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Assessing radiological factors: the role of pelvic tilt in surgery for geriatric patients with degenerative spinal disorders

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Abstract

Background Adult Degenerative Spinal Disorders (ADSD) pose significant clinical challenges, especially among elderly population. Currently, the decision-making process regarding surgical intervention primarily relies on the severity of clinical symptoms. However, there is no well-established standard for determining which patients are appropriate candidates for surgery. In addition, there is a noticeable lack of research focusing on the radiological assessment of patients to determine the necessity for surgical intervention. Hence, this study aims to explore potential influencing factors for surgery in terms of radiological features.

Methods A retrospective analysis was conducted on 381 geriatric patients with ADSD. All patients underwent radiological assessments utilizing the EOS 2D/3D imaging system. We collected demographic information and a comprehensive set of 20 radiological features, including pelvic tilt (PT), sacral slope, thoracic kyphosis, pelvic incidence (PI), lumbar lordosis (LL), T1 pelvic angle, global tilt, pelvic shift, and the alignment of the C7 plumb line relative to the Center Sacral Vertical Line (CSVL). Logistic regression analysis was employed to identify risk factors associated with surgical intervention, while Restricted Cubic Spline (RCS) curve analysis was used to examine the relationship between risk factors and surgical decisions.

Results The overall surgical intervention rate among the cohort was 29.4%. Subgroup analyses indicated that patients exhibiting higher PT ($P < 0.001$), higher PI ($P = 0.007$), greater PI-LL ($P = 0.001$), reduced lower lumbar lordosis ($P = 0.048$), elevated T1 pelvic angle ($P < 0.001$), increased global tilt ($P < 0.001$), and greater pelvic shift ($P = 0.025$) were more likely to pursue surgical treatment. Binary logistic regression confirmed these trends, and multinomial logistic regression revealed that PT remained significantly correlated with the decision to undergo surgery (Odds Ratio [OR] = 1.085, 95% Confidence Interval [CI]: 1.028–1.146, $P = 0.003$). When PT was classified into a binary variable based on the optimal threshold, patients with a PT exceeding 18.4 degree were 3.142 times (95% CI: 1.611–6.129) more likely to undergo surgery compared to those with PT at or below 18.4 degree ($P < 0.001$) after adjusting for potential confounding factors. In a four-class classification, patients with PT > 18.0 degree and ≦ 25.3 degree were 3.903

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times (95% CI: 1.588–9.591) more likely, while those with PT > 25.3 degree were 4.987 times (95% CI: 1.472–16.893) more likely to require surgery compared to patients with PT ≦ 11.4 degree ($P = 0.003$ and $P = 0.010$ respectively) after adjusting for potential confounding factors. The RCS analysis demonstrated a significant association between PT and the predicted probability of surgery after adjusting for all other variables, but no non-linear relationships were identified, indicating that the association between PT and surgery was primarily linear across the different models analyzed.

Conclusions The findings of this study suggest that PT is a critical radiological factor associated with undergoing surgery in geriatric patients with ADSD. Higher degrees of PT significantly correlate with an increased likelihood of surgical intervention. These insights may assist clinicians in evaluating surgical options for patients with ADSD and underline the importance of radiological assessments in decision-making processes.

Trial registration This study was registered at the Chinese Clinical Trial Registry (Registration ID: ChiCTR2400090679, retrospectively registered).

Keywords Degenerative spinal disorders, Surgery candidacy, Radiological features, Influencing factor, PT

Introduction

Adult Degenerative Spinal Disorders (ADSD) are among the most prevalent musculoskeletal conditions affecting the aging population, with a particularly profound impact on geriatric individuals [1, 2]. As life expectancy increases globally, the prevalence of ADSD is expected to rise, making it a significant public health concern. These disorders, characterized by progressive degeneration of the spinal structures, can result in debilitating back pain, reduced mobility, and diminished quality of life [3, 4]. Elderly patients are disproportionately affected by spinal degenerative conditions due to age-related changes, including reduced bone density, degeneration of muscles and ligaments, and intervertebral disc degeneration. These changes lead to a cascade of pathological processes, such as abnormal mechanical stress, inflammatory responses, muscle and ligament strain, spinal instability, and nerve compression, which collectively contribute to the development and progression of chronic pain and functional impairment. The resulting complications, including spinal stenosis, spondylolisthesis, and deformities, often lead to severe functional impairments, social isolation, and increased healthcare utilization [5, 6], underscoring the need for effective management strategies in this vulnerable population.

Despite advances in spinal surgery, there remains a lack of clear guidelines regarding surgical intervention for ADSD [7]. This uncertainty mainly stems from the complex interplay of patient-specific factors, including comorbidities, functional status, and imaging findings. While numerous studies have demonstrated a relationship between preoperative radiological features and postoperative outcomes [8–10], the association between these features and the decision to undergo surgery remains inadequately defined. Spino-pelvic radiological characteristics, in particular, play a critical role in understanding sagittal alignment and compensatory mechanisms, offering valuable insights into surgical planning [11, 12]. However, the relationship between these factors and final surgery decision-making has not been fully elucidated. The ability to identify specific imaging parameters that correlate with surgical necessity could bridge this gap, providing a more evidence-based approach to treatment.

Therefore, this study aims to address the challenge by investigating radiological factors that are closely associated with eventually undergoing surgery in geriatric patients with ADSD. Specifically, the research focuses on analyzing the relationship between spino-pelvic parameters and surgical decision-making, with an emphasis on pelvic tilt (PT) [13, 14] and its implications for clinical practice. By identifying key radiological indicators and their predictive value for surgery, this study seeks to enhance the decision-making process, ensuring more targeted and effective interventions for elderly patients suffering from ADSD.

Patients and methods

Patients

This retrospective study included 381 patients who presented with chief complaints of low back pain, lower extremity radiculopathy, or intermittent claudication to the Department of Spine Surgery at the First Medical Center of the PLA General Hospital between September 2022 and August 2024. Physical examination revealed tenderness over the spinous processes or paravertebral muscles, as well as positive nerve root tension signs such as the straight leg raise test or femoral nerve stretch test. To evaluate spinal, pelvic, and lower extremity osseous and morphological changes, all patients underwent examination of EOS imaging system (EOS Imaging, Paris, France) which reveals global imbalance, abnormal spinal alignment, and reduced intervertebral disc space. Additionally, a subset of patients underwent further MR imaging as needed to assess disc degeneration and spinal canal dimensions. Based on the integration of clinical symptoms, physical examination findings, and imaging characteristics, the patients were diagnosed with adult degenerative spinal disorders (ADSD), including lumbar spinal stenosis, lumbar disc herniation, spondylolistheses, and degenerative scoliosis. Inclusion criteria for the study required patients with ADSD, aged 60 years or older, and to have complete radiological data available for analysis. Patients were excluded if they had a history of prior spinal surgery, congenital dysplasia of the hip joint, congenital scoliosis, idiopathic scoliosis, neuromuscular disorders, traumatic injuries, poor alignment and positioning following pelvic and lower limb surgeries, rheumatoid arthritis, infectious arthritis of the hip, congenital deformities of the pelvis and lower limbs, or spinal tuberculosis. A flowchart detailing the patient selection process is illustrated in Fig. 1.

This study was approved by the Ethics Committee of the First Medical Center of the PLA General Hospital (approval number: S2024-556-01) and was also registered with the Chinese Clinical Trial Registry (registration number: ChiCTR2400090679). All procedures adhered to the principles outlined in the Declaration of Helsinki and complied with relevant institutional and national guidelines. Due to the retrospective nature of the study, informed consent was waived, as approved by the ethics committee.

Collection of radiological features

We collected variables that included a variety of anatomical and clinical measurements relevant to the spinal and lower limb alignment. These variables encompassed demographic factors such as sex and age, as well as specific radiological measurements, including Pelvic Tilt (PT), Sacral slope, thoracic kyphosis, and various indices including Pelvic Incidence (PI), Lumbar Lordosis (LL), and the PI and LL mismatch (PI-LL). Additional parameters such as lower lumbar lordosis, lordosis distribution index, chin-brow vertical angle, T1 pelvic angle, and Sagittal Vertical Axis (SVA) were collected to understand spinal alignment. The distance from the Cranial SVA to the center of the hip (CrSVA-H), global tilt, and pelvic shift were further recorded to elaborate on spino-pelvic

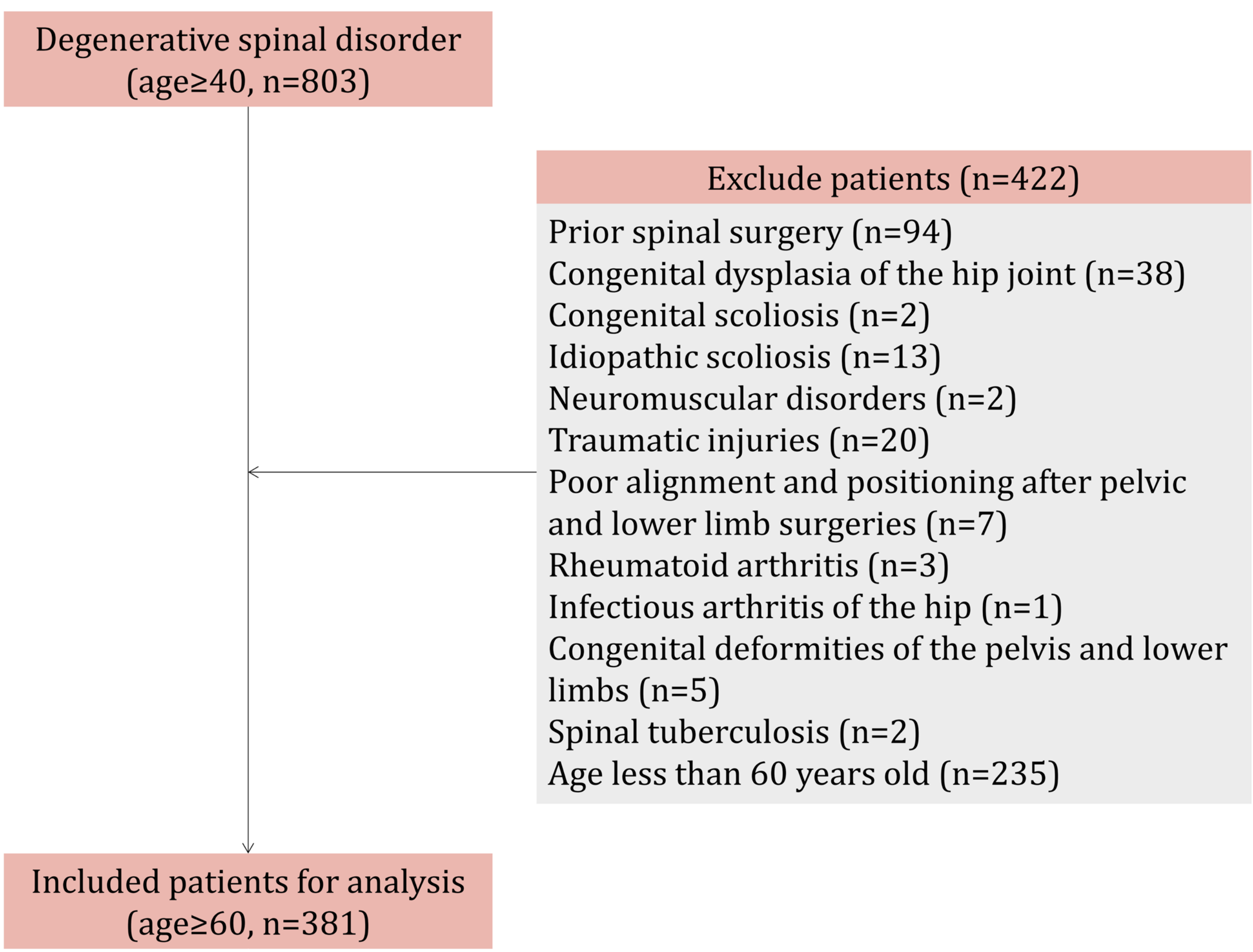

Fig. 1 Patient's flowchart

alignment, while dynamic measurements such as knee flexion angle, femoral obliquity angle, and coronal T1 pelvic tilt (CTPT) angle were collected to provide insights into joint positioning. Lastly, the Cobb angle and C7-CSVL (Cervical 7 - C7 SVA) and hip-knee ankle angle were collected to assess overall postural alignment and biomechanics.

Radiological characteristics were captured from patients using the EOS 2D/3D imaging system (EOS Imaging, Paris, France). This advanced technology produces digital radiographic images of skeletal structures while significantly minimizing radiation exposure. Specifically designed for orthopedic applications, the system utilizes exceptionally sensitive detection methods. One of its key features is the ability to simultaneously acquire full-body, weight-bearing orthogonal digital biplanar images. Research has consistently shown that the EOS system excels in providing precise, reliable, and reproducible measurements of spinal curvature, making it a valuable tool in the field of orthopedics [15]. Subsequently, the radiological characteristics were measured by two observers with over 5 years of experience in spinal surgery using Surgimap (Nemaris Inc., Ver 2.3.2.1, NY USA), In cases where interobserver discrepancies were identified, the measurements were repeated by both observers, followed by a thorough cross-verification process to establish a consensus on the final results.

Definition of the main radiological features

The PT refers to the angle formed between a ray extending from the center of the femoral heads to the midpoint of the sacral plate and a vertically oriented line. The sacral slope measures the angle between the horizontal plane and the sacral plate itself [16]. PI is determined by the angle formed between a line perpendicular to the midsection of the sacral plate and a line that connects this midpoint to the axis of the femoral head [17]. Thoracic kyphosis is defined as the angle between the superior endplate of the fourth thoracic vertebra (T4) and the inferior endplate of the twelfth thoracic vertebra (T12), while LL is the angle between the superior endplate of L1 and the endplate of S1. The PI-LL refers to the difference between PI and LL. Lower lumbar lordosis, assessed via lumbar lateral X-ray using the Cobb method, is the angle between the superior endplates of L4 and S1. The lordosis distribution index is expressed as a percentage, representing the ratio of lower lumbar lordosis to total lumbar lordosis. The chin-brow vertical angle is formed by a vertical line and a line extending from the forehead to the chin. The T1 pelvic angle is calculated between the line from the axis of the femoral head to the centroid of T1 and the line extending from the femoral head axis to the midpoint of the S1 superior endplate. The sagittal vertical axis measures the distance in millimeters from the C7 plumb line to the posterior superior corner of the S1 upper margin. CrSVA-H denotes the distance from the Cranial SVA to the hip centers, which is the distance from a plumb line originating from the cranial center of mass to the hip center. Global tilt is defined as the angle formed where two lines intersect: one extending from C7 to the center of the sacral endplate, and the other from the femoral heads to the center of the sacral endplate. Pelvic shift describes the sagittal displacement between the posterosuperior corner of the sacrum and the anterior cortex of the distal tibia. The knee flexion angle is the angle between the mechanical axes of the femur and tibia in the sagittal plane. The femoral obliquity angle is the angle between the femoral axis and a vertical line. The coronal T1 pelvic tilt angle is defined by the angle between a vertical line and the line connecting the midpoint of the S1 endplate to the centroid of T1. The Cobb angle represents the angle formed by the upper endplate of the most inclined vertebrae and lower endplates of the most inclined vertebrae body below involved in a curvature. Finally, C7-CSVL assesses the alignment of the C7 plumb line concerning the center sacral vertical line, while the hip-knee-ankle angle indicates the angle between the mechanical axes of the femur and tibia.

Surgical indications

In this study, the surgical patients underwent posterior lumbar laminectomy, discectomy, cage implantation, interbody fusion, and internal fixation. In some cases, the internal fixation was extended to the thoracic spine for deformity corrective or stabilization purposes. The decision to recommend surgery was primarily based on several critical indications. Foremost among these was the presence of persistent and debilitating pain that significantly disrupts daily activities. Additionally, patients exhibiting neurological deficits—such as progressive weakness or numbness caused by nerve compression—were closely evaluated. Spinal instability, which poses a considerable risk of further neurological harm, was another key factor in determining the need for surgical intervention. Moreover, when patients had exhausted all non-surgical options, including physical therapy, medications, and injections, without achieving any positive outcomes, the possibility of surgical treatment became more viable. Another important consideration was the presence of progressive spinal deformities like scoliosis or kyphosis. These conditions not only led to functional impairments but also negatively impacted the overall quality of life, thereby necessitating surgical procedures aimed at restoring both spinal stability and alignment.

Statistical analysis

In this study, qualitative data were presented as proportions, while quantitative data were reported as means with standard deviations. For inter-group comparisons, qualitative data were analyzed using the Chi-square test, and quantitative data were evaluated using the t-test or Wilcoxon rank test. Variables with a *p*-value less than 0.10 in the group analysis were included in logistic regression analysis to identify risk factors for surgery. The optimal cut-off value for PT was determined using Receiver Operating Characteristic (ROC) curve analysis. Based on this cut-off point, PT was subsequently converted into binary classifications according to the optimal threshold, as well as into a four-class classification system based on quartiles. Model 1 employed univariate logistic regression analysis for both binary and four-class classifications related to surgery. Model 2 performed logistic regression analysis after controlling for age and sex. Model 3 further adjusted for age, sex, PI, lower lumbar lordosis, PI-LL, T1 pelvic angle, global tilt, pelvic shift, and the 7-CSVL. The AUC analysis was utilized to assess the predictive performance of PT for surgical intervention. Lastly, Restricted Cubic Spline (RCS) curve analysis was conducted to explore the detailed relationship between PT and the predicted probability of surgical decisions. In this analysis, the crude model did not control for any other variables; Model 1 adjusted for age and sex; Model 2 controlled for age, sex, PI, lower lumbar lordosis, PI-LL, T1 pelvic angle, global tilt, pelvic shift, and the 7-CSVL; and Model 3 accounted for all other variables considered in this study. All statistical analyses were conducted using R software (version 4.1.2), with a significance threshold set at $P<0.05$.

Table 1 Patient's clinical baseline characteristics

Characteristics	Overall
n	381
Sex (%)	
Female	109 (28.6)
Male	272 (71.4)
Age (years, mean (SD))	68.91 (6.01)
PT (°, mean (SD))	18.15 (10.52)
Sacral slope (°, mean (SD))	30.27 (12.00)
Thoracic kyphosis (°, mean (SD))	24.52 (20.53)
PI (°, mean (SD))	48.44 (11.83)
LL (°, mean (SD))	39.09 (19.71)
PI-LL (mean (SD))	9.35 (18.18)
Lower lumbar lordosis (°, mean (SD))	31.37 (11.57)
Lordosis distribution index (mean (SD))	1.52 (7.91)
Chin-brow vertical angle (°, mean (SD))	-1.77 (7.58)
T1 pelvic angle (°, mean (SD))	15.98 (11.40)
SVA (mm, mean (SD))	30.76 (46.81)
CrSVA-H (mm, mean (SD))	2.19 (50.68)
Global tilt (°, mean (SD))	20.63 (13.87)
Pelvic shift (mm, mean (SD))	28.82 (33.36)
Knee flexion angle (°, mean (SD))	10.22 (8.04)
Femoral obliquity angle (°, mean (SD))	3.12 (4.90)
Coronal T1 pelvic tilt angle (°, mean (SD))	1.70 (1.72)
Cobb angle (°, mean (SD))	13.29 (11.35)
C7-CSVL (mm, mean (SD))	12.42 (11.26)
Hip-knee ankle angle (°, mean (SD))	3.53 (4.41)
Surgery (%)	
No	269 (70.6%)
Yes	112 (29.4%)

SD, Standard Deviation; PT, Pelvic Tilt; PI, Pelvic Incidence; LL, Lumbar Lordosis; SVA, Sagittal Vertical Axis; CrSVA-H, The distance from the Cranial Sagittal Vertical Axis (CrSVA) to the center of the Hip; C7-CSVL, The alignment of the C7 plumb line in relation to the Center Sacral Vertical Line (CSVL)

Results

Baseline characteristics

The clinical baseline characteristics of the study population, which included 381 patients, are summarized in Table 1. The cohort consisted of 28.6% females and 71.4% males, with an average age of 68.91 years (SD: 6.01). Key pelvic and spinal alignment measurements revealed a mean PT of 18.15 degrees, a sacral slope of 30.27 degrees, and thoracic kyphosis averaging 24.52 degrees. The mean PI was 48.44 degrees, with LL averaging 39.09 degrees and a PI-LL of 9.35 degrees. Additional measurements included a mean lower lumbar lordosis of 31.37 degrees and a lordosis distribution index of 1.52. The chin-brow vertical angle averaged – 1.77 degrees, while the T1 pelvic angle was 15.98 degrees. The SVA measured 30.76 mm, with a CrSVA-H of 2.19 mm. The global tilt averaged 20.63 degrees, and pelvic shift measured 28.82 mm. Knee flexion angle averaged 10.22 degrees, and femoral obliquity angle was 3.12 degrees. The coronal T1 PT angle was 1.70 degrees, with a Cobb angle of 13.29 degrees and a C7-CSVL of 12.42 mm. The hip-knee ankle angle averaged 3.53 degrees. Regarding surgical history, 70.6% of patients did not undergo surgery, while 29.4% had surgical intervention. These patients generally underwent decompression at one to three levels. The majority of patients underwent two-segment vertebral fixation, comprising 50 cases (44.6%), with a declining trend observed as the number of fixed vertebral segments increased (Fig. 2). This above data provided a comprehensive overview of the clinical characteristics and demographic distribution of the patient population studied.

Subgroup analysis stratified by surgery

Table 2 summarizes the comparison of clinical characteristics between patients who underwent surgery and those who did not. Among the 269 patients who did not undergo surgery and the 112 patients who had surgery, significant differences were observed in several key measurements. The PT was notably higher in the surgical group, with a mean of 21.86 degrees compared to 16.61 degrees in the non-surgical group ($P<0.001$). Additionally, PI was significantly greater in the surgical group, averaging 50.96 degrees versus 47.40 degrees in the non-surgical group ($P=0.007$). The difference in PI-LL was

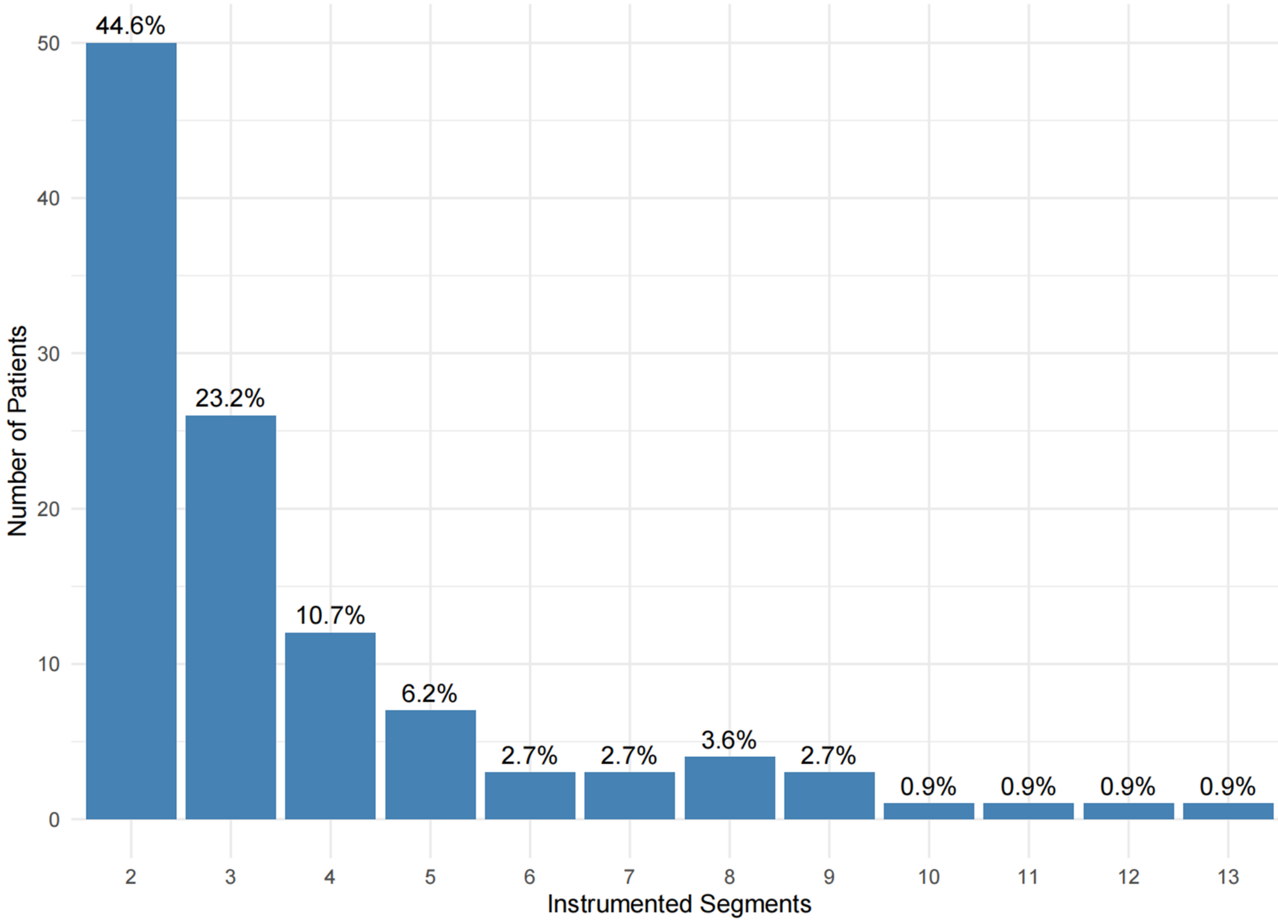

Fig. 2 Bar graph of instrumented segments of spinal surgery

also significant, with means of 14.17 degrees for the surgical group and 7.35 degrees for the non-surgical group ($P = 0.001$). Lower lumbar lordosis measurements showed a significant difference as well, with the surgical group averaging 29.55 degrees compared to 32.12 degrees in the non-surgical group ($P = 0.048$). Furthermore, the T1 pelvic angle was significantly higher in the surgical cohort, averaging 19.25 degrees compared to 14.62 degrees in the non-surgical group ($P < 0.001$). Similar trend was also observed in global tilt, with 24.46 mm in the surgical group and 19.03 mm in the non-surgical group ($P < 0.001$). Pelvic shift was also significantly greater in the surgical group, with a mean of 34.74 mm versus 26.35 mm in the non-surgical patients ($P = 0.025$). Lastly, the comparison of the C7-CSVL nearly approached significance, with means of 13.94 mm in the surgical group and 11.79 mm in the non-surgical group ($P = 0.089$). These findings suggested significant differences in pelvic and spinal alignment characteristics between surgical and non-surgical candidates.

Risk factor analysis for surgery

In the binary logistic regression, PT emerged as a significant predictor, with an odds ratio (OR) of 1.051 (95% CI: 1.027–1.074, $P < 0.001$), indicating that for each degree increase in PT, the odds of being a surgical candidate increased (Table 3). Additionally, PI also showed significance with an OR of 1.026 (95% CI: 1.007–1.045, $P = 0.008$). Lower lumbar lordosis was marginally significant, with an OR of 0.981 (95% CI: 0.963–1.000, $P = 0.049$), suggesting that increased lower lumbar lordosis may be associated with decreased likelihood of surgical candidacy. The PI-LL demonstrated an OR of 1.021 (95% CI: 1.008–1.033, $P = 0.001$), and the T1 pelvic angle had an OR of 1.037 (95% CI: 1.016–1.057, $P < 0.001$). Global tilt was significant with an OR of 1.029 (95% CI: 1.012–1.046, $P = 0.001$), while pelvic shift had an OR of 1.008 (95% CI: 1.001–1.014, $P = 0.026$). The C7-CSVL approached significance with an OR of 1.016 (95% CI: 0.997–1.036, $P = 0.092$). However, in the multinomial logistic regression analysis, only the OR for PT (OR: 1.085, 95% CI: 1.028–1.146, $P = 0.003$) remained significant (Fig. 3), while other radiological variables were not statistically significant. These findings identified several

Table 2 A comparison of clinical characteristics stratified by surgery among patients

Characteristics	Surgery		*p*
	No	Yes	
n	269	112	
Sex (%)			0.909
Female	76 (28.3)	33 (29.5)	
Male	193 (71.7)	79 (70.5)	
Age (years, mean (SD))	68.70 (6.25)	69.41 (5.39)	0.295
PT (°, mean (SD))	16.61 (10.62)	21.86 (9.32)	< 0.001
Sacral slope (°, mean (SD))	30.80 (12.50)	29.02 (10.66)	0.189
Thoracic kyphosis (°, mean (SD))	25.59 (22.88)	21.93 (12.98)	0.113
PI (°, mean (SD))	47.40 (11.89)	50.96 (11.34)	0.007
LL (°, mean (SD))	40.05 (20.02)	36.79 (18.85)	0.142
PI-LL (°, mean (SD))	7.35 (18.44)	14.17 (16.64)	0.001
Lower lumbar lordosis (°, mean (SD))	32.12 (11.99)	29.55 (10.32)	0.048
Lordosis distribution index (mean (SD))	1.17 (3.27)	2.36 (13.69)	0.181
Chin-brow vertical angle (°, mean (SD))	-1.78 (7.36)	-1.76 (8.11)	0.981
T1 pelvic angle (°, mean (SD))	14.62 (11.58)	19.25 (10.27)	< 0.001
SVA (mm, mean (SD))	29.69 (48.67)	33.33 (42.09)	0.489
CrSVA-H (mm, mean (SD))	4.79 (52.14)	-4.06 (46.63)	0.120
Global tilt (°, mean (SD))	19.03 (14.12)	24.46 (12.48)	< 0.001
Pelvic shift (mm, mean (SD))	26.35 (34.21)	34.74 (30.54)	0.025
Knee flexion angle (°, mean (SD))	9.98 (8.18)	10.79 (7.71)	0.370
Femoral obliquity angle (°, mean (SD))	2.93 (5.16)	3.59 (4.21)	0.225
Coronal T1 pelvic tilt angle (°, mean (SD))	1.68 (1.67)	1.76 (1.84)	0.683
Cobb angle (°, mean (SD))	13.57 (11.71)	12.63 (10.45)	0.464
C7-CSVL (mm, mean (SD))	11.79 (11.31)	13.94 (11.05)	0.089
Hip-knee ankle angle (°, mean (SD))	3.58 (4.65)	3.40 (3.81)	0.717

SD, Standard Deviation; PT, Pelvic Tilt; PI, Pelvic Incidence; LL, Lumbar Lordosis; SVA, Sagittal Vertical Axis; CrSVA-H, The distance from the Cranial Sagittal Vertical Axis (CrSVA) to the center of the Hip; C7-CSVL, The alignment of the C7 plumb line in relation to the Center Sacral Vertical Line (CSVL)

Table 3 Logistic regression analysis of clinical characteristics for surgery

Characteristics	Binary logistic regression		Multinomial logistic regression	
	OR (95% CI)	*P*	OR (95% CI)	*P*
(Intercept)	NA	NA	0.148 (0.043–0.507)	0.002
PT	1.051 (1.027–1.074)	< 0.001	1.085 (1.028–1.146)	0.003
PI	1.026 (1.007–1.045)	0.008	1.012 (0.987–1.037)	0.341
Lower lumbar lordosis	0.981 (0.963-1.000)	0.049	0.991 (0.967–1.016)	0.488
PI-LL	1.021 (1.008–1.033)	0.001	1.006 (0.978–1.035)	0.660
T1 pelvic angle	1.037 (1.016–1.057)	< 0.001	1.188 (0.864–1.632)	0.289
Global tilt	1.029 (1.012–1.046)	0.001	0.828 (0.642–1.068)	0.146
Pelvic shift	1.008 (1.001–1.014)	0.026	1.003 (0.994–1.012)	0.473
C7-CSVL	1.016 (0.997–1.036)	0.092	1.013 (0.992–1.035)	0.214

NA, Not Applicable; PT, Pelvic Tilt; PI, Pelvic Incidence; C7-CSVL, The alignment of the C7 plumb line in relation to the Center Sacral Vertical Line (CSVL)

clinical characteristics that may influence surgical candidacy, and demonstrated that PT was an independent risk factor for surgery.

Evaluation of categorical PT for surgery

Table 4 details the results of the logistic regression analysis examining the impact of categorical PT on the likelihood of undergoing surgery. The analysis presents three models, each adjusting for different sets of variables. When PT was classified into a binary variable based on the optimal threshold, in all models, a PT greater than 18.4 degrees significantly increased the odds of being a surgical candidate. In Model 1, the OR was 3.117 (95% CI: 1.961–4.955, $P < 0.001$) for patients with PT > 18.4 degree compared to the reference group (PT ≦ 18.4 degree). This finding was consistent across Models 2 and 3, with ORs of 3.209 (95% CI: 1.987–5.183, $P < 0.001$) after controlling age and sex, and 3.142 (95% CI: 1.611–6.129, $P = 0.001$) after controlling age, sex, PI, lower lumbar lordosis, PI-LL, T1 pelvic angle, global title, pelvic

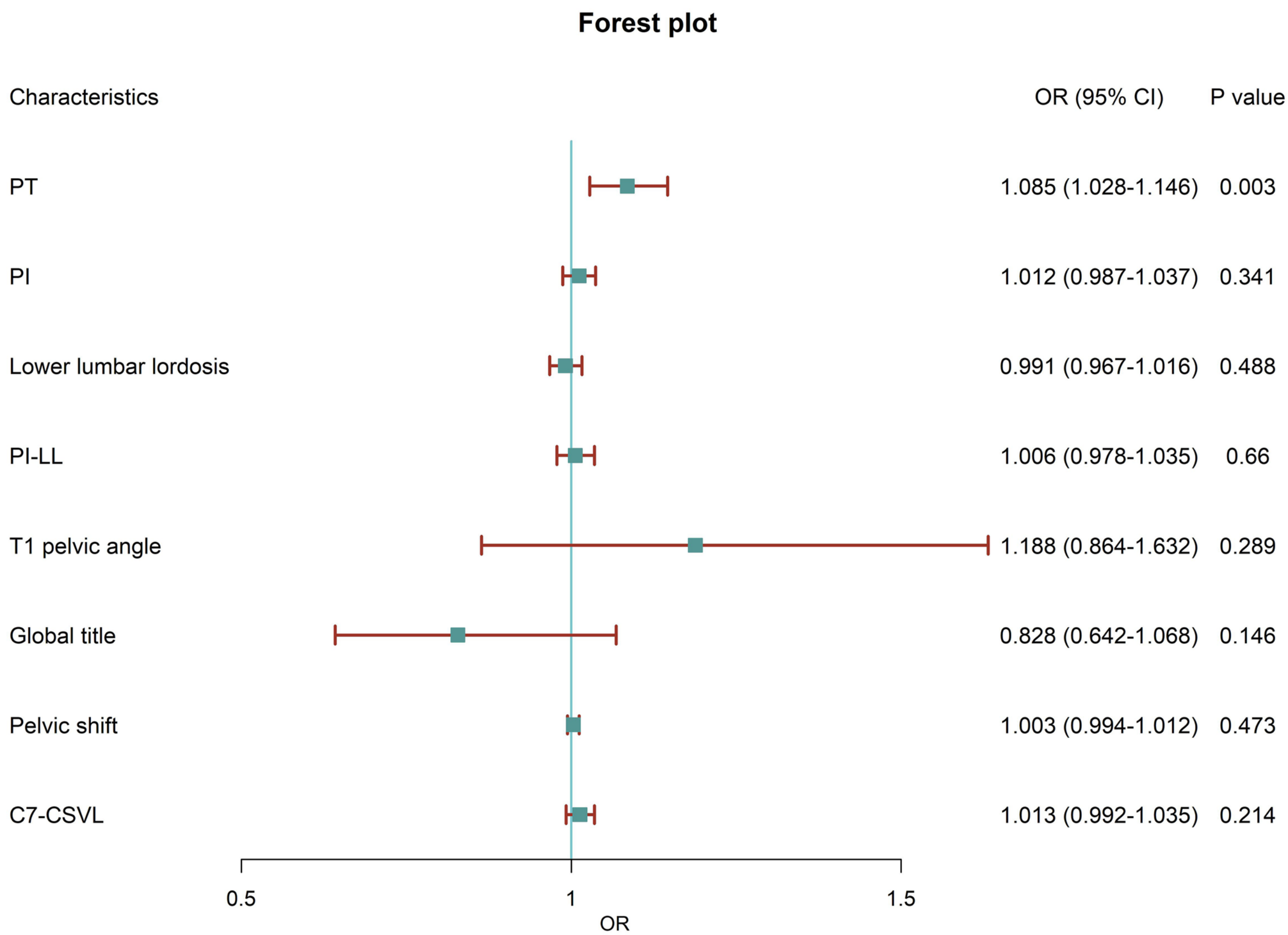

Fig. 3 Forest plot of radiological features for surgery. PT, Pelvic Tilt; PI, Pelvic Incidence; C7-CSVL, The alignment of the C7 plumb line in relation to the Center Sacral Vertical Line (CSVL)

shift, and C7-CSVL. When analyzing PT across four classifications based on quartile thresholds, PT > 11.4 degree and ≦ 18.0 degree did not show significant differences in surgical candidacy, as indicated by ORs of 1.298 (95% CI: 0.623–2.708, $P = 0.486$) in Model 1, 1.349 (95% CI: 0.642–2.834, $P = 0.430$) in Model 2, and 1.408 (95% CI: 0.625–3.175, $P = 0.409$) in Model 3. However, for patients with PT > 18.0 degree and ≦ 25.3 degree, the risk significantly increased, with ORs of 3.269 (95% CI: 1.663–6.428, $P = 0.001$) in Model 1, 3.502 (95% CI: 1.732–7.078, $P < 0.001$) in Model 2, and 3.903 (95% CI: 1.588–9.591, $P = 0.003$) in Model 3. Patients with PT > 25.3 degree had the highest odds of being surgical candidates, with ORs of 3.796 (95% CI: 1.935–7.448, $P < 0.001$) in Model 1, 4.074 (95% CI: 2.024–8.198, $P < 0.001$) in Model 2, and 4.987 (95% CI: 1.472–16.893, $P = 0.010$) in Model 3. The analysis indicated that higher PT was consistently associated with an increased likelihood of surgical candidacy, particularly at thresholds above 18.4 degree and 25.3 degree, irrespective of the adjustment for confounding variables.

Prediction performance of PT for surgery

The prediction performance of PT for determining surgical candidacy across different classification methods (Table 5). The AUC for the continuity measure of PT was 0.652 (95% CI: 0.594–0.711) (Fig. 4), indicating a fair level of discrimination, while the binary classification yielded an AUC of 0.638 (95% CI: 0.585–0.690) (Fig. 5A) and the four-class classification had an AUC of 0.647 (95% CI: 0.589–0.705) (Fig. 5B), suggesting moderate predictive ability across all methods. Accuracy was consistent at 0.625 for both the continuity and binary classifications, with slightly lower accuracy at 0.614 for the four-class classification. Specificity was measured at 0.606 for both the continuity and binary classifications, indicating that approximately 60.6% of non-surgical candidates were correctly identified using the PT variable alone, while the four-class classification showed a slight decrease to 0.584. Sensitivity was highest for the four-class classifications at 0.688, reflecting better identification of actual surgical candidates. The Youden index, which combines sensitivity and specificity, was 1.276 for both the continuity and binary classifications, and 1.271 for the

Table 4 Logistic regression analysis of PT for surgery

Characteristics	OR	95% CI		P
		LL	UL	
PT (Model 1)				
≦18.4°	Ref.			
> 18.4°	3.117	1.961	4.955	< 0.001
PT (Model 2)				
≦18.4°	Ref.			
> 18.4°	3.209	1.987	5.183	< 0.001
PT (Model 3)				
≦18.4°	Ref.			
> 18.4°	3.142	1.611	6.129	0.001
PT (Model 1)				
≦11.4°	Ref.			
> 11.4° and ≦18.0°	1.298	0.623	2.708	0.486
> 18.0° and ≦25.3°	3.269	1.663	6.428	0.001
> 25.3°	3.796	1.935	7.448	< 0.001
PT (Model 2)				
≦11.4°	Ref.			
> 11.4° and ≦18.0°	1.349	0.642	2.834	0.430
> 18.0° and ≦25.3°	3.502	1.732	7.078	< 0.001
> 25.3°	4.074	2.024	8.198	< 0.001
PT (Model 3)				
≦11.4°	Ref.			
> 11.4° and ≦18.0°	1.408	0.625	3.175	0.409
> 18.0° and ≦25.3°	3.903	1.588	9.591	0.003
> 25.3°	4.987	1.472	16.893	0.010

PT, Pelvic Tilt; OR, Odds Ratio; LL, Lower Limit; UL, Upper Limit; CI, Confident Interval; Ref., Reference

Note: The optimal threshold of the continuous variable PT was 18.4°, leading to the development of a binary classification (≦18.4° vs. >18.4°). Additionally, the first quartile of PT was 11.4°, the median was 18.0°, and the third quartile was 25.3°, resulting in the establishment of a four-class classification (≦11.4° vs. >11.4°, ≦18.0° vs. >18.0°, and ≦25.3° vs. >25.3°)

Model 1: adjusted for none variables;

Model 2: adjusted for age and sex;

Model 3: adjusted for age, sex, PI, lower lumbar lordosis, PI-LL, T1 pelvic angle, global title, pelvic shift, and C7-CSVL

Table 5 Prediction performance of PT for surgery

Metrics	PT		
	Continuity	Binary classification	Four-class classification
AUC (95% CI)	0.652 (0.594–0.711)	0.638 (0.585–0.690)	0.647 (0.589–0.705)
Accuracy	0.625	0.625	0.614
Specificity	0.606	0.606	0.584
Sensitivity	0.670	0.670	0.688
Precision	0.414	0.414	0.407
Youden index	1.276	1.276	1.271

PT, Pelvic Tilt; AUC, Area Under the Curve; CI, Confident Interval

Note: Binary classification was developed using the optimal threshold of the continuous variable PT; four-class classification was established based on the interquartile range

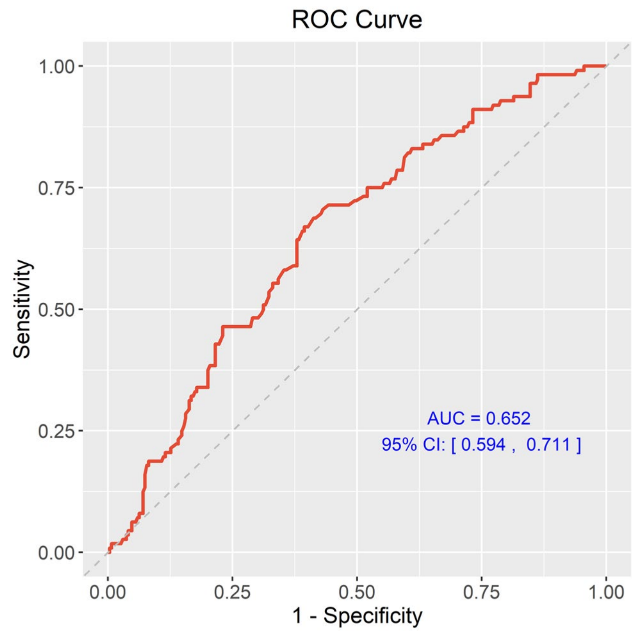

Fig. 4 Area under the curve analysis of the continuous variable of pelvic tilt for surgery

four-class classification, indicating fair overall performance in distinguishing between surgical and non-surgical candidates.

The relationship between PT and surgery

To further explore the relationship between PT and the predicted probability of undergoing surgery, we conducted an analysis using four distinct models, each adjusted for varying sets of variables. In the unadjusted model, the overall *P* value was <0.001, indicating a significant association between PT and the predicted probability of surgery; however, the non-linear *P* value was 0.085 (Fig. 6A). In Model 1, which adjusted for age and sex, the overall *P* value remained <0.001, while the non-linear *P* value decreased slightly to 0.078 (Fig. 6B). Model 2 incorporated additional adjustments for age, sex, PI, lower lumbar lordosis, PI-LL, T1 pelvic angle, global tilt, pelvic shift, and C7-CSVL. In this model, the overall *P* value was 0.007, and the non-linear *P* value was 0.150 (Fig. 6C). Finally, in model 3, which adjusted for all other, we found an overall value of 0.006, while the non-linear P was 0.131 (Fig. 6D). These results collectively suggested a robust linear relationship between PT and the likelihood of surgery, with the non-linear relationship showing no statistical significance. The findings indicated that the association between PT and surgery was primarily linear across the different models analyzed.

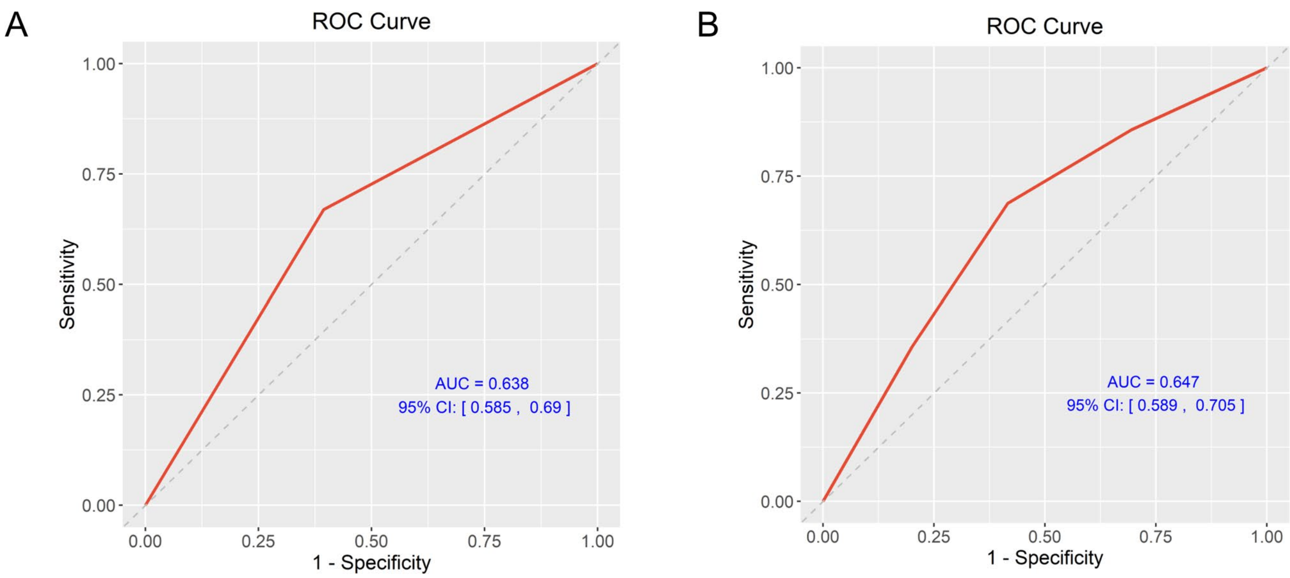

Fig. 5 Area under the curve analysis of pelvic tilt for surgery. (**A**) Binary classification based on the best cut-off value of pelvic tilt; (**B**) Four-class classification based on the interquartile range of pelvic tilt

Discussion

Principal findings

This study provides important insights into the role of PT as a significant radiological factor associated with eventually surgery decision-making for geriatric patients suffering from ADSD. The analysis of 381 patients revealed that a significant proportion (29.4%) opted for surgical intervention, underlining the clinical importance of evaluating potential surgical candidates among this population. The findings of the study demonstrate a clear association between higher PT and an increased likelihood of surgery, with statistical significance established through both binary and multinomial logistic regression analyses. Furthermore, the RCS analysis demonstrated that the association between PT and surgery was primarily linear across the different models analyzed. In addition to PT, other radiological features such as PI, PI-LL, and T1 pelvic angle were also correlated with surgical candidacy. However, PT stood out as a primary factor, as evidenced by its consistent significance in the logistic models and its strong relationship with the predicted risk of surgery identified through RCS analysis. These findings suggest that PT should be systematically evaluated in geriatric patients with ADSD when considering surgical options.

The importance of PT

PT is a crucial anatomical parameter defined as the angle formed by a vertical line passing through the center of the femoral heads and the line connecting the center of the femoral axis to the midpoint of the sacral end plate [18]. In recent years, several researchers have proposed innovative methods for measuring PT. For instance, Chai et al. [19] introduced a novel technique utilizing anteroposterior radiographs to estimate PT by measuring vertical distances from the pelvic outlet and obturator foramen. Their study correlated these parameters with PT defined anatomically (anterior pelvic plane) and mechanically (centers of femoral heads and sacral plate), reporting the Pearson correlation coefficients ranging from 0.75 to 0.77, with mean absolute errors between 3.7° and 4.5°. While these methods provided a multidimensional foundation for PT measurement, their wide validation and application were limited, necessitating the continued use of traditional clinical methods in our study. We employed the EOS 2D/3D imaging system to capture radiological characteristics from patients, and various radiological features were measured. Notably, previous research has consistently demonstrated that the EOS system excels in delivering precise [20], reliable, and reproducible measurements of spinal curvature, thereby making it a valuable asset in orthopedic practice [21].

Pelvic tilt serves as compensatory mechanism that enables patients to attain sagittal balance in context of diminished lumbar lordosis with the primary strategy of hip and knee flexion [18]. A normal PT is typically considered to be less than approximately 15 degrees. Increase in PT, which is also referred to as pelvic retroversion, has its limits. Younger individuals can often have greater PT as a compensatory response to LL loss; however, as individuals age and experience the loss of lumbar flexibility and the onset of degenerative hip changes, their ability to extend at the hips diminishes, leading to sagittal imbalance. Our study specifically focuses on the geriatric population, with data revealing an average PT of 18.15 degrees. Studies have shown that an increasing

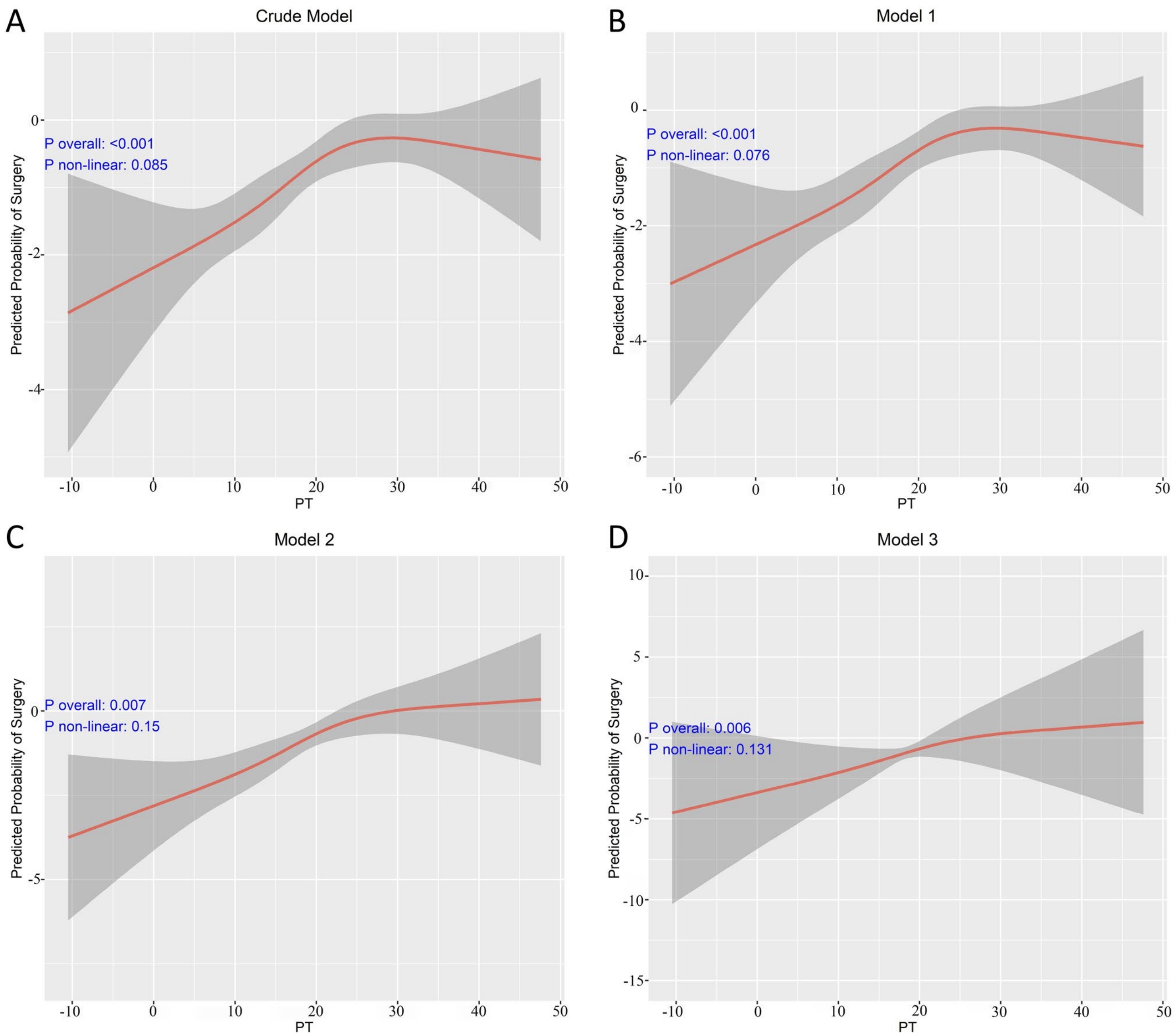

Fig. 6 Restricted Cubic Spline (RCS) curve analysis to examine the relationship between pelvic tilt and predicted probability of surgery. (**A**) RCS curve analysis after adjusting for none variables; (**B**) RCS curve analysis after adjusting for age and sex; (**C**) RCS curve analysis after adjusting for age, sex, pelvic incidence, lower lumbar lordosis, the difference of pelvic incidence and lumbar lordosis, T1 pelvic angle, global title, pelvic shift, and C7-CSVL; (**D**) RCS curve analysis after adjusting for all other variables

PT is directly correlated with worsening symptoms in the context of adult spinal deformity, with a PT greater than 22 degrees predicting an ODI above 40 [13]. Additionally, a higher PT is most strongly associated with increased pain during ambulation [14].

Pelvic tilt holds significant clinical importance in various aspects of musculoskeletal health. For instance, Mendiguchia et al. [22] investigated the impact of anterior pelvic tilt on hamstring muscle strain injuries. Their findings revealed that increased PT elongates the hamstring complex, particularly affecting the proximal regions more than the distal ones. The study suggested that pelvic positioning plays a crucial role in regulating hamstring strain, which has important implications for injury rehabilitation, prevention strategies, and the accuracy of musculoskeletal models. In another study conducted by Zahn et al. [23], the relationship between PT and functional acetabular anteversion was examined while subjects were in a supine position. Their research highlighted PT's essential role in determining the functional orientation of the acetabulum. A meta-analysis also evaluated the correlation between the sacro-femoral-pubic angle and PT across various demographic groups [24]. The overall pooled correlation coefficient was found to be 0.61, indicating a moderate correlation that is generally insufficient for clinical applicability. Lastly, another study investigated the relationship between PT in the sagittal plane and muscle stiffness in the lumbo-pelvic-hip complex using tensiomyography [25]. The study significant differences in maximal muscle displacement among various PT groups for several muscles, such as the Erector Spinae Gluteus Maximus. Correlation analysis revealed significant relationships between pelvic tilt and muscle stiffness for certain muscles; however, the anticipated changes in stiffness associated with Lower Crossed Syndrome were not confirmed.

Surgical strategies based on PT

Surgical intervention does not directly alter PT. Instead, when a patient's LL is brought into alignment with their PI, the compensatory mechanisms become unnecessary, leading to improved PT. This improvement occurs as the hips move out of terminal extension and the pelvis rotates forward. Studies have identified that restoring PT to less than 25 degrees is a major goal in adult spinal deformity surgery [26]. In our study, patients with PT greater than 18.4 degrees were over three times more likely to undergo surgical treatment compared to those with a PT of 18.4 degrees or less. Furthermore, refined classifications revealed that patients with PT values between 18.0 and 25.3 degrees, as well as those exceeding 25.3 degrees, exhibited even higher odds ratios for surgical intervention. These findings highlight the critical role of PT in surgical decision-making.

The significance of PT in guiding surgical decisions extends beyond its association with deformity severity. Understanding the relationship between PT and postoperative outcomes offers crucial insights into how surgical corrections affect pelvic alignment and overall spinal balance. Recent research has examined how PT influences complications such as proximal junctional kyphosis (PJK) [8], a common issue following long fusion surgeries for adult spinal deformity. These studies underscore the importance of incorporating PT evaluation into surgical planning, not only to predict the likelihood of surgery but also to anticipate potential postoperative risks. For example, Ponchelet et al. [8] explored the relationship between PT and PJK in patients undergoing long fusion surgery for adult spinal deformity. Their retrospective analysis of 76 patients revealed that individuals with PJK experienced greater corrections in lumbar lordosis and thoracic kyphosis compared to those without PJK. Notably, postoperative PT was significantly lower in the PJK group, suggesting that aggressive reduction of PT may increase the risk of PJK. Additionally, patients with high preoperative PT were found to undergo more substantial corrections during surgery, which may influence postoperative outcomes. Although the study concluded that PT itself does not directly cause PJK, it emphasized the need for cautious consideration of PT adjustments during surgical planning, as drastic reductions could predispose patients to complications. Similarly, the influence of PT on surgical outcomes has been observed in total hip arthroplasty. A recent study developed a machine learning model to predict changes in pelvic flexion angle after surgery, identifying PT as a key predictive factor [9]. This further highlights the role of PT as an essential parameter in evaluating surgical outcomes across different types of orthopedic interventions.

Clinical implications and future directions

These findings suggest that PT should be systematically evaluated in geriatric patients with ADSD when considering surgical options. Comprehensive radiological assessments, incorporating PT measurements, are crucial for tailoring treatment strategies to individual patient needs [27]. This approach may help optimize spinal alignment, minimize postoperative complications, and enhance functional recovery in this vulnerable population. Additionally, the integration of PT analysis into preoperative planning may improve surgical precision, allowing for better prediction of postoperative spinal balance and reducing the likelihood of revision surgeries. From a clinical perspective, PT evaluation can aid in identifying patients who may benefit from non-surgical interventions, such as targeted physical therapy or bracing, before considering invasive procedures. Furthermore, PT values can serve as a useful metric for monitoring disease progression and treatment response, guiding clinicians in timely decision-making. Given the association between PT and compensatory mechanisms such as pelvic retroversion and hip extension, a thorough understanding of PT dynamics can also contribute to improved pain management and functional outcomes in patients with ADSD. In surgical planning, PT assessment can inform decisions regarding the extent of spinal correction required and the choice of surgical techniques, such as the use of osteotomies or fusion levels. This ensures that surgical goals are aligned with the patient's specific sagittal alignment needs, thereby reducing the risk of postoperative complications like PJK. Additionally, assessing PT in conjunction with other radiographic parameters, such as SVA and PI-LL, allows for a more comprehensive evaluation of overall spinal alignment and balance.

Future research should focus on unraveling the mechanisms linking PT with spinal alignment and surgical outcomes. Studies should explore the role of PT in influencing adjacent segment degeneration, postoperative mobility, and overall quality of life. Investigating the interplay between PT and factors such as muscle strength, joint flexibility, and biomechanical loading may provide deeper insights into optimizing patient-specific surgical approaches. In addition, long-term studies are also necessary to assess the durability of surgical corrections based on PT measurements and to evaluate how changes in PT impact functional outcomes over time.

This includes examining the influence of age-related musculoskeletal changes and comorbidities on postoperative alignment and patient satisfaction. Furthermore, while PT alone may not achieve high predictive accuracy (as indicated by its AUC value in our study), this underscores the need for future studies to integrate multiple indicators—such as advanced imaging techniques, laboratory biomarkers, and clinical assessment scores—into predictive models. A multi-faceted approach incorporating machine learning algorithms could enhance model accuracy and improve clinical decision-making by offering personalized risk stratification and surgical planning. Overall, further research is required to deepen our understanding of the complex interactions between PT, spinal alignment, and functional outcomes. Addressing these gaps will facilitate the development of more effective therapeutic strategies, ultimately improving patient care and long-term quality of life of these patients.

Limitations

Despite the valuable insights gained from this study, several limitations should be acknowledged. The retrospective design restricts the ability to establish causal relationships between PT and surgical intervention, and the single-center nature of the research may limit the diversity of the patient population, potentially affecting the generalizability of the findings. Although various demographic and radiological factors were controlled for, unmeasured confounders, such as comorbidities and patient preferences, may still influence both PT and decisions regarding surgery. The variability in patients' decision-making timelines for surgery may result in some non-surgical cases eventually opting for surgical intervention in the future, highlighting the need for longer-term follow-up to accurately assess patients' final treatment choices and outcomes. Additionally, the study does not address long-term outcomes related to surgical interventions, necessitating further research to evaluate how these factors impact postoperative recovery and patient satisfaction. Variability in measurement techniques, despite the use of a standardized imaging system, could introduce errors, and the focus on radiological features without assessing functional outcomes limits the understanding of the overall patient experience. Lastly, although the sample size of 381 patients is relatively strong, subgroup analyses may result in smaller groups with limited statistical power, affecting the reliability of findings related to specific classifications of PT. Acknowledging these limitations is essential for contextualizing the results and guiding future research in the field of geriatric spinal surgery and radiological assessment.

Conclusions

This study highlights the significant role of PT as a critical radiological factor associated with eventually surgery for geriatric patients with ADSD. The analysis of a diverse cohort of 381 patients demonstrated a clear association between higher PT and an increased likelihood of surgical intervention, emphasizing the importance of thorough radiological assessments in clinical decision-making. Patients with PT values exceeding specific threshold (18.4 degrees) were found to have markedly higher odds of opting for surgery, underscoring the potential of PT as a key indicator for evaluating surgical candidates. These findings suggest that incorporating PT evaluations into preoperative assessments could lead to more tailored treatment strategies, ultimately improving surgical outcomes for this vulnerable population.

Abbreviations

PT	Pelvic tilt
PI	Pelvic incidence
SS	Sacral slope
LL	Lumbar lordosis
GT	Global tilt
TPA	T1 pelvic angle
CBVA	Chin-brow vertical angle
SVA	Sagittal vertical axis
CTPT	Coronal T1 pelvic tilt angle

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Author contributions
YF and HY contributed to the collection of cases and the writing of the manuscript. YH was responsible for data measurement. CX reviewed and provided feedback on the manuscript. YW and GZ contributed to the conceptualization of the study and critically reviewed the manuscript. All authors read and approved the final manuscript.

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No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
This study was performed in accordance with the ethical standards in the 1964 Declaration of Helsinki. Permission to waive the informed consent was obtained from the institutional review board (the First Medical Center of Chinese People's Liberation Army General Hospital) for this study. Informed consent was obtained from all individual participants included in the study.

Consent for publication
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Competing interests
The authors declare no competing interests.

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