

# Deep Learning-Based Three-Dimensional Paraspinal Muscle Quantification in Adult Degenerative Scoliosis: Associations with Alignment and Clinical Outcomes

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## Article

**Keywords:** adult degenerative scoliosis, spinopelvic parameters, paraspinal muscles, deep learning, lightweight 2D U-Net

**Posted Date:** October 1st, 2026

**DOI:** <https://doi.org/10.21203/rs.3.rs-10501740/v1>

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**Additional Declarations:** No competing interests reported.

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# Abstract

This retrospective two-center study developed and evaluated a lightweight 2D U-Net for automated three-dimensional quantification of lumbar paraspinal muscles in 108 patients with adult degenerative scoliosis (ADS). The model segmented the multifidus (MF), erector spinae (ES), and psoas muscles (PS) on computed tomography (CT) images. Center 1 supported development and internal testing, whereas Center 2 provided external testing. Three-dimensional reconstructions were used to calculate fat infiltration (FI) and relative muscle volume (rMV). Performance was assessed using the Dice coefficient and pixel accuracy (PA). Associations with spinopelvic parameters, pain, and disability were examined using Pearson correlation and multivariable linear regression adjusted for age, sex, and body mass index (BMI). Dice coefficients exceeded 0.80 and PA exceeded 0.90 for all muscles. MF FI was independently associated with the Cobb angle and correlated positively with visual analog scale (VAS) and Oswestry Disability Index (ODI) scores. ES rMV was independently and inversely associated with pelvic incidence–lumbar lordosis (PI–LL) mismatch and correlated negatively with ODI, whereas PS rMV was independently and inversely associated with pelvic tilt (PT). Automated three-dimensional muscle quantification may complement imaging markers of deformity severity, sagittal compensation, pain, and functional status in ADS.

## Introduction

Adult degenerative scoliosis (ADS) is a spinal deformity that develops after skeletal maturity as a consequence of degenerative changes in the intervertebral discs, facet joints, ligaments, and vertebral bodies<sup>[1]</sup>. It commonly manifests as coronal curvature, vertebral rotation, loss of lumbar lordosis, and varying degrees of pelvic compensation<sup>[2]</sup>. With population aging, the prevalence of ADS and its associated clinical burden continues to increase. Beyond low back pain, lower-extremity neurological symptoms, and restricted mobility, sagittal imbalance is closely associated with poorer quality of life and influences surgical decision-making<sup>[3]</sup>. Consequently, the Cobb angle alone cannot adequately characterize the overall pathological profile of ADS. Comprehensive assessment should also incorporate spinopelvic alignment and the status of soft tissues involved in maintaining postural stability.

Among the soft tissues involved in postural stability, the paraspinal muscles (PSM) are key dynamic stabilizers of the lumbar spine and trunk. The multifidus (MF) primarily contributes to segmental stabilization and rotational control<sup>[4]</sup>. The erector spinae (ES) generates the posterior extensor torque required to preserve lumbar lordosis and an upright posture. The psoas muscle (PS) spans the lumbar spine, pelvis, and femur, thereby contributing to coordinated function across the lumbopelvic-hip complex<sup>[5]</sup>. During ADS progression, chronic asymmetric loading, pain-related muscle inhibition, and reduced physical activity may promote muscle atrophy, fatty infiltration, and loss of strength. In turn, diminished muscle reserve may further compromise spinal stability and reduce the capacity for pelvic compensation.

Spinopelvic parameters provide the principal radiographic framework for evaluating adult spinal deformity. Within this framework, the Cobb angle and coronal balance distance (CBD) characterize coronal deformity and trunk deviation, respectively. The sagittal vertical axis (SVA), lumbar lordosis (LL), pelvic incidence (PI), sacral slope (SS), pelvic tilt (PT), and PI–LL mismatch describe sagittal alignment, pelvic morphology<sup>[6]</sup>, and compensatory status<sup>[7]</sup>. However, current ADS assessment and treatment strategies still rely predominantly on radiographic measures of osseous alignment. These measures do not directly capture the muscle condition or functional reserve required to maintain posture<sup>[8]</sup>. Whether PSM characteristics are specifically associated with key measures, including the Cobb angle, PI–LL mismatch, and PT, therefore remains to be clarified.

Previous studies have typically evaluated degeneration of the PSM using cross-sectional area (CSA) or fatty infiltration measured at a single axial level<sup>[9]</sup>. However, these two-dimensional metrics are sensitive to level selection, irregular muscle morphology, side-to-side asymmetry, and operator-dependent variability in muscle delineation. Consequently, they may not adequately represent overall muscle reserve throughout the lumbar spine. Although slice-by-slice manual segmentation can provide three-dimensional volumetric information<sup>[10]</sup>, the process is time-consuming and strongly dependent on operator expertise. These practical limitations restrict the use of manual segmentation in large-scale studies and rapid clinical assessment.

To address these limitations, we employed a lightweight 2D U-Net model to automatically segment the MF, ES, and PS in lumbar CT images from patients with ADS. The segmented muscles were reconstructed in three dimensions to quantify fat infiltration (FI) and relative muscle volume (rMV). We then examined associations between these three-dimensional muscle metrics and spinopelvic parameters. The primary objective was to identify muscle factors independently associated with the Cobb angle, PI–LL mismatch, and PT. The resulting framework may inform personalized imaging assessment and targeted rehabilitation strategies for ADS.

## Materials and Methods

### Patient Selection

This retrospective study included 108 patients who were newly diagnosed with ADS at their initial visit between January 2022 and August 2025. Demographic data, standing full-length spinal radiographs, and lumbar CT images were collected for each patient. All included patients had complete clinical records and imaging data suitable for segmentation of the PSM.

The study protocol was approved by the Ethics Committee of Tianjin Union Medical Center (approval no. 2024C39; Center 1). Additional approval was granted by the Ethics Committee of the 983 Hospital of the Joint Support Force (approval no. 202603; Center 2). The study was conducted in accordance with the Declaration of Helsinki<sup>[11]</sup>. All patient data were anonymized and de-identified before any analyses were

performed. Given the retrospective design, the requirement for informed consent was waived by both ethics committees.

Patients were eligible for inclusion if they met all of the following criteria: (1) age  $\geq 50$  years; (2) complete clinical and imaging data; (3) a coronal Cobb angle  $> 10^\circ$  on standing anteroposterior lumbar radiographs; and (4) clinical and imaging findings consistent with ADS. Patients were excluded if any of the following criteria were met: (1) adolescent idiopathic or congenital scoliosis; (2) confirmed sarcopenia or a systemic myopathy that could affect muscle assessment; (3) a history of spinal surgery; or (4) concomitant spinal fracture, tumor, or infection, or cardiovascular, cerebrovascular, or other comorbid conditions that severely limited mobility.

## Lumbar CT image acquisition and annotation

Lumbar computed tomography (CT) images were acquired using an Optima CT660 multidetector CT scanner with a tube voltage of 120 kV and a tube current–time product of 250–750 mAs. The collimation width and slice thickness were both 0.625 mm. Three senior clinicians manually delineated the bilateral MF, ES, and PS slice by slice on axial images, generating six muscle regions of interest (ROIs). The initial annotations were reviewed by an associate chief physician in spine surgery with 20 years of clinical experience. A chief physician in spine surgery with 30 years of clinical experience performed the final review. Intraobserver intraclass correlation coefficients (ICCs) ranged from 0.919 to 0.963, whereas interobserver ICCs ranged from 0.913 to 0.977. Together, these values indicated good-to-excellent measurement reliability across all muscle ROIs (Table 1)<sup>[12]</sup>. To meet the input requirements of the 2D network, axial slices were cropped and zero-padded to  $256 \times 256$  pixels without resampling. CT attenuation values were clipped to  $[-200, 300]$  HU and then mapped to  $[-1, 1]$  using min–max normalization. This preprocessing step enhanced the contrast between the muscles and surrounding tissues.

Table 1  
Intra- and inter-observer reliability analysis of paraspinal muscle ROI annotations

| Variable                                                                                                                                                                                                 | Intra-observer | P value        | Inter-observer | P value        |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------|----------------|----------------|----------------|
| Left MF                                                                                                                                                                                                  | 0.941          | $< 0.001^{**}$ | 0.928          | $< 0.001^{**}$ |
| Right MF                                                                                                                                                                                                 | 0.935          | $< 0.001^{**}$ | 0.927          | $< 0.001^{**}$ |
| Left ES                                                                                                                                                                                                  | 0.924          | $< 0.001^{**}$ | 0.913          | $< 0.001^{**}$ |
| Right ES                                                                                                                                                                                                 | 0.919          | $< 0.001^{**}$ | 0.931          | $< 0.001^{**}$ |
| Left PS                                                                                                                                                                                                  | 0.952          | $< 0.001^{**}$ | 0.953          | $< 0.001^{**}$ |
| Right PS                                                                                                                                                                                                 | 0.963          | $< 0.001^{**}$ | 0.977          | $< 0.001^{**}$ |
| ROI, region of interest; MF, multifidus; ES, erector spinae; PS, psoas muscle. Consistency was evaluated using the intraclass correlation coefficient (ICC). $P < 0.001$ indicates excellent reliability |                |                |                |                |

## Model development

All CT datasets were converted to three-dimensional Neuroimaging Informatics Technology Initiative (NIfTI) format, and incomplete or corrupted datasets were excluded before training. Data from Center 1 were randomly divided into training, internal validation, and internal test sets using a 70:20:10 ratio. Data from Center 2 served exclusively as an external test set to evaluate model generalizability. Training batches primarily comprised axial slices containing muscle foreground, with 10% background-only slices included to reduce false-positive predictions<sup>[13]</sup>. During each epoch, 12,000 slices were sampled for training and 3,000 for evaluation. Random cropping was applied as data augmentation during model training. During evaluation, center cropping and a fixed sample order were used to maintain a consistent evaluation procedure<sup>[14]</sup>.

The model used a lightweight 2D U-Net architecture with 32 initial feature channels. The encoder contained three downsampling stages, each comprising two bias-free  $3 \times 3$  convolutions with batch normalization and rectified linear unit (ReLU) activation, followed by  $2 \times 2$  max pooling. The decoder contained three symmetric transposed-convolution upsampling stages and used skip connections to integrate multiscale features. A final  $1 \times 1$  convolution generated pixelwise classifications for six muscle classes and one background class (Fig. 1).

The model was implemented in PyTorch and trained under Windows 11 using an NVIDIA GeForce RTX 5060 GPU. Cross-entropy loss was optimized using AdamW with an initial learning rate of  $3 \times 10^{-4}$  and weight decay of  $1 \times 10^{-4}$ . Cosine annealing learning-rate scheduling and automatic mixed-precision (AMP) training were also applied. AMP dynamically combined half- and single-precision computation to reduce GPU memory consumption and accelerate training. Automatic loss scaling was used to maintain gradient stability and improve training efficiency.

## Model evaluation and three-dimensional reconstruction

Segmentation performance was evaluated using the Dice similarity coefficient and pixel accuracy (PA). After automatic segmentation of the PSM, consecutive axial segmentation masks were imported into 3D Slicer for three-dimensional reconstruction (Fig. 2). Within the segmentation masks generated by the lightweight 2D U-Net, CT attenuation values ranging from  $-29$  to  $150$  HU were classified as muscle tissue. This threshold was applied to distinguish muscle tissue from the surrounding tissues<sup>[15]</sup> and to calculate total and effective muscle volumes (Fig. 3). Muscle volumes were normalized to body mass index (BMI), after which FI and rMV were calculated using the following equations:

$$FI = 1 - EMV / MV$$

$$rMV = MV / BMI$$

EMV: effective muscle volume ( $\text{mm}^3$ ); MV: the total paraspinal muscle volume ( $\text{mm}^3$ ); BMI: body mass index ( $\text{kg}/\text{m}^2$ ).

## Measurement of spinopelvic parameters

Spinopelvic parameters were measured on standing full-length anteroposterior and lateral spinal radiographs. Coronal parameters included the Cobb angle and CBD, whereas sagittal parameters included SVA, LL, PI, SS, PT, and PI–LL mismatch. Two experienced spine surgeons independently measured all radiographic parameters. Each surgeon performed three repeated measurements for every patient. The final value for each parameter was calculated as the mean of all six measurements to reduce measurement error.

## VAS and ODI

Pain and functional disability scores obtained at the initial visit were also collected, including the visual analog scale (VAS) and Oswestry Disability Index (ODI). The VAS was used to assess the severity of low back or lower-extremity pain, whereas the ODI quantified lumbar spine-related disability. All clinical assessments were performed concurrently with the imaging examinations or during the same episode of care.

## Statistical analyses

Statistical analyses were performed using IBM SPSS Statistics version 27.0. Normality of continuous variables was assessed using the Shapiro–Wilk test. Normally distributed variables were summarized as the mean  $\pm$  standard (Mean + SD) deviation. Pearson correlation coefficients were calculated to assess bivariate associations between continuous variables. Separate multiple linear regression models were fitted with the Cobb angle, PI–LL mismatch, and PT as dependent variables. The independent variables were age, sex, BMI, and the FI and rMV values of the MF, ES, and PS. Multicollinearity among the independent variables was assessed using variance inflation factors (VIF). Regression results were reported as unstandardized coefficients (B), 95% confidence intervals (CI), standardized coefficients ( $\beta$ ), and P values, with statistical significance set at  $P < 0.05$ .

## Results

### Patient demographics and characteristics

A total of 108 patients with ADS were included, comprising 46 men (42.6%) and 62 women (57.4%). The mean age was  $64.23 \pm 6.19$  years, and the mean BMI was  $25.59 \pm 4.00$  kg/m<sup>2</sup>. The radiographic parameters and quantitative PSM measurements are summarized in Table 2.

Table 2

Patient demographics, radiographic, and paraspinal muscle quantitative parameters (Mean  $\pm$  SD or n)

| Variable                                                                                                                                                                                                                                          | Mean $\pm$ SD or n     |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------|
| Age                                                                                                                                                                                                                                               | 64.23 $\pm$ 6.19       |
| Sex (male/female)                                                                                                                                                                                                                                 | 46/62                  |
| BMI                                                                                                                                                                                                                                               | 25.59 $\pm$ 4.00       |
| Spinopelvic parameters                                                                                                                                                                                                                            |                        |
| CBD (mm)                                                                                                                                                                                                                                          | 23.83 $\pm$ 11.44      |
| Cobb angle ( $^{\circ}$ )                                                                                                                                                                                                                         | 19.35 $\pm$ 10.70      |
| SVA (mm)                                                                                                                                                                                                                                          | 30.38 $\pm$ 14.48      |
| LL ( $^{\circ}$ )                                                                                                                                                                                                                                 | 36.87 $\pm$ 10.43      |
| PI-LL ( $^{\circ}$ )                                                                                                                                                                                                                              | 15.05 $\pm$ 23.84      |
| SS ( $^{\circ}$ )                                                                                                                                                                                                                                 | 29.50 $\pm$ 10.30      |
| PT ( $^{\circ}$ )                                                                                                                                                                                                                                 | 21.04 $\pm$ 19.44      |
| PI ( $^{\circ}$ )                                                                                                                                                                                                                                 | 51.92 $\pm$ 10.03      |
| Fat infiltration                                                                                                                                                                                                                                  |                        |
| MF FI                                                                                                                                                                                                                                             | 0.22 $\pm$ 0.09        |
| ES FI                                                                                                                                                                                                                                             | 0.25 $\pm$ 0.12        |
| PS FI                                                                                                                                                                                                                                             | 0.09 $\pm$ 0.04        |
| Relative muscle volume (mm <sup>3</sup> /[kg/m <sup>2</sup> ])                                                                                                                                                                                    |                        |
| MF rMV                                                                                                                                                                                                                                            | 7896.84 $\pm$ 2530.49  |
| ES rMV                                                                                                                                                                                                                                            | 16178.23 $\pm$ 4065.24 |
| PS rMV                                                                                                                                                                                                                                            | 8859.07 $\pm$ 2382.89  |
| BMI, body mass index; CBD, coronal balance distance; Cobb, coronal Cobb angle; SVA, sagittal vertical axis; LL, lumbar lordosis; PI-LL, pelvic incidence minus lumbar lordosis mismatch; SS, sacral slope; PT, pelvic tilt; PI, pelvic incidence. |                        |

## Performance of the paraspinal muscle segmentation model

### Primary segmentation metrics

Using manual clinician annotations as the reference standard, the automated segmentations generated by the lightweight 2D U-Net showed high spatial overlap on the test set. Dice similarity coefficients exceeded 0.80 for all target muscles, while PA values exceeded 0.90 (Fig. 4). These results supported the use of the model-generated masks for subsequent three-dimensional reconstruction and quantitative analysis.

## **Level-specific comparison between automatic and manual segmentations**

Across vertebral levels L1–L5, the model-generated segmentations showed overall agreement with the manual annotations, with no visually apparent level-dependent discrepancies (Fig. 5). This concordance supported automated identification of the MF, ES, and PS throughout the lumbar spine. The resulting masks were subsequently used to quantify three-dimensional muscle volume and FI.

## **Correlations between paraspinal muscle metrics and spinopelvic parameters**

Pearson correlation analysis showed no statistically significant associations between SVA and either FI or rMV for any of the three muscles. LL was positively correlated with PS rMV ( $r = 0.275$ ,  $P = 0.004$ ), indicating that a greater relative psoas volume was associated with greater lumbar lordosis.

The Cobb angle was positively correlated with MF FI ( $r = 0.746$ ,  $P < 0.001$ ) and ES FI ( $r = 0.626$ ,  $P < 0.001$ ).

PI–LL mismatch was positively correlated with MF FI ( $r = 0.210$ ,  $P = 0.029$ ) and ES FI ( $r = 0.212$ ,  $P = 0.027$ ). Conversely, PI–LL mismatch was negatively correlated with MF rMV ( $r = -0.269$ ,  $P = 0.005$ ), ES rMV ( $r = -0.641$ ,  $P < 0.001$ ), and PS rMV ( $r = -0.299$ ,  $P = 0.002$ ). Among these muscle metrics, ES rMV showed the strongest correlation with PI–LL mismatch.

PT was positively correlated with MF FI ( $r = 0.274$ ,  $P = 0.004$ ), ES FI ( $r = 0.222$ ,  $P = 0.021$ ), and PS FI ( $r = 0.206$ ,  $P = 0.033$ ). In contrast, PT was negatively correlated with MF rMV ( $r = -0.361$ ,  $P < 0.001$ ), ES rMV ( $r = -0.390$ ,  $P < 0.001$ ), and PS rMV ( $r = -0.669$ ,  $P < 0.001$ ), with PS rMV exhibiting the strongest correlation. The complete correlation analysis is presented in Table 3.

Table 3

Pearson correlation analysis between paraspinal muscle indices and spinopelvic parameters

| Parameter                                                                               |          | Fat infiltration |         |        | Relative muscle volume |          |          |
|-----------------------------------------------------------------------------------------|----------|------------------|---------|--------|------------------------|----------|----------|
|                                                                                         |          | MF               | ES      | PS     | MF                     | ES       | PS       |
| SVA                                                                                     | <i>R</i> | 0.169            | 0.162   | 0.038  | -0.135                 | -0.170   | -0.178   |
|                                                                                         | P value  | 0.081            | 0.094   | 0.694  | 0.165                  | 0.079    | 0.065    |
| LL                                                                                      | <i>R</i> | -0.165           | 0.016   | -0.094 | 0.160                  | 0.092    | 0.275**  |
|                                                                                         | P value  | 0.087            | 0.873   | 0.335  | 0.099                  | 0.345    | 0.004    |
| PI-LL                                                                                   | <i>R</i> | 0.210*           | 0.212*  | 0.076  | -0.269**               | -0.641** | -0.299** |
|                                                                                         | P value  | 0.029            | 0.027   | 0.437  | 0.005                  | < 0.001  | 0.002    |
| SS                                                                                      | <i>R</i> | 0.273**          | 0.223*  | 0.054  | 0.017                  | 0.152    | 0.011    |
|                                                                                         | P value  | 0.004            | 0.020   | 0.580  | 0.863                  | 0.115    | 0.910    |
| PT                                                                                      | <i>R</i> | 0.274**          | 0.222*  | 0.206* | -0.361**               | -0.390** | -0.669** |
|                                                                                         | P value  | 0.004            | 0.021   | 0.033  | < 0.001                | < 0.001  | < 0.001  |
| PI                                                                                      | <i>R</i> | 0.250**          | 0.201*  | 0.094  | -0.231*                | -0.110   | -0.176   |
|                                                                                         | P value  | 0.009            | 0.037   | 0.332  | 0.016                  | 0.255    | 0.069    |
| CBD                                                                                     | <i>R</i> | 0.022            | -0.040  | -0.021 | 0.110                  | 0.148    | 0.023    |
|                                                                                         | P value  | 0.822            | 0.684   | 0.827  | 0.258                  | 0.127    | 0.817    |
| Cobb                                                                                    | <i>R</i> | 0.746**          | 0.626** | 0.146  | -0.120                 | -0.189   | -0.176   |
|                                                                                         | P value  | < 0.001          | < 0.001 | 0.133  | 0.215                  | 0.050    | 0.068    |
| * $P < 0.05$ , ** $P < 0.01$ ; <i>R</i> represents the Pearson correlation coefficient. |          |                  |         |        |                        |          |          |

Table 4

Multivariable Linear Regression Analyses of Factors Associated With Key Spinopelvic Parameters

| Dependent variable                                                                                                                                                                                                                                              | Adjusted R <sup>2</sup> | Predictor | B coefficient (95% CI)  | Standardized β | P value |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------|-----------|-------------------------|----------------|---------|
| Cobb                                                                                                                                                                                                                                                            | 0.755                   | Age       | 0.82 (0.62, 1.03)       | 0.48           | < 0.001 |
| Cobb                                                                                                                                                                                                                                                            |                         | MF FI     | 64.59 (46.77, 82.42)    | 0.55           | < 0.001 |
| PI-LL                                                                                                                                                                                                                                                           | 0.442                   | BMI       | 1.45 (0.31, 2.59)       | 0.24           | 0.013   |
| PI-LL                                                                                                                                                                                                                                                           |                         | ES rMV    | -0.003 (-0.004, -0.002) | -0.52          | < 0.001 |
| PT                                                                                                                                                                                                                                                              | 0.529                   | Age       | 0.86 (0.35, 1.38)       | 0.28           | 0.001   |
| PT                                                                                                                                                                                                                                                              |                         | PS rMV    | -0.004 (-0.006, -0.003) | -0.55          | < 0.001 |
| Note: All models included age, sex, BMI, MF FI, ES FI, PS FI, MF rMV, ES rMV and PS rMV as candidate independent variables. Only variables with <i>P</i> < 0.05 are shown; B, unstandardized coefficient; CI, confidence interval; β, standardized coefficient. |                         |           |                         |                |         |

Table 5

Pearson correlation analysis between paraspinal muscle indices and VAS and ODI scores

|                                                                                                                                                     |          | Fat infiltration |       |        | Relative muscle volume |         |        |
|-----------------------------------------------------------------------------------------------------------------------------------------------------|----------|------------------|-------|--------|------------------------|---------|--------|
|                                                                                                                                                     |          | MF               | ES    | PS     | MF                     | ES      | PS     |
| VAS                                                                                                                                                 | <i>R</i> | 0.297**          | 0.182 | -0.082 | -0.131                 | -0.092  | -0.154 |
|                                                                                                                                                     | P value  | 0.002            | 0.060 | 0.400  | 0.176                  | 0.343   | 0.111  |
| ODI                                                                                                                                                 | <i>R</i> | 0.317**          | 0.157 | 0.128  | 0.037                  | -0.242* | -0.044 |
|                                                                                                                                                     | P value  | < 0.001          | 0.105 | 0.186  | 0.700                  | 0.012   | 0.652  |
| * $P < 0.05$ , ** $P < 0.01$ ; <i>R</i> represents the Pearson correlation coefficient. VAS, visual analogue scale; ODI, Oswestry Disability Index. |          |                  |       |        |                        |         |        |

## Multivariable linear regression analyses

All predictors included in the multivariable regression models had VIFs below 5 (range, 1.106–2.801), indicating no substantial multicollinearity among the demographic variables and paraspinal muscle metrics.

The model with Cobb angle as the dependent variable accounted for 75.5% of the variance and was statistically significant (adjusted  $R^2 = 0.755$ , overall  $P < 0.001$ ). Age and MF FI were independently associated with the Cobb angle. Of these factors, MF FI showed the strongest association ( $B = 64.59$ , 95% CI, 46.77 to 82.42; standardized  $\beta = 0.55$ ,  $P < 0.001$ ).

The model for PI–LL mismatch accounted for 44.2% of the variance and was statistically significant (adjusted  $R^2 = 0.442$ , overall  $P < 0.001$ ). BMI and ES rMV were independently associated with PI–LL mismatch. ES rMV was inversely associated with PI–LL mismatch ( $B = -0.003$ , 95% CI,  $-0.004$  to  $-0.002$ ; standardized  $\beta = -0.52$ ,  $P < 0.001$ ). Thus, lower ES rMV was associated with greater PI–LL mismatch after adjustment for the other included covariates.

The model for PT accounted for 52.9% of the variance and was statistically significant (adjusted  $R^2 = 0.529$ , overall  $P < 0.001$ ). Age and PS rMV were independently associated with PT. Age was positively associated with PT ( $B = 0.86$ , 95% CI, 0.35 to 1.38; standardized  $\beta = 0.28$ ,  $P = 0.001$ ). Conversely, PS rMV was inversely associated with PT ( $B = -0.004$ , 95% CI,  $-0.006$  to  $-0.003$ ; standardized  $\beta = -0.55$ ,  $P < 0.001$ ). After adjustment for the other included covariates, lower PS rMV remained independently associated with greater pelvic retroversion.

## Correlations of paraspinal muscle metrics with VAS and ODI scores

Further analyses examined the correlations of three-dimensional paraspinal muscle metrics with pain severity and functional disability. MF FI was positively correlated with both VAS ( $r = 0.297$ ,  $P = 0.002$ ) and ODI scores ( $r = 0.317$ ,  $P < 0.001$ ). ES rMV was negatively correlated with ODI scores ( $r = -0.242$ ,  $P = 0.012$ ), indicating that lower ES rMV was associated with greater functional disability.

## Discussion

In this study, a lightweight 2D U-Net-based automatic segmentation model was used to reconstruct the MF, ES, and PS in three dimensions from consecutive axial lumbar CT images of patients with ADS. We then analyzed the associations between FI, rMV, and spinopelvic parameters. The main findings were as follows. First, MF FI remained independently associated with the Cobb angle, suggesting that degeneration of this deep segmental stabilizer may more closely reflect the severity of coronal deformity. Second, ES rMV remained independently and negatively associated with PI–LL mismatch, suggesting that reduced posterior extensor muscle reserve may coexist with spinopelvic mismatch. Third, PS rMV remained independently and negatively associated with PT, suggesting that reduced psoas muscle volume may be associated with an increased need for compensatory pelvic retroversion.

This study integrated automatic segmentation, three-dimensional quantification, and spinopelvic parameter analysis into a single workflow. Conventional single-slice measurements of CSA or FI can characterize local muscle status. However, they may not adequately capture segmental variations, asymmetric changes near the apical vertebra<sup>[16]</sup>, or overall muscle reserve in ADS<sup>[17]</sup>. In a series of

previous studies, our group used semiautomatic three-dimensional reconstruction to investigate the associations of paraspinal muscles with degenerative scoliosis<sup>[10, 18]</sup> and cervical lordosis<sup>[19]</sup>. Building on this work, the present study used a lightweight model to obtain three-dimensional FI and rMV measurements across the entire lumbar spine. This approach reduced the time required for manual slice-by-slice delineation and interobserver variability while facilitating quantitative analysis across multiple muscle groups and parameters.

Regarding coronal deformity, MF FI showed the strongest correlation with the Cobb angle ( $r = 0.746$ ,  $P < 0.001$ ), while ES FI was also positively correlated. However, after multivariable adjustment, only MF FI remained independently associated with the Cobb angle (standardized  $\beta = 0.55$ ,  $P < 0.001$ ). This finding is anatomically plausible. The MF lies deep, comprises short fascicles, and is closely adjacent to the posterior bony structures, making it important for controlling segmental micromotion and vertebral rotation<sup>[20]</sup>. Chronic asymmetric loading and vertebral rotation in ADS may promote fatty infiltration of the MF. In turn, deterioration of MF quality may weaken segmental stability and further increase asymmetric loading<sup>[21]</sup>. Previous studies have examined paraspinal muscle atrophy near the apical vertebra<sup>[22]</sup>, concave-convex asymmetry, and fat infiltration<sup>[10]</sup>. Collectively, their findings support an association between degeneration of the deep stabilizing muscles and coronal deformity. An additional finding of this study was that ES FI was significant in the correlation analysis but not in the multivariable model. This difference suggests that ES FI and MF FI may capture overlapping aspects of muscle degeneration. It does not imply that the ES is unrelated to coronal stability. Rather, MF FI may represent a more sensitive marker of coronal muscle quality when multiple muscle groups are considered.

With respect to lumbopelvic alignment, the rMV of all three muscles was negatively correlated with PI–LL mismatch. ES rMV showed the strongest correlation ( $r = -0.641$ ,  $P < 0.001$ ) and remained independently associated in the multivariable model (standardized  $\beta = -0.52$ ,  $P < 0.001$ ). Yagi et al. reported that paraspinal muscle status was closely associated with global spinal alignment in patients with degenerative lumbar scoliosis<sup>[17]</sup>. Han et al. further indicated that paraspinal muscle morphology and endurance are both involved in the compensatory chain of sagittal imbalance<sup>[23]</sup>. These studies support a general association between muscle reserve and sagittal alignment. The present study further showed that, when different muscle groups and both phenotypes were considered together, ES rMV emerged as the muscular factor most strongly associated with PI–LL mismatch. The ES spans multiple lumbar levels and has a long extensor moment arm, making it important for maintaining lumbar lordosis and resisting forward-flexion moments. Previous studies have also associated paraspinal muscle degeneration<sup>[18]</sup>, reduced muscle mass, and insufficient muscle endurance<sup>[24]</sup> with abnormal sagittal alignment<sup>[23]</sup>. Therefore, lower ES rMV may reflect limited compensatory capacity of the lumbar extensors and may be associated with greater PI–LL mismatch. Conversely, persistent PI–LL mismatch may also contribute to disuse atrophy of the ES. The independent positive association between BMI and PI–LL mismatch suggests that greater body loading may increase the posterior extensor reserve required to maintain lumbar lordosis.

PT was positively correlated with FI and negatively correlated with rMV for all three muscles. PS rMV showed the strongest correlation ( $r = -0.669$ ,  $P < 0.001$ ) and remained independently associated with PT in the multivariable model (standardized  $\beta = -0.55$ ,  $P < 0.001$ ). Age was also independently associated with PT (standardized  $\beta = 0.28$ ,  $P = 0.001$ ). Previous studies have linked the status of the paraspinal and psoas muscles to global spinal alignment<sup>[17]</sup>. They have also suggested complementary changes between the posterior paraspinal muscles and the psoas<sup>[25]</sup>. Psoas morphology may vary with lumbar lordosis and body position<sup>[26]</sup>, while muscle morphology and endurance may jointly participate in the sagittal compensatory cascade<sup>[23]</sup>. Collectively, these findings suggest that the psoas is not simply a hip flexor but an important component of the lumbopelvic-hip mechanical chain. After adjustment for MF and ES metrics, PS muscle volume remained independently associated with static PT. This finding suggests that PS rMV may reflect anterior muscle reserve during compensatory pelvic retroversion. However, multivariable evidence directly examining the relationship between PS volume and PT remains limited. Therefore, PS rMV may be considered a candidate imaging phenotype that requires validation in external cohorts and longitudinal studies before its clinical value can be established.

Analysis of the clinical scores further suggested that paraspinal muscle degeneration may be associated not only with abnormal spinopelvic alignment but also with patient-reported symptoms and functional status. MF FI was positively correlated with VAS and ODI scores, in line with previous mainstream studies<sup>[8]</sup>, indicating that increased fat infiltration of deep paraspinal muscles is associated with aggravated pain and functional impairment. In contrast, ES rMV was negatively correlated with ODI, suggesting that reduced erector spinae muscle reserve may be particularly relevant to functional disability.

This study has several limitations. First, its retrospective cross-sectional design precluded determination of the causal relationship between paraspinal muscle degeneration and spinopelvic imbalance. Second, although the analyses were adjusted for age, sex, and BMI, other potential confounders may still have influenced the results. These factors include osteoporosis, pain severity, physical activity level, neural compression, disease duration, and previous treatment. Finally, although the lightweight 2D U-Net model improved measurement efficiency and consistency, its generalizability requires further validation in larger, multicenter cohorts that include patients with varying degrees of deformity severity.

## Conclusion

MF FI was independently associated with the Cobb angle and positively correlated with higher VAS and ODI scores. Lower ES rMV and PS rMV were independently associated with greater PI–LL mismatch and PT, respectively. Lower ES rMV was also correlated with higher ODI scores. These three-dimensional quantitative metrics, derived using a lightweight U-Net, may complement conventional paraspinal muscle measurements and provide objective information for a more comprehensive assessment of deformity severity and clinical symptoms in patients with ADS.

## Declarations

## Competing interests

The authors have no conflicts of interest relevant to this article.

## Funding

This work was funded by Tianjin Union Medical Center (2024YJ009), Tianjin Key Medical Discipline (Specialty) Construction Project (TJYXZDXK-064B), Tianjin Health Commission Science and Technology Project (ZC3005), Tianjin Health Science and Technology Project (24JCYBJC01940,TJWJ2024QN045).

## Author Contribution

HC, XW, and HY completed the data analysis and wrote the manuscript text. HY and XT checked the results and revised the manuscript. HC and PL prepared the figures. RL and SF prepared the tables. MZ and RZ designed this project. All authors reviewed the manuscript.

## Data Availability

The data used to support the results of this study can be found in this article.

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## Figures

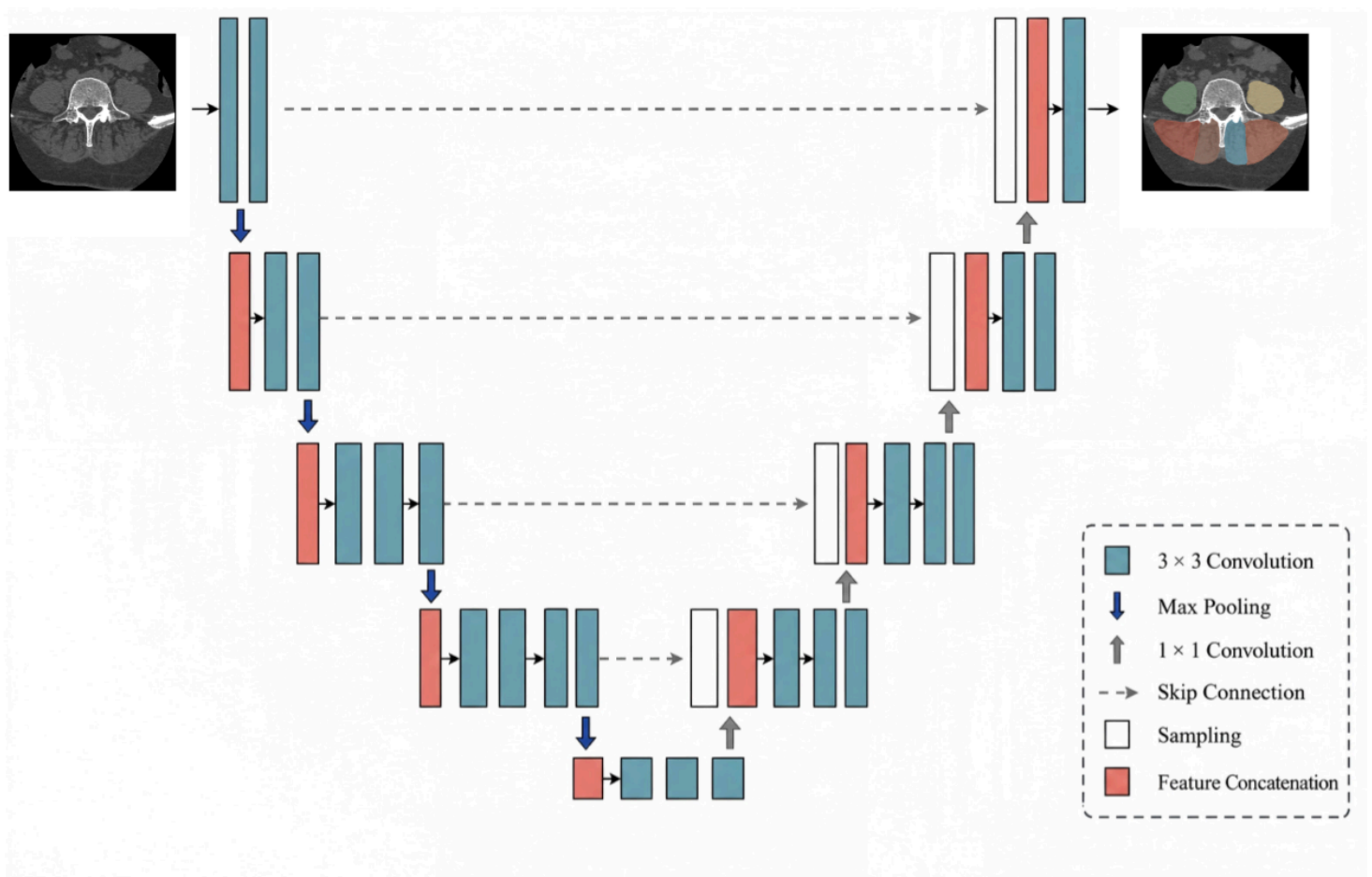


Figure 1

Network architecture diagram of a lightweight 2D U-Net for paraspinal muscle segmentation.

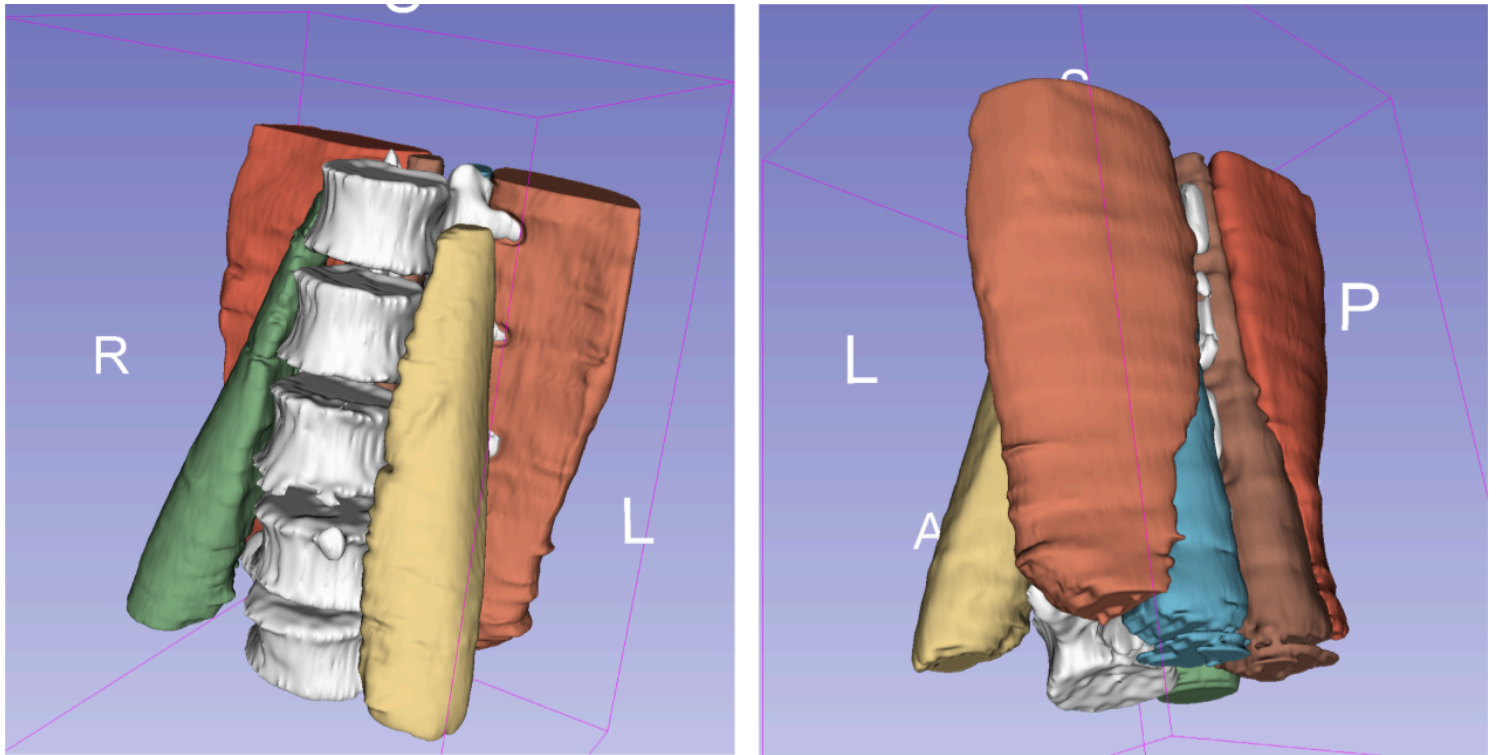


**Figure 2**

Examples of 3D reconstruction of lumbar paraspinal muscles in patients with ADS.

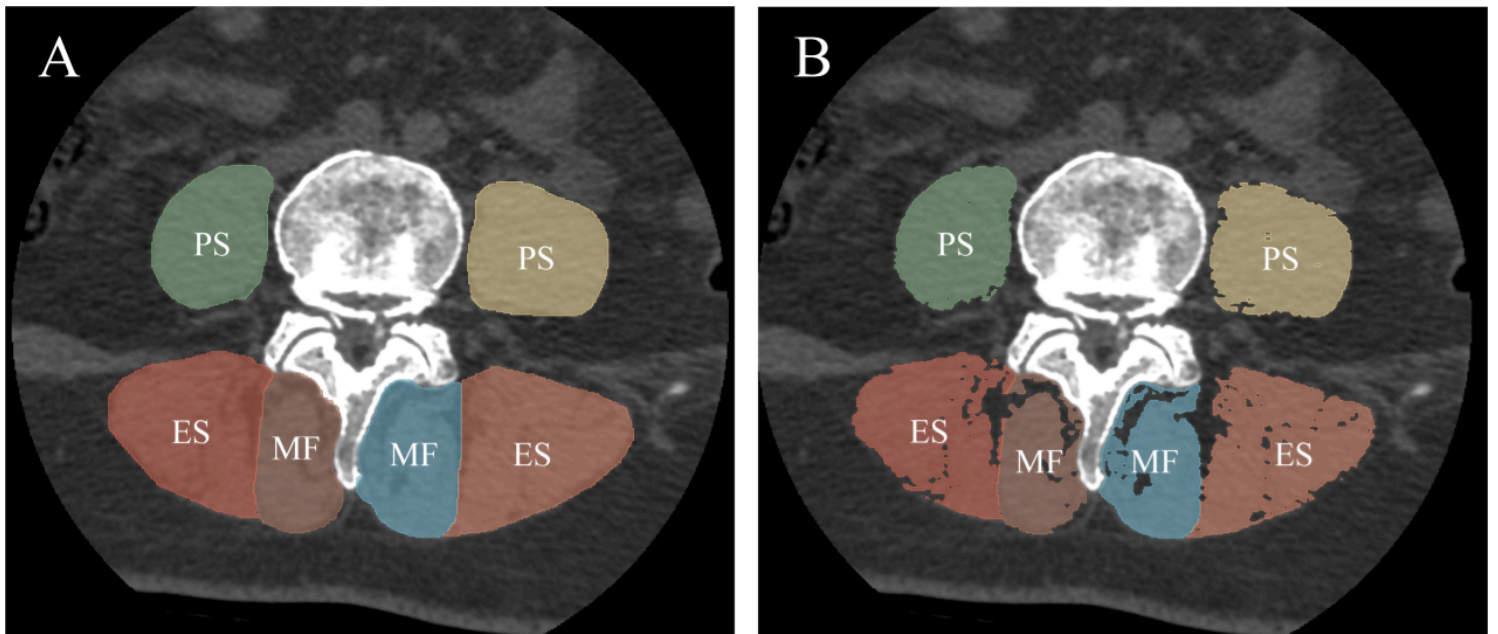


**Figure 3**

Example of automatic paraspinal muscle segmentation and volume measurement based on grayscale thresholds at the L4-L5 level. A: Automatic segmentation mask generated by the lightweight 2D U-Net model. B: Based on the segmentation mask, the CT value threshold of muscle tissue was restricted to

-29 to +150 HU to exclude fat tissue and calculate the effective muscle volume. MF, multifidus; ES, erector spinae; PS, psoas muscle.

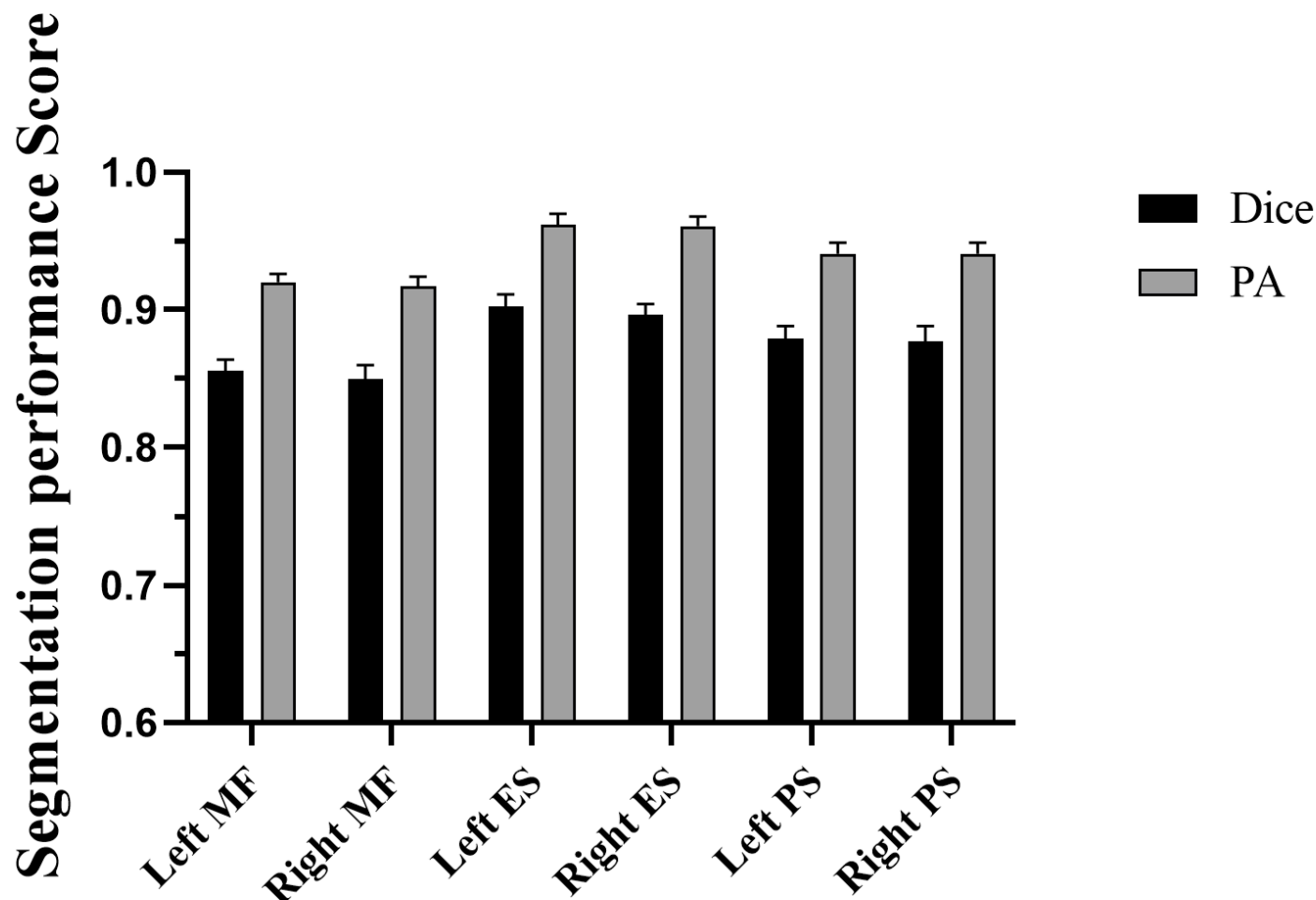
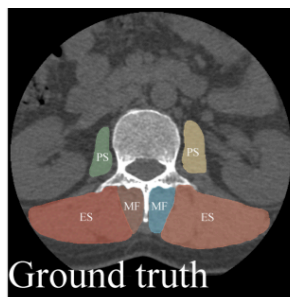


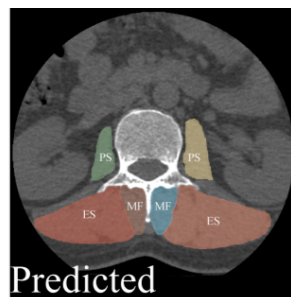
**Figure 4**

Comparison of Dice and PA for the paraspinal muscle segmentation model. Dice: Dice coefficients; pixel accuracy: PA.

**L1**

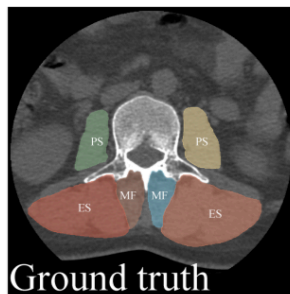


Ground truth

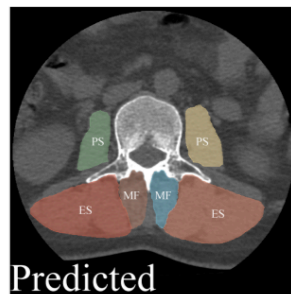


Predicted

**L2**

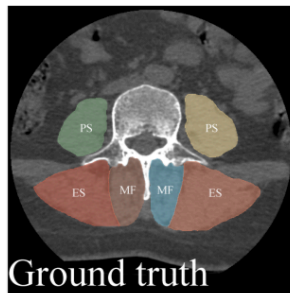


Ground truth

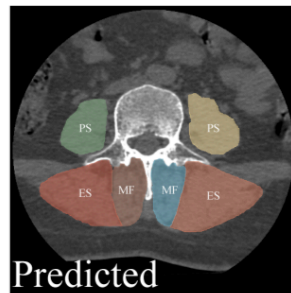


Predicted

**L3**

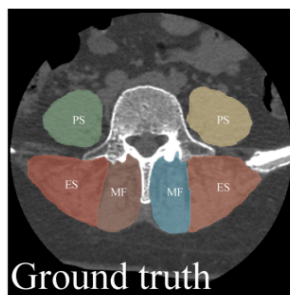


Ground truth

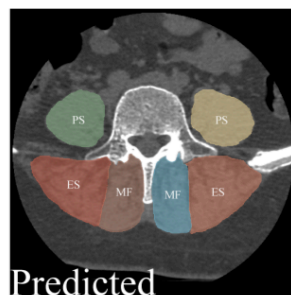


Predicted

**L4**

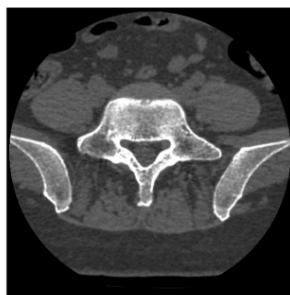
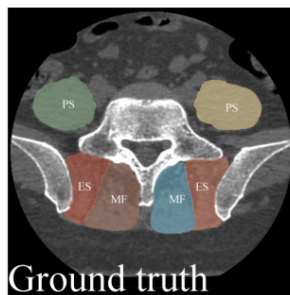


Ground truth

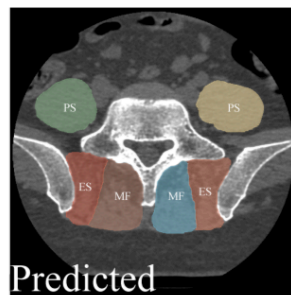


Predicted

**L5**



Ground truth



Predicted

**Figure 5**

Comparison of CT images, manual segmentation, and model-automatic segmentation results of paraspinal muscles at lumbar L1–L5 segments.