Beyond X-Rays: exploring correlation with surface topography measurements for safer scoliosis surveillance.

LAYMAN SUMMARY

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Adolescent idiopathic scoliosis (AIS) is a condition that usually appears during early puberty without a known cause, in which the spine develops a curve in the three dimensions (3D). This condition can progress, altering as well the shape of the ribcage and, in severe cases, affecting the function of the lungs and heart, among other consequences. To monitor AIS, patients traditionally need to take periodic X-ray images of the full spine. However, frequent exposure to radiation from these X-rays can increase the risk of developing cancer in the future.

To find a safer alternative, this research study investigated a non-radiating method called surface topography (ST). ST captures the 3D shape of the patient's trunk, which also reflects changes due to the spinal curvature. Several studies have already proved ST to be a useful method for measuring the progression of AIS, however, they often used very specialized devices and programs for spine analysis. This study employed a hand-held scanning device that can be used for scanning any physical object, and ST scans were analysed using free, widely used 3D modelling softwares, making the approach more accessible and possibly easier to implement.

Different measurements taken in X-ray images and ST scans of the same patients were analyzed to explore their correlation and the reliability of ST measurements. Our results indicated that the ST measurements were highly reliable. In addition, ST measurements strongly correlated with the Cobb angle, which measures the magnitude of the spinal curve in the X-ray images and is essential for diagnosing and monitoring AIS. On the other hand, ST measurements did not correlate with frontal trunk balance or pelvic obliquity, also measured in AIS X-rays.

Nevertheless, ST still shows great potential for evaluating the progression of AIS and may help reduce the frequency of X-rays. While it cannot completely replace radiographic examinations due to the useful information they provide about the bone structures, combining both methods could diminish patients' exposure to radiation.

Beyond X-rays: exploring correlation with surface topography measurements for safer scoliosis surveillance.

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***Abstract*—The management of adolescent idiopathic scoliosis (AIS) generally involves the repeated acquisition of full-spine radiographs, which leads to an increased risk of developing cancer due to cumulative radiation exposure. For this reason, several non-radiating techniques, such as surface topography (ST) are being investigated. In this study, 3D ST scans of 10 female AIS patients and their corresponding full-spine radiographs were obtained to study the correlation between measurements in both modalities, as well as the reliability of ST metrics. Specifically, the Cobb angle, coronal balance and pelvic obliquity were measured in the plain X-rays, while Root Mean Square (RMS), Posterior Trunk Symmetry Index (POTSI) and Horizontal Plane Deformity Index (DHOPI) were calculated in the ST volumes. All ST measurements achieved intra-observer correlation coefficients exceeding 0.89, demonstrating high reliability. Significant correlations were found between ST metrics and the main curve Cobb angle (0.83 for RMS, 0.87 for POTSI, and 0.76 for DHOPI), indicating strong agreement with the gold standard. However, correlations with coronal balance and pelvic obliquity were not statistically significant (p-value > 0.05). These findings suggest that ST holds great potential for quantifying spinal deformity, potentially reducing the dependence with radiographs. Even though ST cannot yet replace X-ray evaluation entirely, a combined approach could help reduce radiation exposure in the management of AIS patients.**

Keywords—adolescent idiopathic scoliosis, X-ray, surface topography, Cobb angle.

I. INTRODUCTION

Scoliosis is a three-dimensional (3D) spinal deformity that can arise from congenital, neuromuscular or idiopathic origin. Idiopathic scoliosis is diagnosed after ruling out other causes. Specifically, adolescent idiopathic scoliosis (AIS) is the most common type, typically appearing during the early puberty and affecting 1-4% of adolescents, with a higher prevalence among females [1], [2].

Currently, the gold standard for diagnosing and monitoring scoliosis, in addition to physical examination, relies on radiological methods, in which the Cobb angle is measured in full-spine radiographs in the coronal plane. The Cobb angle is formed by the intersection of the lines parallel to the superior and inferior plates of the vertebrae that define the curve’s boundaries on the upper and lower ends, respectively. Scoliosis is diagnosed when the Cobb angle is $\geq 10^{\circ}$ and vertebral rotation is associated [1], [2]. Additional radiographic measurements, such as the coronal and sagittal balance, thoracic kyphosis angles or cervical and lumbar lordosis angles also provide further insight into the severity and characteristics of the deformation [3].

Regardless of the treatment approach required for patients with AIS (including observation, bracing and/or surgery), regular follow-up by means of full spine radiographs is crucial to monitor curve progression and treatment effectiveness [4]. However, this practice entails a cumulative dose of radiation, that contributes to a higher risk of cancer in AIS patients compared to the general population [4], [5]. A 2016 study in Denmark reported a five times higher incidence of cancer in patients with AIS, with breast and endometrial cancers being the most common types [5].

Radiation-free alternatives are being investigated to monitor scoliosis progression in a robust and accurate manner. In addition, it is of great interest for clinicians and researchers to develop methods that can better characterize the 3D nature of scoliosis. One promising technique is surface topography (ST), which captures the 3D shape and contours of the patient’s trunk, providing detailed information of the asymmetries and deformities associated with scoliosis [6]. ST systems typically operate by projecting parallel lines or structured light beams onto the patient’s torso to capture and analyse its surface distortions [6], [7]. Examples of these systems are the Moiré topography method, the Formetric 4D (Diers International GmbH, Germany) and the Quantec Shape Imaging System (Quantec Image Processing, United Kingdom) [7]. Additionally, some studies have explored the use of more generic hand-held scanning devices to obtain 3D models of the back surface [8]. Examples of these devices are shown in Figure A1 in the Appendix.

Several studies have assessed the effectiveness of ST systems in estimating Cobb angle, vertebral rotation and other spinal and thoracic deformation metrics, evaluating their reliability, validity and, in some cases, correlation with radiographic measurements [9], [10]. Most investigations have demonstrated reliable and reproducible measurements of spinal and thoracic deformity, and moderate to strong correlations with conventional X-ray variables [8], [9], [11], [12]. However, it is concluded that, while ST methods hold great potential for screening and monitoring scoliosis, they cannot completely replace the radiographic analysis at the moment, due to their limitations in evaluating the actual morphology of the spinal bones [12]. Therefore, a combined approach that integrates both ST and X-ray methods appears optimal, allowing for a reduced radiation exposure and enabling a more comprehensive analysis of the curvature and its induced deformities in the patient's torso [8], [9], [11].

Nevertheless, the current analysis and extraction of metrics has often been conducted using device-specific software tools (e.g. Formetric 4D's integrated software), which limits the scope for potential improvements and innovations. While some studies have developed their own analysis tools [13], [14], there are numerous, free, general-purpose and highly versatile 3D modelling and analysis programs, such as Blender 4.0 (Blender Foundation, Amsterdam, Netherlands) or MeshLab 2023.12 (ISTI-CNR, Pisa, Italy) that could still be thoroughly explored in this context. Utilizing these advanced tools could enhance the accuracy and robustness of measurements, facilitate the creation of new analytical methods, and ultimately lead to more precise and comprehensive assessments of the spinal and thoracic deformity in the 3D space.

The main goal of this project is to further explore the correlation between conventional radiographic measurements and different metrics derived from 3D surface topography scans of the entire patient's torso. By utilizing a general-purpose hand-held scanning device and advanced 3D modelling and analysis programs, this study aims to contribute to the current efforts in providing a more comprehensive and reliable evaluation of scoliosis and its induced thoracic deformity, potentially reducing the need for repetitive exposure to ionizing radiation.

This research work presents the following structure: after the Introduction, the Materials and Methods chapter describes the patient population studied, the pre-processing strategies and a detailed explanation of the radiographic and ST measurements that will be studied, as well as the statistical approach. Next, Results are presented, illustrating the reliability of the ST metrics and their correlation with the radiographic measurements. These outcomes are examined and interpreted in the Discussion section. The final chapter provides the conclusions of this study.

II. MATERIALS AND METHODS

A. *Data*

This research study received the approval from the Ethics Committee of Hospital Infantil Universitario Niño Jesús. Ten female patients diagnosed with AIS were included, with a mean age of 12 years (ranging from 11 to 16 years). Inclusion criteria comprised patients managed by Hospital Infantil Universitario Niño Jesús and currently undergoing treatment with a brace for AIS, since the ST scans had already been acquired during the creation and fitting of these braces. Patients were required to have undergone a spine X-ray and ST scan within a maximum interval of two weeks. Exclusion criteria encompassed patients younger than 10 years or diagnosed with congenital, neuromuscular or syndromic scoliosis, as well as individuals with other musculoskeletal pathologies.

Therefore, the present project was a retrospective research study where each patient had previously received an antero-posterior full-spine X-ray (available in either DICOM or JPG format) and had been scanned using the portable, hand-held 3D scanner device from Einstar (Shining 3D, China) to obtain a surface topography in STL format, a standard format used to represent 3D surfaces through a triangle mesh. This scanner utilizes a structured light technology, that captures the shape and characteristics of an object by projecting a light pattern and registering it in an acquisition system consisting of one or several cameras. This device utilizes a laser-free technology, utilizing blue or white LED light, ensuring its safety for scanning individuals [15]. Scanning sessions employing this device usually take from 5 to 10 minutes, in which the patient must remove their upper garments and stand still while the technician carefully scans their complete torso. Removal of noisy components may be required posteriorly. Figure 1 presents an X-ray image and its corresponding surface topography for the same patient.

B. *Preprocessing*

Preprocessing steps were not necessary for the X-ray images. In contrast, all surface topography files underwent several procedures to ensure consistency and accuracy in the subsequent analysis. Initially, each topography was aligned with the coordinate axis in the 3D space. This involved derotating the volume in the vertical, sagittal or frontal axis to achieve a standardized orientation across all scans, minimizing potential discrepancies due to variations in patient positioning during the scanning process. For every patient, a sagittal plane was positioned in line with the gluteal cleft and set as a common plane of symmetry for all subsequent measurements. This is shown in Figure 2. This process was carried out using the software Blender 4.0 (Blender Foundation, Amsterdam, Netherlands). An additional preprocessing step involved generating mirrored surface topography scans for each patient, over the designated plane of symmetry, using Python codes. In some cases, the number of faces (i.e. triangles) in the meshes had to be reduced to decrease computation time.

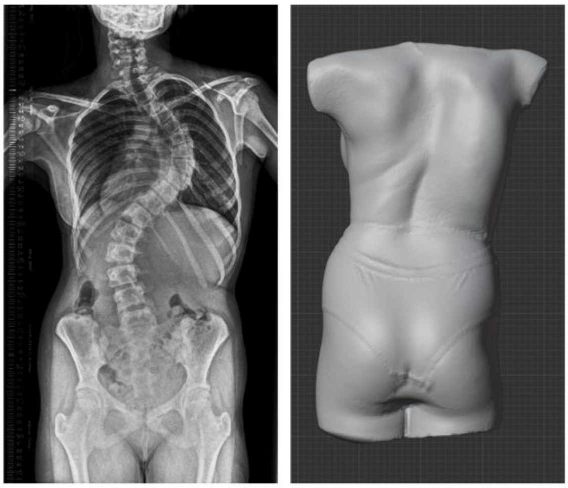


Fig 1. X-ray and corresponding surface topography scan from an AIS patient.

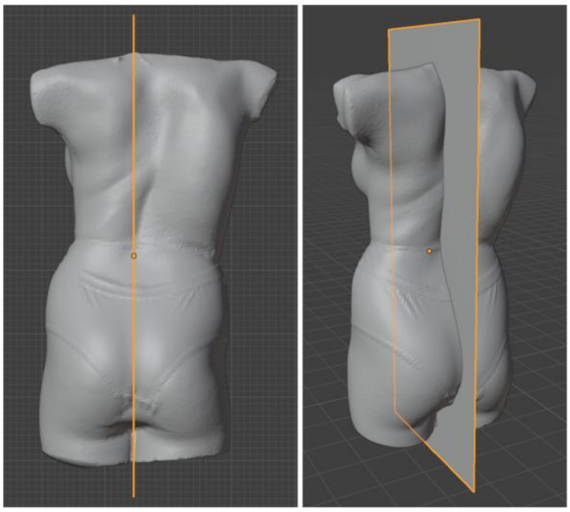


Fig 2. Surface topography of an AIS patient with its correspoding symmetry plane, aligned with the gluteal cleft.

C. X-ray measurements

Several measurements were calculated in the antero-posterior X-ray images using the Surgimap Spine software (Nemaris Inc, New York, USA):

- *Cobb angle*: the angle formed by the intersection of two parallel lines drawn along the superior endplate of the superior terminal vertebra and the inferior endplate of the inferior terminal vertebra. These terminal vertebrae define the extent of the spinal curvature, being usually the most tilted [16].
- *Coronal balance*: the distance between the central sacral vertical line and the vertical line, or plumb line, that crosses the centre of C7 vertebral body [3], [16]. Due to variations in the image format (some radiographs were in DICOM format while others were in JPG format), this distance was normalized by the vertical distance between C7 and S1.
- *Pelvic obliquity*: the angle formed by a horizontal reference line and the line connecting the superior edges of both iliac crests. A pelvic obliquity angle ≤ 15º is considered 'balanced'[3].

D. Surface topography measurements

All surface topographies were analysed and measured using the programs MeshLab 2023.12 (ISTI-CNR, Pisa, Italy) and Blender 4.0. The three variables employed to quantify the deformity of the thoracic surface are described hereafter. These variables, or metrics, describe the thoracic asymmetry in all three spatial dimensions.

Root-mean-square (RMS)

It is calculated as the root-mean square of the point-to-point distances after superimposing the original surface topography volume and its mirrored counterpart [8], [9]. The *Distance from reference mesh* module in MeshLab was used to compute the RMS metric, following this formula

$$RMS = \sqrt{\frac{x_1^2 + x_2^2 + \cdots + x_n^2}{n}}$$

where $x_1, x_2, \cdots, x_n$ are the distances measured between the closest corresponding points on the original and mirrored surface topographies [8].

The surface topography volumes were cropped over the baseline of the gluteal cleft, to remove the influence of the glutes and upper legs from the calculations. Besides calculating the RMS value over the entire torso, the volumes were also divided into thoracic and lumbar regions, with the corresponding RMS values equally obtained.

Figure 3 provides a graphical description of this process, as well as a qualitative illustration of these distances, displaying a colour map over the patient's torso. Warmer regions (red, orange, yellow) indicate positive deviations between the original and mirrored surfaces, meaning that the original surface protrudes out from the mirrored one. Conversely, blue regions represent negative deviations, indicating that the original surface indents into the mirrored one. Green areas represent low distances between the original and mirrored torsos, indicating lower asymmetry and less thoracic deformation caused by scoliosis.

Posterior Trunk Symmetry Index (POTSI)

It is obtained as the sum of two metrics: Frontal Asymmetry Index (FAI), quantifying asymmetry in the left-right dimension, and Height Asymmetry Index (HAI), quantifying asymmetry in the vertical direction [17]. To derive these metrics, 8 landmarks were manually identified on the surface topography volumes: the vertebra prominens (or seventh cervical vertebra), the highest points of both shoulders, the axillar folds, the waist creases and the baseline of the gluteal cleft.

For FAI, the distances from the C7 vertebra, both axillar folds and both waist creases to the symmetry plane passing

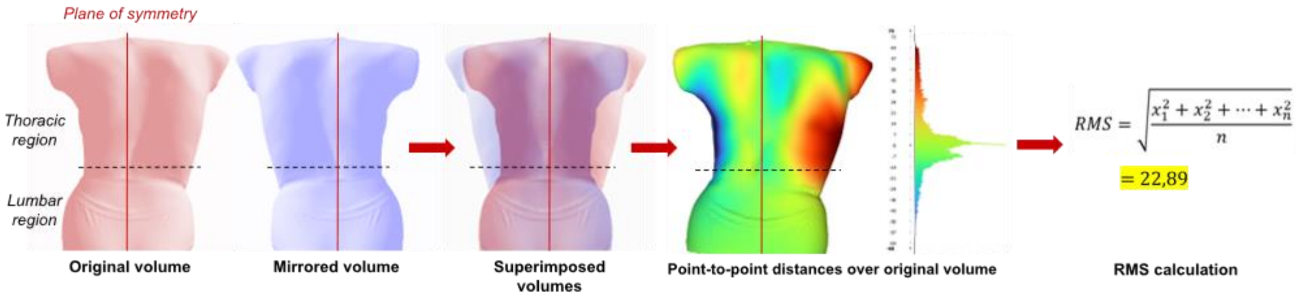


Fig 3. Process for calculating the Root Mean Square value on a surface topography scan.

through the gluteal cleft were measured and normalized using the equations provided in Figure 4. The three resulting numbers are added together to obtain FAI. To determine HAI, height differences between corresponding landmarks on each side of the body (shoulders, axillar folds and waist creases) were calculated and normalized by the vertical distance between the baseline of the gluteal cleft and C7 vertebra. As with FAI, the three results are added, yielding HAI [17].

Horizontal Plane Deformity Index (DHOPI)

To calculate DHOPI, two lines were drawn between the most prominent points of each scapula and between the least prominent points of the waist, at each side of the symmetry plane. To facilitate locating these points, shading nodes were applied in Blender 4.0 to display an ‘altitude’ colour map over the surface topography volume, as shown in Figure 5. Posteriorly, the symmetrical point of the most prominent point on each of the two lines is located over that line. Ultimately, the differences in depth (in the antero-posterior direction) between the symmetrical points are added and normalized by the vertical distance between the baseline of the gluteal cleft and C7 vertebra [13].

Figure A2 in the Appendix depicts a patient with all the described angles and distances calculated in X-ray and ST, using Surgimap Spine, Blender 4.0 and MeshLab 2023.12.

E. *Statistical analysis*

The three ST variables were measured by the same observer twice, to study the intra-observer reliability of these variables and the employed measurement protocol. Both measurements were separated by approximately 1.5 weeks.

The statistical analysis was carried out using Python 3.11.5, with the libraries *Pandas, Pingouin and Scipy*. The intra-observer reliability of the ST measurements was estimated by calculating the Intraclass Correlation Coefficient. The normality of the data was assessed using the Shapiro-Wilk test. Since data didn’t follow a normal distribution (i.e. p-value < 0.05), the correlation between X-ray and surface topography variables was evaluated by calculating Spearman’s correlation coefficient. A p-value less than 0.05 was considered significant for this correlation test. To calculate the correlation of the ST metrics with the radiographic ones, the mean between the first and second ST measurements was employed.

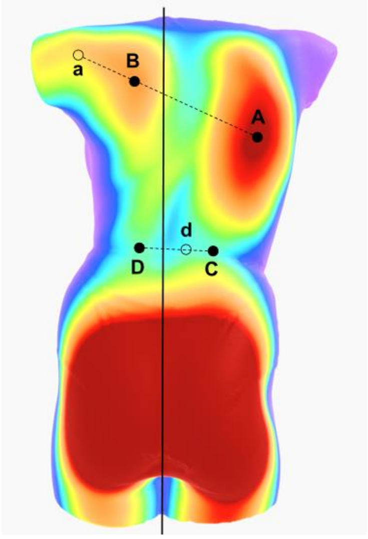


Fig 5. Key landmarks for calculating the Horizontal Plande Deformity Index (DHOPI) on a surface topography scan. The *altitude colour map* is displayed over the ST surface to facilitate the localization of these landmarks.

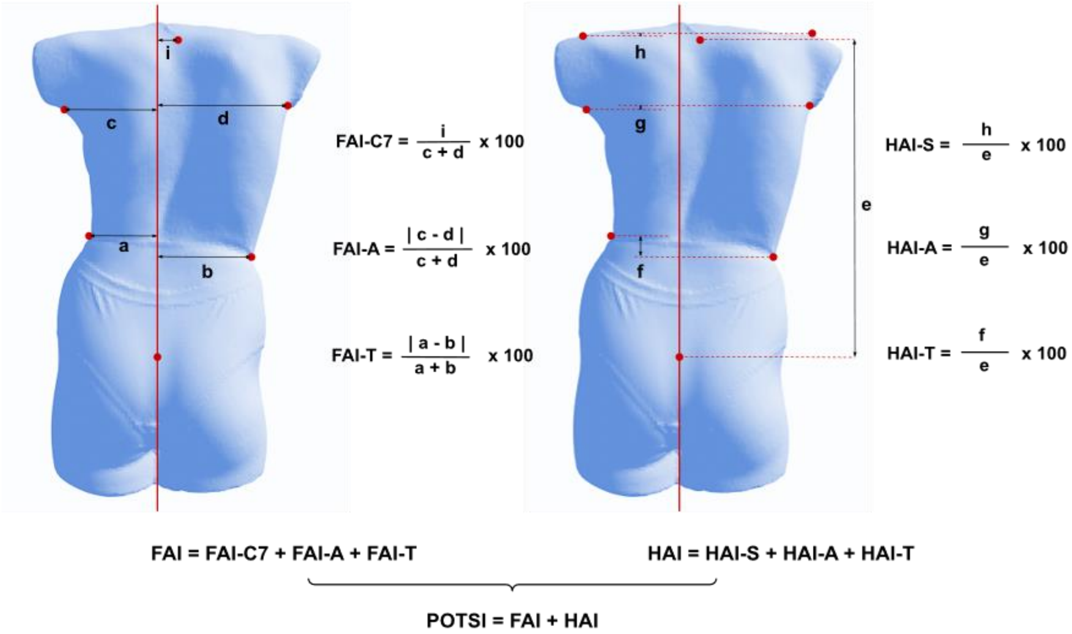


Fig 4. Key landmarks, distances and equations for calculating the Posterior Trunk Symmetry Index (POTSI) on a surface topography scan.

III. RESULTS

A. X-ray measurements

Nine of the ten patients presented a main thoracic curve, only one patient presented a main lumbar curve. The mean Cobb angle of the main curvature was 37.53 degrees, with a standard deviation of ±17.30. In the thoracic region, the Cobb angle averaged 36.90 degrees (±17.60), while in the lumbar region, the mean Cobb angle was 29.43 degrees (±17.46). The calculated and normalized coronal balance exhibited a mean value of 0.03, accompanied by a standard deviation of ±0.03. Lastly, the pelvic obliquity had a mean angle of 1.58 degrees, with a standard deviation of ±1.31. All ten patients in this study had a balanced pelvis.

B. Surface topography measurements

In the first measurement, the mean POTSI value was 25.79 ± 16.60, which slightly decreased in the second measurement, with a mean value of 25.63 ± 16.95. For DHOPI, the mean value was 4.39 ± 4.43 for the first measurement and 4.28 ± 4.62 for the second measurement.

Regarding the RMS, the first measurement yielded a mean value of 13.33 ± 4.55. When broken down by region, the thoracic region had a mean RMS of 15.50 ± 5.85, while the lumbar region had a mean RMS of 8.23 ± 2.30. In the second measurement, the mean RMS slightly increased to 13.57 ± 4.52, with the thoracic and lumbar regions showing mean values of 15.46 ± 5.93 and 8.63 ± 2.46, respectively.

C. Intra-observer reliability of the surfae topography measurements

The Intraclass Correlation Coefficients for intra-observer measurements in the surface topographies were 0.987 for RMS (with ICC values of 0.983 for thoracic RMS and 0.895 for lumbar RMSs), 0.992 for POTSI and 0.984 for DHOPI. All these measurements were statistically significant, with p-values less than 0.05.

D. Correlation between X-ray and surface topography measurements

Figure 6 shows the Spearman correlation values between all studied metrics. Most surface topography metrics exhibited a strong correlation with the main curvature Cobb angle. RMS, POTSI and DHOPI showed correlations of 0.830, 0.867 and 0.758, respectively, with the main Cobb angle. All of these were statistically significant, with p-values of 0.002, 0.001 and 0.011, respectively. For FAI and HAI (i.e. the metrics used to obtain POTSI), a statistically significant strong correlation (0.855) was observed between FAI and the main curvature Cobb angle, whereas HAI showed a moderate correlation (0.6) that was not statistically significant.

None of the surface topography metrics showed statistically significant correlations with the coronal balance and the pelvic obliquity in patients with adolescent idiopathic scoliosis.

In addition, most surface topography metrics demonstrated moderate to strong, statistically significant, correlations with each other. The exceptions were FAI and HAI, which showed a low correlation between them, that was not statistically significant.

Table 1 illustrates the Spearman correlations of thoracic RMS and lumbar RMS with the thoracic and lumbar Cobb angles, respectively. Only the thoracic RMS showed a strong, significant correlation with the thoracic Cobb angle. In contrast, lumbar RMS was weakly correlated with lumbar Cobb, and this correlation was not statistically significant. Furthermore, no significant correlations were found between the lumbar RMS and the pelvic obliquity or even between the lumbar cobb angle and pelvic obliquity.

		Correlation coefficient (r)	***p-value***
RMS	Main Cobb	0.830	0.003
Thoracic RMS	Thoracic Cobb	0.891	0.001
Lumbar RMS	Lumbar Cobb	0.297	0.400
Lumbar RMS	Pelvic Obliquity	-0.316	0.370
Lumbar Cobb	Pelvic Obliquity	-0.006	0.990

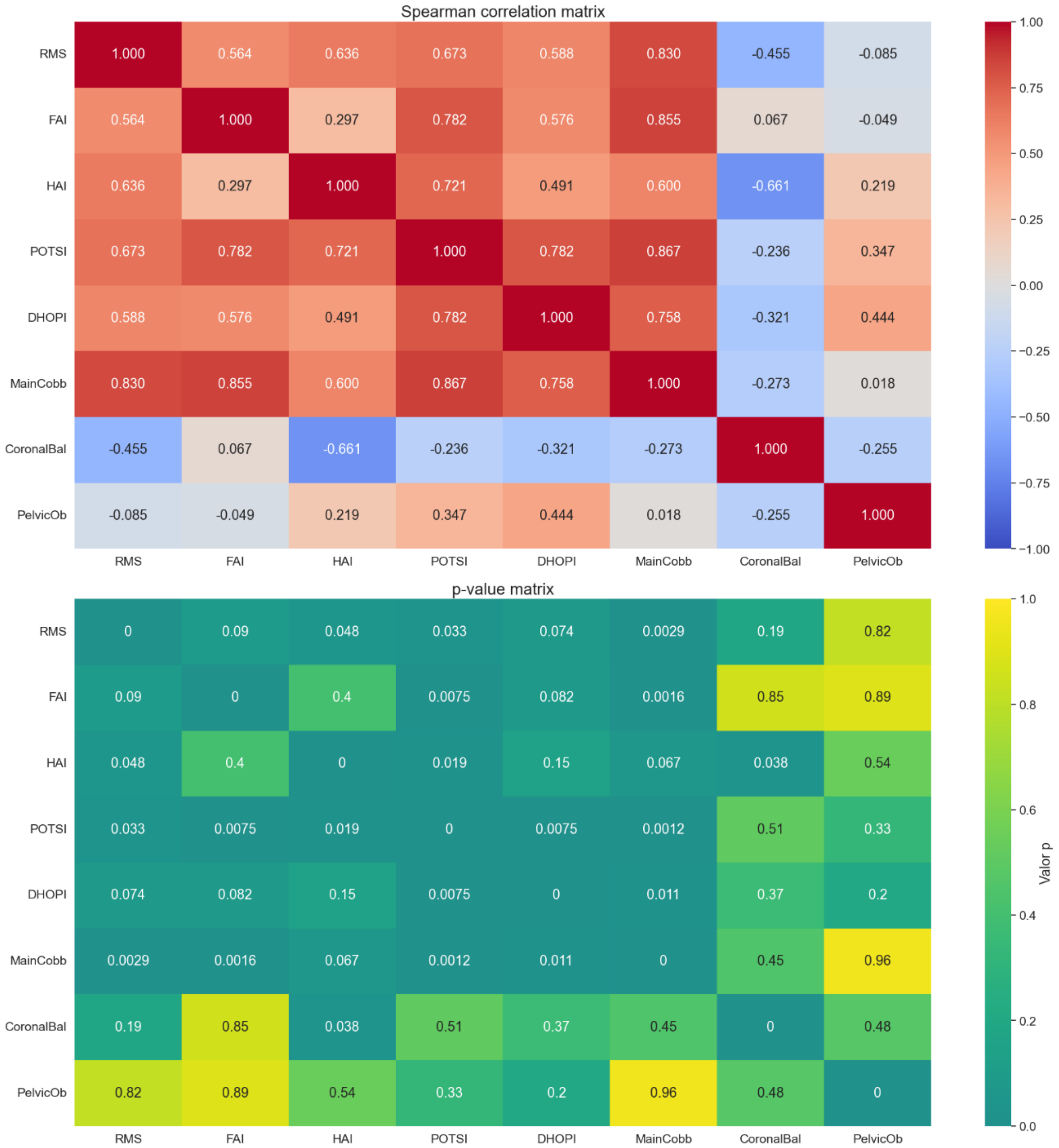
Table 1. Spearman correlation coefficients between the RMS and Cobb angle, in the main curvature and separating by thoracic or lumbar region. Correlations between pelvic obliquity and lumbar RMS and Cobb angle are also included.

Finally, Figure 7 depicts the Spearman correlations of the surface topography metrics, RMS, POTSI and DHOPI with the main curvature Cobb angle.

IV. DISCUSSION

In this study, the reliability of several ST measurements performed in 3D modelling software programs, as well as their correlation with conventional radiographic variables, was explored. All ST variables (RMS, POTSI and DHOPI) exhibited high and significant intraclass correlation coefficients, all exceeding 0.89. Additionally, these measurements showed moderate to strong Spearman correlation values with the Cobb angle. Notably, thoracic RMS showed a strong correlation with the thoracic Cobb angle, while the correlation between lumbar RMS and the lumbar Cobb angle was low and not statistically significant. On the other hand, the ST metrics displayed weak and non-significant correlations with the coronal balance or pelvic-obliquity parameters.

These results show that measurements in ST scans using 3D modelling and mesh analysis programs, such as Blender and MeshLab, show great intra-observer repeatability. The strong correlation of ST metrics with the Cobb angle, the gold standard metric for quantifying the magnitude of spinal deformity, proves the great potential of ST for monitoring the progression of AIS. These findings improved those presented by L. Pino-Almero [13], who also studied the correlation between the Cobb angle and the ST



Spearman correlation matrix

	RMS	FAI	HAI	POTSI	DHOPI	MainCobb	CoronalBal	PelvicOb
RMS	1.000	0.564	0.636	0.673	0.588	0.830	-0.455	-0.085
FAI	0.564	1.000	0.297	0.782	0.576	0.855	0.067	-0.049
HAI	0.636	0.297	1.000	0.721	0.491	0.600	-0.661	0.219
POTSI	0.673	0.782	0.721	1.000	0.782	0.867	-0.236	0.347
DHOPI	0.588	0.576	0.491	0.782	1.000	0.758	-0.321	0.444
MainCobb	0.830	0.855	0.600	0.867	0.758	1.000	-0.273	0.018
CoronalBal	-0.455	0.067	-0.661	-0.236	-0.321	-0.273	1.000	-0.255
PelvicOb	-0.085	-0.049	0.219	0.347	0.444	0.018	-0.255	1.000

p-value matrix

	RMS	FAI	HAI	POTSI	DHOPI	MainCobb	CoronalBal	PelvicOb
RMS	0	0.09	0.048	0.033	0.074	0.0029	0.19	0.82
FAI	0.09	0	0.4	0.0075	0.082	0.0016	0.85	0.89
HAI	0.048	0.4	0	0.019	0.15	0.067	0.038	0.54
POTSI	0.033	0.0075	0.019	0	0.0075	0.0012	0.51	0.33
DHOPI	0.074	0.082	0.15	0.0075	0	0.011	0.37	0.2
MainCobb	0.0029	0.0016	0.067	0.0012	0.011	0	0.45	0.96
CoronalBal	0.19	0.85	0.038	0.51	0.37	0.45	0	0.48
PelvicOb	0.82	0.89	0.54	0.33	0.2	0.96	0.48	0

Fig 6. Spearman correlation matrix and corresponding p-value matrix, illustrating the relationship or correlation among the studied measurements in X-ray images and ST scans along with their statistical significances.

metrics POTSI and DHOPI using an automatic landmark finding tool. Similarly, Y. Yildirim [8] and A. Komeili [14] also studied thoracic asymmetry by calculating the distance deviation between the original and mirrored scans. Both achieved good qualitative and quantitative correspondences with the scoliosis-induced deformity and the Cobb angle, respectively. The results obtained in the present study aligned with the qualitative analysis carried out by A. Komeili, and slightly outperformed Y. Yildirim's in the thoracic region, who reported a correlation of 0.8 between the thoracic RMS and the Cobb angle. Additionally, it is noteworthy that these studies employed sample sizes of 31 to 46 patients, in contrast to our limited sample sizes of 10 patients.

The weak correlations of the ST measurements with pelvic obliquity and coronal balance, although not favourable, can be attributed to the low degrees of pelvic obliquity and trunk imbalance observed in the patient cohort. Severe pelvic obliquity and trunk imbalance are generally more commonly associated with scoliosis of neuromuscular origin [18]. Similarly, the low and non-significant correlations found between lumbar RMS and lumbar Cobb angles may be explained by the predominance of main thoracic curves in the patients studied in this work, which likely induced the overall trunk deformity in a greater extent than the lumbar curves. As well, the difficulty in precisely delineating the boundary between the lumbar and

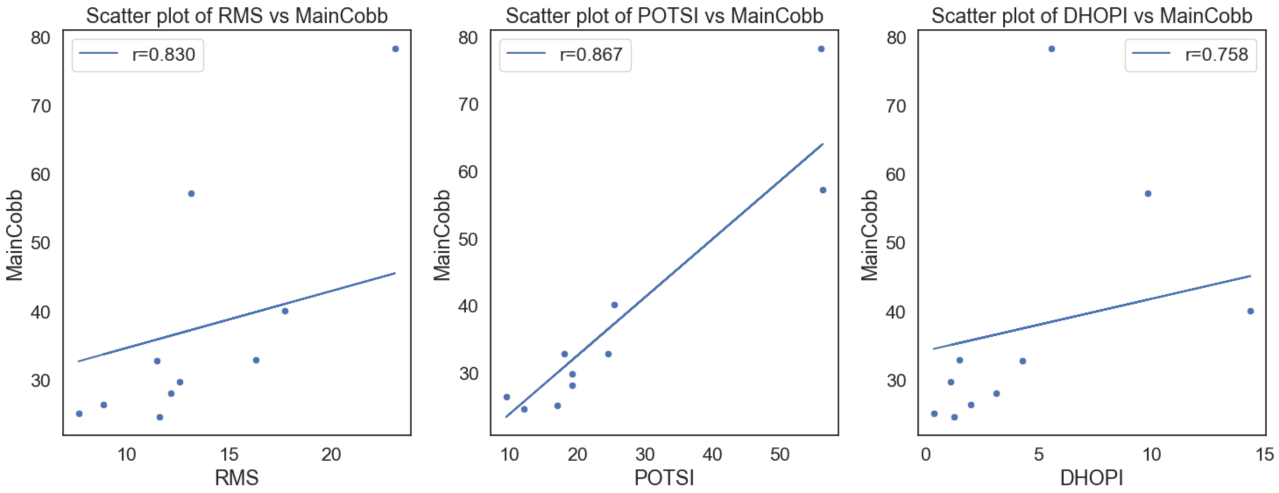


Fig 7. Scatter plots depicting the relationship between the main curvature Cobb angle and ST metrics (RMS, POTSI and DHOPI). Spearman correlations are illustrated.

thoracic regions in the ST scans could have reduced the accuracy of this specific analysis.

Although ST scans cannot completely replace radiographic tests and, particularly, the precise quantification of deformity provided by the Cobb angle, they hold significant potential for monitoring scoliosis progression. Demonstrating the strong correlation of metrics such as RMS, POTSI or DHOPI with the current gold standard not only fosters the reduction in radiation exposure during follow-up, but also enhances the understanding of the deformity by further describing it in three dimensions. In addition, these metrics can also provide a means of quantifying aesthetic appearance, a major concern during AIS treatment [19]. Moreover, validating new programs and tools for these measurements also contributes to achieving the most accurate quantification of the surface deformity, that attains the strongest correlation with the gold standard. As well, the tools employed in this study (a hand-held scanning device, and free 3D modelling and analysis software programs, both widely used for multiple purposes) are more accessible and possibly easier to implement than the specialized devices employed in previous research. This could promote a more widespread adoption of ST in the clinical practice, in areas or centres with fewer resources, or as a screening method for early detection of scoliosis.

However, this study had several limitations. The small sample size requires a cautious interpretation of the results. Such a limited dataset can increase result variability, making conclusions less definitive. In addition, our patient cohort was not representative of the entire population of AIS, as it only included patients with specific characteristics, related to age and severity of the disease. Specifically, our study only studied female patients older than 10 years, with skeletal maturity and severity level suitable for a brace treatment. This may limit the generalizability of our results to other patient groups, such as those presenting milder or more severe deformities, or early-onset idiopathic scoliosis.

Due to personnel constraints, measurements were conducted by a single observer. However, to reinforce the robustness of the studied metrics, it would have been desirable to investigate the inter-observer reliability. Ideally, involving both clinicians and researchers would likely provide a broader perspective and enhance the validity of these measurements. This would be an important consideration for future studies.

As well, it is crucial for future research to include a larger and more diverse group of AIS patients in these analyses. Furthermore, incorporating a set of healthy individuals or subjects without any kind of spinal deformity or musculoskeletal condition would be beneficial for investigating the ST metrics in normal cases and determine normative ranges. This could provide deeper insight and understanding of these variables, from which now we primarily understand that higher values indicate more severe scoliosis-induced asymmetries.

Moreover, future studies could also explore the correlation of ST metrics with other radiographic measurements in the sagittal plane, such as the degree of kyphosis or lordosis, sagittal balance, etc. New ST metrics, such as the Columnar Profile described by L. Pino-Almero [13], can be developed and investigated for this purpose. As well, evaluating the axial or transverse plane is of great interest for AIS. Correlations between X-ray measurements that describe vertebral rotation (e.g. Nash and Moe method), with axial surface rotation or rib hump calculated from surface topographies should be further studied.

This application could also aim to assess pre- and post-surgery changes. Considering the aesthetic concerns of both patients and surgeons, ST metrics also have the potential of providing an effective means of evaluating and quantifying surgical outcomes on the whole torso.

Still, a key goal of these research lines would be to develop automated tools capable of precisely locating the landmarks without human supervision. The present study employed a manual landmark location approach to ensure the most accurate reliability study of ST metrics and their correlation with radiographic measurements.

Finally, with the results of these ST analyses, it is crucial to establish standardized protocols for monitoring and even predicting scoliosis progression. These have primarily been determined using radiological indicators, along with other with patient-specific risk factors [20]. By incorporating ST measurements, more comprehensive protocols can be developed, that could reduce the number of X-rays taken by patients while still enabling continuous, accurate monitoring and the implementation of suitable treatment plans.

V. CONCLUSIONS

This study investigated the correlation between radiographic measurements (Cobb angle, coronal balance, pelvic obliquity) and ST measurements (RMS, POTSI, DHOPI) to assess the severity of AIS-induced deformity and evaluate the potential of ST in monitoring the progression of this condition. Measurements in the ST scans were carried out in 3D modelling and mesh analysis programs, aiming to provide a more accurate extraction of metrics. The outcomes of this research revealed that all ST metrics had a good intra-observer repeatability and strongly correlated with the main curvature Cobb angle. However, weak and non-significant correlations were found between the ST measurements and the coronal balance or pelvic obliquity. Additionally, the RMS metric did not significantly correlate with the Cobb angle in the lumbar region. Nevertheless, the strong correlation achieved with the thoracic Cobb angle, which measured the main curve in 9 out of 10 patients evaluated in this study, demonstrates the potential of ST for monitoring the magnitude and progression of AIS. This could reduce the number of X-rays that patients are required to take during their follow-up, and therefore reduce the cumulative radiation dose they receive. Yet, a combined method is still needed to perform a comprehensive evaluation of all aspects of this deformity.

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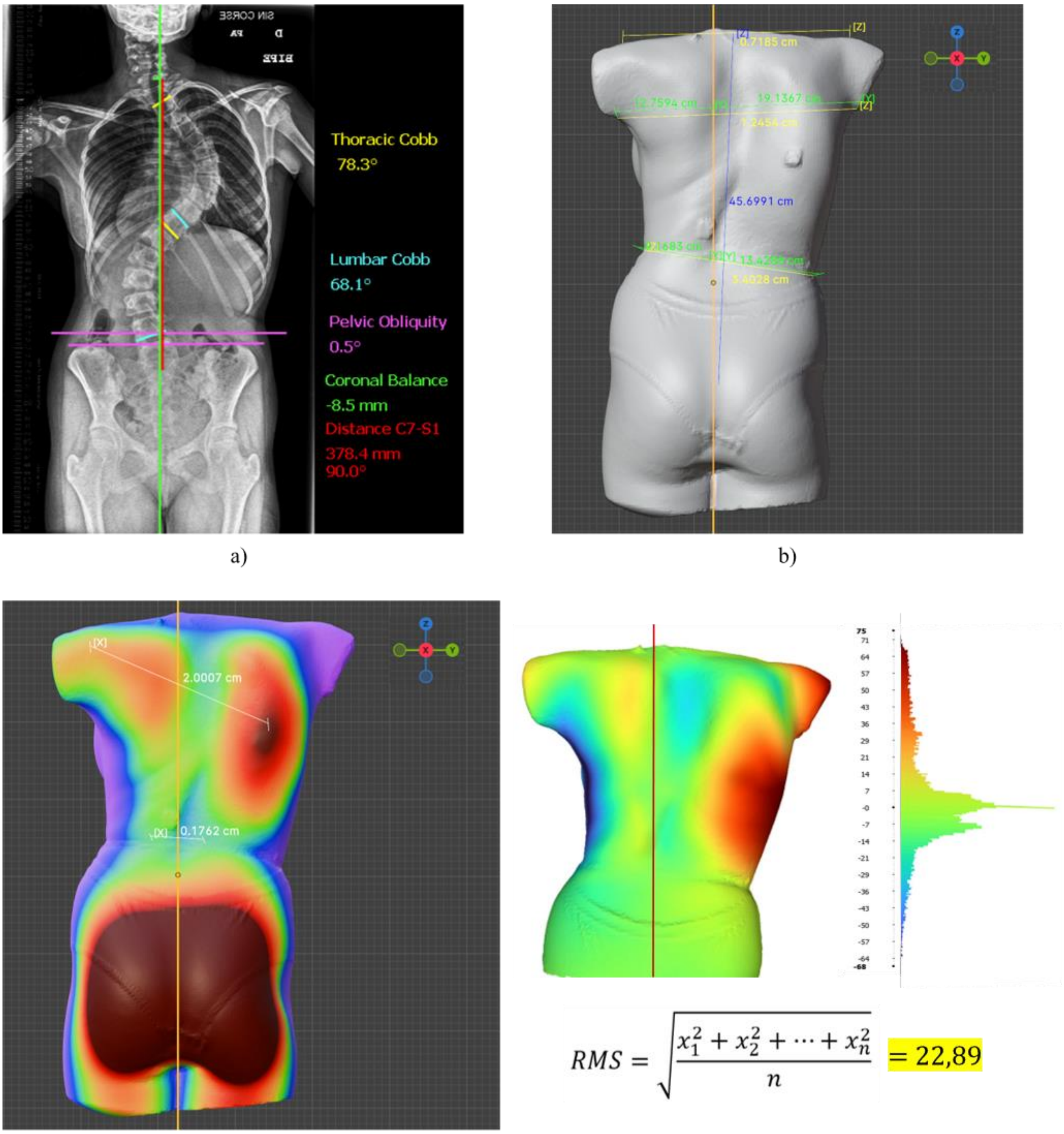
APPENDIX

a) b) c) d) e)

Fig A1. Examples of some common surface topography systems for the evaluation of scoliosis. a) Moiré method (back image, projection of parallel lines, Moiré image reconstruction) [21]. b) Formetric 4D system (Diers International GmbH, Germany) [22]. c) Quantec Shape Imaging System (Quantec Image Processing, United Kingdom) [7]. d) Hand-held 3D scanner Artec EVA (Artec Group 2013, Luxembourg) [8], [23]. e) Hand-held 3D scanner Einstar (Shining 3D, China) [15], employed in this research study.



a)

b)

c)

d)

Fig A2. Example patient with measurements performed in X-ray and ST scans. a) Full-spine antero-posterior X-ray with spinal deformity calculations performed in Surgimap Spine (Nemaris Inc, New York, USA). b) Distances for POTSI calculation (FAI + HAI). These were automatically calculated in Blender 4.0. (Blender Foundation, Amsterdam, Netherlands) after landmark selection. The axes over which these distances are calculated are selected and depicted in the image. c) Distances (in antero-posterior direction) for DHOPI calculation. Altitude colour map is displayed over patient's ST scan to aid landmark location. d) Illustration of the point-to-point distances in the original ST scan with respect to the mirrored ST scan. These distances are employed in the calculation of the RMS metric by the software MeshLab 2023.12 (ISTI-CNR, Pisa, Italy).