Periodica Polytechnica
Civil Engineering

62(4), pp. 1021–1029, 2018
https://doi.org/10.3311/PPci.10531

RESEARCH ARTICLE

Validation of a Generally Applicable Method for the Characterization of Scoliotic Deformities and Sagittal Spinal Curvatures

Bence Jáger[1*], Dávid Jáger[2], Tamás Kristóf [2], Mária Takács[3], Péter Tamás[2], Rita M. Kiss[2]

Received 19 October 2017; Revised 24 March 2018; Accepted 10 June 2018

Abstract

The oldest and most precise way to determine the curvatures of the spine is two directional X-ray measurement from the sagittal and coronal planes. By using X-ray, patients are exposed to radiation, which limits the repeatability of the measurements even in serious deformities, thus X-ray is not applicable for frequent monitoring. Therefore new alternative non-invasive radiation-free measurement systems appeared, which measure the external shape of the spine on the back surface. The goal of the present study is to validate the new tangential calculation method by Cobb method based radiographic analysis and by two other alternative calculation methods. In the study 22 young patients suffering from scoliotic deformities are examined. Thoracic kyphosis, lumbar lordosis and scoliotic deformity, as the three characterizing angles of spinal curvatures, are calculated by four different methods. The results show that the newly developed tangent line method could be applicable for the evaluation of spinal curvatures.

Keywords

spinal curvatures, thoracic kyphosis, lumbar lordosis, scoliosis, tangent line

1 Department of Structural Engineering,
Faculty of Civil Engineering,
Budapest University of Technology and Economics
H-1111 Budapest, Műegyetem rkp. 3., Hungary
2 Department of Mechatronics,
Optics and Mechanical Engineering Informatics,
Faculty of Mechanical Engineering,
Budapest University of Technology and Economics,
H-1111 Budapest, Műegyetem rkp. 3., Hungary
3 Department of Orthopaedics,
MÁV Hospital,
H-5000 Szolnok, Verseghy street 6–8, Hungary
* Corresponding author, email: jager.bence@epito.bme.hu

1 Introduction

Frequent monitoring of the posture of young children with reliable evaluation methods avoiding radiation exposure is still an open problem to be solved. The most regular and precise way to determine spinal curvatures is to make two directional radiographic images of the spine which has harmful effects. Doody et al. [1] showed that the risk of breast cancer in females is increased due to radiographic measurements of scoliotic patients. Therefore the Study Group on Scoliosis Orthopedic and Rehabilitation Treatment (SOSORT) draws attention to the problem and recommends reducing the use of X-ray even in serious diseases [2]. Due to the consensus and to the risk factors, the way towards the further improvement of alternative, non-invasive, radiation-free methods is open. Nowadays many non-invasive spine examination methods are available (SpinalMouse, SpinalTouch, Zebris, Moiré-method, flexicurve, inclinometer, kyphometer, goniometer, arcometer) which can be used for the measurement of the spinal shape [3].

The non-invasive spine examination methods measure the external shape of the spine (surface of the back). The external curvature of the spine differs from the internal curvature (measured by X-ray), which was analysed and estimated by Mansour et al. [4] for the lumbar spine in the sagittal plane. They performed the analysis by one MRI measurement for each patient. The results obtained from radiographic images differ from the results of the Zebris measurement system, but theoretically the correlation should be high (0.94) between the two methods ($R^2 = 0.88$) if the examination is performed precisely [4].

Tanure et al. [5] performed statistical analysis on scoliotic curvature using manual and digital X-ray evaluation based on the Cobb method. The results show that both methods can be used simultaneously with high reliability. It was concluded and forecasted that involving functions may be useful in the assessment of spine curvatures.

Earlier studies calculated the curvatures of the spine only from few points [6–11]. Takács et al. [10] analysed the spinal curvatures of young patients by applying X-ray examinations with the Cobb method used for evaluation (internal curvatures) and the Pointer Mobility system of Zebris with its WinSpine software. The results showed that the correlations between the two methods are 0.80 and 0.94 in case of thoracic kyphosis and lumbar lordosis while it is 0.68 and 0.73 for thoracic and lumbar scoliosis, respectively.

Earlier calculation methods (Cobb method – Fig 1a, WinSpine-based method and traditional method – Fig 1b) used only few measured points for characterizing the shape of the spine, and they also failed to exploit the possibility that the spatial coordinates of several points of the spine are also available from measurements. The shape of the spine can be described by a fitted spline function using the spatial coordinates of nearly 100 measured points. The characterizing angles can be calculated by forming tangential lines over the inflection points of the related curve using linear regression (Fig 1c). The goal of the present study is to validate the new tangential calculation method by Cobb method based radiographic analysis and by two other calculation methods (WinSpine-based method and traditional method) based on the measured data of the ultrasound-based spine measuring method (Zebris GmbH, Isny, Germany).

2 Materials and methods

2.1 Subjects

22 young patients with scoliotic deformities were subjected to the present study. At least one year prior to this examination, the scoliotic deformation was diagnosed separately by two orthopedists. The demographical data of the examined patients is included in Table 1 according to age, weight and height, but not divided by gender.

The examinations were authorized by the Research Ethics Committee of MÁV Hospital (licence number: FI/5-93/2007). The parents of the subjects received detailed verbal and written information in each case before they signed the consent form.

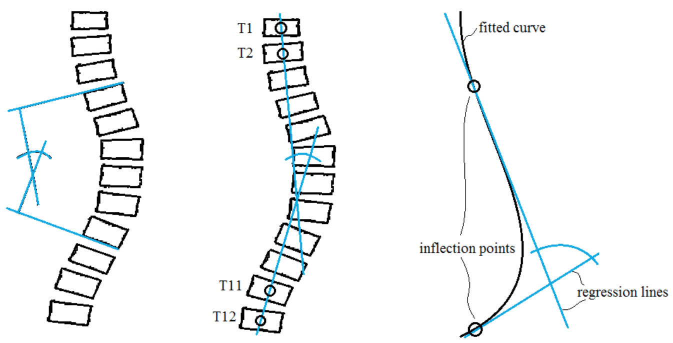


Fig. 1 Schematic drawings of the calculation methods

Table 1 Statistical data of patients

	Age [year]	Weight [kg]	Height [cm]
Average	14.75	51.21	163.58
SD	2.44	14.62	12.89
CoV	0.17	0.29	0.08
Min	8.00	23.00	126.00
Max	18.00	78.00	183.00

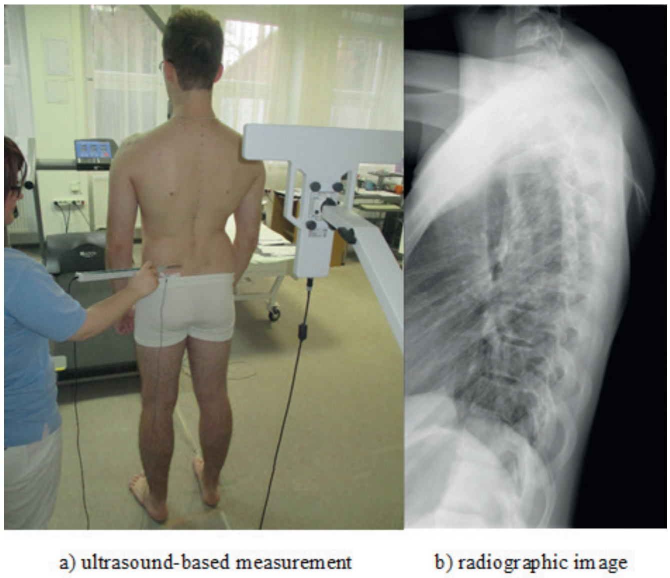


Fig. 2 Measurement arrangement of the Zebris Pointer Mobility system (a) and radiographic image of the thoracic spine in the sagittal plane (b)

2.2 Measurements

Two radiographic recordings were taken of every patient, one from the frontal direction in standing position with lowered arms and another one from the sagittal direction, standing with the arms raised in order to exclude the disturbing effect of the arms [12, 13]. The X-ray examination was performed at the Radiology Department of MÁV Hospital in Szolnok (Hungary).

The external shape of the spine was measured by a Zebris ultrasound-based motion analysis system (Zebris Medizintechnik GmbH, Isny, Germany) in the Biomechanical Laboratory of MÁV Hospital in Szolnok. The spatial position of the processus spinosus of the vertebrae was recorded and numerically stored by the WinSpine measurement control software (Zebris Medizintechnik GmbH, Isny, Germany). The process is also known briefly as ultrasound-based spine examination [14]. The details of the measuring process were summarized in [15]. All patients were examined twice: first in standing position with the arms raised, and then standing with lowered arms in order to be able to compare the data with the results of the analog X-ray examinations. Fig. 2a shows one patient during the ultrasound-based examination process and Fig. 2b shows his radiographic record in the sagittal plane.

2.3 Methodology of calculation

The characterizing angles of spine curvatures can be determined by the Cobb method (Fig 1a) or the traditional method (Fig 1b). However, other alternative computer-aided calculation methods have appeared recently, such as the superposition of the angles between the corresponding vertebrae (WinSpine software of Zebris; hereinafter called WinSpine-based method). Our newly developed tangent line method calculates the angles characterizing spine curvatures as the angle of the lines tangential to the inflection points of the spine curve. (Fig 1c). The aforementioned four methods are described as follows:

2.3.1 Cobb method

The Cobb method is a well-known and the most generally used method for the characterization of internal spinal curvatures (Fig. 1a). It defines the complementary angles formed between lines parallel to the superior and inferior endplates of the vertebrae including the curvatures related to the thoracic and lumbar spine separately in both the sagittal and coronal planes. The main disadvantage of the method is its dependence on the examiner's judgement, thus human error is involved. This method is only used for radiographic analysis. Both examiners had evaluated the same radiographic images for each patient.

2.3.2 Traditional method (TRAD)

The traditional method can be used to determine the characterizing angles of:

- *Thoracic kyphosis* by calculating the complementary angle between the lines passing through the 1st and 2nd thoracic vertebra's, and the 11th and 12th thoracic vertebra's processus spinousus in the sagittal plane (Fig. 1b).
- *Lumbar lordosis* by calculating the complementary angle between the lines passing through the 1st and 2nd lumbar vertebra's, and the 4th and 5th lumbar vertebra's processus spinousus in the sagittal plane.
- *Scoliotic deformity* by having the greater calculated complementary angle from thoracic scoliosis and lumbar scoliosis as in the case for sagittal plane.

It is also applicable in case of radiographic analysis and in case of radiation-free measurement system based analysis where the external shape of the spine is captured.

2.3.3 WinSpine-based method (WS)

The WinSpine commercial software estimates the location of each vertebra from the measured data - from the external shape of the spine measured on the surface of the back - by means of anatomical considerations. The angles between each vertebra are calculated and the angles characterizing spinal curvatures can be determined by applying the concept of superposition [16].

2.3.4 Tangent line method (TLM)

The shape of the spine can be described by a fitted natural cubic spline function using the spatial coordinates of nearly 100 measured points. The characterizing angles of spine curves can be calculated by forming tangential lines over the inflection points of the fitted curve using linear regression even in the sagittal and in the coronal planes (Fig. 1c). With the lack of inflection points at the top and bottom parts of the curves, the tangent lines having the absolute maximum slope are determined. To determine the tangents, a maximization problem needs to be solved, where the minimal and maximal slopes from the solutions of an overdetermined system of equations should be determined, then the complementary angles between these regression lines can be calculated. Since the method does not depend on the location of vertebrae but the shape of the spine, thus it can be used for processing data measured with Zebris, SpinalTouch, SpinalMouse and even with radiographic image processing.

2.4 Evaluation methodologies by statistical analysis

The angle values characterizing the spinal curvatures related to thoracic kyphosis (TK), lumbar lordosis (LL) and scoliosis (SC) are determined for each patient using all the above mentioned methods. Parameter distribution is assumed to be normal (checked by Kolmogorov-Smirnov and Chi-square goodness-of-fit tests) and the homoscedasticity is checked. The average, standard deviation, minimum and maximum values of all angles are calculated.

The comparison of the radiographic results provided by the two examiners is analyzed by a two-tailed one-sample paired T-test (test value = 0).

For the comparison of the different calculation methods, the radiography-based Cobb angles are used as reference values and the results of the other methods are compared to the Cobb angles. The average, SD, and the maximum and minimum values of differences are calculated. All the characterizing angles of each patient obtained from the three calculation methods (TRAD, WS, TLM) are evaluated by calculating a two-tailed Pearson product-moment correlation coefficient (r), and by calculating the slope of the regression line (m) [17].

Statistical analysis is performed using the SAS System for Windows (Rel. 7, SAS Institute Inc, Cary, NC, USA). Statistical significance is defined as $P < 0.05$ for all comparisons using Microsoft Excel with hand calculation control.

3 Results

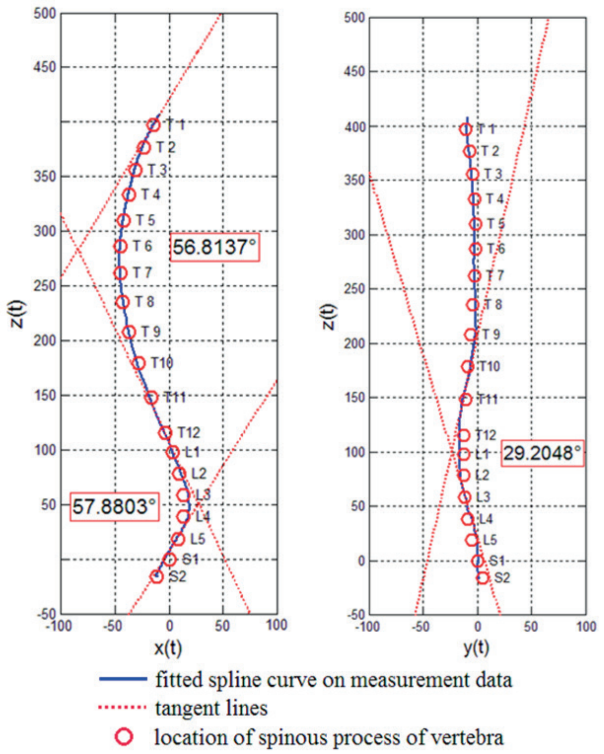
The angles characterizing spinal curvatures, coming from the different methods, are presented and compared in this section. The results in the sagittal and the coronal planes are analyzed separately. In the sagittal plane, the two angles characterizing the thoracic (TK) and the lumbar curvatures (LL) are investigated by comparing the results of the Cobb method (Examiner 1 and Examiner 2), the WinSpine-based, the tangent line and the traditional methods, respectively. In the frontal plane, the scoliosis angle (SC) is investigated by all four methods.

The overall statistical evaluation of the results provided by the different calculation methods in both planes is presented in Table 2, which contains the average (Ave), standard deviation (SD), minimum (Min) and maximum (Max) figures as yielded by each calculation method. The values in Table 2 are gray if radiographic results fail to match them.

It can be observed that in case of thoracic kyphosis there are slight differences between the averages obtained (29.7 – Ex1, 26.3 – Ex2, 29.1 – WS, 35.6 – TLM, 24.5 – TRAD); however,

Table 2 Statistics of internal and external curvatures based results

		Based on internal curvatures of spine column						Based on external shape of spine column								
		Radiographic analysis (Cobb-method)						WinSpine (angles between vertebrae)			TLM (tangent line method)			Traditional method		
		Examiner 1			Examiner 2											
		TK	LL	SC	TK	LL	SC	TK	LL	SC	TK	LL	SC	TK	LL	SC
Ave	lowered arms	-	-	19.8	-	-	18.6	37.1	30.2	12.8	43.6	42.3	25.6	35.2	19.8	14.4
	raised arms	29.7	38.8	-	26.3	42.2	-	29.1	37.2	13.5	35.6	48.4	25.8	24.5	22.5	12.3
SD	lowered arms	-	-	9.8	-	-	9.4	13.0	13.1	8.6	13.0	13.3	9.5	11.5	6.6	9.5
	raised arms	13.0	8.2	-	12.0	7.7	-	15.4	9.8	8.8	13.3	13.9	9.9	14.3	6.7	8.8
Min	lowered arms	-	-	5.0	-	-	5.0	13.1	0.0	0.0	20.8	13.2	12.2	16.0	6.1	2.8
	raised arms	7.0	20.0	-	5.0	25.0	-	0.0	16.9	0.0	12.0	24.0	10.4	1.2	10.5	0.4
Max	lowered arms	-	-	50.0	-	-	50.0	66.0	50.0	28.3	82.7	66.9	49.5	59.4	31.5	32.5
	raised arms	55.0	55.0	-	50.0	58.0	-	56.6	50.0	33.4	63.6	79.7	52.9	53.6	36.9	31.4



a) sagittal plane b)frontal plane

Fig. 3 Results of TLM in the sagittal and frontal planes at a patient

in case of lumbar lordosis the TLM provides greater values on average (48.4) since it takes the real inflection points of the external shape of the spinal column into account which may be located in the sacral and the thoracic spine. Furthermore, it is depicted that the WinSpine-based and the traditional methods underestimate the value of scoliotic deformity on average (12.8 – WS, 14.4 – TRAD) and the tangent line method yields higher values (25.6 – TLM) in comparison with radiographic analysis results (19.8 – Ex1, 18.6 – Ex2).

3.1 Visualization of results

The results displayed using TLM are shown in case of one patient in standing position. In Fig. 3 the outputs of TLM can be seen with reference to the sagittal and the frontal planes, respectively.

Table 3 Statistical evaluation of analog X-ray results

	Sagittal curvatures (raised arms)		Frontal curvatures (lowered arms)
	TK	LL	SC
Average of differences	7.70	4.40	2.50
SD of differences	5.92	3.79	2.61
Min of differences	0.00	0.00	0.00
Max of differences	21.00	11.00	8.00
Pearson's correlation (r)	0.75	0.88	0.96
Slope of regression line (m)	0.87	0.98	0.86
Standard error of regression	9.38	4.13	3.15
Significance of differences (p)	~0	~0	~0
95% confidence interval	2.77	1.77	3.74

In Fig. 3 the red circles represent the location of the processus spinosus of vertebrae (estimated by WinSpine); the blue continuous line represents the fitted spline curve through the measured data; while the red dashed lines demonstrate the tangent lines going through the global inflection points. Using the tangent line method, the results are obtained to 56.8, 57.9 and 29.2 degrees regarding external thoracic kyphosis, lumbar lordosis and scoliosis, respectively. The corresponding Cobb angles for the same patient are obtained to 42, 42 and 20 degrees, respectively.

3.2 Evaluation of radiographic analysis

Analog radiographic analysis has been performed independently by two orthopedics specialists, which provides an opportunity for analyzing the subjectivity effect of individuals. The comparison of the results provided by the two examiners is shown in Fig. 4 where the red continuous line represents the equivalence between the diagnosed angles. The statistics of the comparison are given in Table 3 where the columns summarize the statistics related to thoracic kyphosis (TK), lumbar lordosis (LL) and scoliosis (SC).

It can be observed from the comparison that the most unreliable results were diagnosed in case of thoracic kyphosis, where even 7 degrees of difference could be provided on average due to the subjective judgment of the examiners ($r = 0.75$). However,

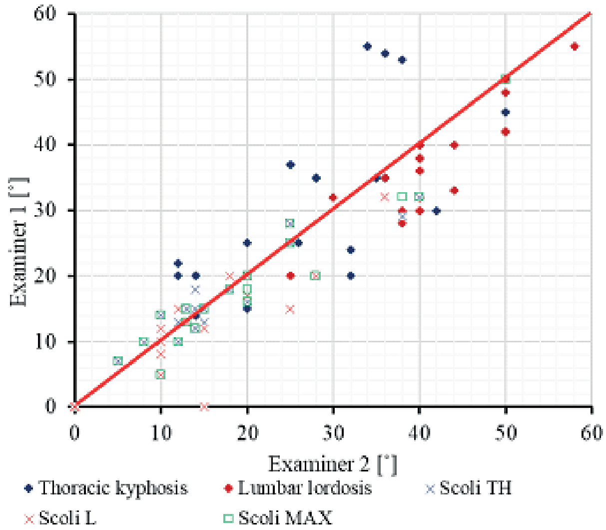


Fig. 4 Comparison of analog X-ray results

more reliable results are yielded regarding lumbar lordosis and scoliosis, where the correlation coefficients (r) are obtained to over 0.88. Mean differences are significant between the results of Examiner 1 and Examiner 2. The 95% confidence intervals for the true mean differences are obtained to 7.70 ± 2.77, 4.40 ± 1.77 and 2.50 ± 3.74 regarding TK, LL and SC, respectively, which can be statistically interpreted that the true differences are likely to be outside of these limits.

3.3 Evaluation of alternative methods

This section discusses the comparison and evaluation of the different methods. As shown in the previous section, there are significant differences between the results of Examiner 1 and 2, therefore the results of Examiner 1 (Ex1) is handled as reference in this section.

3.3.1 Evaluation of results in sagittal plane

Table 4 summarizes the comparison of the results of the internal shape based Cobb method (Examiner 1) from X-ray records and of other external shape based methods related to the sagittal plane. In Fig. 5 the blue, red and green dots represent the angles related to WS, TLM and TRAD, respectively, with reference to thoracic kyphosis. The red continuous line demonstrates equality between them. The correlations between the results are obtained to 0.77, 0.72 and 0.76, the differences are obtained to 7.15 ± 6.66, 9.24 ± 6.56 and 8.51 ± 6.69 degrees (Table 4 columns #2 to #4).

In Fig. 6 the blue, red and green dots represent the angles related to WS, TLM and TRAD, respectively, with reference to lumbar lordosis. The correlations between the results are obtained to 0.82, 0.85 and 0.77, respectively and the differences are obtained to 4.28 ± 3.82, 10.35 ± 7.16 and 17.18 ± 4.75 (Table 4 columns #2 to #4). It can be observed that TLM shows the smallest correlation with radiographic analysis in case of thoracic kyphosis; however, it provides the highest correlation in case of lumbar lordosis, which can be attributed to the fact that TLM considers the global inflection points and tangent lines of the spine, which cannot be detected clearly by the examiners or the recording process of the shape of the spine column is not appropriate enough.

Besides the comparison with radiographic analysis, further statistical evaluation has been conducted by the comparison of the angles provided by the alternative methods (Table 4 columns #5 to #7). It can be observed that the correlations between the alternative methods are very high. In terms of thoracic kyphosis they are obtained to 0.93, 0.88 and 0.95 between the angles provided by WS and TLM, TLM and TRAD, and WS and TRAD, respectively. In terms of lumbar lordosis they are obtained to 0.92, 0.90 and 0.91, respectively.

Additional comparison has also been made between the results of WS and TLM by applying the tangent line method on the vertebrae estimated by WS (red curve in Fig. 7a and column #8 in Table 4). The results obviously showed higher correlations with 0.98 and 0.94 (in the previous paragraph: 0.93 and 0.92) regarding thoracic kyphosis and lumbar lordosis, respectively. Furthermore, it is clearly observed from the

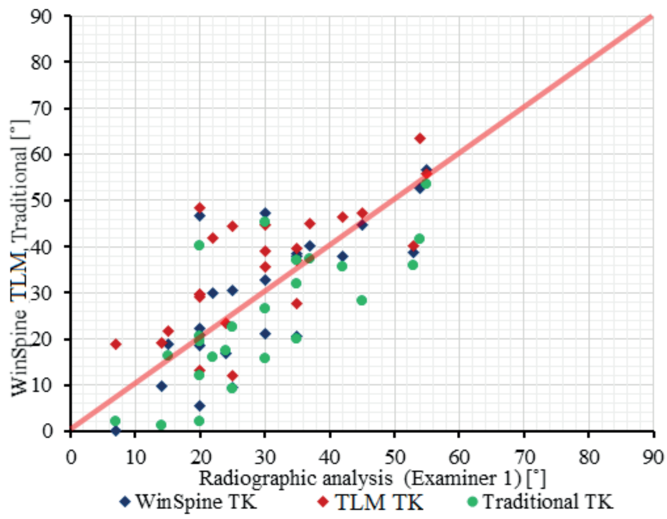


Fig. 5 Comparison of the results regarding thoracic kyphosis

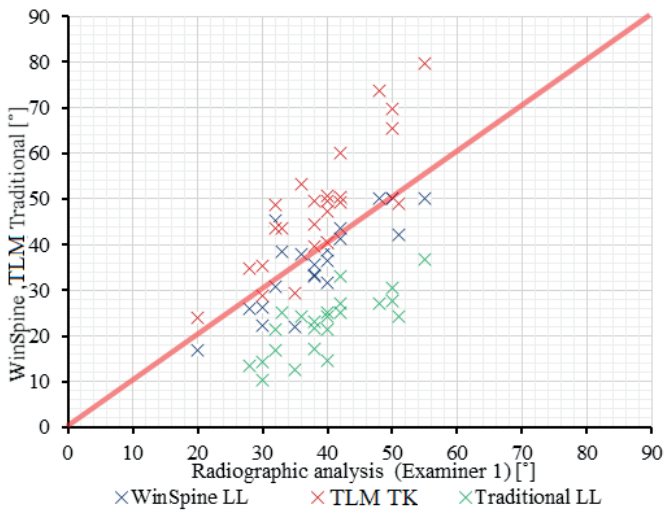
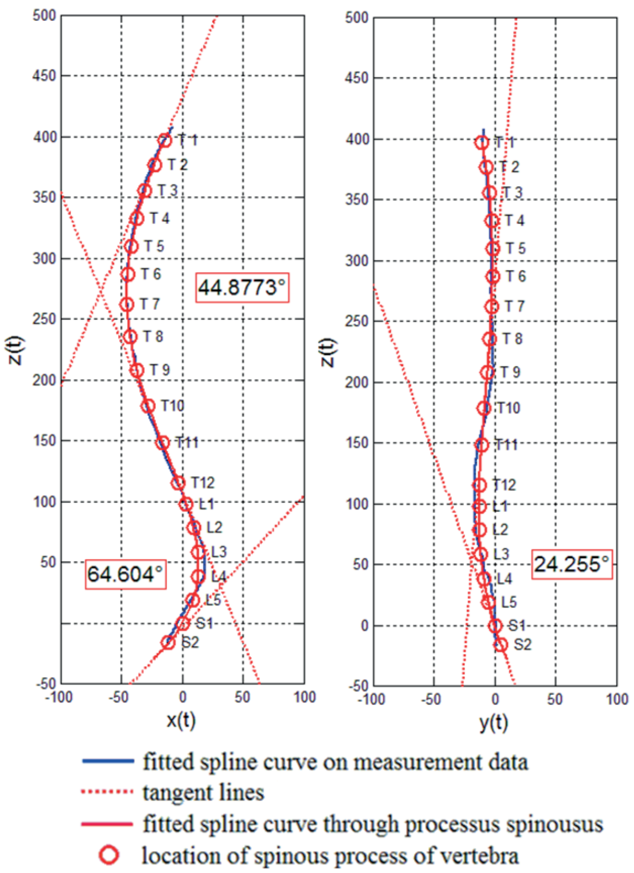


Fig. 6 Comparison of the results regarding thoracic kyphosis

Table 4 Statistics of the results

	Thoracic kyphosis (TK)						
	WS-Ex1	TLM-Ex1	Trad-Ex1	WS-TRAD	TLM-TRAD	WS-TRAD	WS-TLM
Average of differences	7.15	9.24	8.51	7.03	9.81	4.49	2.93
SD of differences	6.66	6.56	6.69	4.68	6.60	3.62	1.99
Min of differences	0.20	0.50	0.22	0.69	0.34	0.19	0.00
Max of differences	26.60	28.52	20.12	18.86	26.00	16.44	9.56
Pearson's correlation	0.77	0.72	0.76	0.93	0.88	0.95	0.98
Slope of regression line	0.91	0.74	0.84	0.86	0.86	0.90	0.89
Standard error of regression	10.02	9.41	9.57	5.12	6.48	4.57	2.96
	Lumbar lordosis (LL)						
	WS-Ex1	TLM-Ex1	Trad-Ex1	WS-TLM	TLM-TRAD	WS-TRAD	WS-TLM
Average of differences	4.28	10.35	17.18	11.64	24.65	13.62	16.07
SD of differences	3.82	7.16	4.75	5.39	7.93	4.90	5.22
Min of differences	0.00	0.54	7.79	3.40	7.06	0.48	0.00
Max of differences	13.40	25.64	26.80	29.71	46.48	24.00	28.07
Pearson's correlation	0.82	0.85	0.77	0.92	0.90	0.91	0.94
Slope of regression line	0.97	1.43	0.70	1.06	1.83	0.52	1.06
Standard error of regression	5.72	7.46	4.39	5.40	5.85	2.84	4.94



a) sagittal plane b)frontal plane

Fig. 7 Comparison of the results regarding thoracic kyphosis

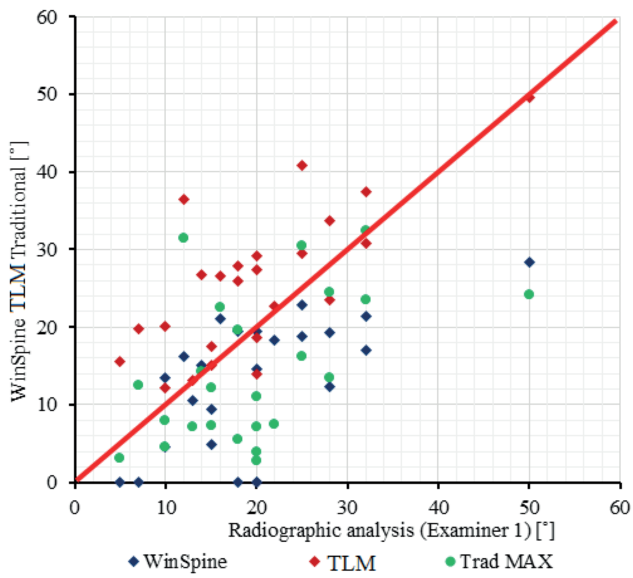


Fig. 8 Comparison of the results regarding scoliosis

results that the tangent line method (TLM) always provides greater values for the characterizing angles, which is confirmed by the statistics results. It means that the WS underestimates the angles characterizing the external curvatures in the sagittal plane. Moreover, it should be emphasized that smaller correlations are obtained by comparing these TLM results with the radiographic analysis results. Therefore it may be more relevant to apply the tangent line method (TLM) directly on the measured data.

3.3.2 Evaluation of results in the coronal plane

Fig. 8 and Table 5 show the comparison of the results of the internal shape based Cobb method (Examiner 1) and of other external shape based methods in the coronal plane. The blue, red and green dots in Fig. 8 represent the angle values with respect to WS, TLM and TRAD, respectively, and the red continuous line demonstrates equality between the results. It can be seen that the correlations are obtained to 0.63, 0.73 and 0.50 with respect to WS, TLM and TRAD in standing position, respectively. The average differences with standard deviations are obtained to 8.27 ± 6.59, 6.94 ± 5.90 and 8.68 ± 6.67 degrees.

Furthermore, the calculated angles related to the external shape of the spine (WS, TLM, TRAD) are compared. The comparison is conducted not just in standing position (columns #5 to #7) but also in standing position with the arms raised (columns #8 to #10). The correlations obtained are 0.68, 0.54 and 0.79 for standing and 0.82, 0.43 and 0.55 for standing with the arms raised.

An additional comparison has also been conducted between WS and TLM results by applying the tangent line method on the vertebrae estimated by WS (red curve in Fig. 7b and columns #11 to #12 in Table 5). The results obviously showed higher correlations with 0.82 and 0.92 regarding standing and standing with the arms raised, respectively.

4 Discussion

Based on a comparison of the results of different calculation methods considering the characterization of curvatures of the spine, namely thoracic kyphosis, lumbar lordosis and scoliosis, the main aim of the current paper is to validate the newly developed tangent line method. The shape of the spine of 22 young patients with scoliotic deformities was recorded by X-rays and by the ultrasound-based spine examination using the Pointer Mobility system of Zebris. Radiographic analysis specifies the accurate location of the vertebrae (internal curve), and ultrasound-based spine examination records the external shape of the spine column on the back surface. Radiographic images are evaluated by two orthopedists independently from each other using the Cobb method, while the measuring data determined by ultrasound-based spine examination are processed by three different calculation procedures, namely with the WinSpine software, with the tangent line method and with the traditional method. Table 2 shows the overall statistics of the results yielded by each method. It can be observed that in comparison with the radiographic analysis based Cobb method, in case of thoracic kyphosis and lumbar lordosis the WinSpine provides nearly the same results on average, the tangent line method provides greater values, and the traditional method provides smaller values on average. Furthermore, in case of scoliosis the WinSpine and the traditional methods yield smaller values and the TLM provides higher values than the Cobb method. The measurements with ultrasound-based spine examination are performed during standing with lowered arms and with raised arms. This provides an opportunity to compare the results related to the positions of standing and standing with the arms raised, respectively. It is found that by raising the arms the thoracic curvature decreases for the benefit of lumbar curvature. However, the results show that the scoliotic deformity is not influenced significantly by raising the arms as a rule (Table 2). The results of the Cobb method are compared in this article. It has been concluded that there can be significant differences ($p \ll 0.05$) between the Cobb angles diagnosed by different examiners. According to the results, the difference can be as many as 20 degrees at a maximum and as many as 7 degrees on average in case of thoracic kyphosis, as shown in Table 3. In lumbar lordosis and scoliosis the differences are more consolidated but not comforting, although the correlations are obtained between 0.88 and 0.96, which may be judged to be acceptable. For further investigation, the results of Examiner 1 are used as reference.

Table 4 shows the statistics of the differences of the angles determined by different methods with reference to thoracic kyphosis and lumbar lordosis. The results show that the WinSpine-based method estimates mostly the same angles as those yielded by radiographic analysis, since the slopes of the regression lines are obtained to 0.91 (row #8 – thoracic kyphosis) and 0.97 (row #17 – lumbar lordosis) with the least average differences (7.15 and 4.28), as also shown by the blue dots in Fig. 5 and 6. However, the tangent line method provides higher correlation with radiographic analysis in terms of lumbar lordosis (red dots in Fig. 6), where the correlation coefficient is obtained to 0.85. Furthermore, it should be mentioned that the traditional method provides the poorest results out of the three alternative calculation methods in comparison with radiographic analysis.

The results confirm the results of Mansour et al. [4] that theoretically, correlation between the external and internal curvatures must be high. According to Mansour's results for

Table 5 Statistics regarding scoliosis

	Lowered arms						Raised arms			WS-TLM	
	Comparison with radiographic analysis			Comparison of alternative methods			Comparison of alternative methods			lowered arms	raised arms
	WS-Ex1	TLM-Ex1	TRAD-Ex1	WS-TLM	WS-TRAD	TLM-TRAD	WS-TLM	WS-TRAD	TLM-TRAD		
Average of differences	8.27	6.94	8.68	12.8	6.71	11.3	12.3	7.67	13.5	6.42	5.77
SD of differences	6.59	5.90	6.67	7.26	5.52	5.92	5.62	5.39	8.90	4.96	3.96
Min of differences	0.50	0.08	0.25	2.58	0.10	1.65	1.26	0.71	0.97	0.71	0.00
Max of differences	21.7	24.5	25.9	29.2	19.7	25.4	21.2	17.2	35.4	24.25	14.71
Pearson's correlation	0.63	0.73	0.50	0.68	0.54	0.79	0.82	0.43	0.55	0.82	0.92
Slope of regression line	0.55	0.71	0.48	0.75	0.60	0.79	0.93	0.42	0.49	0.88	0.81
Standard error of regression	6.82	6.63	8.40	7.10	8.13	5.98	5.72	8.10	7.53	4.97	3.55

the lumbar spine in the sagittal plane it could be 0.94 (R^2 = 0.88 [4]), while our results show 0.85 (column #3 row #16 in Table 4). However, Mansour et al. [4] obtained information for the external and internal curvatures of the lumbar spine from one MRI measurement for each patient and they performed the analysis on a much smaller sample than the group of subjects in the current paper.

In addition, the comparison of the three alternative methods confirmed the results of the authors in [18] since the correlations between the tangent line method and the traditional method are obtained between 0.88 and 0.90. In [18] it was obtained between 0.86 and 0.90. However, smaller correlations are obtained between the WinSpine-based method and radiographic analysis with values of 0.77 and 0.82 than in the observation of Takács et al. [10] with 0.80 and 0.94.

In terms of scoliosis, the statistics is included in Table 5. By comparing the results of alternative calculation methods with the Cobb method results (columns #2 to #4) – related to standing position – it can be stated that the tangent line method provides the best correlation (0.73) with the minimum average difference (6.94 ± 5.90). However, slightly smaller correlations are obtained between the WinSpine-based method and radiographic analysis with a value of 0.63 than in the observation of Takács et al. [10] with 0.67 and 0.73. Furthermore, the results of alternative calculation methods are also compared with each other regarding standing position (found in columns #5 to #7) and standing position with the arms raised (found in columns #8 to #10). It is shown that the correlation between WinSpine's and TLM's results are 0.68 and 0.82, which may be attributed to the observation that WinSpine underestimates the real angles characterizing the spinal curvatures by turns.

In addition, investigation has been performed by applying the tangent line method on the measured data and on the estimated coordinates of the vertebra's processus spinousus using WinSpine. The results show that by using the measured data the highest correlations can be achieved with radiographic analysis (0.73 in Table 5), which means that the tangent line method may be generally used for the processing of the outputs of digital radiographic images and the output data of different external shape capturing systems.

Based on comprehensive statistical analysis and evaluation between different calculation methods for thoracic kyphosis, lumbar lordosis and scoliosis, the newly developed computer-aided tangent line method is validated since all the three alternative methods have high correlations with each other and the tangent line method correlates mostly with the results of radiographic analysis, with correlation coefficients of 0.72, 0.85 and 0.73, respectively (3rd columns of Table 4 and 5). However, the results of WinSpine and the traditional method provide correlations with the radiographic analysis in between 0.63 – 0.82 and 0.50 – 0.77, respectively. Furthermore, it was also observed – in both planes – that the tangent line method always provides higher values for the characterizing angles and WinSpine underestimates the angles characterizing the external scoliotic deformity. Moreover, it should be emphasized that by applying the tangent line method on the estimated coordinates of the vertebra's processus spinousus by WinSpine, smaller correlations are provided by comparing these TLM results with the radiographic analysis results. Therefore the validation of the tangent line method is performed and its direct application on the measured data could be more relevant.

Limitation of the study:

The examinations were performed only in young patients with scoliotic deformities. Besides, more patients of different ages and with different deformities should be involved. In the future X-ray images should be recorded by digital techniques.

5 Conclusions

In present article a recently developed tangent-line method is introduced and validated by comparing it to different methods (Cobb method, WinSpine method and traditional method) for the characterization of the internal and external spinal curvatures. The newly developed calculation method is based on the real tangent lines through the inflection points of the measured data. It has been seen and understood that the newly validated method does consider the shape of the spine and the location of the inflection points, which makes the calculation process more precise and reliable. Furthermore, the tangent line method developed provides results directly after the measurement process and the effect of human errors can be reduced. Moreover, the new method is based on the shape of the spine, therefore it provides more insight into the curvature of the patient's spine. The spinal curvatures calculated by the tangent line method provide higher values compared to the values calculated by the WinSpine-based and the traditional methods. Correlations between the alternative methods are high (0.88 – 0.95) in the sagittal plane but in some cases poor correlations are observed in the coronal plane (0.43 – 0.92). In addition, the highest correlations are obtained to the tangent line method (0.72 – 0.85) in comparison with radiographic analysis.

Based on our measurement results, it can be concluded that the spline curve fitting and the characterizing angles at the intersection of the tangential regression lines fitted to the inflection points of the spline curve together can be a useful method for the screening of spinal diseases and for the examination of spinal rehabilitation processes.

Finally, the tangent line method may be generally used for processing the outputs of digital radiographic images and the output data of different external shape capturing systems (such as Zebris, SpinalTouch and SpinalMouse). In addition, the method handles 3D data, thus vistas for further development may open up for spatial processing.

Acknowledgement

The authors would like to express their thanks to orthopedist Mihály Nagy for his invaluable assistance in the performance of the measurements.

References

[1] Doody, M. M., Lonstein, J. E., Stovall, M., Hacker, D. G., Luckyanov, N., Land, C. E. "Breast cancer mortality after diagnostic radiography: findings from the U.S. Scoliosis Cohort Study". *Spine*, 25(16), pp. 2052–2063. 2000. https://www.ncbi.nlm.nih.gov/pubmed/10954636

[2] Knott, P., Pappo, E., Cameron M., deMauroy, J. C., Rivard, C., Kotwicki, T., Zaina, F., Wynne, J., Stikeleather, L., Bettany-Saltikov, J., Grivas, T. B., Durmala, J., Maruyama, T., Negrini, S., O'Brien, J. P., Rigo, M. "SOSORT 2012 consensus paper: reducing x-ray exposure in pediatric patients with scoliosis". *Scoliosis*, 9(4), p. 9. 2014. https://doi.org/10.1186/1748-7161-9-4

[3] Harrop, J. S., Birknes, J., Shaffrey, C. I. "Noninvasive measurement and screening techniques for spinal deformities". *Neurosurgery*, 63(3), pp. 46–53. Sept. 2008. https://doi.org/10.1227/01.NEU.0000325678.25152.A7

[4] Mansour, K. B., Dao, T. T., Ho Ba Tho, M. C., Marin, F. "Prediction of internal spine curvature using back surface information". In: *10th International Symposium on Biomechanics and Biomedical Engineering*. Berlin. 2012. https://doi.org/10.13140/2.1.4897.2485

[5] Tanure, M. C., Pinheiro, A. P., Oliveira, A. S. "Reliability assessment of Cobb angle measurements using manual and digital methods". *The Spine Journal*, 10(9), pp. 769–774. 2010. https://doi.org/10.1016/j.spinee.2010.02.020

[6] Malmström, E-M., Karlberg, M., Melander, A., Magnusson, M. "Zebris versus Myrin: A comparative study between a three-dimensional ultrasound movement analysis and inclinometer/compass method". *Spine*, 28(21), pp. 433–440. 2003. https://doi.org/10.1097/01.BRS.0000090840.45802.D4

[7] Mannion, A. F., Knecht, K., Balaban, G., Dvorak, J., Grob, D. "A new skin-surface device for measuring the curvature and global and segmental range of motion of the spine: reliability of measurements and comparison with data review from the literature". *European Spine Journal*, 13(2), pp. 122–136. 2004. https://doi.org/10.1007/s00586-003-0618-8

[8] Geldhof, E., Cardon, G., Bourdeaudhuij, I. D., Danneels, L., Coorevits, P., Vanderstraeten, G., Clercq, D. D. "Effects of back posture education on elementary schoolchildren's back function". *European Spine Journal*, 16(6), pp. 829–839. 2007. https://doi.org/10.1007/s00586-006-0199-4

[9] Kiss, R. M. "*Biomechanikai modellezés*". TERC Kiadó, BME Építőmérnöki Kar, pp. 225–242. Budapest, 2012.

[10] Takács, M., Rudner, E., Nagy, I., Jurák, M., Kiss, R. M., Kocsis, L. "The new processing of the results of examinations made with Zebris WIN-SPINE spine-measuring method and its validation". *Biomechanica Hungarica*, 6(1), pp. 29–37. 2013. https://doi.org/10.17489/biohun/2013/1/04

[11] Kiss, R. M. "Verification of determining the curvatures and range of motion of the spine by electromechanical-based skin-surface device". *Periodica Polytechnica Civil Engineering*, 52(1), pp. 3-13. 2008. https://doi.org/10.3311/pp.ci.2008-1.01

[12] Aota, Y., Saito, T., Uesugi, M., Ishida, K., Shinoda, K., Mizuma, K. "Does the fists-on-clavicles position represent a functional standing position". *Spine*, 34(8), pp. 808–812. 2009. https://doi.org/10.1097/BRS.0b013e31819e2191

[13] Aota, Y., Saito, T., Uesugi, M., Kato, S., Kuniya, H., Koh, R. "Optimal arm position for evaluation of spinal sagittal balance". *Journal of Spinal Disorders and Techniques*, 24(2), pp. 105–109. 2011. https://doi.org/10.1097/BSD.0b013e3181da36c4

[14] Zsidai, A., Kocsis, L. "Ultrasound-based measuring-diagnostic and muscle activity measuring system for spinal analysis". *Technology and Health Care*, 14(4–5), pp. 243–250. 2006. http://dl.acm.org/citation.cfm?id=2690959

[15] Takács, M., Rudner, E., Kovács, A., Orlovits, Zs., Kiss, R. M. "The assessment of the spinal curvatures in the sagittal plane of children using an ultrasound-based motion analysis system". *Annals of Biomedical Engineering*, 43(2), pp. 348–362. Febr. 2015. https://doi.org/10.1007/s10439-014-1160-z

[16] Zsidai, A., Kocsis, L. "Ultrasound-based spinal column examination system". *Facta Universitatis - Physical Education and Sport*, 1(8), pp. 1–12. 2001.

[17] Bland, J. M., Altman, D. G. "Statistical methods for assessing agreement between two methods of clinical measurement". *Lancet*, 8(1), pp. 307–310. 1986. https://www.ncbi.nlm.nih.gov/pubmed/2868172

[18] Jáger, B., Kristóf, T., Kiss, R. M. "Mathematical description of spinal curvature using the results of in-vivo measurement systems". In: (Jobbágy Á. (Eds)) *First European Biomedical Engineering Conference for Young Investigators*. IFMBE Proceedings, 50. Springer, Singapore, 2015. https://doi.org/10.1007/978-981-287-573-0_20