decreased ($p < 0.001$), while age, BMI, pain and disability significantly increased with the severity of degeneration. Demographic and functional parameters of the three groups are presented in table 1.

Table 1. Demographic and Functional Characteristics According to Degeneration Severity

Variable	Minimal/No (n=112)	Early (n=118)	Moderate–Advanced (n=90)	p-value
Age, years	43.8 ± 11.6	52.9 ± 10.8	63.2 ± 9.7	<0.001
BMI, kg/m²	24.8 ± 3.2	27.1 ± 3.6	28.9 ± 4.1	<0.001
Pain score	2.1 ± 1.3	4.3 ± 1.5	6.5 ± 1.5	<0.001
Disability score	14.6 ± 8.7	31.8 ± 11.4	52.7 ± 13.6	<0.001
Mobility score	88.2 ± 7.9	73.5 ± 10.6	56.9 ± 12.4	<0.001

Progressive structural deterioration was seen in the quantitative imaging. The area of the spinal canal, the foraminal area and the disc height reduced as the severity increased and the degeneration and endplate irregularity scores were significantly raised. As seen in figure 1, there is a progressive decrease in normalized disc height and in table 2 the main quantitative imaging measurements are shown.

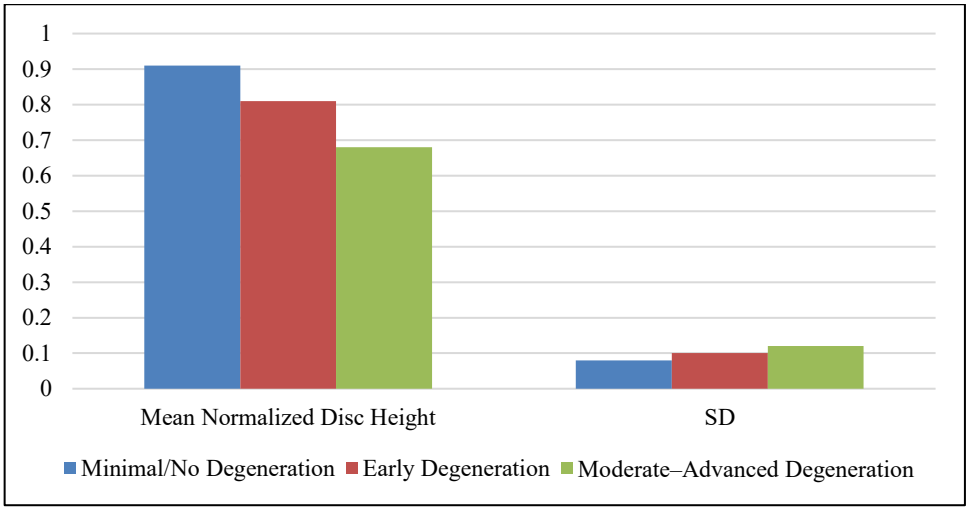

Figure 1. Normalized Intervertebral Disc Height Across Degeneration Severity Groups
X-axis: Degeneration severity group; Y-axis: Normalized disc height.

Table 2. Quantitative Imaging Characteristics Across Degeneration Severity Groups

Imaging Parameter	Minimal/No	Early	Moderate–Advanced	p-value
Normalized disc height	0.91 ± 0.08	0.81 ± 0.10	0.68 ± 0.12	<0.001
Spinal canal area, mm²	184.7 ± 24.6	165.3 ± 27.1	139.8 ± 30.4	<0.001
Foraminal area, mm²	104.8 ± 16.7	88.9 ± 18.5	69.6 ± 19.8	<0.001
Endplate irregularity	0.18 ± 0.12	0.39 ± 0.18	0.67 ± 0.21	<0.001
Degeneration score	1.42 ± 0.61	2.87 ± 0.74	4.36 ± 0.81	<0.001

There was a significant association between imaging abnormalities and functional impairment. Degeneration score had a positive correlation with disability ($r = 0.71$, $p < 0.001$) and pain ($r = 0.64$, $p < 0.001$), while disc height had a negative correlation with disability ($r = -0.62$, $p < 0.001$). The degeneration score was positively related to functional disability, as seen in figure 2.

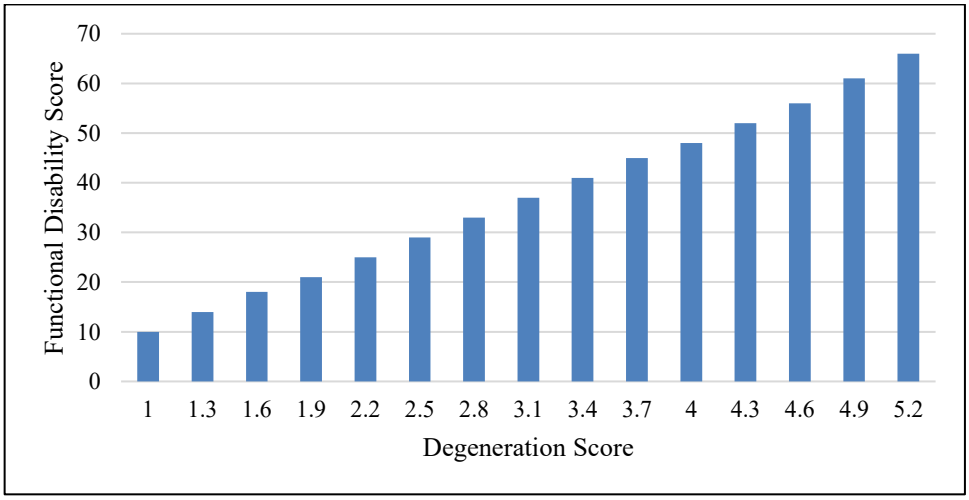

Figure 2. Association Between Quantitative Degeneration Score and Functional Disability

X-axis: Quantitative degeneration score; Y-axis: Functional disability score.
These variables were: degeneration score, disc height, foraminal area, disability, pain and age. As shown in table 3 quantitative degeneration score had the highest positive association with disease severity (adjusted OR = 2.84, $p < 0.001$).

Table 3. Multivariable Predictors of Degenerative Spine Severity

Predictor	Adjusted OR	95% CI	p-value
Degeneration score	2.84	2.11–3.83	<0.001
Normalized disc height	0.42	0.27–0.65	<0.001
Foraminal area	0.71	0.57–0.89	0.003
Disability score	1.78	1.39–2.28	<0.001
Pain intensity	1.46	1.18–1.81	<0.001
Age	1.31	1.08–1.59	0.006

The integrated imaging–functional model achieved an AUC of 0.92, exceeding the imaging-only (AUC = 0.84) and functional-only (AUC = 0.79) models. Its sensitivity, specificity, and accuracy were 88.1%, 84.7%, and 86.6%, respectively. Figure 3 shows the superior discriminatory performance of the integrated framework.

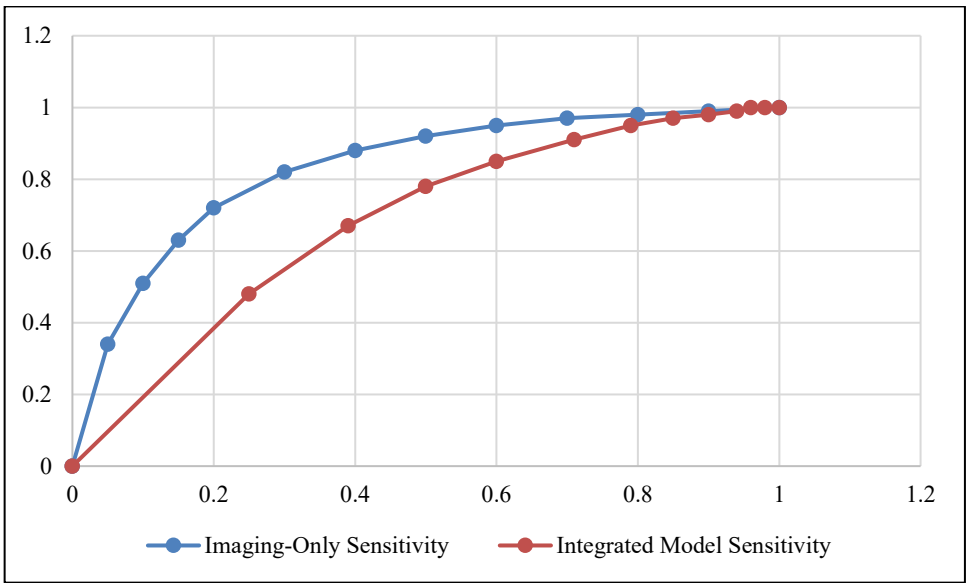

Figure 3. ROC Curves Comparing Imaging-Only, Functional-Only, and Integrated

4. DISCUSSION

Results reveal a uniform correlation between structural degeneration and functional deterioration with increasing grades of degenerative spine. More degenerate participants had lower normalized disc height, spinal canal area and foraminal area, as well as higher endplate irregularity scores and higher degeneration scores. As these changes were accompanied by progressive pain and disability and reduced mobility, quantitative anatomical changes can be used to provide clinically useful information when combined with functional measures. In the same vein, attempts to correlate imaging phenotypes with functional outcomes have led to the identification of patterns that go beyond the mere anatomical interpretation and are clinically relevant (Enzendorfer et al., 2025).

There is high correlation between quantitative degeneration score and disability ($r = 0.71$) indicating that the more the structure is degenerated the more the functional capacity is lost. There was also a negative correlation with disability for disc height ($r = -0.62$), which suggests that it may be a useful metric to track disease progression. The power of integrating structural and functional assessment has been appreciated in other progressive disorders, where the simultaneous assessment can help in identifying early alterations associated with the disease (Ribarič, 2023). This could be very applicable with spinal degeneration, since imaging abnormalities and clinical symptoms do not always go hand in hand.

Further evidence for quantitative stratification of spinal disease is the progressive differences seen between the minimal/no, early, and moderate to advanced degeneration groups. More recent research, to which we were able to contribute data, further highlighted the variability of the ways in which degenerative changes develop in people with chronic low back pain (McSweeney et al., 2026). In the current era of clinical management of lumbar degenerations, both morphological findings and clinical presentation should be considered when deciding on the best treatment options (Beyer et al., 2025). The current results take this principle one step further and show for the first time measurable associations between imaging features and functional burden.

The imaging-functional integrated model was able to obtain an AUC of 0.92, whereas imaging alone obtained an AUC of 0.84 and functional assessment alone obtained an AUC of 0.79. Its sensitivity (88.1%), specificity (84.7%) and accuracy (86.6%) suggest that the complementary structural and functional information discriminated better than each alone. The integrated approach could become relevant, as degenerative spine disease is a large clinical burden and has a variety of treatment options including conservative and surgical treatment (Buser et al., 2018). Stratification could thus be improved to help inform more site-specific monitoring and management decisions.

Information from the functional measurements may also be provided that cannot be completely seen from the structural assessment. Objective physiological measures have been found to be promising in stratifying patients who undergo spinal decompression and in determining relationships with early postoperative pain (Abdulhak et al., 2025). However, patient-level factors should continue to be included in clinical interpretation. Metabolic factors such as diabetes and metabolic syndrome may affect the outcomes after spine surgery and may also affect the risk in an independent manner from the phenotype of structural degeneration (Bajaj et al., 2023). Similarly, quantitative spinopelvic parameters can also be useful for information about spine alignment and structural problems (Fernando, 2026).

The framework could eventually be used as an instrument to aid in risk stratification. Risk adjusted assessment that involves characteristics of patients and alignment of the spine is already found to be relevant for adverse mechanical postoperative outcomes in complex spinal surgery (Passias et al., 2021). Some limitations need to be recognised, such as the lack of longitudinal follow-up and external validation. Prospective assessment of this framework in other populations and whether additions of longitudinal imaging–functional changes enhance the prediction of progression and treatment response should be assessed in future studies.

5. CONCLUSION

This study highlighted the importance of combination of quantitative imaging and functional evaluation in the characterization of degenerative spine conditions. As the severity of the disease increased, so did the loss of normalized disc height, spinal canal area, and foraminal area, and an increase in endplate irregularity and degeneration scores. These structural changes coincided with an increase in pain and disability and a decrease in mobility. The excellent positive correlation between degeneration score and disability also confirmed that structural degeneration was associated with functional impairment, as was the negative correlation between disc height and disability. The integrated imaging–functional model was able to deliver an AUC of 0.92, which was higher than the imaging-only and functional-only models, and a sensitivity of 88.1%, a specificity of 84.7% and an accuracy of 86.6%. These results suggest that a combination of assessment approaches should be adopted for early detection of degeneration and stratification of the severity of disease. Longitudinal and external validation are needed prior to clinical implementation, to confirm its validity in predicting disease progression and treatment response.

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