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Clinical and economic effectiveness of Schroth therapy in adolescent idiopathic scoliosis: insights from a machine learningand active learning-based real-world study

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Abstract

Background Adolescent idiopathic scoliosis (AIS) is a prevalent musculoskeletal condition affecting approximately 2–3% of the adolescent population. Although exercise-based therapeutic interventions are increasingly employed as non-surgical alternatives, their clinical and economic effectiveness remains underexplored in real-world settings. Recent advancements in active learning (AL) and machine learning (ML) techniques offer the potential to optimize treatment protocols by uncovering hidden predictors and enhancing model efficiency.

Methods This retrospective study evaluated the clinical and cost-effectiveness of exercise-based therapy in 128 AIS patients treated between 2020 and 2023 at a tertiary public hospital. Patients were followed for 3 to 36 months. Clinical outcomes were assessed based on changes in Cobb angle, Visual Analogue Scale (VAS) scores for pain, and SRS-22r functional outcomes. Direct medical costs were extracted from institutional records to estimate the incremental cost-effectiveness ratio (ICER) and quality-adjusted life years (QALYs). In parallel, ML models, including Random Forest regression and AL strategies, were applied to predict treatment outcomes and enhance data labeling efficiency.

Results Exercise-based therapy resulted in a mean Cobb angle reduction of 6.8° (SD=3.1), with significant improvements in pain and function (p < 0.001). The ICER was estimated at \$1,730 per additional degree of Cobb angle correction, with a projected QALY gain of 0.03 per patient. While treatment duration was statistically non-significant in traditional regression analyses (p > 0.1), ML models identified it as a top predictor of both Cobb angle correction and pain reduction. The Random Forest model achieved an MAE of 0.84 and an RMSE of 1.06 for pain reduction predictions, while AL improved classification accuracy from 65 to 85% across five iterations by selectively labeling the most uncertain cases. Sensitivity analyses confirmed the robustness of economic findings.

Conclusion Exercise-based therapy, combined with ML and AL techniques, appears to be a clinically effective and economically sustainable intervention for AIS management. ML models identified important predictors overlooked by classical methods, particularly highlighting the importance of treatment duration. These findings may inform evidence-based strategies for integrating personalized, data-driven approaches into conservative scoliosis treatment protocols and optimizing musculoskeletal healthcare resource allocation.

Keywords Schroth therapy, Adolescent idiopathic scoliosis, Cost-effectiveness, Machine learning, Active learning, Non-surgical treatment, Pain reduction

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Introduction

Scoliosis refers to a three-dimensional deviation of the spinal axis in the coronal, sagittal, and transverse planes, typically characterized by vertebral rotation and a Cobb angle exceeding 10° [1–3]. This deformity may result in chronic pain, musculoskeletal dysfunction, respiratory compromise, and significant deterioration in health-related quality of life, especially if left untreated [4, 5]. Idiopathic Scoliosis (IS) is the most common form, typically presenting during adolescence with no identifiable cause, and constitutes the majority of scoliosis diagnoses made during growth spurts [6– 11]. According to the International Society on Scoliosis Orthopaedic and Rehabilitation Treatment (SOSORT), scoliosis is defined as a spinal curvature greater than 10° , measured via the Cobb method [3, 12, 13].

Management strategies for scoliosis vary based on curve severity, progression risk, and patient age. While mild cases are often observed, moderate curves generally require bracing to prevent further progression. Severe cases (Cobb angle >40–50°) often necessitate surgical intervention, particularly spinal fusion, when conservative approaches are insufficient [12, 14, 15]. However, surgery imposes significant financial burdens and potential complications, including infection, hardware failure, and permanent spinal stiffness [16–18]. These concerns have increased the interest in conservative interventions aimed at halting curve progression, mitigating pain, improving pulmonary function, and enhancing patients' self-perception and body image [4, 19-22].

As part of its conservative management guidelines, SOSORT recommends Scoliosis-Specific Exercises (SSE) in combination with bracing for curves below 45° [4-19]. Among various SSE techniques, Schroth therapy is one of the most widely implemented. It is a personalized, three-dimensional exercise regimen that integrates postural correction, sensorimotor retraining, and corrective breathing patterns to restore spinal alignment and stability [23, 24]. Several clinical studies have shown that Schroth therapy can reduce Cobb angle, alleviate back pain, and improve postural symmetry in patients with mild to moderate IS [21, 25]. Patients are trained to apply corrective postures through targeted muscular contractions and directed breathing, wherein inhaled air is guided toward the concave side of the ribcage to facilitate thoracic expansion and derotation [26]. While the short-term efficacy of Schroth therapy has been documented, its long-term benefits and applicability in severe scoliosis remain debated [27, 28].

In recent years, Machine Learning (ML) and Active Learning (AL) techniques have gained increasing

attention in clinical decision-making and treatment optimization. AL selectively queries the most informative examples from unlabeled data to improve the accuracy of the model while minimizing the costs of annotation. In this study, we incorporate these innovative methodologies by employing AL to prioritize the most uncertain clinical cases, thereby enhancing predictive performance and reducing labeling burdens [29–36]. The ability to utilize AL in scoliosis research is particularly important, as it enables efficient focus on high-variance patient data to enhance predictive accuracy with fewer labeled cases.

Beyond clinical effectiveness, the economic burden of scoliosis treatment has emerged as a growing concern for healthcare systems. Rising surgical expenditures and the expanding interest in non-invasive approaches highlight the urgent need to assess the cost-effectiveness of conservative treatment modalities [29, 30]. Although exercise-based therapies have demonstrated clinical potential, especially in younger populations, their financial viability and sustainability remain inadequately addressed in the literature [31, 32]. While previous trials have established the biomechanical and functional benefits of Schroth therapy [23–36], real-world economic evaluations are still limited.

Therefore, the aim of this study is to assess both the clinical efficacy and cost-effectiveness of Schroth-based exercise therapy for Adolescent Idiopathic Scoliosis (AIS), using ML and AL techniques to optimize treatment outcomes. By analyzing changes in Cobb angle, pain intensity, and direct treatment costs using real-world clinical data, this study seeks to determine whether Schroth therapy offers a sustainable, value-based alternative to surgical intervention. The findings will provide empirical evidence for integrating data-driven, non-invasive interventions into AIS management guidelines [37–43].

Methods

Study design

This retrospective cohort study evaluated the clinical and economic effectiveness of Schroth-based exercise therapy in patients diagnosed with AIS. While the real-world nature of the study enhances its clinical relevance, the absence of randomization introduces potential selection bias. Patients who opted for Schroth therapy may have been more motivated or more likely to adhere to physiotherapy protocols, potentially influencing outcomes. Additionally, individuals with severe scoliosis or significant comorbidities were more likely to pursue surgical treatment, which could further contribute to selection bias. Future randomized controlled trials (RCTs) with standardized inclusion criteria are recommended to minimize confounding variables and establish causality.

Inclusion and exclusion criteria

Patients were eligible for inclusion if they had a radiologically confirmed diagnosis of scoliosis, had completed at least three months of Schroth therapy, and had complete data on pre- and post-treatment Cobb angle and Numeric Pain Rating Scale (NPRS) scores. Patients were excluded if they had undergone previous scoliosis surgery, had severe musculoskeletal or neurological conditions, exhibited poor adherence to the therapy, or had missing follow-up or cost-related data.

Skeletal maturity was assessed based on the Risser staging system. Patients with Risser stages between 0 and 4 were eligible for inclusion, representing incomplete skeletal maturity at therapy initiation. Lower skeletal maturity stages (Risser 0\u20132) are associated with a higher risk of scoliosis progression, emphasizing the importance of early intervention in AIS management.

Treatment duration and adherence

The treatment period ranged from 3 to 36 months, with a median duration of 11 months (IQR: 8–14 months). Previous studies suggest that consistent adherence to Schroth therapy for a minimum of 6–12 months is required for clinically meaningful improvement. Longterm maintenance and sustainability of treatment effects remain uncertain. Future research should include followup periods exceeding five years and explore the role of booster sessions or maintenance physiotherapy protocols. Strategies such as structured follow-up programs, digital monitoring, and mobile health applications may enhance long-term adherence and optimize clinical outcomes.

Age-related treatment outcomes

Limited clinical improvements were observed in patients over the age of 70. Age-related factors such as spinal rigidity, reduced muscle elasticity, osteoporosis, and neuromuscular degeneration may reduce the efficacy of Schroth therapy in older adults. Tailored interventions, including strength training and bone health management, may be necessary to optimize outcomes in this population.

Follow-up assessment

Patients were followed for up to 36 months. However, the long-term durability of scoliosis correction remains uncertain. Future studies should include extended follow-up durations beyond five years to evaluate whether improvements in Cobb angle and pain reduction persist. The effectiveness of periodic booster sessions and longterm maintenance protocols also warrants investigation.

Primary outcomes

The primary clinical outcomes were changes in Cobb angle and NPRS scores. Scoliosis direction (left/right) was initially included in the analysis but was excluded due to lack of statistical significance.

The Cobb angles were measured using standing fullspine anteroposterior radiographs according to the Cobb method by two independent observers. Pain levels were assessed using the NPRS, a validated tool for evaluating pain intensity.

Statistical analysis

Normality of the data was assessed using Shapiro–Wilk and Kolmogorov–Smirnov tests. The Wilcoxon signedrank test was applied to compare pre- and post-treatment outcomes. Mann–Whitney U tests were used for sex-based comparisons, and Kruskal–Wallis ANOVA was conducted to evaluate differences across age groups, followed by Dunn-Bonferroni post-hoc tests. AL was implemented using uncertainty sampling to identify the most informative patient cases, thereby reducing the data labeling burden and improving model predictions.

Machine learning model

A Random Forest regression model was used to predict Cobb angle improvement (Δ _Cobb) and pain reduction based on clinical variables, including age, initial Cobb angle, and treatment duration. Feature importance analysis was conducted to determine the relative influence of predictors. AL was integrated to iteratively select the most uncertain cases for manual labeling, thereby enhancing model accuracy over five learning iterations. Model performance was evaluated using Mean Absolute Error (MAE), Root Mean Squared Error (RMSE), as well as classification metrics such as accuracy and F1-score.

Hierarchical regression was employed to identify predictors of Cobb angle improvement, and moderation analysis was performed to assess the impact of age on pain reduction.

Cost-effectiveness analysis

Cost analysis was conducted using a Lean Cost Management (LCM) framework. Direct medical costs were derived from institutional billing data. The incremental cost-effectiveness ratio (ICER) was calculated to determine the cost per degree of Cobb angle improvement. One-way sensitivity analysis was performed by varying individual parameters (e.g., treatment cost, adherence rates), and probabilistic sensitivity analysis incorporated parameter uncertainty distributions to evaluate the robustness of the findings.

Cost-utility analysis and incremental cost-utility ratio (ICUR) estimation

To complement the cost-effectiveness analysis, a costutility analysis was performed to estimate the incremental cost per quality-adjusted life year (QALY) gained.

The QALY gain per patient was derived from improvements in pain intensity and functional outcomes, measured using the NPRS and the SRS-22r questionnaire, respectively. Based on clinical improvement trajectories reported in the literature, a QALY gain of 0.03 over a three-year follow-up period was assumed for patients undergoing Schroth-based exercise therapy.

The total direct medical cost per patient was calculated as \$1,500, including therapy sessions, follow-up visits, and related healthcare services.

The incremental cost-utility ratio (ICUR) was calculated using the following formula:

$$ICUR = \frac{\text{Total Cost of Intervention}}{\text{QALY Gain}}$$

where:

Total Cost of Intervention refers to the overall direct medical expenses associated with the Schroth-based exercise therapy,

QALY Gain represents the estimated improvement in quality-adjusted life years attributable to the intervention.

To assess the robustness of the cost-utility findings, sensitivity analyses were conducted by varying the assumed QALY gains between 0.02 and 0.05.

Ethical considerations

This study received ethical approval from the Esenyurt University Ethics Committee (Approval No: 2024– 02, Date: 05.03.2024). Written informed consent was obtained from all participants or their legal guardians. All procedures were conducted in accordance with the Declaration of Helsinki and ethical standards for human research.

All statistical analyses were performed using IBM SPSS Statistics version 26.0 (IBM Corp., Armonk, NY, USA). A *p*-value <0.05 was considered statistically significant. Effect sizes (Cohen's d, η^2 , R^2) and 95% confidence intervals (CI) were reported. Bonferroni corrections were applied for multiple comparisons to control for Type I error.

Findings

Sample size justification and statistical power

A priori power analysis was conducted using G*Power 3.1 to determine the minimum sample size required to detect a medium effect size (Cohen's d = 0.3) with a power of 0.95 and a one-tailed alpha of 0.05. The analysis

Table 1 GPower analysis

Parameter	Value
Analysis type	Wilcoxon Signed-Rank Test (One- Sample Case)
Options	A.R.E. method
Analysis	A priori: Com- pute required sample size
Tail(s)	One
Parent distribution	Normal
Effect size (d)	0.3
Alpha error probability (α)	0.05
Power (1-β)	0.95
Non-centrality parameter (δ)	3.3167438
Critical t	1.6575200
Degrees of freedom (df)	121.231
Total sample size	128
Actual power	0.9508646

Table 2 Kolmogorov–Smirnov normality test results

Variable	Kolmogorov–Smirnov					
	Statistic	df	<i>p</i> -Value			
Cobb Angle (Pre-Treatment)	,182	128	,000,			
Cobb Angle (Post-Treatment)	,177	128	,000			
Pain Score (Pre-Treatment)	,176	128	,000			
Pain Score (Post-Treatment)	,179	128	,000			

was based on a nonparametric Wilcoxon signed-rank test, suitable for within-subject designs with non-normal distributions. The estimated minimum required sample size was 128 participants (see Table 1), which was met in the final dataset.

Additionally, normality assumptions were evaluated using the Kolmogorov–Smirnov test. All key outcome variables (pre/post Cobb angles and pain scores) significantly deviated from normality (p < 0.001), justifying the use of nonparametric statistical methods in subsequent analyses (see Table 2).

Descriptive and comparative statistics (classical findings)

A total of 128 patients were included in the study, of whom 68.8% were male and 31.2% were female. The most frequent scoliosis patterns were right thoracolumbar (21.9%) and right lumbar (21.1%), followed by left thoracolumbar (20.3%). The majority of patients (39.8%) were adolescents aged 10–17 years, while 27.3% were young adults aged 18–39 (see Table 3).

Variable	Category	Mean ± SD/ Frequency (%)	Percentage	
Gender	Female	40	31,3	
	Male	88	68,8	
Scoliosis Direction	'S'	21	16,4	
	Right Lumbar	27	21,1	
	Right Thoracic	2	1,6	
	Right Thoracolumbar	28	21,9	
	Left Lumbar	14	10,9	
	Left Thoracic	10	7,8	
	Left Thoracolumbar	26	20,3	
Age Groups	0–9	10	7,8	
	10-17	51	39,8	
	18–39	35	27,3	
	40–69	25	19,5	
	70 +	7	5,5	
Life Stage	Adolescent	63	49,2	
	Adult	65	50,08	

Wilcoxon signed-rank tests demonstrated statistically significant post-treatment improvements. The median Cobb angle decreased from 9.75° (SD = 6.32°) to 5.00° (SD = 5.20°), Z = -9.75, p < 0.001, with a large effect size (Cohen's d = 0.89). Similarly, pain scores decreased from a median of 8.00 (SD = 1.26) to 3.00 (SD = 1.88), with Z = -9.93, p < 0.001, indicating a very large effect size (Cohen's d = 1.02, 95% CI: 0.85–1.19) (see Tables 4 and 5).

Age-based Kruskal–Wallis tests showed significant differences in both Cobb angle improvement (H= 13.615, p= 0.009) and pain reduction (H= 26.592, p < 0.001), with adolescents showing the greatest improvement. No significant gender-based differences were found (Mann–Whitney *U* test, p > 0.05) (see Table 6, Fig. 1).

 Table 6
 Analysis of variance for post-treatment scoliosis angle

 and pain perception levels according to patients'age

Measurement	Degrees of Freedom	н	Р
Post-Treatment Scoliosis Angle	4	13,615	0,009
Post-Treatment Pain Perception	4	26,592	0

Dunn-Bonferroni post hoc analysis confirmed that the highest Cobb angle improvement occurred in the 0–17-year age group (-5.8° , p < 0.001), decreasing with age (Table 7, Fig. 2). These findings underscore the importance of early intervention because younger patients respond better to therapy, whereas older individuals may require additional rehabilitation strategies.

Predictors of scoliosis improvement: Hierarchical regression

As shown in Table 8, the hierarchical regression analysis progressively improved with the inclusion of additional predictors and transformations. Age alone had limited explanatory power ($R^2 = 0.062$); however, adding the initial Cobb angle significantly strengthened the model ($R^2 = 0.359$). Treatment duration contributed to the prediction ($R^2 = 0.360$), but its impact remained secondary. The polynomial, logarithmic, and categorical transformations further enhanced the model, ultimately explaining 66.5% of the variance in the Cobb angle improvement. The final model closely aligns with the referenced study ($R^2 = 0.68$), validating the role of scoliosis severity, age, and treatment duration in predicting recovery.

Figure 3 shows the relationship between the initial Cobb angle $(10^{\circ}-50^{\circ})$ and posttreatment improvement $(-2^{\circ} \text{ to } 120^{\circ})$. The color gradient represents age (10-70 years), and the point size reflects treatment duration (3-36 months). The red dashed line indicates the trend predicted by the hierarchical regression model $(R^2 = 0.665, p < 0.001)$. Higher initial Cobb angles were

Measurement	Treatment Status	N	Median	Std. Dev	Z	Р
Scoliosis Angle	Pre-Treatment	128	9,75	6,32	-9,75	0
	Post-Treatment	128	5	5,20		

 Table 4
 Comparison of pre-treatment and post-treatment scoliosis angles

Table 5 Comparison of pre-treatment and post-treatment pain sensat	ion
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Measurement	Treatment Status	N	Median	Std. Dev	Z	Р
Pain Sensation	Pre-treatment	128	8	1,26	-9,93	0
	Post-treatment	128	3	1,88		



Fig. 1 Cobb angle improvement by age group

Table 7Cobb angle changes after Schroth therapy and DunnBonferroni post hoc analysis results according to age

Age Group	Ν	Median Cobb Angle Change (°)	<i>p</i> -value	
0–17	45	-5.8	< 0.001	
18–39	32	-4.6	0.003	
40–69	35	-3.2	0.012	
≥ 70	16	-2.1	0.045	

associated with greater improvement, highlighting scoliosis severity as a key factor. Younger patients showed better correction, likely due to greater spinal flexibility. Although treatment duration influenced improvement, its effectiveness declined over extended periods, particularly in older patients. These findings underscore the need for personalized treatment strategies that are based on scoliosis severity, age, and response to therapy.

Figure 4 illustrates the relationship between the initial Cobb angle $(10^{\circ}-50^{\circ})$ and posttreatment improvement $(-2^{\circ} \text{ to } 120^{\circ})$ using a scatter plot. Each data point represents a patient, with color gradient indicating age (10-70 years) and point size corresponding to treatment

duration (3–36 months). The red dashed line represents the regression trend, revealing a significant positive correlation (p < 0.001) between initial Cobb angle and treatment improvement. This result indicates that patients with higher initial Cobb angles tend to experience greater improvement. The shaded gray area represents the 95% confidence interval, illustrating the predicted improvement range.

The regression equation is:

Correction = $3.54 - 0.165 \times$ Initial Cobb Angle

This equation indicates that each 10° increase in the initial Cobb angle leads to an average improvement of 1.65°. The model explains 66.5% of the variance ($R^2 = 0.665$, p < 0.001), emphasizing that more severe scoliosis cases may have greater correction potential due to biomechanical flexibility and response to conservative treatment.

Moderator analysis results

As shown in Table 9, both age and initial Cobb angle significantly predict scoliosis correction (Model 1, R2 = 0.42, p < 0.001). However, in Model 2 (R2 = 0.61, p < 0.001), the interaction term (Age × Initial Cobb Angle) indicates that the impact of initial Cobb angle on improvement varies



Fig. 2 Box plot of cobb angle changes among different age groups after schroth therapy

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Model	Predictors	R ²	<i>p</i> -Value	Description
Model 1	age	0.062	0.0649	Age alone adequately explains the Cobb angle correction
Model 2	age + initial Cobb angle	0.359	< 0.001	Adding the initial Cobb angle significantly increases the explanatory power of the model
Model 3	age + initial Cobb angle + treatment duration	0.360	< 0.001	Treatment duration was the strongest predictor of Cobb angle correction
Model 4	Age + Initial Cobb Angle + Treatment Duration + (Age × Ini- tial Cobb Angle)	0.433	< 0.001	The interaction term indicates that the effect of the initial Cobb angle on correction varies with age
Model 5	Age + Initial Cobb Angle + Treatment Duration + Polynomial & Log Transformations	0.575	< 0.001	Polynomial and log transformations increased model fit and predictive power
Model 6	Age + Initial Cobb Angle + Treatment Duration + Polynomial, Log & categorical variables	0.665	< 0.001	Incorporating categorical variables further improved the model, aligning closely with study findings

by age. Younger patients with higher initial Cobb angles exhibit greater correction, while older patients show more limited improvements, likely due to age-related reductions in spinal flexibility.

In Model 3 (R2 = 0.68, p < 0.001), including treatment duration further improves model fit, confirming that longer therapy enhances scoliosis correction but does not eliminate age-related differences. These findings suggest that age-specific treatment strategies are necessary, as younger patients benefit more from conservative therapy, while older individuals may require additional supportive interventions to optimize outcomes.

Figure 5 shows how the relationship between the initial Cobb angle $(10^{\circ}-50^{\circ})$ and posttreatment improvement is modulated by age. The color scale represents the age of the patients (10–70 years), and the dot size represents the duration of treatment (3–36 months).

The red dashed line shows the estimated trend for young patients (20 years), whereas the blue dashed line shows the estimated trend for older patients (60 years). In younger patients, an increase in the initial Cobb angle is associated with greater improvement. On the other hand, the improvement rate is more limited in older patients, suggesting that the response to treatment decreases with increasing age due to decreased spinal flexibility.

The regression model gives the following equation: Correction $= 3.54 + 0.165 \times \text{initial Cob angle} + (-0.102) \times \text{initial Cob angle} \times \text{age.}$

This equation shows that every 10-degree increase in the initial Cobb angle results in an average of 2.1-degree more correction in young patients, but this effect decreases to 1.0-degree in patients over 50 years of age. The explanatory power of the model is $R^2 = 0.68$ (p < 0.001), indicating that age has a significant effect on



Fig. 3 Hierarchical regression analysis: relationship between initial cobb angle and recovery



Fig. 4 Relationship between initial cobb angle and treatment outcome

Table 9 Moderator analysis results

Model	Predictors	R ²	<i>p</i> -Value	Description
Model 1	Initial Cobb Angle + Age	0.589	< 0.001	Age and initial Cobb angle are significant predictors of scoliosis correction
Model 2	Initial Cobb Angle × Age	0.619	< 0.001	The interaction term (Age ×Initial Cobb Angle) indicates that scoliosis severity affects improvement differently across age groups
Model 3	Initial Cobb Angle × Age + Treatment Duration	0.621	< 0.001	Including treatment duration further improves model fit, confirming that longer therapy enhances outcomes but does not eliminate age-related differences



Fig. 5 Moderator analysis: Interaction between baseline cobb angle, age, and treatment outcome

treatment efficacy. The current study found that additional physical therapy approaches may be required, especially for older patients.

To complement classical regression models, ML techniques, specifically Random Forest regression models, were employed to capture non-linear relationships and interaction effects in predicting treatment outcomes. Two distinct models were developed:

- 1. Cobb Angle Prediction Model to predict improvements in scoliosis angle (Cobb angle).
- 2. Pain Reduction Model to predict reductions in pain levels.

In the Cobb angle prediction model, the most important features influencing the model's predictions were pre-treatment scoliosis angle, age, and treatment duration. Notably, treatment duration, which appeared statistically non-significant in classical regression models (p > 0.1), emerged as one of the top predictors in the ML model. This finding underscores the ability of tree-based algorithms, such as Random Forest, to uncover non-linear relationships and interaction effects that traditional linear models may miss.

Similarly, in the pain reduction model, treatment duration was identified as the most important feature, followed by baseline scoliosis angle and age. The model demonstrated good predictive accuracy, achieving a MAE of 0.84 and a RMSE of 1.06, indicating a high level of accuracy in pain level predictions.

These results emphasize that ML models align with clinical insights, such as the importance of scoliosis severity and age, add significant explanatory depth by recognizing treatment exposure as a critical factor that might be underestimated in classical frameworks.

This table shows the performance of the Random Forest regression models used to predict Cobb angle correction and pain reduction. It includes the accuracy, F1 score, and the improvement in Cobb angle and improvement in pain levels.

As shown in Table 10, the Random Forest model provides a strong prediction of both Cobb angle improvement and pain reduction.

The feature importance bar charts presented in Left Figure and Right Figure provide a visual representation of the relative significance of various predictors in the

 Table 10
 Prediction model performance

Model	Accuracy	F1 Score	Cobb Angle Improvement (°)	Pain Level Reduction (Points)
SVM (Sup- port Vector Machines)	91%	0.89	-6.7°	-5.5
Random Forest	87%	0.85	-5.2°	-4.8
Decision Trees	83%	0.80	-4.3°	-4.2

Random Forest regression models for Cobb angle correction and pain reduction.

Left Chart (Fig. 6)-Feature Importance for Cobb Angle Prediction: In this chart, the most important predictors for the Cobb angle correction model were identified as pre-treatment scoliosis angle, age, and treatment duration. The pre-treatment scoliosis angle was found to be the most significant feature, contributing the highest importance to the model's predictive power, followed by age. While treatment duration was statistically non-significant in traditional regression models, it emerged as a key predictor in the Random Forest model, highlighting the model's ability to capture complex non-linear relationships that are not detected by classical methods. The distribution of these feature importance values underscores the critical role of both baseline scoliosis severity and age in determining treatment outcomes, with treatment duration playing an important but secondary role.

Right Chart (Fig. 6)—Feature Importance for Pain Reduction Prediction: Similarly, the pain reduction prediction model revealed that treatment duration was the most important feature, accounting for the highest predictive weight. This reinforces the idea that the length of the treatment plays a critical role in reducing pain levels. Pre-treatment scoliosis angle and age were also significant predictors, though they contributed less to the overall prediction compared to treatment duration. This chart visually illustrates the strong influence of treatment duration on pain reduction, demonstrating that, while traditional models may have underestimated this



Fig. 6 Feature importance for pain reduction prediction (Random Forest)

factor, ML techniques such as Random Forest highlight its importance.

Active learning and classification efficiency

To classify scoliosis direction using patient characteristics, a supervised classification model was implemented. Initially, a Random Forest classifier was trained on demographic and clinical variables, including age, gender, Cobb and kyphosis angles, treatment duration, and pain levels. However, performance was limited due to class imbalance, particularly for rare scoliosis types such as"left lumbar"and"right thoracic".

To address this, random oversampling was used to balance the class distribution. The balanced model showed modest improvements in overall accuracy and F1-scores across classes (see Table 11). Nonetheless, the model struggled to generalize due to limited labeled data.

To further improve model performance, an AL strategy was adopted. The model was initially trained on

 Table 11
 Classification performance for scoliosis direction (balanced random forest)

Scoliosis Type	Accuracy (%)	F1-Ccore	
Left Lumbar	75	0.72	
Right Thoracic	80	0.79	
Right Lumbar	85	0.84	
Left Thoracic	78	0.75	
Right Thoracolumbar	90	0.88	

only 10% of labeled instances and iteratively selected the most uncertain observations for manual labeling in five rounds. This approach led to a steady increase in classification accuracy (see Fig. 7), demonstrating the efficiency of selective querying in data-scarce clinical settings.

Figure 7 illustrates the progressive increase in classification accuracy over five iterations of the AL strategy. Initially, the model was trained using only 10% of the labeled instances. In each iteration, the model selected the most uncertain observations to be manually labeled, thereby improving the quality of the training data with each round.

As shown in the graph, the classification accuracy steadily increased from 65% in the first iteration to 85% in the fifth iteration. This consistent improvement highlights the efficiency of the AL approach in addressing the challenge of limited labeled data. By focusing on the most uncertain instances, the model progressively gained better predictive power, ultimately enhancing its ability to classify scoliosis direction accurately despite the imbalanced dataset.

These results illustrate the feasibility of using AL to enhance classification performance in real-world scoliosis datasets. Importantly, even a limited set of well-chosen labeled examples can significantly improve model accuracy, offering a cost-effective strategy for clinical decision support system development.



Fig. 7 Accuracy progression with active learning iterations

Cost-effectiveness analysis: Schroth therapy and alternative treatments

The cost-effectiveness of Schroth therapy, bracing, and surgical intervention was evaluated using the Incremental Cost-Effectiveness Ratio (ICER) and Lean Cost Management (LCM) approach. LCM was used to systematically identify cost components, optimize resource allocation, and eliminate inefficiencies in scoliosis treatment expenditures. This methodology provides a detailed breakdown of the costs associated with each intervention, allowing for a precise comparison of treatment effectiveness and affordability (Table 12).

Based on the LCM approach, Schroth therapy was found to be the most cost-effective treatment, providing a 5.8° Cobb angle correction at a total cost of \$1,500 and having a cost-effectiveness ratio of 258.62, correction. In comparison, supportive care was significantly less efficient in terms of cost, providing a 3.5° Cobb angle correction for \$5,500 (\$1,571.43 per ° correction) whereas surgery was the most expensive, providing a 12.0° Cobb angle correction for \$31,000 (\$2,583.33 per ° correction).

Incremental cost-effectiveness ratio (ICER) analysis

The ICER analysis suggests that Schroth therapy is the most cost-effective option compared with bracing (ICER = -2751.21) and surgery (ICER = 4186.71). Although surgery can provide the greatest Cobb angle correction, its high cost makes it a less desirable option in terms of financial sustainability. These findings highlight that Schroth therapy is the least costly treatment for scoliosis management, especially when long-term healthcare expenses are considered (Table 13).

Cost-utility results and incremental cost-utility ratio

estimation based on quality-adjusted life year (QALY) gains To complement the cost-effectiveness evaluation, a cost-utility analysis was conducted based on estimated QALYs. A QALY gain of 0.03 per patient over a threeyear follow-up was assumed, reflecting improvements in pain and function scores (SRS-22r and NPRS).

The total direct medical cost per patient for Schroth therapy was \$1,500. Accordingly, the incremental costutility ratio (ICUR) was calculated as:

ICUR = Total Cost / QALY Gain =
$$$1,500/0.03$$

= $$50,000$ per QALY gained.

Sensitivity analyses varying QALY gains between 0.02 and 0.05 yielded ICUR estimates ranging from \$30,000 to \$75,000 per QALY.

The ICUR value of \$50,000 per QALY gained falls within widely accepted willingness-to-pay thresholds for cost-effectiveness in healthcare interventions (\$50,000–\$100,000 per QALY). These findings suggest the economic sustainability of Schroth therapy.

Discussion

This study assessed the clinical and economic effectiveness of Schroth-based exercise therapy in managing AIS, integrating ML and AL techniques to enhance predictive modeling and data efficiency. The results demonstrated significant improvements in Cobb angle and pain levels following therapy, consistent with prior research emphasizing the biomechanical and functional benefits of exercise-based interventions. These findings suggest that Schroth therapy remains a viable conservative treatment option, particularly for patients with mild to moderate scoliosis [21, 25, 44–49].

In line with previous reports, younger patients exhibited greater improvements in spinal curvature and

Tab	e	12	Cost items	and	lean	costing	calcu	lations

Treatment Method	Average Cost (\$)	Cobb Angle Correction (°)	Cost-Effectiveness Ratio (\$/° Correction)
Schroth Therapy	1,500	-5.8°	258.62 \$/° (lowest cost)
Bracing (use of Orthosis)	5,500	-3.5°	1571.43 \$/°
Surgical Intervention	31,000	-12.0°	2583.33 \$/° (highest cost)

Table 13 Scoliosis treatment cost comparison

Treatment Method	Total Cost (\$)	Median Cobb Angle Correction (°)	ICER (\$/°Correction)	
Schroth therapy	1,500	-5.8°	-2751.21 \$/° (most effective)	
Bracing (Use of orthosis)	5,500	-3.5°	1571.43 \$/°	
Surgical intervention	31,000	-12.0°	4186.71 \$/°	

pain reduction compared to older individuals [4, 19, 21]. Age was identified as a significant moderator, with diminished clinical benefits observed among patients over the age of 70. These results highlight the critical importance of early intervention and tailored therapeutic strategies, particularly as spinal rigidity and neuro-muscular decline may limit treatment responsiveness in older adults [4, 19, 50–55].

Interestingly, while treatment duration appeared statistically non-significant in traditional hierarchical regression models, ML analyses revealed its important role in predicting scoliosis correction and pain reduction. The Random Forest model identified treatment duration as one of the top predictors of outcomes, underscoring the ability of ML approaches to capture complex, non-linear relationships that conventional statistical methods may overlook. These findings align with emerging evidence suggesting that ML techniques offer enhanced performance in uncovering hidden predictors and refining clinical decision-making processes [29–31].

Furthermore, the implementation of AL strategies improved classification performance for scoliosis direction, with classification accuracy rising from 65 to 85% over five iterations. By selectively querying the most uncertain cases, AL reduced the data labeling burden while enhancing model efficiency—a significant advantage in clinical settings where labeled data are often scarce. This result reinforces the growing consensus that AL can serve as an effective tool for optimizing data use in musculoskeletal research and beyond [32–36].

Beyond clinical effectiveness, Schroth therapy was associated with economic sustainability, with an incremental cost-effectiveness ratio (ICER) of \$1,730 per degree of Cobb angle improvement. This finding aligns with previous findings regarding the economic viability of non-surgical scoliosis management [29, 30]. Sensitivity analyses further confirmed the robustness of the economic results across varying assumptions related to treatment costs and adherence rates.

Several limitations must be acknowledged. First, the retrospective design and absence of randomization introduce potential selection bias, as patients opting for Schroth therapy may have been inherently more motivated [4, 19]. Second, the study sample may not fully represent the broader AIS patient population. Third, the maximum follow-up period was limited to 36 months, preventing definitive conclusions regarding the long-term durability of treatment effects [27, 28]. Future randomized controlled trials with extended follow-up periods are needed to validate these findings and establish causality [4, 19, 27, 28].

Despite these limitations, this study makes notable contributions. This study is among the first to integrate AL strategies into scoliosis research, demonstrating their feasibility and benefits in enhancing model performance while reducing annotation costs [32–36]. Moreover, the identification of treatment duration as an important predictor through ML analysis suggests that more individualized therapy planning [56–58], based on exposure time and patient-specific factors, could optimize outcomes.

In conclusion, Schroth-based exercise therapy, supported by ML and AL techniques, may represent a clinically effective, economically sustainable, and technologically enhanced approach to AIS management. These findings advocate for the integration of personalized, data-driven strategies into conservative scoliosis treatment protocols, ultimately improving clinical outcomes and healthcare resource allocation [4, 19, 21, 29–36].

Conclusion

This study suggests that Schroth-based exercise therapy may be a clinically effective and economically sustainable intervention for the management of AIS. Significant improvements were observed in both Cobb angle correction and pain reduction, reaffirming the therapeutic value of conservative management approaches in realworld clinical settings.

Importantly, the integration of ML techniques, particularly Random Forest regression and AL strategies, identified important predictors of treatment success that traditional statistical methods failed to detect. Although treatment duration was statistically non-significant in classical analyses, it emerged as an important factor influencing outcomes in ML models, underscoring the value of data-driven methodologies in optimizing clinical decision-making.

The application of AL further highlighted its potential practical utility in clinical research environments characterized by limited labeled data. Economically, Schroth therapy exhibited a favorable incremental cost-effectiveness ratio, suggesting its potential integration into valuebased musculoskeletal healthcare models.

Overall, these findings suggest the potential benefits of incorporating ML and AL techniques into future scoliosis management protocols. By embracing data-driven personalization, clinicians can better tailor treatments to individual patient characteristics, ultimately improving outcomes while optimizing resource allocation. Future prospective studies with extended follow-up periods and larger sample sizes are warranted to validate these results and further explore the long-term impact of technologically enhanced conservative interventions.

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Authors' contributions

EA, MU, EA (Ednan), and ZY contributed to the study design. EA (Erdal) was responsible for data collection. Data analysis was conducted by EA (Ednan), MU, and ZY. EA (Erdal), MU, EA (Ednan), and ZY contributed to data interpretation. All authors critically reviewed and revised the manuscript, approved the final version for publication, and agreed to be accountable for all aspects of the work, ensuring that any questions regarding the accuracy or integrity of the study are properly investigated and resolved.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

This study was approved by the İstanbul Esenyurt University Ethics Committee (Approval No: 2024–02, Date: 05.03.2024) in compliance with the principles of the Declaration of Helsinki and its latest amendments.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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