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Posted Date: 6 October 2025

doi: 10.20944/preprints202510.0374.v1

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Thoracic and Spinal Status in Mild to Moderate Idiopathic Scoliosis Patients Prior to Initiating PSSEs and Bracing: Implications for Scoliogenesis

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Abstract

Introduction – aim: There is a lack of studies focusing on the thoracic and spinal condition in mild to moderate idiopathic scoliosis (IS) patients prior to the initiation treatment. This report aims to address the above issue in children who are about to begin nonoperative treatment, whether through Physiotheraputic Scoliosis Specific Exercises PSSE, bracing, or a combination of both. The outcomes may also enhance our understanding of scoliogenesis. **Method and Materials**: N = 252 scoliotic children in total were studied. Two groups were formed, a) Group 1 with curves of 10 -25 Cobb angle, n= 34 males (24%) and 110 females (76%) and b) Group 2 with curves of 26 – 40 Cobb angle, n= 18 males (17%) and 90 females (83%). The assessment included age, sex, body height, scoliometry, Cobb angle, apical vertebra, apical vertebra rotation (AVR), and segmental Rib Index (SRI) in the lateral spinal radiographs. Moreover, the Rib index (RI) was assessed at the level of the maximum Double Rib Contour Sign (DRCS) distance, the average SRI value across T1-T12, the average difference between these two variables and RI at the apical vertebra of the primary curvature, (rib apical vertebra - RIAV). It is considered that in RI equal or more than 1,45-1,50 express a significant thoracic deformity in the transverse plane. In statistical analysis the following tools were included to examine distributional properties, predictive relationships, and subgroup differences relevant to the study's objectives. These were histograms, Q–Q plots, Kolmogorov–Smirnov and Shapiro–Wilk, descriptive statistics, including measures of central tendency and dispersion, linear regression analysis, model adequacy using coefficient of determination (R^2), standardized beta coefficients and residual diagnostics, a multifactorial General Linear Model (GLM) , including all two-way and three-way interactions on Cobb angle and vertebra rotation (VR), a correlation analysis applying Pearson's correlation coefficient, one-way analysis of variance (ANOVA) and Bonferroni correction. Statistical significance was determined at the conventional threshold of $p < 0.05$. Results yielding p-values between 0.05 and 0.10 were interpreted as borderline significant, warranting cautious consideration in the context of effect size and theoretical relevance. All analyses were performed using IBM SPSS Statistics for Windows, Version 30.0 (IBM Corp., released 2023, Armonk, NY, USA). **Results:** For all groups rib asymmetry, as measured by SRI showed level- and severity-dependent associations with VR and Cobb angle. In mild scoliosis (Cobb 10°–25°), significant effects of SRI were mainly observed at lower thoracic levels (T10–T12) for VR, while associations with Cobb angle were weak and largely non-significant. In moderate scoliosis (Cobb 26°–40°), SRI effects were stronger, particularly at T10–T12, with VR and Cobb angle showing significant associations. Age contributed modestly to VR in mild scoliosis, whereas gender effects were mostly weak, occasionally reaching borderline significance. Curve type significantly influenced VR in moderate scoliosis, highlighting structural differences in thoracic anatomy. Adjusted R^2 values indicate that RI alone accounts for a moderate proportion of variance in VR (up to ~24%) and a smaller proportion in Cobb angle (up to ~8–10%), consistent with scoliosis being a multifactorial condition. Rib asymmetry is a better predictor of VR than Cobb angle, particularly in moderate scoliosis. Significant effects are concentrated in the mid- and lower thoracic spine (T7–T12), suggesting regional vulnerability. SRI measures may provide additional clinical insight into three-dimensional deformity beyond standard Cobb assessment. **Discussion:** The findings of this research highlight the important role of thoracic deformity in cases of mild and moderate IS. The observed correlation in mild IS between the SRI and mainly rotation not to the Cobb angle suggests that asymmetric rib growth, exerting unequal pressure/force on the vertebrae, may initiate spinal rotation. Within the context of the pathoremodeling sequence in IS, these results align with earlier studies which proposed that spinal deformity in the frontal plane originates at the level of the intervertebral discs than the vertebral bodies (Grivas et al., 2006; Will et al., 2009). Furthermore, this study supports the view that scoliotic deformity likely come first in the thoracic cage and then the spine. The diurnal "accordion-like" phenomenon observed in the intervertebral discs may then contribute to vertebral deformation and subsequent progression of IS. In conclusion, this study demonstrates that the use of RI and SRI methods provides valuable insight into scoliogeny of mild and moderate IS and emphasizes the critical role of the thoracic cage in its development.

Keywords: idiopathic scoliosis; IS; rib index; RI; double rib contour sign; DRCS; segmental rib index; SRI; cobb angle; VR; physiotherapy scoliosis-specific exercises; PSSE; bracing; scoliometry; scoliogeny

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Introduction

It's important to review the definitions of scoliosis severity. Mild idiopathic scoliosis is characterized by a Cobb angle ≥ 10 and < 30 degree [1] or of > 10 but less < 25 degrees [2], or of > 10 but < 20 degrees [3]. Moderate IS is characterized by a Cobb angle of 25–40 degrees, which is indicated for non-operative treatment [4], and a Cobb angle > 21 to 35 degrees, [5]. We consider as mild curves those with a Cobb angle of >10 but < 25 degrees and as moderate those with a Cobb angle of > 25 to 35–40 degrees. The above published definitions are listed as we consider that "at initiating and mild IS, the patho-biomechanics are dissimilar from the biomechanics when the curve is severe". It appears that at initiating and mild IS, genetics, epigenetics, and biology have the dominant / protagonistic aetiological role, when it has non or minimal structural skeletal changes; however, it should not must be overlooked the non-protagonistic role of patho-biomechanics, which later become dominant for progressive IS, when the skeletal deformities are well established.

The aim of non-surgical treatment of IS is to maintain spinal mobility and avoid spinal fusion, halt or improve curve deterioration in adolescence, prevent or treat respiratory dysfunction, prevent or treat spinal pain syndromes and improve aesthetics through posture correction, [5]. It is tailored aiming to control the curve and alter the natural history of mild and moderate IS.

Braces for IS are externally worn devices designed to apply corrective forces to the spine and thorax. These forces aim to temporarily correct spinal curvature while the brace is in use, and theoretically harness biomechanical principles such as the Hueter-Volkmann Law [6], this law suggests that bone growth is inhibited by compression and stimulated by distraction or eccentric cyclical forces, in line with Pauwels' theory of stress and strain [7,50]. Additionally, Wolff's law states that bone structure adapts over time in response to mechanical loading. By strategically applying compression and distraction forces, braces aim to slow curve progression and, in growing individuals, potentially influence spinal growth to achieve permanent structural changes [8].

The aim and the main characteristics of physiotherapeutic scoliosis specific exercises (PSSE) are self-correction in 3 dimensions, training for activities of daily living (ADL), and stabilization of the

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corrected posture [9]. The application of PSSEs and brace treatment has significantly been reduced the incidence of surgery where high-standard conservative treatment is available [9–14].

A key question in the study of scoliogeny is whether the spinal growth changes observed in early and mild cases are primary/inherent or secondary in nature. The answer remains unclear, and there is limited information on this topic in the peer-reviewed literature. Some researchers argue that the pathology originates within the spine itself [15], while others argue that changes in the spine are secondary [16]. The research approach to addressing this issue is multidimensional, involving the examination of various anatomical components of the deformity, including the thoracic cage and the lateral spinal profile [17–19].

Based on these studies, the prevailing view is that reduced thoracic kyphosis, by allowing greater axial rotation, may play a permissive rather than causative role in the development of IS. The slight hypokyphosis observed in the thoracic spine, along with the minimal differences seen in small scoliotic curves compared to non-scoliotic peers, supports the view that reduced kyphosis facilitates axial rotation [17]. In simpler terms, a straight (non-curved) structure rotates more easily than a curved one.

The objective of this report is to examine the condition of the spine and thorax in children with mild to moderate IS prior to initiating nonoperative treatment, either through PSSEs, bracing, or a combination of both. The findings of this study may also contribute to a deeper understanding of the pathogenesis of IS.

Methods and Materials

The patients. The total number of studied patients were 252 children and adolescents. Two groups were formed. Group 1 with 144 scoliotics having Cobb angle 10-25 Cobb, age 5-18 years, and b) group 2 with 108 scoliotics having Cobb angle 26-40 Cobb angle, age 5-18 years. The patients were examined at the Department of Paediatric Rehabilitation, Institute for Physical and Rehabilitation Medicine "Dr Miroslav Zotovic", 78000 Banja Luka, Bosnia and Herzegovina. An overview of basic characteristics of patients for both groups is provided in Appendix Tables 1 and 2 of the Appendix, (see Appendix for these and the rest of Appendix Tables and the all Appendix Figures).

Ethics. The Ethical Committee of the Institute for Physical and Rehabilitation Medicine "Dr Miroslav Zotovic" provided ethical approval to conduct this retrospective research at 13.08.2025 and the number of Ethical approval is 21-40-18084-2/25. In accordance with international ethical standards for biomedical research, this study did not require individual parental consent. As it was a retrospective statistical analysis based on anonymized data extracted from the institutional health care system, no direct patient contact or prospective follow-up was performed. Therefore, the requirement for informed consent from parents/guardians was waived, in line with the Declaration of Helsinki (2013, Article 32) and with national regulations on retrospective studies. Instead, the study was conducted under the approval of the Institutional Ethics Committee of Institute for Physical and Rehabilitation Medicine "Dr Miroslav Zotovic", (No 21-40-18084-2/25), which has the legal and professional authority to review and approve retrospective analyses involving patient data.

The measurements. The documented parameters were gender, age in gears, body height, type of curve – thoracic, thoracolumbar, lumbar – Cobb angle in posteroanterior, (PA), spinal radiographs, apical rotation using the Perdriolle method, segmental rib index – SRI – in the lateral spinal radiographs, the Rib index (RI) at the level of the maximum Double Rib Contour Sign (DRCS) distance (RI_max DRCS) and the SRI_average at T1-T12 levels and scoliometry (ATR). The scoliometer was used at three areas of interest: at thoracic (T4–T8), thoraco-lumbar (T12-L1) and at the lumbar area (L3–L5). In Appendix Table 1 and Appendix Table 2 are shown the basic characteristics of patients.

The Body height follow up and the Δ height will be analyzed in a next research paper.

Group 1 comprised significantly younger patients with IS compared to Group 2, with a mean age difference of 1.95 years (95% CI: 1.37–2.53; $t = 6.60$; $p < 0.001$). As expected, patients in Group 1

 doi:10.20944/preprints202510.0374.v1

were also significantly shorter than those in Group 2, with an average height difference of 8.90 cm (95% CI: 5.58–12.22 cm; $t = 5.28$; $p < 0.001$).

The distribution of patients by sex did not differ significantly between groups ($\chi^2 = 1.82$; $p = 0.178$), nor did the distribution by primary curve location (thoracic, thoracolumbar, lumbar) ($\chi^2 = 4.22$; $p = 0.121$).

The statistical analyses were included to examine distributional properties, predictive relationships, and subgroup differences relevant to the study's objectives. Normality assumptions were evaluated through both visual inspection (histograms, Q–Q plots) and formal statistical tests (Kolmogorov–Smirnov and Shapiro–Wilk). Descriptive statistics were computed for all key variables, including measures of central tendency and dispersion. A simple linear regression analysis was performed to assess the predictive association between SRI and Cobb angle, as well as between SRI and AVR. Model adequacy was evaluated using coefficient of determination (R^2), standardized beta coefficients, and residual diagnostics. A multifactorial General Linear Model (GLM) was applied to assess the effects of scoliometric angle, gender, age, and type of primary curvature — including all two-way and three-way interactions — on Cobb angle and vertebral rotation. Scoliometry was entered as a covariate, whereas all other variables were treated as fixed factors. The model included higher-order interactions to explore the complexity of relationships among predictors. In a separate GLM analysis, the effects of the SRI, gender, age, and type of primary curvature on Cobb angle and vertebral rotation were examined using the same factorial structure.

In addition to regression, a correlation analysis was conducted to explore the linear relationships among variables, applying Pearson's correlation coefficient. Subgroup differences were examined using one-way analysis of variance (ANOVA). For multiple pairwise comparisons, Bonferroni correction was applied to control for the inflation of Type I error. Statistical significance was determined at the conventional threshold of $p < 0.05$. Results yielding p-values between 0.05 and 0.10 were interpreted as borderline significant, warranting cautious consideration in the context of effect size and theoretical relevance. All analyses were performed using IBM SPSS Statistics for Windows, Version 30.0 (IBM Corp., released 2023, Armonk, NY, USA).

Results

I. *Analysis of group 1 with curves of 10 -25 Cobb angle, n= 34 males (24%) and 110 females (76%). *For Tables and Figures please see APENDIX.*

Appendix Table 3 shows the SRI of all the patients (boys and girls), regardless of the type of spinal curve, having Cobb angle 10-25°. At almost all thoracic levels the RI has a value of more than 1.45 , in otherwords in this age group no matter the IS curve type the ribcage is remarkably deformed.

Appendix Table 4 shows the SRI of all patients having Cobb angle 10-25° by type of curve. Appendix Table 5 shows the SRI of boys having Cobb angle 10-25°. Appendix Table 6 shows the SRI of boys having Cobb angle 10-25° by type of curve. Appendix Table 7 shows the Pearson correlation coefficient between RI values and Cobb angle and RI values and vertebral rotation (boys by curve type, Cobb angle 10-25°). After applying the Bonferroni correction, a weak negative but statistically significant correlation between SRI and vertebral rotation was observed in the thoracolumbar segment ($r = -0.180$, $p = 0.020$).

The following plots, Appendix Figure 1 and Appendix Figure 2 show the correlation between all SRI measurements at each thoracic vertebra and the Cobb angle/vertebral rotation, in boys.

Appendix Figure 3 depicts RI T12 vs. apical rotation in male patients with thoracic curve, Cobb 10–25°. The Bonferroni correction adjusts the significance level to control the overall probability of a Type I error (false positive) for multiple hypothesis tests. After applying Bonferroni correction, no statistically significant correlation was observed between SRI and Cobb angle among male patients. A statistically significant correlation between SRI and vertebral rotation was noted at the thoracic curve, and at the T12 level ($r=0.646$, $p=0.013$), Appendix Figure 3.

In Appendix Figure 4 and Appendix Figure 5 it is demonstrated the spinal level of apical vertebra of curve *by type of curve* and *by age*, and spinal level of apical vertebra of curve *by type of curve*

 doi:10.20944/preprints202510.0374.v1

and *by Cobb angle* in boys with Cobb angle 10-25° respectively. The thoracic curves are depicted with blue colour, the thoracolumbar red and for lumbar green respectively. At presentation, it is realized that only for younger ages, (6-9 years of age), in males the apex of the curve may be located in thoracolumbar and lumbar levels. In older scoliotics, (10-16 years of age), is located predominantly at thoracic levels with numerical reduction of curves apex from the thoracic to the lumbar region respectively, Appendix Figure 4. The majority of larger Cobb angle curves have an apical curve vertebral mainly at T8-T10 spinal levels (thoracic curves) while there is a numerical reduction of thoracolumbar curve apex at T12-L1 spinal levels and only a small number of lumbar curves at L2 and L3, Appendix Figure 5.

Appendix Table 8 demonstrates the SRI of all girls having Cobb angle 10-25° regardless of the type of scoliotic curve. It is shown that the value of the SRI is more than 1,45 at T1-T10 thoracic levels. Appendix Table 9 shows the SRI of girls having Cobb angle 10-25° by type of curve.

Appendix Table 10 exhibits the Pearson correlation coefficient between RI values and Cobb angle and RI values and vertebral rotation in girls by curve type and Cobb angle 10-25°.

The following plots, Appendix Figure 6 and Appendix Figure 7 show the correlation between all SRI measurements at each thoracic vertebra and the Cobb angle/vertebral rotation respectively in girls. Appendix Figure 6 shows the SRI by Cobb angle grouped by curve type in girls having Cobb angle 10–25°. Appendix Figure 7 shows the SRI by apical rotation grouped by curve type in girls having Cobb angle 10–25°.

Appendix Table 11 displays the Pearson correlation coefficient between SRI and vertebral rotation in girls with a Cobb angle 10-25°. After applying the Bonferroni correction, no statistically significant correlation was observed between SRI and Cobb angle among female patients. A statistically significant correlation between SRI and vertebral rotation was noted at thoracic curve, and at the levels presented in the Appendix Table 11.

Appendix Figures 8 to 12 show in girls the correlation between RI measurements at each thoracic vertebra and the vertebral rotation at T2, T8., T9, T10, and T11. The strong correlation of SRI and spinal rotation is apparent at T9, T10, and T11 levels. Appendix Figure 13 shows the apical vertebra of curve by type of curve and by age in girls with Cobb angle 10–25°.

II. *Analysis of group 2 with curves of 26 – 40 Cobb angle, n= 18 males (17%) and 90 females (83%).*

Appendix Table 12. shows the SRI of all patients having Cobb angle 26-40°. Appendix Table 12 demonstrates that both boys and girls having Cobb angle 26-40° they have at all thoracic levels SRI ≥ 1,45 except T6. The thorax is very deformed at that stage.

Appendix Table 13 shows the SRI of all patients having Cobb angle 26-40° by type of curve. Appendix Table 14 shows the SRI of boys having Cobb angle 26-40°. Appendix Table 15 shows the SRI of boys having Cobb angle 26-40° by type of curve. Appendix Table 16 shows the Pearson correlation coefficient between RI values and Cobb angle and RI values and vertebral rotation (boys by curve type, Cobb angle 26-40°). Appendix Figure 15: shows the SRI by Cobb angle grouped by curve type in boys with Cobb angle 26–40°. Appendix Table 17 shows the Pearson correlation coefficient between SRI values and vertebral rotation in boys having Cobb angle 26-40°. Appendix Figure 17 depicts the RI at T1 vs apical rotation in male patients with Thoracic curve and Cobb 26–40°.

Appendix Figure 18 depicts the apical vertebra of curve by type of curve and by age in boys with Cobb angle 26–40°. Appendix Figure 19 depicts the apical vertebra of curve by type of curve and by Cobb angle in boys with Cobb angle 26–40°.

Appendix Table 18 shows the SRI of all girls having Cobb angle 26-40°. Appendix Table 19 shows the SRI of girls having Cobb angle 26-40° by type of curve. Appendix Table 20 demonstrates the Pearson correlation coefficient between RI values and Cobb angle and RI values and vertebral rotation in girls by curve type, and Cobb angle 26-40°. Appendix Figure 20 depicts the SRI by Cobb angle grouped by curve type in girls with Cobb angle 26–40°.

Appendix Figure 21: depicts the SRI by apical rotation grouped by curve type in girls with Cobb angle 26–40°. Appendix Table 21 demonstrates the Pearson correlation coefficient between SRI values and vertebral rotation in girls having Cobb angle 26-40°.

Appendix Figure 22 depicts the RI T10 vs. apical rotation in female patients in Thoracic curves with Cobb 26–40°. Appendix Figure 23 depicts the RI T11 vs. apical rotation in female patients in Thoracic curves with Cobb 26–40°.

Appendix Figure 24 depicts the apical vertebra of curve by type of curve and by age in girls, having Cobb angle 26–40°. Appendix Figure 25 depicts the apical vertebra of curve by type of curve and by Cobb angle in girls with Cobb angle 26–40°.

The majority of apex are located at T8 and T9 for the thoracic curves, T12, L1 for the thoracolumbar and L2 for lumbar curves respectively.

The analyses the RI at the level of the maximum DRCS distance (RI_max DRCS), the average SRI value across all twelve vertebrae (SRI_average), and the average difference between these two variables (Difference_RI) are depicted at Appendix Table 22. Appendix Table 22 shows the average values of the RI, SRI and difference between these two variables.

Appendix Table 23 demonstrates the Pearson correlation analysis of RI, Average SRI and RI–SRI Difference. Appendix Figure 26 depicts the linear association between SRI average and RI_max DRCS. Appendix Figure 27 depicts the linear association between Difference_RI and RI_max DRCS. Appendix Figure 28 depicts the linear association between Difference_RI and SRI_average

III. *Analysis of maximum DRCS distance (RI_max DRCS) -average SRI value (SRI_average) - difference between RI_max DRCS and SRI_average (Difference RI),*

moderate, statistically significant positive correlation was observed between the RI at the level of the maximum DRCS distance (RI_max DRCS) and the average SRI value (SRI_average) across all twelve vertebrae, $r = 0.609$, $p < 0.001$, Appendix Figure 26. A moderate to strong statistically significant positive correlation was also found between RI_max DRCS and the difference between RI_max DRCS and SRI_average (Difference RI), $r = 0.737$, $p < 0.001$, Appendix Figure 27. There is no statistically significant linear relationship between SRI_average and Difference RI, $r = -0.087$, $p = 0.168$, Appendix Table 23 and Appendix Figure 28. Based on the coefficients of determination (R^2) illustrated in the scatter plots, the variable RI_max DRCS explains 37.1% of the variance in SRI_average and 54.3% of the variance in Difference RI. In contrast, the variable SRI_average accounts for only 0.8% of the variance in Difference RI, indicating a negligible contribution to this outcome.

Appendix Table 24 shows the Pearson correlation analysis of RI, Average SRI and RI-SRI Difference with Start_radiograph and apical rotation. None of the listed variables show a statistically significant correlation with the Cobb angle or vertebral rotation (Appendix Table 24). The study's finding that the variable RI_max DRCS accounts for 37.1% of the variance in SRI_average and 54.3% of the variance in Difference RI suggests two possible mechanisms: a) a progressive increase in RI difference from the upper end-vertebra toward the apical vertebra, followed by a decline toward the lower end-vertebra, and b) a localized muscular asymmetry at the apical region of the thoracic cage (see the Double Rib Contour Sign - DRCS). These interpretations can be clinically and radiologically validated, as both apical vertebral level in the thoracic spine and rib length asymmetry vary across different types of thoracic or thoracolumbar scoliosis curves.

By analyzing the linear relationship between RI_max DRCS, SRI_average and the Cobb angle, as well as the linear relationship between RI_max DRCS, SRI_average and vertebral rotation, for Cobb angle 10-25°, and for Cobb angle 26-40°, the following results were obtained, Appendix Table 25, Appendix Table 26, Appendix Table 27 and Appendix Table 28 respectively.

Appendix Table 25 demonstrates the Pearson correlation analysis between RI and average SRI with Start_radiograph by gender (Cobb angle 10-25°). Appendix Table 26 demonstrates the Pearson's correlation analysis between RI and average SRI with apical rotation by gender (Cobb angle 10-25°). Appendix Table 27 demonstrates the Pearson correlation analysis between RI and average SRI with Start_radiograph by gender (Cobb angle 26-40°). Appendix Table 28 demonstrates the Pearson's correlation analysis between RI and Average SRI with apical rotation by gender (Cobb angle 26-40°).

Among 89 patients with a primary thoracic curve, in both Group 1 and 2 the RI was measured at the apical vertebra of the primary curvature (RI apical vertebra). The overall mean value was 1.64 ± 0.50, with a mean of 1.54 ± 0.39 in male patients and 1.67 ± 0.53 in female patients. Appendix Table 29 demonstrates the Pearson correlation analysis of apical vertebra RI in start_radiograph and apical rotation.

IV. Analysis of scoliometry (ATR) - vertebral rotation - Cobb angle

Appendix Table 30 demonstrates the influence of scoliometry (ATR), gender, age, and the type of the primary curve (including interactions) on vertebral rotation. Appendix Table 31 demonstrates the Pearson correlation between scoliometry and vertebral rotation by gender and type of curve. Appendix Table 32 demonstrates the influence of scoliometry, gender, age, and the type of the primary curve (including interactions) on Cobb angle. Appendix Table 33 demonstrates the Spearman correlation analysis of scoliometry and Cobb angle stratified by age.

V. General Linear Model (GLM) - Group 1 (Cobb angle 10-25°) - vertebral rotation

ppendix Table 34 to 45 shows the General Linear Model (GLM) - SRI vs rotation – examination of the effects of SRI— assessed individually at each of the twelve thoracic vertebral levels (T1–T12) — as well as gender, age, and type of primary scoliotic curvature, on vertebral rotation in Group 1 with Cobb angle 10-25°.

VI. General Linear Model (GLM) - Group 1 (Cobb angle 10-25°) - Cobb angle

Appendix Table 46 to 57. shows the General Linear Model (GLM) - SRI vs Cobb - examination of the effects of SRI — assessed individually at each of the twelve thoracic vertebral levels (T1–T12) — as well as gender, age, and type of primary scoliotic curvature (on Start_radiograph), on Cobb angle in Group 1 - (Cobb angle 10-25°)

Appendix Table 58 shows the Pearson correlation analyses between Scoliometry (ATR) and vertebral rotation in patients stratified by age, gender and type of curve in Group 1 with Cobb angle 10 – 25°.

VII. General Linear Model (GLM) - Group 2 (Cobb angle 26-40°) - vertebral rotation

ppendix Tables 59 to 70 show the General Linear Model (GLM) - SRI vs rotation – examination of the effects of SRI — assessed individually at each of the twelve thoracic vertebral levels (T1–T12) — as well as gender, age, and type of primary scoliotic curvature, on vertebral rotation in Group 2 - Cobb angle 26-40°.

VIII. General Linear Model (GLM) - Group 2 (Cobb angle 26-40°) - Cobb angle

Appendix Tables 71 to 82 shows the General Linear Model (GLM) - SRI vs Cobb - examination of the effects of Segmental Rib Index (SRI) — assessed individually at each of the twelve thoracic vertebral levels (T1–T12) — as well as gender, age, and type of primary scoliotic curvature at Start_radiograph, on Cobb angle (Group 2 - (Cobb angle 26-40°).

Appendix Table 83 demonstrates the Pearson correlation analyses between Scoliometry (ATR) and vertebral rotation in patients stratified by age, gender and type of curve (Group 2 – Cobb angle 26 – 40

Discussion

In IS the initiation as being silent and imperceptible, it is inconspicuous and not apparent. One of the sings used to identify IS is the existance of a thoracic hump or lumbar lumb during the implementation of the forward bendihg test (Adam Test) [20]. The Adam's forward bend test is a common screening tool for scoliosis, a positive Adam's test, shows trunkal asymmetry in terms of a rib hump or lumbar lumb, and indicate a potential spinal abnormality [21].

This rib hump is essentially due to right – left asymmetric development of the pair of 12 ribs. The development of the rib hump initiates the trunk roration and is measured with a scoliometer assessed as angle of trunk rotation, (ATR).

This 12 pair ribs asymmetry is clearly shown in the standing lateral spinal radiographs as a double rib contour. This was coined as the double rib contour sign (DRCS) and as a novel sign was first presented in 1999 [22] and later published [23,24]. The amount of the asymentry of this DRCS was assessd using the rib index (RI) [25], and the segmental rib index (SRI), method, which assess the thoracic deformity in the transverse plane, [26].

It is theorised that the asymetric funcion of the autonomic nervoys system is responsible for both the creation of the rib asymetry due to asymetric right left blood irrigation and the asymmetric right left muscular function [27–31]. The confirmation that the thoracic deformity preceeds this of the spinal deformity has been earlier reported based on the analysis of the school scoliosis screening data and the use of RI and the Cobb angle of referred children with mild IS [32–34]. RI is a useful tool to evaluate the amound of transverse thoracic deformity in IS, and to assess the outcome a) of PSSEs , b) of bracing, c) of surgical treatment in IS, and finaly d) be used as a predictor of curve progression, [35,36].

In process of developing IS, that is in mild IS, it has been reported that the Cobb angle begins due to wedging of the intervetebral discs and not the deformation of the vertebral body and the thoracic deformity preceedes that in the spine [37,38].

There is ongoing debate in the literature regarding whether scoliogenic changes in mild idiopathic scoliosis (IS) originate in the thorax or the spine. The available evidence on this topic remains limited. Some researchers suggest that the pathology begins within the spine [39], while others propose that spinal changes are secondary to thoracic alterations [40].

In this study, we take a comprehensive approach to assess the thoracic and spinal conditions in patients with mild to moderate IS before the initiation of PSSEs and bracing. By analyzing numerous parameters, we aim to gain insight into the scoliogenic process and provide a more reliable perspective on this unresolved question.

The appropriate methodological approach to obtain a reliable answer to the research question—namely, whether the spinal growth changes observed in early and mild IS cases are primary/inherent or secondary in nature — is the comparative study of boys and girls classified into two groups: Group 1, with curves measuring 10–25° Cobb angle, and Group 2, with curves measuring 26–40° Cobb angle, as presented in Appendix Table 1 and Appendix Table 2.

In this report the thoracic deformity is assessed using apart from the RI and the SRI method, the rib index at the level of the maximum DRCS distance (RI_max DRCS) and the average SRI value (SRI_average) across all twelve vertebrae, which actually indicated the average severity of thoracic deformity in the studied two groups. Additionally, the various parameters of the thoracic deformity were correlated with the spinal parameters of Cobb angle and apical vertebral rotation for boys and girls in the three curve types for group 1 and 2. The ATR (scoliometry) was also correlated with vertebral rotation - Cobb angle in two groups.

Appendix Table 3 shows the SRI of all the patients (boys and girls), regardless of the type of spinal curve, having Cobb angle 10-25°. Notably at almost all thoracic levels the RI has a value of more than 1.45 , in other words in this age group no matter the scoliotic curve type the ribcage is remarkably deformed.

Appendix Table 4 shows the comparison of SRI of all the patients (boys and girls), having Cobb angle 10-25°, by type of curve. It is revealed that the SRI at the thoracic curves at all thoracic levels is increased (having a value more than 1,45). However, in this patients group, the thoracolumbar and lumbar curves it is increased (more than 1,45), only at T1-T4 thoracic levels. This finding reveals that in this group of all patients', (boys and girls), thoracolumbar and lumbar curves, the upper part of the thorax is more deformed than the lower part of it. It was also found that the SRI at thoracic curves was more deformed and statistically significant different of the SRI of thoracolumbar and lumbar curves at T7-T11 levels.

The Least Significant Difference (LSD) test, also known as Fisher's LSD, is a post-hoc statistical test used to determine which specific group means are significantly different from each other after an ANOVA (Analysis of Variance) test has shown a significant overall difference. It essentially performs

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pairwise t-tests between all group means, but with a correction to control for the increased risk of Type I errors (false positives) due to multiple comparisons. Additionally, to statistical analysis which demonstrated a significant variation in the measured SRI across different types of scoliotic curves at the T7 to vertebral levels, the post hoc comparisons using the LSD test indicated statistically significant differences between thoracic and thoracolumbar curves, with p = 0.001 at T7 and p < 0.001 at T8–Th11. Furthermore, significant differences were identified between thoracic and lumbar curves, with p = 0.013 at T8, p = 0.001 at T9, p < 0.001 at T10, and p = 0.026 at T11. However, no statistically significant difference in SRI values was observed between thoracolumbar and lumbar curves.

In particular, analyzing the SRI by gender, in all boys regardless the scoliotic curve type, having Cobb angle 10-25°, it is demonstrated that the value of SRI is more than 1,45 at the T1-T5 and T12 thoracic levels, Appendix Table 5.

The SRI of boys having Cobb angle 10-25°, by type of scoliotic curve, it was demonstrated that at thoracic curves the SRI value was more than 1,45 at T1-T5 and at T12 thoracic level, at thoracolumbar curves was more than 1,45 at T2-T4 and notably at lumbar curves at all the thoracic levels, Appendix Table 6. These findings reveal that the upper part of the ribcage of boys with thoracic curve is more deformed than their lower part and particularly in boys with lumbar cures all the SRI in all the thoracic levels is more than 1,45 that is significantly deformed, while in thoracolumbar curves only at the T2-T4 thoracic levels, Appendix Table 6. Therefore, the thoracic deformity plays a significant role related to the lumbar curves in boys, a novel finding which was not mention earlier in literature. Among male patients, no statistically significant difference in SRI values was observed across the different types of scoliotic curves, Appendix Table 6

In Appendix Table 7 the Pearson correlation coefficient between SRI values and Cobb angle and SRI values and vertebral rotation in boys by curve type with Cobb angle 10-25° is analyzed. The linear relationship between RI values across all thoracic SRI and the Cobb angle, as well as the linear relationship between RI and vertebral rotation across all segments, SRI, show that at mild scoliotic curves in group 1, the spinal deformity in terms of Cobb angle and apical rotation (mean 8,9 degrees) is not statistically significant related to thoracic deformity with is significantly increased at that stage, for thoracic and lumbar curves. In the thoracolumbar curves there is significantly statistical relation only to the apical vertebral rotation, Appendix Table 7. After applying the Bonferroni correction, a weak negative but statistically significant correlation between SRI and vertebral rotation was observed in the thoracolumbar segment (r = –0.180, p = 0.020).

The Appendix Figure 1 shows the SRI by rotation in boys with Cobb angle 10-25°, by type of curve. The following plots, Appendix Figure 1 and Appendix Figure 2 show the correlation between all SRI measurements at each thoracic vertebra and the Cobb angle/vertebral rotation, in boys. After application of the Bonferroni correction, which adjusts the significance level to control the overall probability of a Type I error (false positive) for multiple hypothesis tests shows no statistically significant correlation between SRI and Cobb angle among male patients. A statistically significant correlation between SRI and vertebral rotation was noted at the thoracic curve at the Th12 level (r=0.646, p=0.013), Appendix Figure 3.

In Appendix Figure 4 and Appendix Figure 5 it is demonstrated the spinal level of *apical vertebra* of curve *by type of curve* (boys, cobb angle 10-25°) and *by age,* and spinal level of apical vertebra of curve *by type of curve* (boys, cobb angle 10-25°) and *by Cobb angle* respectively. The thoracic curves are depicted with blue colour, the thoracolumbar red and for lumbar green respectively. At presentation, it is realized that only for younger ages (6-9 years of age) in males the apex of the curve may be located in thoracolumbar and lumbar levels. In older scoliotics (10-16 years of age) is located predominantly at thoracic levels with numerical reduction of curves apex from the thoracic to the lumbar region respectively, Appendix Figure 4. The majority of larger Cobb angle curves have an apical curve vertebral mainly at T8-T10 spinal levels (thoracic curves) while there is a numerical reduction of thoracolumbar curve apex at T12-L1 spinal levels and only a small number of lumbar curves at L2 and L3, Appendix Figure 5.

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In Appendix Table 8 is demonstrated the SRI of girls having cobb angle 10-25° regardless of the type of scoliotic curve. It is shown that the value of the SRI is more than 1,45 at T1-T10 thoracic levels.

In Appendix Table 9 is shown the SRI of girls having Cobb angle 10-25°, by type of curve. In thoracic curves the value of SRI is more than 1,45 at all the thoracic levels except T12, for the thoracolumbar curves at T1-T6 and for the lumbar curves from T1-T3 and T5 respectively. Among female patients, a statistically significant difference in measured SRI values across types of scoliotic curves was observed at the T5 vertebra, as well as at T7 through T10. Post hoc analysis (LSD test), adjusted using the Bonferroni correction to account for multiple comparisons, revealed significant differences between thoracic and lumbar curves at T5 ($p = 0.009$), T7, T8, and T9 ($p = 0.001$), and at T10 ($p = 0.010$). Additionally, significant differences were found between thoracic and thoracolumbar curves at T7, T8, and T9 ($p = 0.001$) and at T10 ($p = 0.008$). No statistically significant difference in SRI values was identified between thoracolumbar and lumbar curves, Appendix Table 9.

In Appendix Table 10 is shown the analysis of the linear relationship (Pearson correlation coefficient) between SRI values across all thoracic segments and the Cobb angle, as well as the linear relationship between SRI and vertebral rotation across all segments in girls having Cobb angle 10-25°. In the thoracic segment, a weak but statistically significant correlation was found between SRI and Cobb angle ($r=0.141$, $p=0.007$), while a weak to moderate positive linear relationship was observed between RI and vertebral rotation ($r=0.378$, $p<0.001$). In plots - Appendix Figure 6 and Appendix Figure 7 is shown the correlation between all SRI measurements at each thoracic vertebra and the Cobb angle/vertebral rotation respectively in girls. After applying the Bonferroni correction, no statistically significant correlation was observed between SRI and Cobb angle among female patients. A statistically significant correlation between SRI and vertebral rotation was noted at thoracic curve, and at the levels presented in girls with a Cobb angle 10-25°, in the Appendix Table 11.

In Appendix Figure 8 to Appendix Figure 12 is shown in girls having Cobb angle 10-25 degrees, the correlation between RI measurements at each thoracic vertebra and the vertebral rotation at T2, T8., T9, T10, and T11. The strong correlation of SRI and spinal rotation is apparent at T9, T10, and T11 levels. In Appendix Figure_08 to Appendix Figure_12 is shown: RIT2 to RI12 vs. apical rotation in female patients with thoracic curve and Cobb 10–25°. This analysis shows that in mild IS the thoracic deformity stimulates the rotation in spine.

In Appendix Figure 13 and Appendix Figure 14 it is demonstrated the *apical vertebra* of curve, in girls having Cobb angle 10-25°, by curve type and age and the apical vertebra of curve in girls having Cobb angle 10-25°, by curve type and by Cobb angle respectively. The thoracic curves are depicted with blue colour, the thoracolumbar red and the lumbar green respectively. At presentation, it is realized that only for younger ages (5-7 years of age) in girls the apex of the curve may be located in thoracic levels, (6 -8 years of age) in thoracolumbar levels. No curve has apex at the lumbar spine in younger ages. In older scoliotics (8-16 years of age) the apex is located predominantly at thoracic levels with numerical reduction of curves apex from the thoracic to the lumbar region respectively, Appendix Figure 13. The majority of larger Cobb angle (19-25 degrees) in thoracic curves have an *apical vertebral* mainly at T8-T11 spinal levels while there is a numerical reduction of thoracolumbar curve apex at T12-L1 spinal levels and only a small number of lumbar curves at L2 and L3, Appendix Figure 14.

In Group 2 with curves of 26 – 40 Cobb angle, as it is expected there are more females (n=90 females (83%) and n= 18 males (17%). In this group it is shown, analyzing for both boys and girls having Cobb angle 26-40°, that they have at all thoracic levels SRI ≥ 1,45 except T6. The thorax is very deformed at that stage, as described in Appendix Table 12.

In both boys and girls, together, having Cobb angle 26-40° by curve type, the thoracic curves have SRI in all the spinal levels is more than 1,45, indicating that thorax is very deformed in all type of curves. For thoracolumbar curves the SRI value is more than 1,55 only at T1-T3 and for the lumbar curves at T1-T9 respectively.

Statistical analysis demonstrated a significant variation in the measured SRI across different types of scoliotic curves at the T8 to T11 vertebral levels. Post hoc comparisons using the LSD test indicated statistically significant differences between thoracic and thoracolumbar curves, with $p = 0.006$ at T8, $p = 0.001$ at T9, $p < 0.001$ at T10 and, $p = 0.001$ at T11. Furthermore, significant differences were identified between thoracic and lumbar curves, with $p = 0.001$ at T10 and $p = 0.005$ at T11. However, no statistically significant difference in SRI values was observed between thoracolumbar and lumbar curves, Appendix Table 13.

The SRI for all scoliotic curve types of boys having Cobb angle 26-40° the analysis show that al all the thoracic levels the value is ≥ 1,45. It appears that the rib cage is very deformed, Appendix Table 14.

Analysis in each of the curve type in boys having Cobb angle 26-40°, SRI is more than 1,45 except in thoracic at T7and T8, in thoracolumbar at T1, T6, T7, T9, T10, and at Lumbar at T8, T10, and T11. It is interesting to note that at the lumbar curves the SRI have a more elevated values than 1,45 in the upper thoracic levels, therefore it seems that at these curves the rib asymmetry play a role in the scoliogeny. No statistically significant differences were observed between thoracic, thoracolumbar and lumbar curves, Appendix Table 15.

By analyzing the linear relationship between RI values across all thoracic segments and the Cobb angle, as well as the linear relationship between RI and vertebral rotation across all segments, the following results were obtained, Appendix Table 16 and Appendix Figure 15 and 16. By analyzing the linear relationship between RI values across all thoracic segments and the Cobb angle, as well as the linear relationship between RI and vertebral rotation across all segments in boys having a Cobb angle 26-40°, it was found a moderate negative statistically significant correlation between SRI and vertebral rotation in the lumbar segment ($r = -0.579$, $p < 0.001$), as well as borderline statistically significant positive correlation between the SRI and Cobb angle in the thoracolumbar segment ($r=0.278$, $p=0.032$), with Bonferroni correction applied, Appendix Table 16 and Appendix Figure 15 and 16.

In Appendix Figure 15 the SRI by Cobb angle grouped by curve type and in Appendix Figure 16 the SRI by apical rotation grouped by curve type in boys, Cobb angle 26–40° respectively.

After applying the Bonferroni correction, no statistically significant correlation was observed between SRI and Cobb angle among male patients. A statistically significant correlation between SRI and vertebral rotation was noted at thoracic and lumbar curve, and at the levels presented in the following Appendix Table 16.

Appendix Table 17 demonstrates the Pearson correlation coefficient between SRI values and vertebral rotation in boys, having Cobb angle 26-40° at T1 $R^2=0.842$, p= 0,009 and Appendix Figure 17.

The findings suggest that although advanced thoracic deformity is evident, as indicated by elevated SRI values, the degree of spinal deformity remains moderate (Cobb angle 26–40°). No correlation was observed between thoracic deformity (SRI) and spinal curvature (Cobb angle); however, vertebral rotation demonstrated a significant association. This relationship implies that asymmetric rib growth within the thorax may contribute to the development of vertebral rotation.

Appendix Figure 18 shows for boys with a Cobb angle 26-40°, the curve *apical vertebra* by type of curve and *by age* and Appendix Figure 19 shows for boys having Cobb angle 26-40° the curve *apical vertebra* by type of curve and *by Cobb angle*. The thoracic curves are depicted with blue colour, the thoracolumbar red and the lumbar green respectively.

Appendix Table 18 shows the SRI for all scoliotic curve types of girls having Cobb angle 26-40°. In all curve types the SRI was found more than 1,45, except in thoracic at T5 and T6 and T12. It appears that the rib cage is very deformed.

Appendix Table 19 shows the SRI of girls having Cobb angle 26-40° by curve type. Notably the SRI in all the thoracic curves is more than 1,45. In thoracolumbar curves the upper thoracic levels (T1, T2, T3) have a SRI more than 1,45. The lumbar curves appear to have increased SRI at the majority of

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the thoracic levels except T1, and T10-T12, therefore, as in boys, it seems that at these curves the rib asymmetry play an important role in the scoliogeny.

A statistically significant difference in the SRI based on the type of scoliotic curve was identified at the T4 and T8 to T12 vertebral levels. Post hoc comparisons using the Bonferroni correction indicated statistically significant differences between thoracic and thoracolumbar curves, with $p = 0.047$ at T4, $p = 0.006$ at T8, $p < 0.004$ at h9, $p = 0.003$ at h10, $p < 0.001$ at T11, and borderline statistically significant differences between thoracic and thoracolumbar curves, with $p = 0.057$ at T12 level. Furthermore, significant differences were identified between thoracic and lumbar curves, with $p = 0.027$ at T10 and $p = 0.012$ at level. However, no statistically significant difference in SRI values was observed between thoracolumbar and lumbar curves.

By analyzing the linear relationship between RI values across all thoracic segments and the Cobb angle, as well as the linear relationship between RI and vertebral rotation across all segments, the results obtained as shown at Appendix Table 20, Appendix Figure 20 and Appendix Figure 21. After applying the Bonferroni correction, a weak positive statistically significant correlation between SRI and vertebral rotation was observed in the thoracolumbar segment ($r = 0.118$, $p = 0.011$), as well as a weak statistically significant positive correlation between the SRI and Cobb angle in the lumbar segment ($r=0.168$, $p=0.020$).

In Appendix Figure 20 is shown the SRI by Cobb angle grouped by curve type in girls with Cobb angle 26–40° and in Appendix Figure 21 the SRI by apical rotation grouped by curve type in girls with Cobb angle 26–40°. After applying the Bonferroni correction, *no statistically significant correlation was observed between SRI and Cobb angle among female patients. A statistically significant correlation between SRI and vertebral rotation was noted at thoracic curve*, and at T10 and T11 levels, Appendix Table 21, Appendix Figure 22 and 23.

Appendix Figure 24 depicts the curve's apical *vertebra* in girls having a Cobb angle 26-40° by curve type and by age and Appendix Figure 25 the curve apical vertebra in girls having a Cobb angle 26-40° by type of curve and by Cobb angle respectivly. The majority of apex are located at T8 and T9 for the thoaraci curves, T12, L1 for the thoracolumbar and L2 for lumbar curves respectively.

The analyses the RI at the level of the maximum DRCS distance (RI_max DRCS), the average SRI value across all twelve vertebrae (SRI_average), and the average difference between these two variables (Difference_RI) may provide useful information on scoliogenesis. The average values of the SRI and difference between these two variables are shown in Appendix Table 22.

Appendix Table 23 shows the Pearson correlation coefficient between RI_max DRCS, SRI_average and Difference _RI. A moderate, statistically significant positive correlation was observed between the RI at the level of the maximum DRCS distance (RI_max DRCS) and the average SRI value (SRI_average) across all twelve vertebrae, $r = 0.609$, $p < 0.001$ Appendix Figure 26. A moderate to strong statistically significant positive correlation was also found between RI_max DRCS and the difference between RI_max DRCS and SRI_average (Difference RI), $r = 0.737$, $p < 0.001$,

Appendix Figure 27 shows that there is no statistically significant linear relationship between SRI_average and Difference RI, $r = -0.087$, $p = 0.168$, (Appendix Table 23 and Appendix Figure 28). Based on the coefficients of determination (R^2) illustrated in the scatter plots, the variable RI_max DRCS explains 37.1% of the variance in SRI_average and 54.3% of the variance in Difference RI. In contrast, the variable SRI_average accounts for only 0.8% of the variance in Difference RI, indicating a negligible contribution to this outcome. The interesting finding is that none of the listed variables show a statistically significant correlation with the Cobb angle or vertebral rotation (Appendix Table 24).

The study's finding that the variable RI_max DRCS accounts for 37.1% of the variance in SRI_average and 54.3% of the variance in Difference RI suggests two possible mechanisms: a) a progressive increase in RI difference from the upper end-vertebra toward the apical vertebra, followed by a decline toward the lower end-vertebra, and b) a localized muscular asymmetry at the apical region of the thoracic cage (see the Double Rib Contour Sign - DRCS). These explanations can

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be clinically and radiologically validated, as both apical vertebral level in the thoracic spine and rib length asymmetry vary across different types of thoracic or thoracolumbar scoliosis curves.

Appendix Table 24 shows the Pearson correlation analysis of RI, Average SRI and RI-SRI Difference with Start radiograph and apical rotation

For analyzing the linear relationship between RI_max DRCS, SRI_average and the Cobb angle, as well as the linear relationship between RI_max DRCS, SRI_average and vertebral rotation, for Cobb angle 10-25°, and for Cobb angle 26-40°, see Appendix Table 25, Appendix Table 26, Appendix Table 27 and Appendix Table 28 respectively. After applying the Bonferroni correction, a moderate, statistically significant positive linear relationship was observed between and SRI_average and vertebral rotation in the thoracic segment among female patients with a Cobb angle ranging from 10° to 25° (r=0.696, p<0.001). Again this may be explained that the RHD starts the rotation in mild scoliosis. Interestingly it was reported that in a number of early onset cases of IS (Type III of infantile IS, [41]) Cobb angle shows some resolution whilst AVR continues to increase during follow up, phenomenon based on the view that biplanar neuromuscular mechanisms involving spinal cord "central pattern generators" (CPGs) control the pattern of scoliosis development in the frontal and transverse planes. Moreover, that progressive infantile idiopathic scoliosis, like adolescent idiopathic scoliosis results, in part, from asymmetry of CPGs controlling movements of the trunk in gait, [41].

Among 89 patients in both Group 1 and 2 with a primary thoracic curve, the RI was measured at the apical vertebra of the primary curvature, (RI apical vertebra). The overall mean value was 1.64 ± 0.50, with a mean of 1.54 ± 0.39 in male patients and 1.67 ± 0.53 in female patients. The Pearson correlation coefficient of RI of the apical vertebrae, to Cobb angle and apical rotation is shown in Appendix Table 29. A weak but statistically significant positive correlation was observed between the RI of apical vertebra and apical rotation in the overall patient group ($r = 0.288$, $p = 0.006$), as well as among female patients with a primary scoliosis ranging from 26° to 40° according to Cobb's angle ($r = 0.421$, $p = 0.011$). Among female patients with a primary scoliosis ranging from 10° to 25° Cobb's angle, a moderate statistically significant positive linear relationship was identified between the RI of apical vertebra and apical rotation ($r = 0.588$, $p = 0.001$).

General Linear Model (GLM) for Groups 1 and 2.

A multifactorial General Linear Model (GLM) was employed to assess the influence of scoliometry (ATR), gender, age, and the type of the primary curve (including interactions) on vertebral rotation, as shown in Appendix Table 30, Scoliometry was entered as a covariate, while the remaining variables were treated as fixed factors. The analysis included all two-way and three-way interactions to explore more complex relationships among the predictors.

The multivariate model reached statistical significance ($F(12,129) = 3.79$, $p < 0.001$), with a coefficient of determination $R^2 = 0.260$, indicating that 26% of the variance in vertebral rotation was explained. Among all predictors, the scoliometric angle demonstrated the strongest independent contribution ($F = 19.54$, $p < 0.001$, $\eta^2 = 0.132$), evidencing that increased scoliometric readings robustly predict greater rotational displacement. Neither gender, age, nor type of curve yielded statistically significant main effects ($p > 0.15$); however, the interaction between gender and type of curve attained significance ($F = 3.16$, $p = 0.046$, $\eta^2 = 0.047$), suggesting that the rotational impact of curve morphology is contingent upon the subject's gender.

In order to assess the direct linear association between scoliometric angle and vertebral rotation, Pearson's correlation coefficient used. The Appendix Table 31, shows the Pearson's correlation coefficient used to assess the direct linear association between scoliometric angle and vertebral rotation. Pearson's r revealed a significant positive correlation between scoliometric measurements and vertebral rotational displacement. Following Bonferroni adjustment ($\alpha_\beta = 0.0083$), significant correlations were observed between scoliometric angle and both thoracic ($r = 0.537$, $p = 0.002$) and thoracolumbar vertebral rotation ($r = 0.410$, $p = 0.008$) in females. This is a strong confirmation of the impact of rib asymmetry development and thus the thoracic deformity on spinal rotation in the commencement of IS.

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A GLM was also conducted to evaluate the influence of scoliometric angle, age category, gender, and curve location on Cobb angle. The overall model reached statistical significance ($F(12, 131) = 1.90$, $p = 0.040$, $R^2 = 0.148$), though the adjusted explanatory power was modest (Adjusted $R^2 = 0.070$).

While scoliometry demonstrated a trend towards significance ($F = 2.91$, $p = 0.091$), only age category showed a statistically significant effect on the dependent variable ($F = 7.02$, $p = 0.009$, partial $\eta^2 = 0.051$), suggesting age-related variations in Cobb angle presentation. Appendix Table 32, shows the evaluation of the influence of scoliometric angle, age category, gender, and curve location on Cobb angle using a General linear model.

Spearman correlation analyses was used to assess the direct linear association between scoliometric angle and vertebral rotation and Cobb angle in IS patients less and more that 13 years of ages, revealed no significant association between scoliometric angle and Cobb angle in participants aged ≤13 years ($r = 0.010$, $p = 0.919$). In subjects older than 13 years, a weak positive correlation was observed ($r = 0.287$, $p = 0.072$), suggesting a potential age-related trend, though it did not reach conventional levels of statistical significance. This finding a strong confirmation of earlier research on the effect of growth on the correlation between the spinal and rib cage deformity [18], as shown in Appendix Table 33, that is Spearman correlation analyses for assessment of the direct linear association between scoliometric angle and Cobb angle.

A GLM was employed to examine the effects of SRI — assessed individually at each of the twelve thoracic vertebral levels (T1–T12) — as well as gender, age, and type of primary scoliotic curvature, on vertebral rotation. Rotation was treated as the dependent variable, while the aforementioned parameters served as independent predictors. To further explore potential compound effects, interaction terms were incorporated to assess synergistic influences among anatomical and demographic factors. The GLM analysis identified a statistically significant predictive relationship between vertebral rotation and the examined set of predictors, comprising SRI at the T10 vertebral level, gender, age, and the type of primary scoliotic curvature.

Among all independent variables, the SRI at T10 emerged as the most influential predictor ($F(1, df_2) = 10.61$, $p = 0.001$, partial $\eta^2 = 0.076$), substantiating the biomechanical relevance of rib cage asymmetry in explaining vertebral rotational displacement. Age also demonstrated a robust effect on rotation ($F(1, df_2) = 8.02$, $p = 0.005$, partial $\eta^2 = 0.059$), indicating that older individuals exhibit more pronounced rotational changes.

Neither gender nor curvature type yielded significant main effects ($p > 0.45$); however, their interaction revealed statistical significance ($F(2, df_2) = 3.44$, $p = 0.035$, partial $\eta^2 = 0.051$), suggesting a gender-dependent modulation of the rotational impact of curvature morphology. Other interactions tested within the model did not reach statistical significance.

The GLM analyses indicate that RI has limited influence on vertebral rotation at upper thoracic levels but becomes more relevant at lower thoracic levels, with a significant effect at T10 and marginal effects at T9, T11, and T12. Age consistently influences vertebral rotation across all levels, reinforcing its role as a key determinant of spinal deformity progression.

The interaction between gender and type of curve suggests that curve patterns may affect vertebral rotation differently in males and females, particularly at lower thoracic levels where the interaction is significant. Other factors, including gender alone and age interactions, did not significantly impact vertebral rotation.

Overall, these results highlight the primary importance of age and the combined effect of gender and curve type on vertebral rotation, while RI may have a level-specific influence, particularly in the mid-to-lower thoracic spine. These findings may inform targeted clinical assessment and guide future research on the biomechanical factors influencing scoliosis progression.

Appendix Table 34 to 45 shows the GLM - SRI vs Rotation – examination of the effects of SRI — assessed individually at each of the twelve thoracic vertebral levels (T1–T12) — as well as gender, age, and type of primary scoliotic curvature, on vertebral rotation.

 doi:10.20944/preprints202510.0374.v1

Appendix Table 46 to 57 shows the GLM - SRI vs Cobb - examination of the effects of SRI — assessed individually at each of the twelve thoracic vertebral levels (T1–T12) — as well as gender, age, and type of primary scoliotic curvature, on Cobb angle.

In patients with mild scoliosis (10°–25° Cobb) these findings indicate that in mild scoliosis, age is the primary determinant of curve magnitude, while RI, gender, and type of curve follows in impact. The results suggest that vertebral rotation and overall Cobb angle may be influenced by different factors. Clinically, age-related monitoring remains essential for early detection and management of curve progression in patients with mild scoliosis

Appendix Table 58. Pearson's correlation analyses assessing the direct linear association between scoliometric angle and vertebral rotation in children ≤13 years and >13 years of age.

In males ≤13 years, a strong and statistically significant positive correlation was identified between the scoliometric angle and vertebral rotation in the thoracic segment ($r = 0.812$, $p = 0.014$). In contrast, the thoracolumbar segment showed a moderately negative association, while the lumbar segment demonstrated a moderately positive trend. However, neither reached statistical significance, likely due to the limited sample size within these subgroups ($r = –0.633$, $p = 0.127$ and $r = 0.643$, $p = 0.357$, respectively). Among older males (>13 years), moderate positive correlation was observed in the thoracic region, but remained non-significant ($r = 0.354$, $p = 0.687$). Thoracolumbar curves exhibited weaker association ($r = 0.188$, $p = 0.687$), while lumbar data were unavailable.

In females ≤13 years statistically significant positive correlation was identified between the scoliometric angle and vertebral rotation in the thoracic segment ($r = 0.520$, $p = 0.007$), thoracolumbar segment ($r = 0.441$, $p = 0.013$) and lumbar segment ($r=0.410$, $p=0.038$). In females >13 years, all correlations were non-significant and attenuated, with thoracic curves showing moderate association ($r = 0.657$, $p = 0.229$), and thoracolumbar and lumbar regions yielding lower values ($r = 0.245$ and $r = -0.273$, respectively; $p > 0.4$).

In males ≤13 years, no statistically significant associations were identified across curvature types. The thoracic segment displayed a weak positive correlation with rotation ($r = 0.147$, $p = 0.729$), while thoracolumbar curves were inversely correlated ($r = –0.425$, $p = 0.341$); both relationships failed to reach statistical significance. Lumbar correlation was negligible ($r = 0.087$, $p = 0.913$). Among older males (>13 years), moderate positive correlation was observed in the thoracic region ($r = 0.487$, $p = 0.327$), but remained non-significant. Thoracolumbar curves exhibited weaker inverse association ($r = –0.276$, $p = 0.550$), while lumbar data were unavailable.

In contrast, females ≤13 years demonstrated a statistically significant positive correlation between thoracic curvature and rotational displacement ($r = 0.681$, $p < 0.001$), highlighting a potentially age- and sex-specific biomechanical interplay. No significant correlations were noted in the thoracolumbar ($r = –0.097$, $p = 0.603$) or lumbar ($r = 0.140$, $p = 0.496$) segments. In females >13 years, all correlations were non-significant and attenuated, with thoracic curves showing moderate association ($r = 0.343$, $p = 0.572$), and thoracolumbar and lumbar regions yielding lower values ($r = 0.236$ and $r = 0.288$, respectively; $p > 0.4$).

These finding reveal that the trunkal rotation (ATR), that is the thoracic deformity, with SRI more than 1,45 in females ≤13 years of age play an importan role for the initiation of the spinal rotational deformity.

Appendix Table 59 to 70 shows the GLM - SRI vs Rotation – examination of the effects of SRI — assessed individually at each of the twelve thoracic vertebral levels (T1–T12) — as well as gender, age, and type of primary scoliotic curvature, on vertebral rotation in Group 2 - Cobb angle 26-40°.

In patients with moderate scoliosis (Cobb 26°–40°), RI significantly predicted vertebral rotation at several thoracic levels, particularly T10– (RI10: $F = 8.253$, $p = 0.005$; RI11: $F = 15.346$, $p < 0.001$; RI12: $F = 7.782$, $p = 0.006$). At upper thoracic levels (T1–T9), RI showed non-significant or marginal trends (F range 0.049–3.314, p ranges 0.072–0.826).

The type of curve was a significant predictor across almost all levels (T1–T12, F range 5.016–9.979, $p < 0.05$, partial η^2 0.096–0.174). Gender showed marginal significance at multiple levels (T1–T9, $p = 0.055–0.079$), while age was generally not significant. A significant three-way interaction

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(gender × age × type of curve) was observed at T11 ($F = 4.364$, $p = 0.039$), suggesting a complex interplay in vertebral rotation at this level. The model fit improved at lower thoracic levels, with adjusted R^2 ranging from 0.119–0.241, indicating moderate explanatory power. Results are summarized in Appendix Table 59 to 70. Therefore, in moderate scoliosis, vertebral rotation is primarily influenced by type of curve and RI at lower thoracic levels. Gender and age have limited impact. The significant three-way interaction at T11 suggests that combined effects of gender, age, and curve type may be relevant at specific levels. These results indicate that structural factors such as curve type and rib asymmetry become increasingly important with larger Cobb angles, supporting targeted monitoring and assessment in patients with moderate scoliosis.

Appendix Table 71 to 82 shows the GLM - SRI vs Cobb - examination of the effects of SRI — assessed individually at each of the twelve thoracic vertebral levels (T1–T12) — as well as gender, age, and type of primary scoliotic curvature, on Cobb angle in Group 2 - Cobb angle 26-40°.

The GLM analyses were conducted to examine the association between RI at thoracic levels T1–T12 and Cobb angle in patients with moderate scoliosis (Cobb angle 26°–40°). Across the thoracic spine, RI values showed varying levels of association with Cobb angle. At upper thoracic levels (T1–T4), RI was not significantly associated with Cobb angle ($p > 0.3$). At mid-thoracic levels (T5–T9) demonstrated trends toward significance, with RI at T7 showing borderline significance ($F = 3.937$, $p = 0.050$, partial $\eta^2 = 0.039$). Lower thoracic levels (T10–T12) revealed the strongest associations. RI at T10 was significantly associated with Cobb angle ($F = 5.257$, $p = 0.024$, partial $\eta^2 = 0.052$), while RI at T12 approached significance ($F = 3.700$, $p = 0.057$, partial $\eta^2 = 0.037$). Other factors including gender, age, type of curve, and their interactions generally did not show significant effects. Model R^2 values ranged from 0.134 to 0.177, indicating that RI and the included covariates explained a modest proportion of the variance in Cobb angle. Results are summarized in Appendix Table 71 to 82.

These findings suggest that RI measurements at lower thoracic levels may be more closely associated with the magnitude of scoliosis in patients with moderate curves. The observed trend of increasing effect sizes from upper to lower thoracic levels (partial r^2 up to 0.052 at T10) indicates that vertebral rotation and rib deformity in the mid- to lower thoracic spine may contribute more substantially to curve severity.

The generally low R^2 values indicate that additional factors not included in the models—such as spinal flexibility, sagittal alignment, or growth-related variables—likely contribute to Cobb angle variability. Gender, age, and curve type did not significantly influence the RI–Cobb relationship in this cohort, suggesting that the observed associations are relatively consistent across these subgroups. Overall, these results support the clinical utility of RI, particularly at lower thoracic levels, as an adjunctive radiographic parameter for assessing curve severity in moderate scoliosis.

The Appendix Table_83 shows the Pearson correlation analyses between Scoliometry and Vertebral rotation in patients stratified by age, gender and type of curve in Group 2 – Cobb angle 26 – 40°.

The findings of this study shows to role of the thoracic deformity in terms of SRI and ATR for the formation of mild to moderate IS patients prior to initiating PSSEs and Bracing. These findings are in line with previous studies [33,35].

It is shown that the asymetric rib development are initiating the rotation in the spine, as it is reveiled by the above described statistical analysis, as the thoracic asymetry in terms of SRI is corelated with the spinal rotation and not the Cobb angle. And this is more evident in younger girls, see also [32].

The more posible mechanism for the impact of the rib cage deformity on the spine is the one decsribed by prof. Sevastik [42,43], that is the asymmetry of ANS function.

The rib asymmetry is also shown that is related to spinal deformity for the lumbar curves particularly for boys. This finding is in line with previous publications, see [44]. Additionally this novel interesting finding that there is SRI more than 1,45 in the upper part of the ribcage in lumbar curves in boys may also explain the relationship of the role of rib cage deformity in IS according to the concept of the Nottingham theory of IS which reports “ that from a developmental abnormality

 doi:10.20944/preprints202510.0374.v1

in the central nervous system creating rib-vertebra angle asymmetry which leads to a cyclical failure of mechanisms of rotation control in the trunk; these involve rotation-inducing (pelvic) and rotation-defending (discal, ligamentous and costal) mechanisms acting mainly in gait." [45]. The costal involvement in the IS is similarly shown in previous reports which highlighted the underdevelopment of the ribcage in infinite and mild AIS [46–49]. Furthermore, this study supports the view that scoliotic deformity likely come first in the thoracic cage. The diurnal "accordion-like" phenomenon observed in the intervertebral discs may then contribute to vertebral deformation and subsequent progression of IS [7].

8. Conclusions and Key Insights

A rib cage deformity with a RI between 1.45 and 1.50 is considered a significant thoracic abnormality. For all Groups rib asymmetry, as measured by SRI showed level- and severity-dependent associations with vertebral rotation and Cobb angle. In mild scoliosis (Cobb 10°–25°), significant effects of SRI were mainly observed at lower thoracic levels (T10–T12) for vertebral rotation, while associations with Cobb angle were weak and largely non-significant. In moderate scoliosis (Cobb 26°–40°), SRI effects were stronger, particularly at T10–T12, with vertebral rotation and Cobb angle showing significant associations (e.g., T11 VR: $F = 15.35$, $p < 0.001$, partial $\eta^2 = 0.139$; T10 CA: $F = 5.26$, $p = 0.024$, partial $\eta^2 = 0.052$).

Age contributed modestly to vertebral rotation in mild scoliosis, whereas gender effects were mostly weak, occasionally reaching borderline significance. Curve type significantly influenced vertebral rotation in moderate scoliosis, highlighting structural differences in thoracic anatomy. Adjusted R^2 values indicate that RI alone accounts for a moderate proportion of variance in vertebral rotation (up to ~24%) and a smaller proportion in Cobb angle (up to ~8–10%), consistent with scoliosis being a multifactorial condition.

Rib asymmetry is a better predictor of vertebral rotation than Cobb angle, particularly in moderate scoliosis. Significant effects are concentrated in the mid- and lower thoracic spine (T7–T12), suggesting regional vulnerability. SRI measures may provide additional clinical insight into three-dimensional deformity beyond standard Cobb assessment.

In this cohort of IS patients—many of whom exhibit minimal spinal curvature, with some having Cobb angles as low as 14 degrees and especially those under 25 degrees—these findings highlight the critical role of thoracic deformity in the development of scoliosis.

Currently, the management of IS remains symptomatic rather than etiological. With a clearer understanding of its underlying causes, therapeutic strategies could be directed toward the primary pathology. However, as the etiology of IS has not yet been fully elucidated, the findings of the present study highlight the importance of encouraging healthcare providers to develop and refine early interventions aimed at limiting asymmetric rib cage development. Such asymmetry appears to play a contributory role in the progression of spinal deformity.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org.

Author Contributions: T.B.G.: conceptualization, literature search, original draft preparation; S.P.: examination of the scoliotics, review, N.B.S. , N.J.review, T.G. review, FG: statistical analysis, contribution to draft preparation, V.D., measurement of outcomes, B.R., measurement of outcomes

Funding: This research received no external funding.

Conflicts of Interest: T.B.G no conflict of interest. S.P. International Schroth instructor for doctors N.B.S. no conflict of interest. N.J. International Schroth instructor for physical therapists FG: . no conflict of interest. V.D. no conflict of interest. B.R. no conflict of interest. T.G. no conflict of interest.

Abbreviations

ADL = activities of daily living
ANOVA = one-way analysis of variance
ATR = angle of trunk rotation
AVR = apical vertebral rotation
Difference RI = the average difference between RI_max DRCS and SRI_average
DRCS = Double Rib Contour Sign
GLM = General Linear Model
PSSE = Physiotheraputic Scoliosis Specific Exercises.
RI_AV = rib apical vertebra – RI
RI_max DRCS = Rib Index at the maximum Double Rib Contour Sign (DRCS) distance
SRI_average = average SRI value
SRI = segmental Rib Index

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