



Detecting scoliosis at scale using automated cobb angle analysis in the UK biobank

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Abstract

Purpose Adult degenerative scoliosis arises after skeletal maturity in an initially normal spine, primarily driven by age-related degeneration. The Cobb angle, the angle between the most tilted vertebrae typically derived from radiographs, remains the clinical standard for assessing curvature severity, yet large-scale evaluation using MRI has not been feasible. This study developed an automated method for Cobb angle estimation from chemical-shift-based water-fat separation (Dixon) MRI and applied it to the UK Biobank to characterise the prevalence and curvature within the general population.

Methods Abdominal Dixon MRI data from 33,889 UK Biobank participants were analysed. Vertebral bone marrow compartments were segmented using a neural network based model, and spinal curvature was quantified using a centroid-based spline-fitting algorithm. Sex-stratified linear regression analyses were performed to explore associations between spinal curvature and anthropometric, socioeconomic, and health-related traits, including back pain and body composition.

Results While scoliosis was clinically diagnosed or self-reported in only 0.5% of participants, the automated approach detected scoliosis (Cobb angle > 10°) in 28%, of which 95% were mild (< 25°). Females exhibited higher average Cobb angles and greater curvature across all age groups. Multivariable linear regression revealed significant associations between Cobb angle and age, paraspinal muscle fat infiltration, chronic back pain, and visceral adipose tissue in both sexes, and with iliopsoas muscle volume in males only (all $p < 0.00055$, Bonferroni-adjusted threshold).

Conclusion This fully automated approach enables large-scale, population-based assessment of spinal curvature, revealing adult scoliosis to be substantially under-recognised and closely linked to muscle quality and back pain.

Keywords Scoliosis · Magnetic resonance imaging · Artificial intelligence · UK Biobank · Cobb angle · Back pain

Introduction

Scoliosis is characterised by an abnormal lateral curvature of the spine. Idiopathic scoliosis, most often diagnosed during adolescence, is the predominant form, whereas in adults

it manifests either as residual adolescent idiopathic scoliosis or as de novo degenerative scoliosis following skeletal maturity.

Adult degenerative scoliosis develops after skeletal maturity through asymmetric degeneration of intervertebral

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discs and facet joints, with extracellular matrix breakdown and inflammation accelerating tissue damage [1, 2]. Osteoporosis, sarcopenia, and vertebral fractures further weaken spinal support, and increasing longevity is driving both scoliosis prevalence and treatment demand [3, 4].

Reported adult degenerative scoliosis prevalence ranges from 2% to 68%, with a pooled prevalence of 38% [5]. The condition is more common in women and adults over 60. Although many remain asymptomatic, symptomatic cases present with chronic back pain and neurogenic claudication [2]. Large-scale studies to support prevalence estimates were limited until recently.

The diagnostic gold standard for scoliosis is the Cobb angle, formed between the most tilted vertebral endplates [6]. Scoliosis is traditionally defined using Cobb angles measured on standing radiographs, where load-bearing accentuates spinal curvature. However, MRI is acquired in the supine position, which typically yields Cobb angles 7–12° lower than in standing measurements [7]. We retained the conventional threshold of > 10° for comparability while acknowledging the positional difference [2]. Although this technique enables accurate assessment, it requires ionising radiation and manual annotation, leading to inter-observer variability [8]. Automated approaches using vertebral labels [9], corners [10] or spline fitting [8] have been developed to overcome this.

The UK Biobank imaging cohort provides a unique opportunity to assess the prevalence of degenerative scoliosis and explore spinal curvature in relation to musculoskeletal composition affecting spinal alignment. We applied an automated pipeline to segment the vertebrae bone marrow (VBM) compartments on Dixon MRI and derive Cobb angles using a spline-based centroid method. Furthermore, we investigated demographic, anthropometric, and musculoskeletal correlates of spinal curvature, including muscle quality, body composition, and degenerative conditions. This study is intended for epidemiological rather than clinical assessment of scoliosis.

Methods

Data

The UK Biobank recruited over 500,000 participants aged 40–85 years between 2006 and 2014 [11]. A subset of 100,000 participants underwent MRI of the heart, brain, and abdomen. The abdominal MRI data were available from 40,755 participants at the time of analysis. The study was approved by the North West Multi-centre Research Ethics Committee (REC reference: 11/NW/0382) with informed

consent from all participants. Data access was granted under UK Biobank Application number 44,584.

Image processing and MRI measurements

The abdominal neck-to-knee chemical-shift-based water-fat separation (Dixon) MRI data were processed as previously described [12, 13]. The vertebrae segmentation pipeline used here has been previously validated on Dixon MRI [14] (Supplementary Methods). Eighteen VBM compartments, spanning the first thoracic to first sacral vertebrae, were manually annotated in 120 participants, and split 80/20 into training/testing subsets. The model achieved a Dice similarity coefficient of 0.83 on the test set.

A cubic spline was fitted through the centroids of the VBM compartments using their x-z coordinates to estimate spinal curvature in the coronal plane. Model complexity was set to $(n + 1) / 2$, where n represents the number of VBM compartments. Inflection points from the second derivative of the spline were used to calculate Cobb angles between perpendicular lines to the spline at adjacent points. Cobb angles were also measured between terminal vertebrae and their nearest inflection points. The maximum Cobb angle was recorded as the image-derived phenotype (IDP) representing scoliosis severity (Fig. 1).

To evaluate relationships with muscle-fat body compartments, additional IDPs from our previous work [13, 15] were included: total skeletal, thigh (left and right) and iliopsoas (left and right) muscle volumes; visceral (VAT) and abdominal subcutaneous adipose tissue (ASAT) volumes; and paraspinal proton density fat fraction (PDFF). The paraspinal muscles included the erector spinae and multifidus muscles.

Quality control

Visual quality control was performed on three subsets of 50 participants each - those with the highest Cobb angles, the lowest Cobb angles, and a random sample. Spurious labels requiring correction were identified almost exclusively within the highest Cobb angle subset, where erroneous labels near shoulders of hips could artificially inflate the spline derived Cobb angle (Supplementary Fig. 1). Labels were iteratively corrected until all 50 participants in this subset were confirmed to have accurate vertebral segmentations. In total, 115 vertebral labels were corrected. Separately, the 49 participants with a clinical scoliosis diagnosis but an algorithm-derived Cobb angle < 10° were also visually reviewed and confirmed to have accurate segmentations.

Intra-rater reliability and agreement between manual and automated Cobb angle measurements were evaluated using Bland-Altman analysis. A radiologist with 21 years

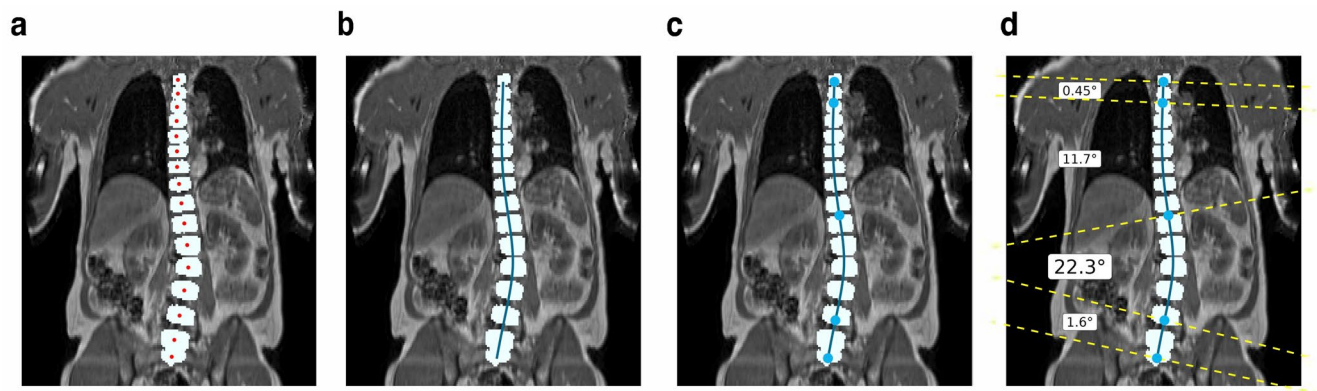


Fig. 1 Cobb angle measurement workflow. **(a)** Coronal mid-slice of abdominal MRI of one participant with vertebral bone marrow labels (white) and the corresponding centroids for each compartment (red dots). **(b)** Spline fit through the centroids (dark blue line). **(c)** Points of inflexion derived from the second-order derivatives of the fitted spline

(light blue dots). **(d)** Cobb angles were estimated by calculating the angle between perpendicular lines to the spline at each pair of adjacent inflexion points throughout the whole spine, where the maximal Cobb angle was taken as a single measure for each participant

of experience (D.A.) performed manual measurements of Cobb angles in 35 participants, selected to ensure representation across sex and scoliosis-severity categories for a balanced reliability assessment, and repeated them after an average interval of 11–30 days. The same scans were used to derive automated Cobb angle measurements for comparison. Bland-Altman analysis quantified bias and limits of agreement for both intra-rater and manual-automated comparisons.

Anthropometric factors and disease definitions

Demographic, lifestyle, biometric, and health data were obtained from the imaging visit and linked healthcare records. Except for sex, ethnicity, Townsend deprivation index, and serum biomarkers, variables were taken from the imaging visit. Ethnicity (field 21000) was classified as White or Non-white, with missing values supplemented by genetic ancestry.

Pre-existing diseases were identified from healthcare records, self-reported medical questionnaires, and UK Biobank specific fields, binarised for presence before imaging. Osteoporosis and osteopenia were defined by diagnostic codes and dual-energy X-ray derived bone mineral density (BMD) T-scores (fields 23204–23301; ≤ -2.5 and $-2.5 < \text{T-score} \leq -1$, respectively) [16].

Scoliosis and pain definitions

Participants with scoliosis were identified using UK Biobank fields (Supplementary Table 1). Childhood scoliosis was defined by ICD-10 code M41.1 (juvenile or idiopathic) or a diagnosis before age 18 and was excluded from analysis. Self-reported scoliosis was derived from fields 131,907

and 20,002. Algorithm-derived scoliosis was defined as a maximum Cobb angle $> 10^\circ$ [17] and further categorised by severity: none ($0\text{--}9^\circ$), mild ($10\text{--}24^\circ$), moderate ($25\text{--}39^\circ$), or severe ($\geq 40^\circ$) [10].

Participants reported back pain, its duration, and falls at the imaging visit. Individuals reporting back pain duration ≤ 3 months were classified as acute and > 3 months as chronic [18].

Study design and cohort

From 40,769 participants with Dixon MRI data, subjects with missing demographic, anthropometric or health-related data were excluded. Non-imaging based variables were age, ethnicity, height, Townsend deprivation index, smoking status, moderate-to-vigorous physical activity (according to metabolic equivalent task values), type 2 diabetes, back pain and leg pain levels, osteoporosis, degenerative disc disease (Supplementary Table 2). Imaging based variables were VAT, ASAT, iliopsoas muscle volume and paraspinal muscle PDFF. Participants with juvenile or adolescent scoliosis or who were diagnosed before the age of 18 were excluded. The final study population included 33,889 participants (Supplementary Fig. 2).

Statistical analysis

Analyses were performed in R v4.3.2 [19]. Continuous variables are reported as mean $\pm$ standard deviation (SD), and categorical variables as counts and proportions. Spearman correlation assessed relationships between Cobb angles and other variables. Since Cobb angles ranged from 0° to 90° and lacked circularity, standard linear statistical methods were used.

Table 1 Study population demographic characteristics, separated by sex

Variable	Overall <i>n</i> =33,889 ¹	Female <i>n</i> =16,907 ¹	Male <i>n</i> =16,982 ¹
Anthropometric			
Ethnicity			
White	32,908 (97%)	16,423 (97%)	16,485 (97%)
Non-white	981 (2.9%)	484 (2.9%)	497 (2.9%)
Age (years)	63.85±7.68	63.04±7.48	64.64±7.80
Townsend deprivation index	-1.90±2.72	-1.83±2.72	-1.96±2.71
Height (cm)	169.56±9.23	162.91±6.22	176.18±6.61
Weight (kg)	76.23±15.07	68.77±12.98	83.65±13.22
Body mass index (kg/m ²)	26.42±4.32	25.91±4.69	26.93±3.85
Waist circumference (cm)	88.36±12.62	82.45±11.70	94.22±10.60
Hip circumference (cm)	100.65±8.61	100.63±9.76	100.66±7.30
Waist to hip ratio	0.88±0.09	0.82±0.07	0.93±0.06
Hand grip strength - dominant (kg)	31.75±10.56	24.31±5.99	39.09±8.80
Moderate-to-vigorous MET (hours/week)	19.43±13.58	19.17±13.40	19.68±13.75
Smoking status			
Never	21,170 (62%)	11,150 (66%)	10,020 (59%)
Previous	11,575 (34%)	5,269 (31%)	6,306 (37%)
Current	1,144 (3.4%)	488 (2.9%)	656 (3.9%)
Alcohol status			
Never	1,045 (3.1%)	669 (4.0%)	376 (2.2%)
Current	31,729 (94%)	15,668 (93%)	16,061 (95%)
Previous	1,107 (3.3%)	568 (3.4%)	539 (3.2%)
Femur neck BMD (T-score)	-0.67±1.05	-0.72±1.08	-0.63±1.03
Lumbar BMD (T-score)	-0.08±1.62	-0.52±1.49	0.35±1.62
Image derived			
Abdominal subcutaneous adipose tissue volume (L)	8.36±4.07	9.74±4.36	7.00±3.24
Visceral adipose tissue volume (L)	3.96±2.31	2.77±1.56	5.15±2.33
Total muscle volume (L)	18.00±4.63	14.10±1.95	21.88±2.99
Iliopsoas muscle volume (L)	0.65±0.17	0.51±0.08	0.79±0.12
Thigh muscle volume (L)	8.56±2.24	6.72±1.00	10.38±1.51
Paraspinal muscle PDFF (%)	7.27±3.79	7.73±3.97	6.81±3.54
Conditions			
Back pain levels			
Never	27,358 (81%)	13,755 (81%)	13,603 (80%)
Acute	2,245 (6.6%)	958 (5.7%)	1,287 (7.6%)
Chronic	4,286 (13%)	2,194 (13%)	2,092 (12%)
Leg pain	6,333 (19%)	3,197 (19%)	3,136 (18%)
Type 2 diabetes mellitus	1,745 (5.1%)	554 (3.3%)	1,191 (7.0%)
Osteoporosis	7,923 (23%)	4,540 (27%)	3,383 (20%)
Osteopenia	14,420 (43%)	7,004 (41%)	7,416 (44%)
Degenerative disc disease	157 (0.5%)	90 (0.5%)	67 (0.4%)
Diagnosed scoliosis ²	170 (0.5%)	113 (0.7%)	57 (0.3%)
Cobb angle (°)	8.72±5.21	9.02±5.59	8.44±4.79
Subjects with Cobb angle above 10°	9,497 (28%)	5,086 (30%)	4,411 (26%)
Severity range			
None	24,392 (72%)	11,821 (70%)	12,571 (74%)
Mild	9,005 (27%)	4,776 (28%)	4,229 (25%)
Moderate	397 (1.2%)	248 (1.5%)	149 (0.9%)
Severe	95 (0.3%)	62 (0.4%)	33 (0.2%)

Values are reported as means with standard deviations for continuous variables, and counts with proportion of total population for overall, female and male cohorts for categorical variables. BMD - bone mineral density; MET - metabolically equivalent task; PDFF - proton density fat fraction

¹ Categorical - count (proportion, %); Continuous - mean±standard deviation

² From hospital admission, primary care sources and self-reported data

Multivariable linear regression models were fitted to examine associations between Cobb angles and demographic, anthropometric, and muscle-fat IDPs, adjusting for covariates including age, sex, and physical activity. The Cobb angles were log-transformed, and the covariates were standardised (z-scores). Regression coefficients were reported as standardised β values with 95% confidence intervals and p-values. A Bonferroni-corrected statistical significance threshold of 0.00055 accounted for multiple hypothesis tests.

Results

Abdominal MRI scans from 40,755 participants were processed, all with successfully fitted splines and derived Cobb angles. After excluding 6,845 participants with missing data

and 21 with juvenile scoliosis, the final cohort included 33,889 participants (49.9% female; mean age 63.9 ± 7.7 years) (Table 1).

Representative vertebrae segmentations, fitted splines and Cobb angle measurements are shown in Fig. 2. The average Cobb angle was $8.7 \pm 5.2^\circ$ (range 0.9° – 86.6°), with $9.0 \pm 5.6^\circ$ in females and $8.4 \pm 4.8^\circ$ in males ($p < 0.00055$). Overall, 9,497 participants (28%) had a Cobb angle $> 10^\circ$, 53.6% of whom were female (Fig. 3a). Participants with a clinical or self-reported scoliosis diagnosis ($n = 170$; 0.5%) had Cobb angles between 1.9° and 84.1° . Of them, 49 had a Cobb angle $< 10^\circ$ (Fig. 3b); visual quality control confirmed accurate vertebral segmentation. Using the $> 10^\circ$ threshold, scoliosis was identified in 9,376 additional participants, 95.4% of them mild (Fig. 3c). Spinal curvature increased with age and was consistently higher in females across all age groups (Fig. 4; $p < 0.00055$).

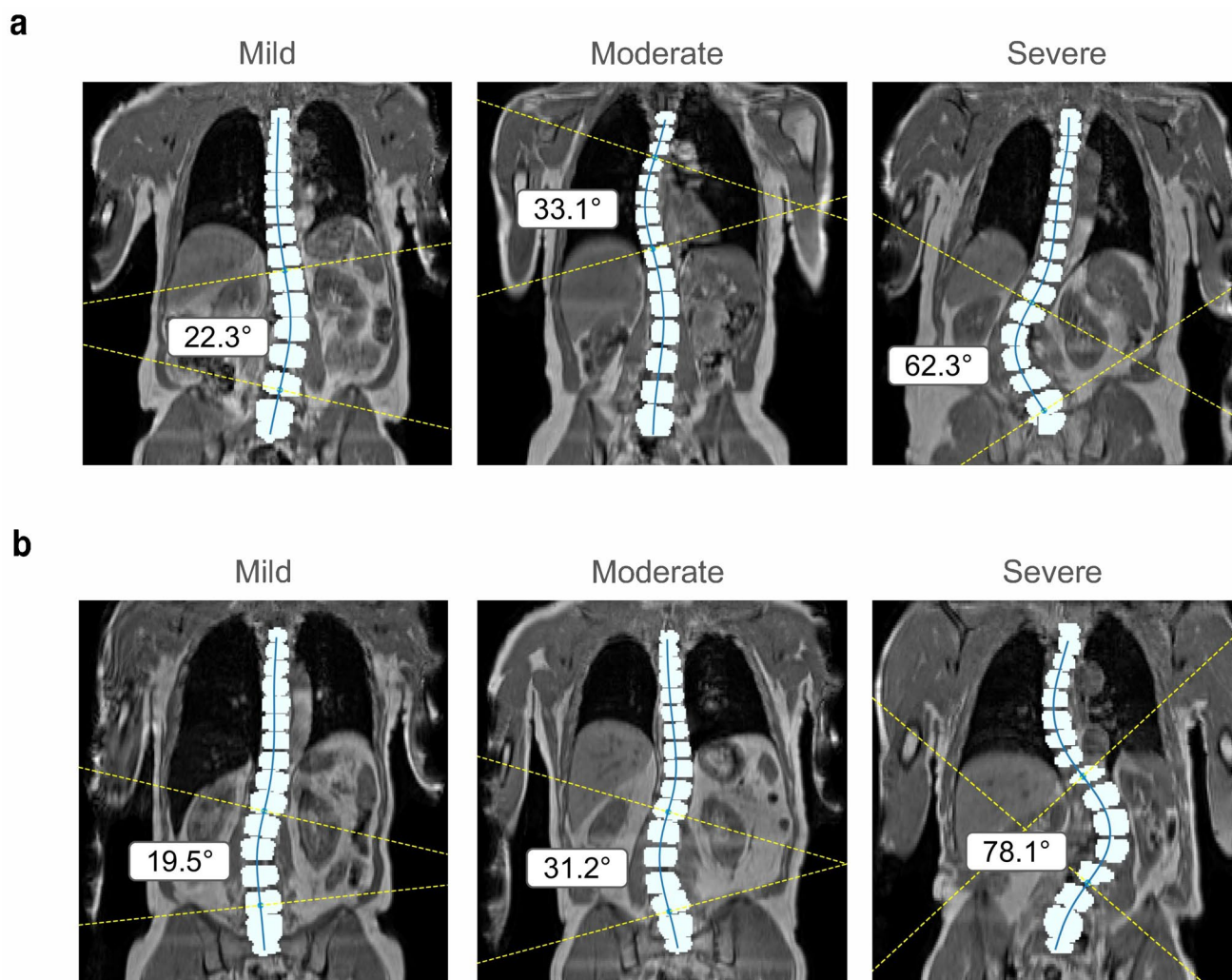
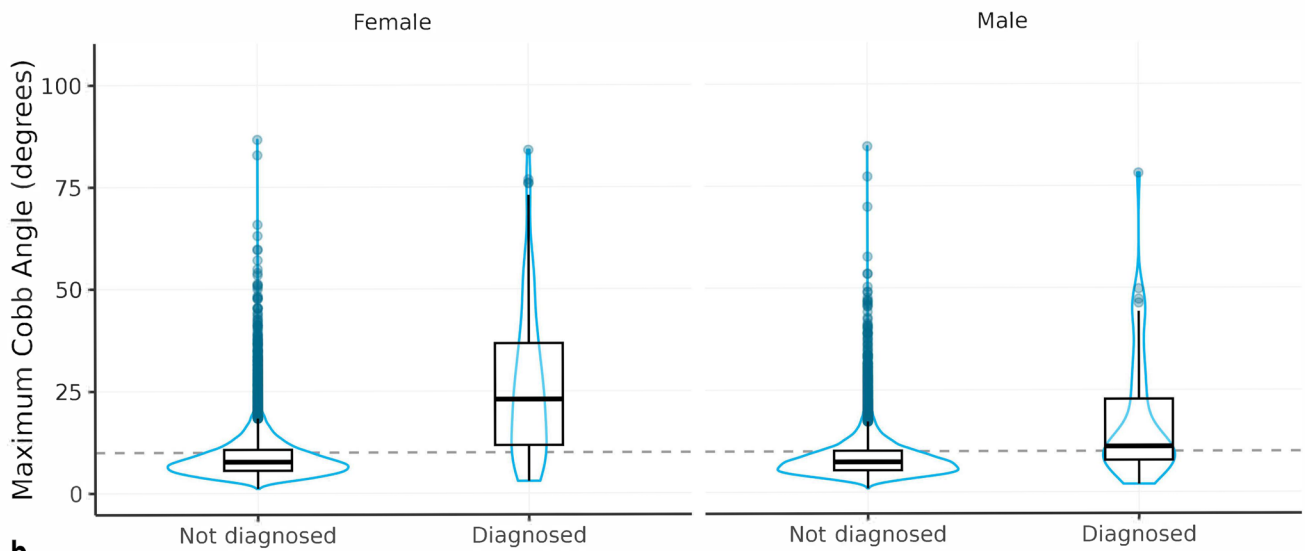


Fig. 2 Representative images of participants with a higher than 10-degree maximal Cobb angle with vertebrae masks and fitted spline. (a) Participants without a clinical scoliosis diagnosis. (b) Participants

with a scoliosis diagnosis. Participants were grouped into scoliosis severity categories based on Cobb angle: mild (10 – 24°), moderate (25 – 39°), and severe ($\geq 40^\circ$)

a Cobb Angle IDP (n = 33,889)
Clinically diagnosed scoliosis n = 170



* based on the maximum Cobb angle threshold of 10°

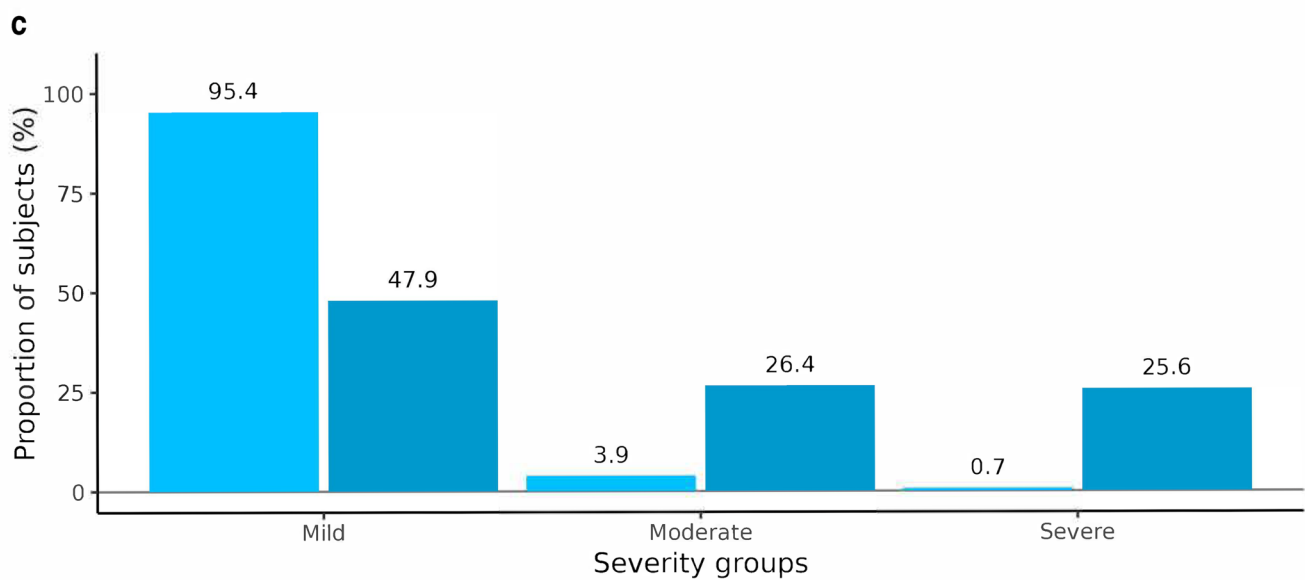


Fig. 3 Analysis of Cobb angle by UK Biobank derived clinical scoliosis diagnosis and algorithm-based diagnosis. **(a)** Gender specific distribution of maximal Cobb angle for participants with and without a scoliosis diagnosis code. Algorithm-based scoliosis diagnosis was assigned to participants with a maximal Cobb angle of over 10° , indicated by the dashed line. **(b)** Confusion matrix illustrating agreement between clinical diagnosis and algorithm-based diagnosis for scoliosis. **(c)** Proportion of participants in scoliosis categories according to diagnosis status and scoliosis severity groups. Diagnosis status combined data from hospital records, private healthcare, self-reports, and an algorithm (Cobb angle $>10^\circ$), distinguishing between cases detected exclusively by the algorithm (Diagnosis - | Algorithm +), cases confirmed by both methods (Diagnosis + | Algorithm +), and cases identified only through healthcare data (Diagnosis + | Algorithm -). Participants were grouped into scoliosis severity categories based on Cobb angle: mild ($10\text{--}24^\circ$), moderate ($25\text{--}39^\circ$), and severe ($\geq 40^\circ$)

Spearman correlations with Cobb angle were modest ($r < 0.25$). Positive correlations were observed with age ($r = 0.24$ in females; $r = 0.21$ in males; $p < 0.00055$) and paraspinal PDFF ($r = 0.10$ in females; $r = 0.07$ in males; $p < 0.00055$). Negative correlations were found for sitting height ($r = -0.12$ in females; $r = -0.10$ in males) and iliopsoas

muscle volume indexed to height ($r = -0.09$ in females; $r = -0.12$ in males; $p < 0.00055$) (Fig. 5; Supplementary Table 3).

Cobb angles were significantly higher in participants reporting chronic back pain compared to those with no or acute pain ($p < 0.00055$; Table 2). Chronic back pain prevalence rose with scoliosis severity: in females, from 12.2% (no scoliosis) to 40.3% (severe); in males, from 11.7% to 21.2%. Differences were also observed for leg pain ($p < 0.00055$; Table 3) and osteoporosis ($p < 0.00055$; Table 4), but not for type 2 diabetes (Supplementary Table 4).

Sex-stratified regression analysis adjusted for age, height, smoking status, Townsend deprivation index, ethnicity, osteoporosis, degenerative disc disease, pain, and body composition IDPs identified age as the strongest correlate of Cobb angle ($p < 0.00055$) (Fig. 6, Supplementary Table 5). Chronic back pain ($p < 0.00055$), paraspinal muscle PDFF ($p < 0.00055$), and height ($p < 0.000549$) were also positively associated with spinal curvature. VAT volume

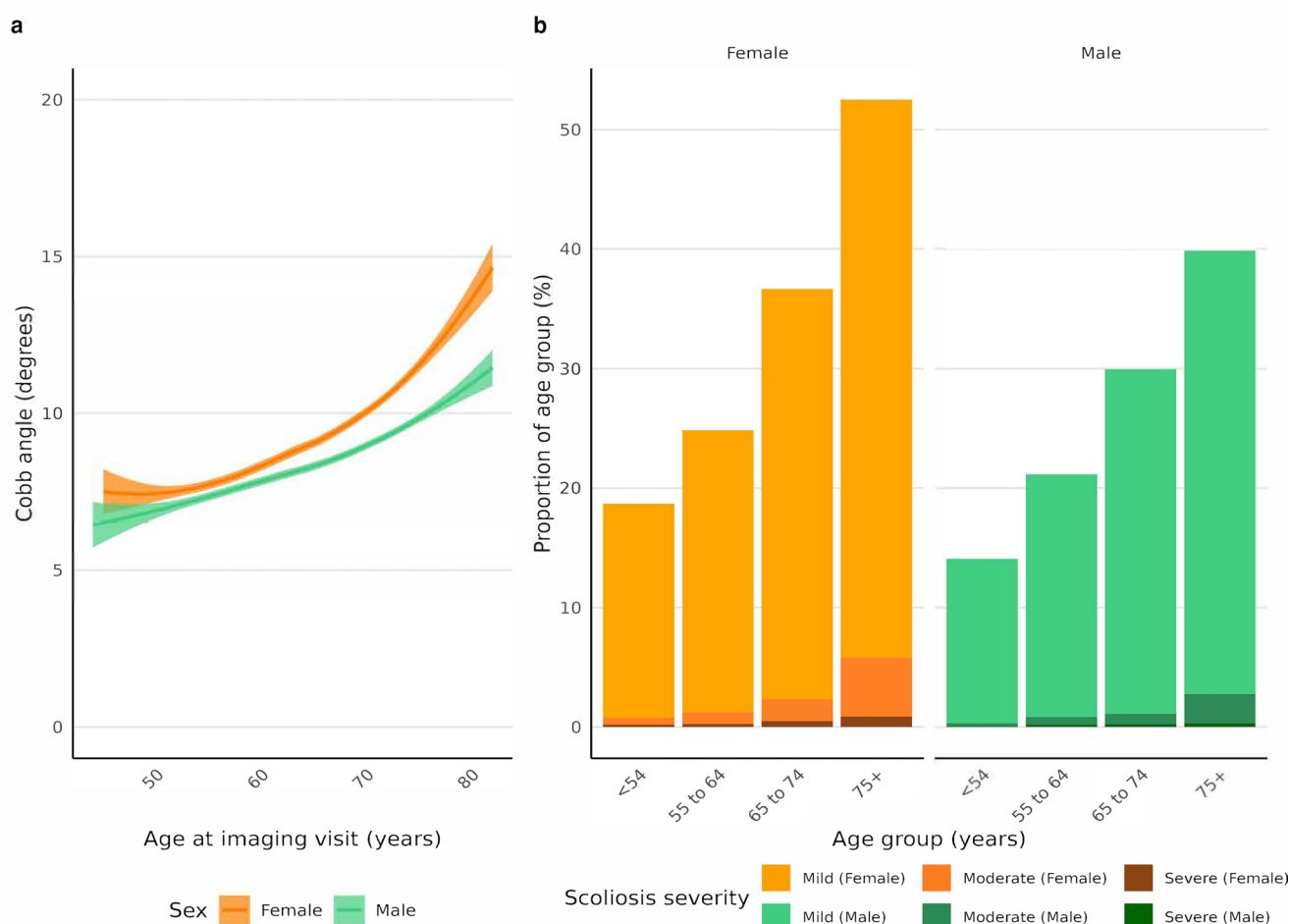


Fig. 4 Relationship between Cobb angles to age and sex. **(a)** A line plot with density plots of Cobb angles for age and sex. **(b)** Prevalence of scoliosis by severity group (mild– $10\text{--}24^\circ$; moderate– $25\text{--}39^\circ$; severe $\geq 40^\circ$) and age group, stratified by sex

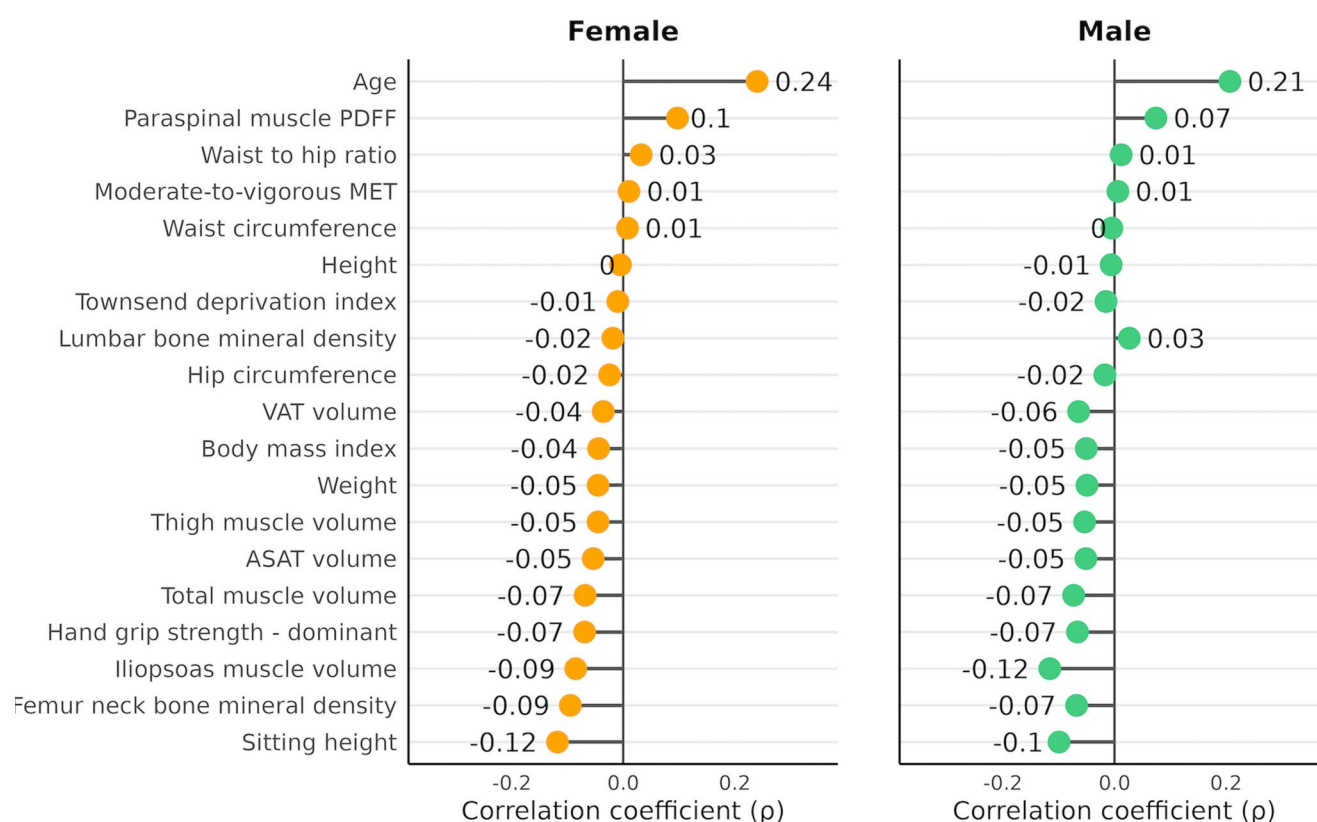


Fig. 5 Sex-stratified correlation coefficients between anthropometric variables and Cobb angles. Spearman's correlation coefficient between the Cobb angle and variables of interest

Table 2 Cobb angle comparison for female and male participants with back pain. Significance was first tested by one-way ANOVA, and if significant, further post-hoc Tukey test. * indicate statistically significant for $p < 0.05$, ** indicate statistically significant after Bonferroni correction

	Female				Male			
	Never	Acute	Chronic	ANOVA	Never	Acute	Chronic	ANOVA
Count (n)	13,755	958	2,194		13,603	1,287	2,092	
Cobb angle (°)	8.9±5.3	8.6±4.97	10.0±7.4 **	<0.001	8.4±4.7	8.2±4.8	8.9±5.2 **	<0.001

Table 3 Cobb angle comparison for female and male participants with leg pain

	Female		Male	
	No leg pain	Leg pain	No leg pain	Leg pain
Count (n)	13,710	3,197	13,846	3,136
Cobb angle (°)	8.9±5.5	9.5±6.1 **	8.4±4.7	8.7±5.0 **

Significance was first tested by Wilcoxon rank-sum test and further adjusted by Bonferroni correction

* Indicate statistically significant associations ($p < 0.05$)

** Indicate statistically significant after Bonferroni correction ($p < 0.00055$)

Table 4 Cobb angle comparison for female and male participants with osteoporosis and osteopenia

	Female				Male			
	None	Osteopenia	Osteoporosis	ANOVA	None	Osteopenia	Osteoporosis	ANOVA
Count (n)	5,363	7,004	4,540		6,183	7,416	3,383	
Cobb angle (°)	8.7±5.2	8.8±5.4	9.7±6.2 **	<0.001	8.2±4.4	8.4±4.7 *	9.0±5.4 **	<0.001

Significance was first tested by one-way ANOVA, and if significant, further post-hoc Tukey test

* Indicate statistically significant associations ($p < 0.05$)

** Indicate statistically significant after Bonferroni correction ($p < 0.00055$)

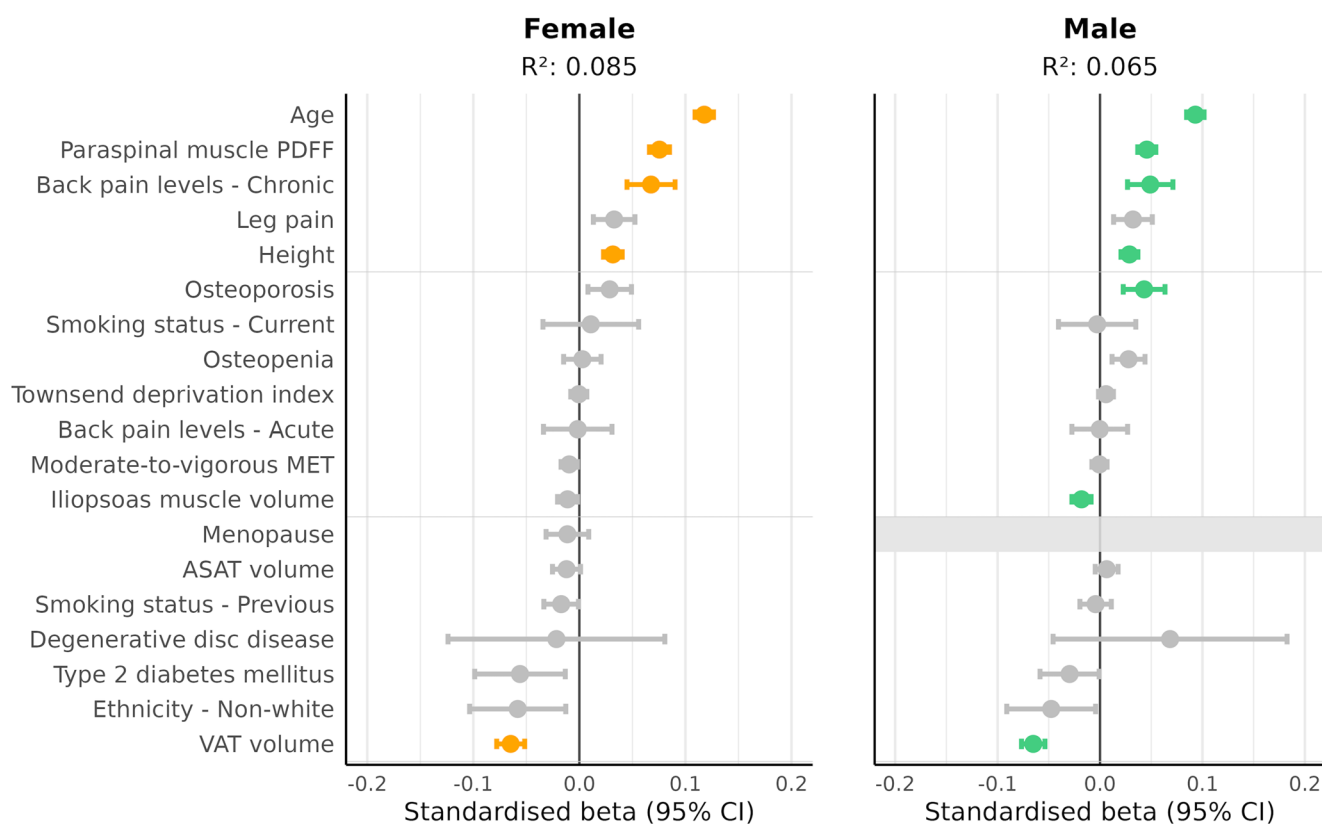


Fig. 6 Sex-stratified linear regression models investigating the relationship between Cobb angles and anthropometric variables, image-derived phenotypes and conditions. Linear regression analysis derived standardised regression coefficients (beta) between log-transformed

Cobb angles and standardised anthropometric variables, image-derived phenotypes and associated conditions. Colourful beta coefficient labels indicate statistically significant associations ($p < 0.000549$) after Bonferroni correction

($p < 0.00055$) and iliopsoas muscle volume ($p < 0.00055$) in male participants were negatively associated with the Cobb angle. Osteoporosis was positively associated in males only ($p < 0.00055$). Adjusted R^2 values (< 0.10) indicated that these variables collectively explained $< 10\%$ of Cobb angle variance.

The Bland-Altman analysis showed the mean difference between repeated manual measurements (bias = -0.8° , LoA $\pm 12.66^\circ$) was smaller than the difference between manual and automated values (bias = 6.73° , LoA $\pm 17.0^\circ$) (Fig. 7). The bias was more pronounced at low-to-mid Cobb angles, indicating systematic overestimation in mild curvature ranges. This may have contributed to the higher number of participants classified as mild scoliosis.

Discussion

We developed an automated approach to estimate Cobb angles from Dixon MRI scans, enabling large-scale, radiation-free evaluation of spinal curvature in a population-based cohort. Because Dixon MRI primarily visualises VBM rather than vertebral cortex, we used a centroid-based

spline-fitting method as a proxy for conventional Cobb angle measurement, consistent with previously described spline-based methods [8]. Using this framework, we quantified scoliosis prevalence and severity as well as investigated associations with anthropometric traits, muscle and fat IDPs, and musculoskeletal and metabolic conditions.

Forty-nine participants had clinically diagnosed scoliosis but an algorithm-derived Cobb angle $< 10^\circ$. Visual inspection confirmed accurate segmentation and spline fitting. Reproducibility analysis showed slight overestimation of Cobb angles compared with manual measurements, although agreement remained within typical intra-observer variability, supporting population-level analyses. The measurement bias was greatest at lower Cobb angles, potentially contributing to the higher proportion of participants classified with mild scoliosis.

We observed a clinically diagnosed scoliosis prevalence of 0.5%, consistent with previous UK Biobank reports (0.8%) [20]. In contrast, the automated MRI-based method identified scoliosis (Cobb angle $> 10^\circ$) in 28% of participants, mostly with mild (10 – 24°) curvature detectable only through imaging. Although most cases were mild and likely

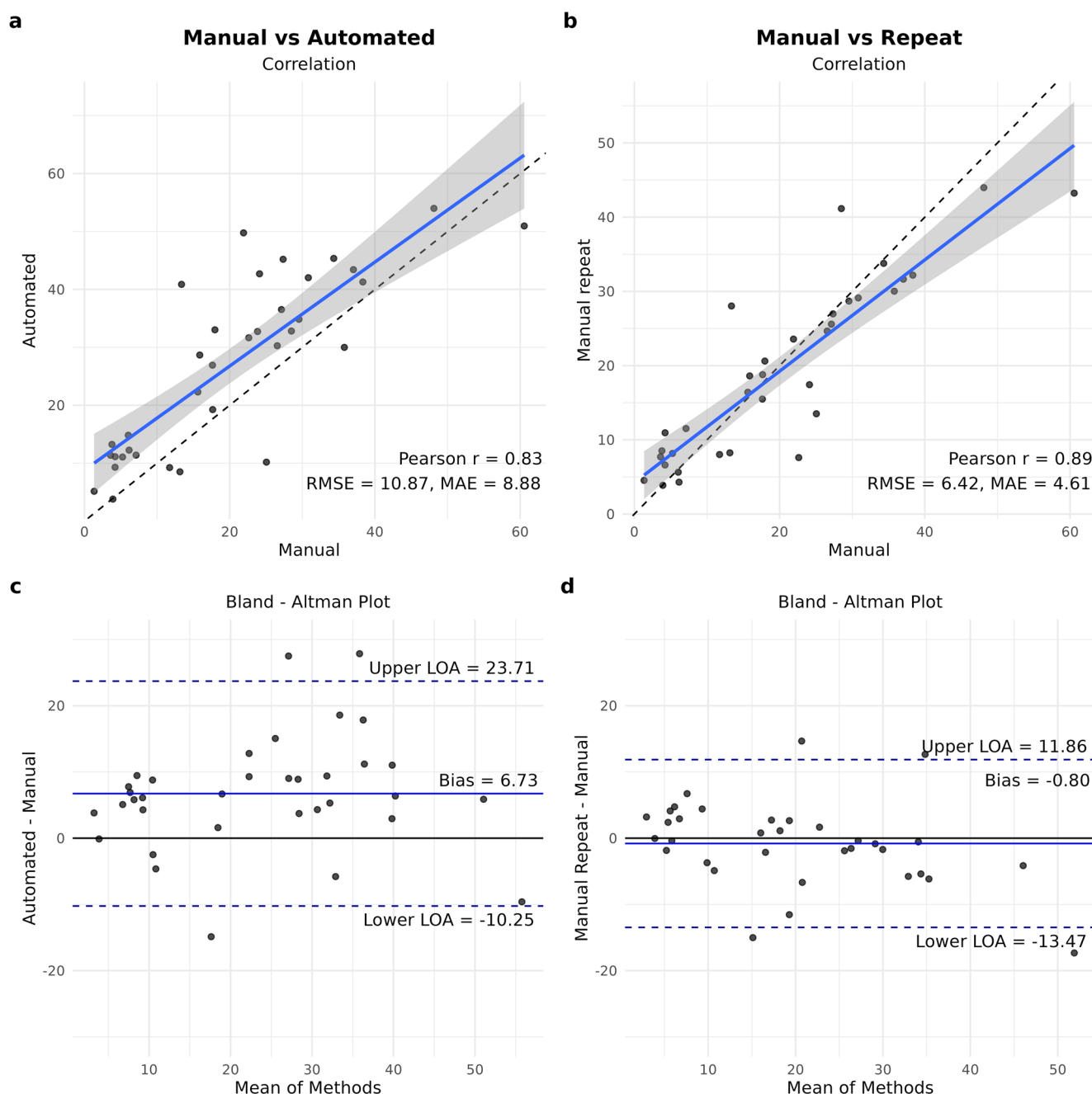


Fig. 7 Correlation and agreement analysis between manual and automated measurements. Panels (a) and (b) show manual against automated value comparisons, and panels (c) and (d) show initial and repeated manual value comparisons. Panels (a) and (c) are correlation

plots along with corresponding Pearson's correlation coefficient (r) value, root mean squared error (RMSE) and mean absolute error (MAE). Panels (b) and (d) are Bland-Altman plots along with the bias line (solid blue) and limits of agreement lines (dashed dark blue)

subclinical, they may reflect age-related changes in spinal alignment that warrant further investigation.

Female participants exhibited higher Cobb angles and steeper age-related increases than males, consistent with known sex differences in scoliosis and musculoskeletal ageing [4, 21]. After multivariable adjustment, age, paraspinous fat infiltration, chronic back pain, and lower iliopsoas muscle volume remained associated with greater curvature,

whereas VAT volume showed an inverse relationship. These findings suggest contributions of muscle quality and body composition to spinal alignment, although the regression models explained $<10\%$ of Cobb-angle variance, indicating additional influences from other factors such as vertebral geometry, posture, and genetic predisposition.

Several studies underscore the stabilising role of torso muscles, particularly iliopsoas and paraspinal muscles [6,

21, 22]. Zhou et al. reported that fat infiltration of all torso stabilisers correlated with Cobb angle in men, whereas only paraspinal fat infiltration correlated in women [22]. Consistent with this, we observed positive associations between paraspinal fat infiltration and Cobb angle in both sexes, yet a negative association between iliopsoas muscle volume and curvature in men only. These findings suggest that women may rely more on paraspinal than psoas muscles for coronal spinal stabilisation.

Chronic back pain prevalence increased with scoliosis severity in both sexes and remained significant after adjusting for known risk factors such as age, degenerative conditions, and muscle composition [3, 7, 23]. While abnormal spinal alignment is recognised as a risk factor for back pain [3, 24], the small absolute Cobb angle differences between pain groups ($<5^\circ$) indicate that curvature severity alone is unlikely to be clinically meaningful at the individual level. Nevertheless, the high proportion of participants without a formal scoliosis diagnosis suggests that continuous Cobb angle measurements may provide greater value than binary classification in population studies of back pain and spinal alignment.

Several limitations of this study should be acknowledged. First, MRI was acquired in the supine position, where Cobb angles are typically $7\text{--}12^\circ$ lower than standing radiographs [7], potentially underestimating scoliosis prevalence when applying a 10° threshold. Second, BMD was incorporated indirectly through osteoporosis and osteopenia classifications. Third, although degenerative disc disease was included as a covariate, the low prevalence of coded degenerative diagnoses limited the ability to fully control for degenerative spinal conditions. Despite adjustment for age, torso muscle volume and quality, and osteoporosis, the linear regression models explained $<10\%$ of Cobb angle variance, suggesting important contributions from genetic predisposition [25], biomechanical characteristics [23], and postural asymmetries [7]. Finally, distinguishing adult-onset from residual adolescent scoliosis remains challenging despite excluding known adolescent diagnoses.

In conclusion, this study presents an automated, radiation-free method to estimate Cobb angles from Dixon MRI, enabling large-scale assessment of spinal curvature. The approach revealed a higher prevalence of mild, previously undiagnosed scoliosis than clinically reported. Associations with age, muscle quality, and back pain highlight the interrelation between spinal alignment and musculoskeletal health. Although limited by supine imaging and low explained variance, this scalable method provides a valuable tool for population studies of spinal ageing and health. It may also support future healthcare applications, including opportunistic assessment of spinal curvature on MRI acquired for

unrelated indications and reducing reliance on radiographic imaging during longitudinal follow-up of adult scoliosis.

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Author contributions M.N.: Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing - original draft, Writing - review & editing. B.W.: Conceptualization, Data curation, Formal analysis, Methodology, Software, Supervision, Writing - review & editing. D.A.: Data curation, Validation, Writing - review & editing. M.T.: Data curation, Investigation, Writing - review & editing. N.B.: Conceptualization, Data curation, Investigation, Methodology, Writing - review & editing. C.B.B.: Data curation; Validation, Writing - review & editing. E.L.T.: Conceptualization, Supervision, Writing - review & editing. J.D.B.: Conceptualization, Project administration, Supervision, Writing - review & editing.

Data availability Our research was conducted using UK Biobank data. Under the standard UK Biobank data sharing agreement, we (and other researchers) cannot directly share raw data obtained or derived from the UK Biobank. However, under this agreement, all of the data generated, and methodologies used in this paper are returned by us to the UK Biobank, where they will be fully available. Access is obtained directly from the UK Biobank to all bona fide researchers upon submitting a health-related research proposal to the UK Biobank <https://www.ukbiobank.ac.uk>.

Declarations

Conflict of interest D.A. - Shareholder MedicaliSight Ltd. B.W. - Shareholder Regeneron, Shareholder Hyperfine.

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