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Sex- and age-specific distributions of intervertebral disc morphology on T2-weighted MR imaging: a population-based study

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Abstract

Objectives To perform a large-scale, automated morphometric analysis of intervertebral discs and characterize age- and sex-specific distributions of intervertebral disc (IVD) height, diameter, volume, and signal intensity in adults aged 19–74 years using T2-weighted MR imaging.

Materials and methods Sagittal T2-weighted MR images from 30,927 participants of the German National Cohort (NAKO) were analyzed. Participants with back pain or osteoporosis were excluded. Intervertebral discs were segmented using a validated machine learning–based algorithm (SPINEPS). Morphometric parameters (IVD height, diameter, volume, and signal intensity) were extracted and analyzed separately for the cervical, thoracic, and lumbar spine. Analyses were stratified by sex and predefined age groups (< 30, 30–39, 40–49, 50–59, ≥ 60 years). Multivariable fractional polynomial regression models were used to assess associations with age, body height, and body weight.

Results After exclusion, 22,979 adults remained (13,307 men, 9672 women; mean age 47.0 ± 12.5 years). Across all spinal regions, IVD height, diameter, and volume were higher in men than in women. Increasing age was associated with progressive reduction in IVD height, volume, and signal intensity, accompanied by an increase in IVD diameter. Higher body weight was associated with increased IVD signal intensity in the lower cervical spine, whereas an inverse association was observed in the lower lumbar spine.

Conclusion Using automated, large-scale MRI, this study characterizes age- and sex-specific distributions of intervertebral disc morphology in a large population-based cohort. These findings provide a comprehensive, normative reference of age- and sex-specific distributions of intervertebral disc morphology across the cervical, thoracic, and lumbar spine, offering a framework to support clinical interpretation, spine research, and surgical planning.

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Key Points

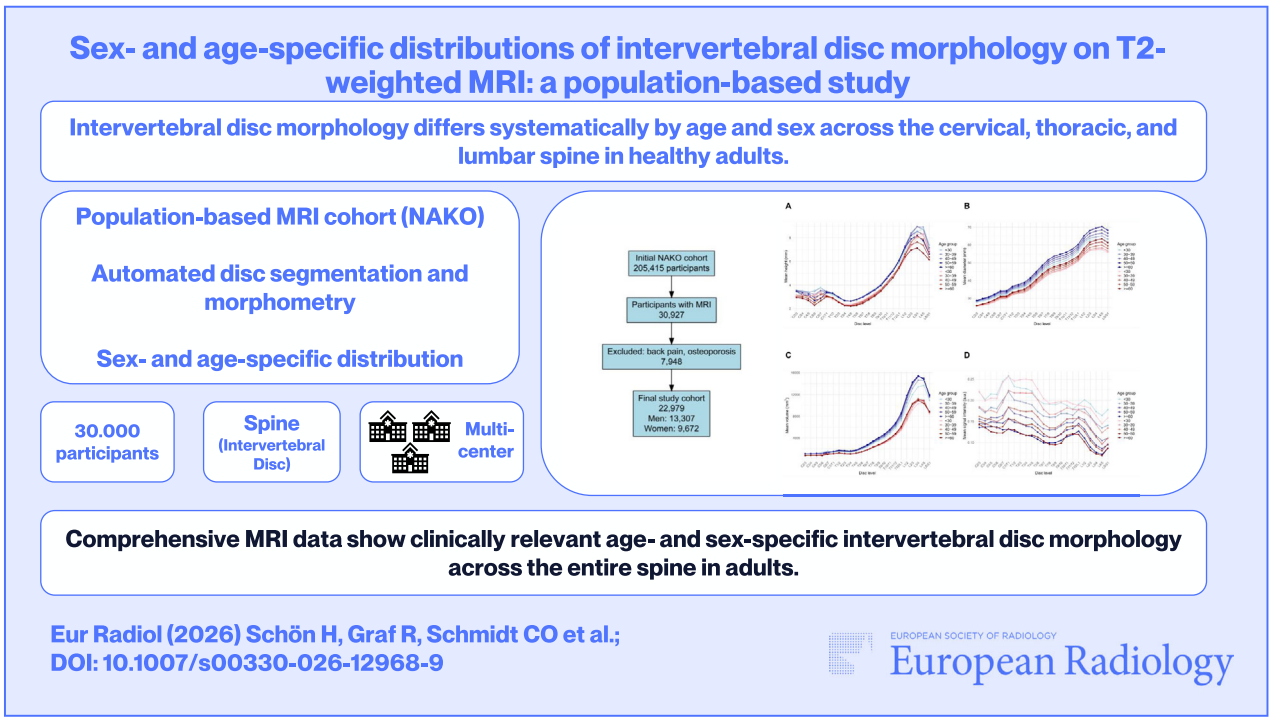
Question *What are the age- and sex-specific distributions of intervertebral disc morphology across the cervical, thoracic, and lumbar spine in a large population-based adult cohort?*

Findings *Men exhibited higher disc height, diameter, and volume than women. Increasing age reduced disc height, volume, and signal intensity, while disc diameter increased.*

Clinical relevance *These population-based data provide descriptive distributions of intervertebral disc morphology, supporting spine imaging interpretation and future clinical, epidemiological, and research applications.*

Keywords: Automated morphometry, Intervertebral disc morphology, Magnetic resonance imaging, Population-based study, T2-weighted imaging

Graphical Abstract



Introduction

The intervertebral disc (IVD) is a fibrocartilaginous structure interposed between adjacent vertebral bodies, consisting of a central nucleus pulposus and surrounding annulus fibrosus [1]. It contributes to spinal load distribution and permits controlled vertebral motion [2]. Disc degeneration is a multifactorial process influenced by mechanical stress and aging, typically characterized by loss of water content, extracellular matrix alterations, and disruption of collagen architecture [3, 4].

T2-weighted magnetic resonance imaging (MRI) is the primary noninvasive modality for assessing IVD morphology and degenerative changes [5]. Common imaging findings include disc desiccation, endplate alterations, osteophytes, and annular fissures, often affecting multiple disc levels simultaneously [6].

Distinguishing age-appropriate from pathological disc degeneration remains challenging in clinical and imaging practice [5]. Qualitative grading systems, such as Pfirrmann classification [7], combine structural and biomechanical changes (disc height and signal intensity) into a single ordinal score. While interobserver agreement is generally good [8], the criteria lack precise definitions for disc space collapse and moderate narrowing, creating ambiguity when morphological and signal changes are discordant. Assessment is further complicated in elderly individuals with osteoporosis, where vertebral body and disc height alterations confound the interpretation [9, 10]. These limitations highlight the need for quantitative

imaging-based measures of intervertebral disc signal intensity.

Although concordant imaging and clinical findings may increase the likelihood that an intervertebral disc represents the source of back pain, a universally accepted diagnostic standard for discogenic pain is currently lacking [11, 12].

Previous MRI studies of age-related disc changes were largely limited to small cohorts and typically restricted to individual spinal regions [13–15]. Consequently, comprehensive population-based data capturing the full disc morphology across the cervical, thoracic, and lumbar spine are lacking. Furthermore, information on sex- and age-specific distributions of IVD height, volume, and signal intensity across adulthood remains scarce.

Addressing this gap, the present study used automated MRI analysis in a large, population-based cohort to characterize age- and sex-specific distributions of intervertebral disc morphology across the entire spine. This approach provides quantitative, reproducible data that may support clinical imaging interpretation, spine research, and surgical planning.

Material and methods

Study design and ethical approval

This retrospective analysis used MRI data from the multicenter German National Cohort (NAKO) study, which was approved by local ethics committees. Written informed consent was obtained from all participants prior to enrollment. Participant recruitment and MRI acquisition occurred between 2014 and 2019.

German National Cohort (NAKO)

The MRI datasets analyzed in this study were derived from the multicenter German National Cohort (NAKO) [16–18]. In total, 205,415 volunteers aged 19–74 years were recruited from the general population. Of these, 30,927 participants underwent whole-body MRI examinations at one of five study centers in Germany (Augsburg, Berlin, Essen, Mannheim, and Neubrandenburg).

All MRI examinations were performed under standardized conditions using 3.0-T MRI scanners (Magnetom Skyra; Siemens Healthineers). Sagittal T2-weighted MRI datasets of the cervical, thoracic, and lumbar spine were acquired (echo time 126 ms; slice thickness 3.0 mm; in-plane resolution 0.9 mm) and preprocessed using manufacturer-provided software [19]. Demographic and anthropometric data, including age, sex, body weight, and body height, were collected during the NAKO baseline examinations prior to MRI acquisition [18]. Sex was recorded as a binary variable (men and women). To account for potential sampling bias, correction weights were calculated using the methodology described by Rach et al [20].

Automated image analysis

Segmentation of intervertebral discs and spinal structures was performed using the Spinal Phase-wise Imaging Network for Paired Segmentation (SPINEPS), a machine learning–based framework [21]. The network was trained on 180 manually annotated sagittal T2-weighted MRI datasets from the NAKO, providing reference masks for intervertebral discs, spinal canal, and vertebral bodies [22]. Segmentation of the osseous spine was refined via modality translation to synthetic Computed tomography (CT) images [23]. The spinal cord was segmented using the Spinal Cord Toolbox (SCT) [24]. These complementary segmentation sources were integrated within SPINEPS and subsequently applied to the entire NAKO MRI dataset.

For automated morphometric analysis, segmented discs were converted into three-dimensional surface meshes. Orientation was standardized by computing eigenvectors derived from principal component analysis (PCA). Disc height was sampled on a 1-mm grid across the disc and averaged to reduce measurement noise. Disc volume was calculated directly from the mesh, and the mean disc diameter was derived from disc height and volume. Signal intensity was defined as the mean MRI signal intensity within the disc mask normalized to the mean signal of cerebrospinal fluid (CSF). Disc masks were eroded by one voxel to reduce partial volume effects.

Descriptive analyses

Participants were stratified by sex and into five predefined age groups. For each intervertebral disc level (C2/3 to L5/S1), mean values of disc height, diameter, volume, and normalized signal intensity were calculated separately for each sex and age group. In addition, percentile distributions, means and standard deviations (SDs) were computed to provide reference values.

Multivariable fractional polynomial regression

Associations between anthropometric and demographic predictors and imaging outcomes were analyzed using multivariable fractional polynomial (MFP) regression to allow for non-linear functional forms [25]. Predictors of interest were age, height, and weight. Prior to modeling, individuals with self-reported back pain or osteoporosis were excluded to focus on morphometric variation in asymptomatic participants. To limit the influence of extreme values, the predictor and outcome distributions were trimmed at the sex-specific 1st and 99th percentiles, except for age. For age, observations below 20 years and above 71 years were excluded due to sparse data ($n = 33$).

Linear regression models with robust variance estimation were fitted using the MFP approach, permitting up to second-degree fractional polynomials with a maximum of four degrees of freedom. Model selection followed a closed testing procedure with a conservative significance threshold ($\alpha = 0.005$) due to the large sample size. Analyses were conducted stratified by sex.

Primary analyses used recalibrated sampling weights (mean = 1) to account for selective participation in the MRI assessment. Given the pronounced right skewness of these weights (SD 1.44; skewness 5.1; kurtosis 45.5), sensitivity analyses were conducted using weights winsorized at the 99th percentile (SD 1.27; skewness 3.13; kurtosis 14.35; maximum 7.68), as well as using unweighted models. Adjusted predicted values and 95% confidence intervals (CIs) were derived across the observed predictor range for graphical display. Results were largely robust across weighting strategies and are reported in the Supplement. Model specifications and coefficient estimates are reported in Supplementary Table 9. Internal model performance was assessed using five-fold cross-validation, repeated separately by outcome and sex. The complete MFP selection procedure was repeated within each training fold. Weighted RMSE, MAE, and R^2 were calculated from pooled out-of-fold predictions (Supplementary Table 10).

Results

Study cohort characteristics

After applying exclusion criteria (osteoporosis, self-reported back pain; Fig. 1), the final study cohort comprised 22,979 individuals (Table 1), including 13,307 men (57.9%) and 9,672 women (42.1%). Participants were stratified into five age groups, separately for men and women (Table 2).

Morphometric overview

Mean disc height

Across the cervical spine (C2/3 to C7/T1), disc height peaked in younger adults at C6/7 (up to 3.8 mm in men and 3.4 mm in women). In older subcohorts, cervical disc height decreased, reaching a minimum at C5/6 (2.7 mm in men and 2.3 mm in women). From C7/T1 to T4/5, disc height showed a slight decline, followed by a gradual and continuous increase toward L1/2, with no relevant age-dependent differences in the thoracic spine.

In the lumbar region, disc height increased from L1/2 to L4/5, with more pronounced values in younger subcohorts. Maximum mean heights were observed at L4/5, reaching 8.8 mm in men and 8.2 mm in women (Fig. 2A). At the L5/S1 level, disc height was consistently lower compared to the more cranial lumbar levels.

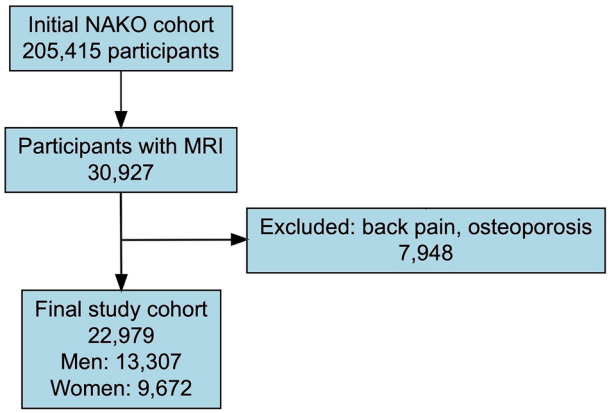


Fig. 1 Participant selection flowchart. Of 205,415 participants enrolled in the German National Cohort (NAKO), 30,927 underwent whole-body MRI. After exclusion of 7948 participants with self-reported back pain or osteoporosis, 22,979 participants were included in the final analysis, comprising 13,307 men and 9672 women. MRI, magnetic resonance imaging; NAKO, German National Cohort

Table 1 Baseline characteristics of the study population

Sex	*n*	Age (years)	Body height (cm)	Body weight (kg)
men	13,307	46.9 ± 12.6	179.2 ± 6.9	86.2 ± 14.3
women	9672	47.2 ± 12.3	165.8 ± 6.5	70.5 ± 14.5

Values are presented as mean ± standard deviation unless otherwise specified. Baseline characteristics include age, body height, and body weight, stratified by sex

Table 2 Distribution of participants across age groups by sex

Age	Men		Women	
	in %	*n* =	in %	*n* =
< 30	58.4	1658	41.6	1183
30–39	60.8	1848	39.2	1192
40–49	57.2	3968	42.8	2965
50–59	56.9	3410	43.1	2581
≥ 60	58.0	2423	42.0	1751
Total	57.9	13,307	42.1	9672

Absolute numbers and percentages of participants in the predefined age groups (< 30, 30–39, 40–49, 50–59, and ≥60 years), stratified by sex

Mean disc diameter

Mean disc diameter increased progressively from the upper cervical spine (C2/3) to the lower lumbar spine. Values ranged from approximately 25.8 mm in women and 28.4 mm in men at C2/3 to a maximum at L4/5, reaching 63.3 mm in women and 70.1 mm in men in the oldest age group, followed by a slight decrease caudally.

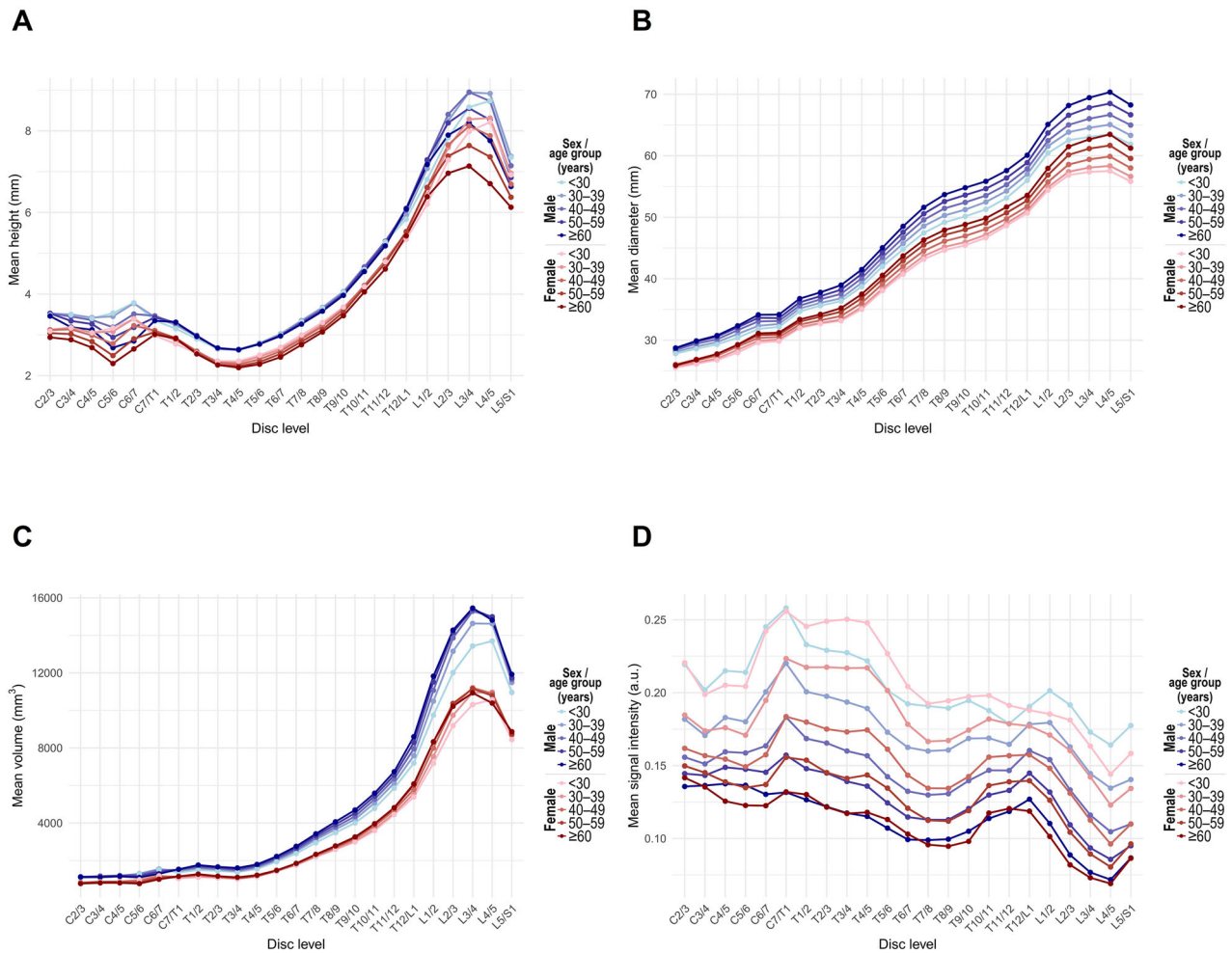


Fig. 2 Mean intervertebral disc morphology across spinal levels by sex and age group. Mean intervertebral disc (IVD) **A** height (mm), **B** diameter (mm), **C** volume (mm^3), and **D** normalized signal intensity from C2/3 to L5/S1. Results are shown separately for men and women and stratified by age group (< 30, 30–39, 40–49, 50–59, and ≥ 60 years). IVD, intervertebral disc

Across all spinal levels, older subcohorts had larger disc diameters than younger individuals, with the most pronounced differences observed between L2/3 and L4/5. In contrast to disc height and volume, diameter showed a relatively uniform age-related increase across all disc levels (Fig. 2B).

Disc volume

Disc volume increased steadily from the cervical spine, measuring approximately 800 mm^3 in women and 1000 mm^3 in men at C2/3, and reached peak values at L3/4 (11,100 mm^3 in women and 15,600 mm^3 in men), followed by a marked decrease toward the lumbosacral junction.

In the cervical and upper thoracic spine, volume differences between age groups were minimal. Beginning in the mid- to lower thoracic spine—approximately at T5/6 in men and T8/9 in women—disc volume increased despite concurrent reductions in disc height. In the lumbar spine, disc volume increased during the first half of adulthood and subsequently remained largely stable, with this pattern being more pronounced in men than in women.

Given the opposing trends observed for disc height and diameter, regional height variations—such as those between C2/3 and C7/T1—were largely attenuated in volume measurements (Fig. 2C).

Disc signal intensity

Across all age groups, lower normalized signal intensity was observed in the lumbar spine from L1/2 to L5/S1. At the L5/S1 level, signal intensity differed slightly from the adjacent L4/5 level. Women exhibited higher signal intensities than men in the thoracic spine, particularly

between T1/2 and T12/L1, with the largest differences noted in younger subcohorts. This sex-related pattern was partially reversed in the cervical and lumbar regions. Independent of spinal level, increasing age was associated with a gradual decline in disc signal intensity (Fig. 2D).

Detailed intervertebral disc values stratified by disc level, sex, and age—including percentile curves (Supplementary Fig. 1), percentile tables (Supplementary Tables 1–4), means and SDs (Supplementary Tables 5–8)—are provided in the Appendix.

Model-based analysis of selected disc levels

To disentangle the independent effects of age, body height, and body weight on intervertebral disc morphology, MFP regression models were computed using the weighting approach described in the "Methods" section. An overview of different weighting strategies for the given parameters is provided in Supplementary Fig. 2.

Detailed observation at C5/6

Age-related changes

At the C5/6 level, increasing age was associated with a progressive increase in disc diameter, accompanied by a concomitant reduction in disc height. Disc volume showed a modest increase in both men and women until approximately 30 years of age, with a more pronounced effect in women, followed by a continuous decline thereafter. Normalized signal intensity decreased steadily with advancing age.

Height-related changes

Increasing body height was associated with higher disc height, diameter, and volume in both men and women. In addition, disc signal intensity demonstrated a positive association with body height across sexes.

Weight-related changes

Disc height at C5/6 showed no relevant association with increasing body weight. In contrast, disc diameter, volume, and signal intensity increased progressively with higher body weight (Fig. 3 and Supplementary Fig. 3).

Detailed observation at L4/5

Age-related changes

At the L4/5 level, disc height increased slightly from early adulthood, peaking at approximately 30 years of age, then declining with further aging. Disc diameter increased continuously across the age spectrum. Disc volume increased in both men and women until approximately 40 years of age, then decreased, beginning around 55 years in women and 60 years in men. Disc signal intensity showed a continuous age-related decline in both sexes.

Height-related changes

Across sexes, increasing body height was associated with higher disc height, diameter, signal intensity and volume at the L4/5 level.

Weight-related changes

With increasing body weight, disc diameter and volume exhibited modest increases. Mean disc height showed a slight increase in men up to higher body weights, followed by a decrease beyond 120 kg, whereas disc height in women remained largely stable across the weight spectrum. Disc signal intensity decreased with increasing body weight in both men and women up to approximately 100 kg in women and 110 kg in men, after which a slight increase in signal intensity was observed (Fig. 4 and Supplementary Fig. 4).

Discussion

In this large population-based MRI study, we provide quantitative, age- and sex-specific data on intervertebral disc height, diameter, volume and signal intensity across the cervical, thoracic, and lumbar spine. Disc height and volume peaked in the lumbar region, while cervical discs were the smallest. Age was associated with declines in disc height, volume, and signal intensity, accompanied by increases in disc diameter, indicating morphological remodeling rather than uniform compressive loss. Body height correlated positively with all disc parameters, whereas body weight showed regional associations with disc size and signal intensity.

Several previous studies have assessed lumbar intervertebral disc morphology using plain radiographs. Consistent with these reports, the highest disc height in both men and women was observed at the L4/5 level in our cohort [26]. However, Radiograph- and CT-based studies tend to overestimate disc dimensions due to projection effects and limited soft-tissue contrast [13, 26].

In our cohort, intervertebral disc dimensions—particularly in the lumbar spine—showed a modest increase until approximately 30 years of age, followed by a gradual decline thereafter. This observation contrasts with earlier reports suggesting a continuous increase in disc height up to the seventh decade of life [27] but aligns with MRI-based studies demonstrating a reduction in disc height associated with progressive degeneration [28]. Sex-specific patterns have also been described previously: Gambacciani et al reported increasing disc height in women until menopause, followed by a marked decline thereafter [29], which is consistent with the sex-dependent trajectories observed in our data.

Beyond absolute height loss, our findings demonstrate that aging is associated with a reduction in mean disc height accompanied by an increase in disc diameter at

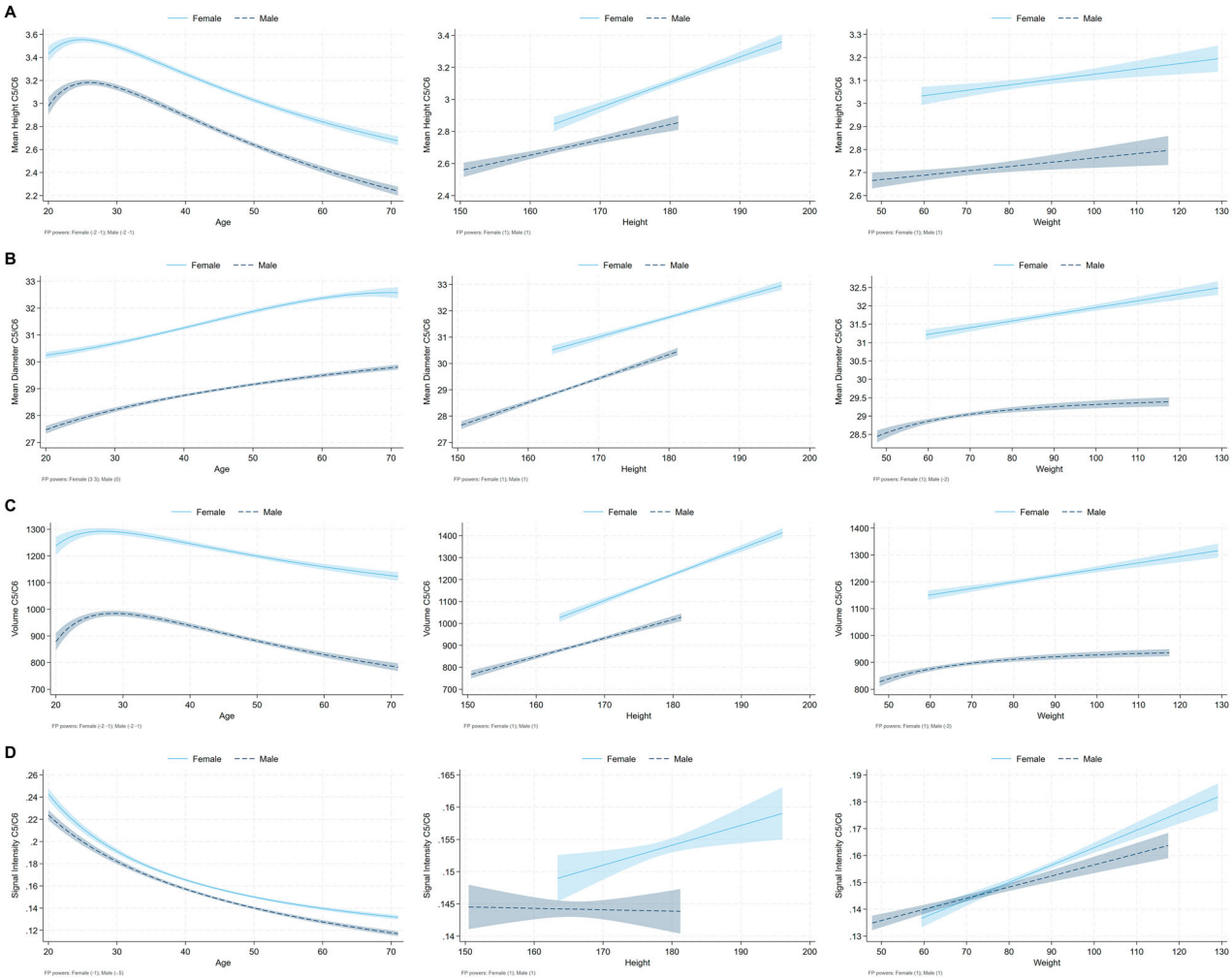


Fig. 3 Adjusted associations of age, body height, and body weight with C5/6 intervertebral disc morphology. Sex-specific adjusted predictions from multivariable fractional polynomial regression models for **A** disc height, **B** disc diameter, **C** disc volume, and **D** normalized disc signal intensity at C5/6. Columns show associations with age (years), body height (cm), and body weight (kg), respectively. Lines represent adjusted predicted mean values; shaded areas represent 95% confidence intervals. Models were fitted separately for men and women using recalibrated sampling weights. The selected fractional polynomial functions are indicated in the individual panels. IVD, intervertebral disc

largely constant volume, particularly in the lumbar spine. As a consequence, trends in disc volume do not mirror those observed for disc height alone. This pattern strongly suggests that age-related disc degeneration is characterized not merely by compressive volume loss but by progressive morphological remodeling toward a flatter and wider disc configuration. While such changes are well recognized in the lumbar spine, our data indicate that similar—albeit less pronounced—patterns also occur in the lower cervical spine.

An additional novel finding of this study is the divergent association between body weight and disc signal intensity across spinal levels. At C5/6, increasing body weight was associated with higher disc signal intensity, whereas at L4/5, disc signal intensity decreased with increasing body weight, despite increased disc volume at both levels. These observations may indicate regional differences in disc hydration or composition related to systemic factors. One possible explanation for increased signal intensity at C5/6 with higher body weight is increased disc water content, potentially mediated by hormonal influences, including estrogen derived from adipose tissue [30]. This hypothesis is supported by prior observations of increasing disc height in women until menopause [29]. In contrast, the reduced signal intensity at L4/5 with higher body weight may reflect the dominant influence of increased mechanical loading in the lumbar spine, which is less pronounced in the cervical region.

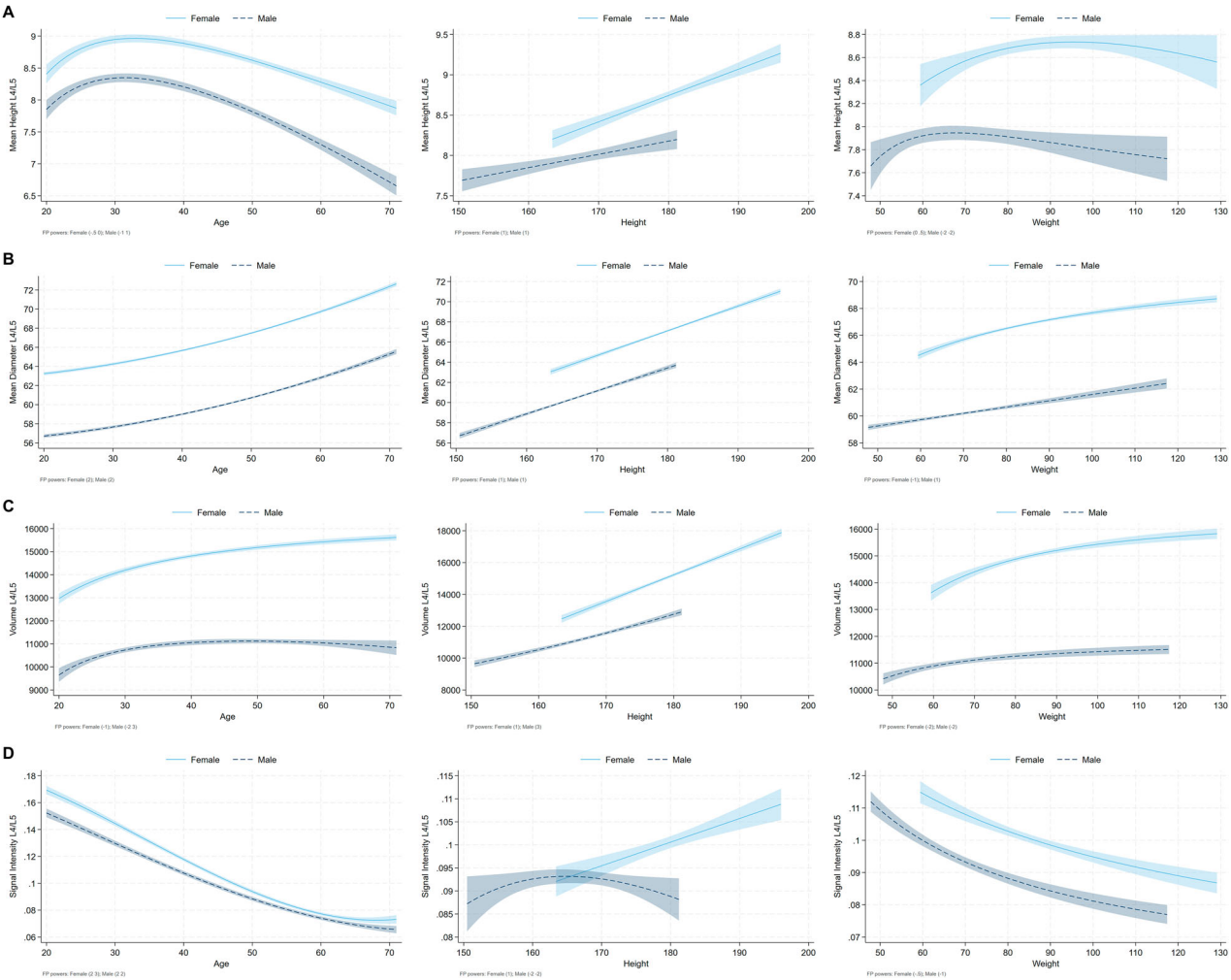


Fig. 4 Adjusted associations of age, body height, and body weight with L4/5 intervertebral disc morphology. Sex-specific adjusted predictions from multivariable fractional polynomial regression models for **A** disc height, **B** disc diameter, **C** disc volume, and **D** normalized disc signal intensity at L4/5. Columns show associations with age (years), body height (cm), and body weight (kg), respectively. Lines represent adjusted predicted mean values; shaded areas represent 95% confidence intervals. Models were fitted separately for men and women using recalibrated sampling weights. The selected fractional polynomial functions are indicated in the individual panels. IVD, intervertebral disc

Several limitations merit consideration. First, the cross-sectional design of this study precludes assessment of longitudinal disc changes and individual degeneration trajectories. Although the cohort is population-based, selection bias cannot be entirely ruled out and may limit generalizability. Cumulative biomechanical, occupational, and lifestyle factors were not explicitly assessed, which may contribute to unmeasured variability in disc morphology.

The availability of robust, age- and sex-specific MRI-based reference values for intervertebral disc morphology has important clinical and scientific implications. Such data enable the development of digital spine twins that incorporate individualized geometry, movement patterns, and biomechanical loading, facilitating investigations into disc degeneration mechanisms and preventive strategies [31]. Furthermore, accurate morphometric values are critical for surgical planning in disc replacement procedures, where appropriate implant sizing remains a major challenge. Oversized implants may result in disc space distraction, altered spinal biomechanics, increased facet joint loading, and unfavorable clinical outcomes. Our findings further inform implant development, underscoring the need for smaller implant dimensions, particularly in the cervical spine [32]. Finally, these normative values provide an objective framework for distinguishing pathological or accelerated disc degeneration from physiological, age-related changes. This enables future studies to correlate disc morphometry and signal characteristics with clinical symptoms such as back pain, thereby opening new avenues for imaging-based phenotyping of spinal disorders.

In conclusion, this study establishes comprehensive, normative values for age- and sex-specific intervertebral disc morphology across the cervical, thoracic, and lumbar spine. These data provide a framework for distinguishing physiological aging from pathological degeneration and support clinical interpretation, spine research, surgical planning, and individualized spine modeling. Age- and sex-specific disc morphometry can serve as an objective benchmark for future studies correlating imaging features with clinical symptoms, ultimately facilitating precision diagnostics and tailored interventions in spine care.

Abbreviations

CT	Computed tomography
IVD	Intervertebral disc
MFP	Multivariable fractional polynomial
MRI	Magnetic resonance imaging
NAKO	German National Cohort
SCT	Spinal Cord Toolbox
SD	Standard deviation
SPINEPS	Spinal Phase-wise Imaging Network for Paired Segmentation
T2w	T2-weighted

Supplementary information

The online version contains supplementary material available at https://doi.org/10.1007/s00330-026-12968-9.

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Compliance with ethical standards

Guarantor

The scientific guarantor of this publication is Hanna Schön.

Conflict of interest

Fabian Bamberg: Bayer Healthcare—consultancy, speakers bureau, unrestricted research grant; Siemens Healthineers—unrestricted research grant. Jan Kirschke: Bonescreen GmbH, Shareholder.

Statistics and biometry

At least one of the authors has significant statistical expertise.

Informed consent

Written informed consent was obtained from all participants in this study.

Ethical approval

Institutional Review Board approval was obtained (A2019-0024). The German National Cohort (NAKO) is conducted with the approval of the relevant local ethics committees and in accordance with national law and the Declaration of Helsinki of 1975 (in its current revised version).

Study subjects or cohorts overlap

Some study subjects or cohorts have been previously reported. Although the NAKO dataset has been used in multiple studies, the intervertebral disc aspects addressed in this study have not been examined to date.

Methodology

- Retrospective
- Cross-sectional study
- Multicenter study

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