Assessment of lumbar lordosis distribution with a novel mathematical approach and its application for investigation of lumbar intervertebral disc degeneration

Ph.D. Thesis

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INTRODUCTION

Low back pain is a major factor that influences both society and economy. The one-time or recurrent low back pain which influences everyday life causes a serious problem in our society today for instance in the absenteeism from work and it is also one cause of incapacity for work. Therapy is complex and no single method has been proved effectively to treat this disease. In Hungary, 21% of the population suffer from low back pain or back pain according to a KSH health survey in 2014, and six out of ten take medication for the disease. In the survey additional 9% of the population have reported low back or back pain as a non-medical diagnosis. A total of three-tenths of people are affected by this problem considering these non-medical cases as well. According to the results in Hungary the prevalence of "Low back or back problem" is on the second place after the "High blood pressure". Based on the experience of intensive research there are four main factors associated with low back pain which are the geometry of the spine, the morphological degeneration, the pain of the patients associated with the degeneration and the degree of the impairment function.

The spine is a multi-curved skeletal part consisting of 33–35 vertebrae. The spine consists of 7 cervical vertebrae, 12 thoracic vertebrae, 5 lumbar vertebrae, 5 sacral vertebrae fused into the sacrum and further 4–6 coccygeal vertebrae frequently fused into the coccyx. The most important connections of the vertebrae are the intervertebral discs which lie between adjacent vertebrae in the vertebral column. During the examination of the spine the investigation of the lumbar lordosis is highly important because it is the most frequently affected section.

In the literature many methods are used to measure and approximate the curvature of lumbar lordosis. Some methods rely on clinical trials while others rely on rather imaging procedures. In clinical trials measurements are made directly on the patients' body while during imaging procedures for example X-rays or MRI scans are used. Each evaluation method has its advantages and disadvantages but the biggest problem is that it is difficult to compare measurements when they are performed with different methods. Over time the Cobb-angle has become a common standard for measuring lumbar lordosis because it is easy to use and its reliability has been proved. However, the most significant limitation of the Cobb-angle is that, due to its definition, two different types of spine curves can result the same angle value. Unfortunately, due to

this constraint, the Cobb-angle does not contain information about the distribution of lumbar lordosis. There is a number of different perspectives and unclear issues regarding to the measurement of lumbar lordosis and its determinants. Different approaches exist for the number of vertebrae used in the measurement or the measurement position of the patients to be examined. Furthermore, the relationship between lumbar lordosis and other factors such as age, gender, ethnicity, sports activities, and occupations is unclear.

In the literature, many grading systems are used to classify the intervertebral disc degeneration. Among the imaging procedures MRI imaging is an accepted tool in the examination of disc degeneration, as on MRI images directly the disc itself can be examined while on X-rays only bone structures can be evaluated. The normal intervertebral discs show sharp borders between nucleus pulposus and anulus fibrosus on MRIs because of the signal brightness. Furthermore, intervertebral disc degeneration shows a reduction in signal. The Pfirrmann grading system is a widely accepted and clinically used scale for determining the extent of lumbar intervertebral disc degeneration. This grading system classifies disc degeneration with an algorithm using criteria of disc structure, distinction of nucleus pulposus and anulus fibrosus, signal intensity and disc height into 5 grades.

It is very important to examine the relationship among low back pain, intervertebral disc degeneration and the shape of lumbar lordosis (both globally and locally) to explore the underlying relationships. Several studies in the literature have examined the association between lumbar lordosis and spinal degenerative diseases. Researchers have found no clear link between the global lumbar lordosis and intervertebral disc degeneration. Another important issue is the relationship between lumbar lordosis and low back pain. Several studies in the literature have examined the relationship between lumbar lordosis and low back pain. Researches have shown no evidence between sagittal spinal curves and health, including spinal pain. Furthermore, the question is unclear whether the global form of lumbar lordosis with low back pain differs from healthy ones or not. However, some researchers have linked low back pain and lumbar intervertebral disc degeneration with each other. One factor may explain the contradiction. Lumbar lordosis is unevenly distributed and most of the total curvature is located in the lower two sections (L4-L5 and L5-S1) where most disc herniations occur

(approximately 95%). Therefore, it is possible that there is a relationship between the local distribution of the global lumbar lordosis and the intervertebral disc degeneration which requires further analyses. Furthermore, the review of the literature reveals the lack of a method which is easy to perform in everyday clinical practice and provides information about the complex geometric features of the lumbar spine to the physician and therapist that can be associated with degenerative morphological changes in the lumbar region.

OBJECTIVES

Based on the literature, there are several deficiencies in the field such as the existence of a method for accurate and effictive measuring the geometric shape of lumbar lordosis, the existence of a reliable and single quantitative parameter for characterization to the distribution of lumbar lordosis or the exact knowledge of the connection between the distribution of lumbar lordosis and lumbar intervertebral disc degeneration.

Taking into consideration the deficiencies revealed in the scientific literature, the objectives of my Ph.D. dissertation are as follows:

1. To develop a new mathematical method which measures the geometric shape of lumbar lordosis more accurately than previously known methods.
2. To develop a new quantitative parameter which characterizes the distribution of lumbar lordosis.
3. To relate the distribution of lumbar lordosis to the lumbar intervertebral disc degeneration using the new quantitative parameter.
4. To develop a new informatic software based on the new method which makes the results of the research available for using in clinical practice.

METHODS

In my research, I used descriptive statistical analyses, reliability analyses, relationships analyses, comparison with control groups and discriminant analysis.

Sample data and its descriptive statistics: The patients were randomly sampled (N = 60) and received outpatient care for low back pain. All patients with a tumor, major spinal deformities, spinal cord disorder, previous spinal trauma or surgery were excluded. The research was approved by the local Research Ethics Committee (Department of Orthopaedics, Health Services of Budavari Local Government) and all anonymised MRIs had been taken for clinical diagnosis previously which are T2-weighted (FSE) sagittal images. Basic physiological data of the patients were recorded. I used the Shapiro-Wilk W test to examine normality and the independent two-sample t-test for gender comparison. In cases where normality was not realised I used the nonparametric equivalent of the independent two-sample t-test, the Mann-Whitney U test.

Reliability analyses: In my first reliability analysis I examined the reliability of the developed software. Using the new software MRIs were examined independently by two observers. After five days the two observers also repeated the measurement independently. In the fisrt reliability analysis I calculated intraclass correlation coefficients (ICCs) to determine the intraobserver reliabilities and the consistency of the two readings of the observers was investigated by interobserver reliability (by Pearson's r coefficients). In my second reliability analysis I examined the reliability of the performed intervertebral disc degeneration test. Two observers independently graded the MRIs using the Pfirrmann grading system. The reliability of the MRI evaluations was estimated using agreement percentage and Cohen's kappa statistics between the two observers (interobserver reliability).

Descriptive statistics of the morphological parameters: I performed the descriptive statistical analysis of the morphological parameters. I used the Shapiro-Wilk W test to examine normality and the independent two-sample t-test for gender comparison. In cases where normality was not realised I used the nonparametric equivalent of the independent two-sample t-test, the Mann-Whitney U test.

Relationships analyses: I performed my first correlation analysis to investigate the relationships among the morphological parameters. In my second correlation

analysis I investigated the relationships between the morphological parameters and the intervertebral disc degeneration. I used the Shapiro-Wilk W test to examine normality and Pearson's r coefficient to express the intensity. Where the normality criterion was not realised I used the nonparametric Spearman's correlation rϱ value procedure.

Comparison with control groups: In my research I also performed a control group comparative analysis. The Pfirrmann grading system was used for the classification of lumbar intervertebral disc degeneration. This grading system is a five-point scale from 1 to 5 where the category number 5 means the most serious degeneration. To form the control group I divided the patients into two parts based on the category of the lumbar intervertebral disc degeneration. The patients who had all degeneration values in category 1, 2, or 3 were included in the control group. So I considered those patients ill who had at least one degeneration value in category 4 or 5. I used analysis of variance (ANOVA) to detect differences between the ill and the healthy control groups, furthermore I used the conservative Scheffe test from the post hoc tests for pairwise comparison. To confirm my results I also performed the Kruskal-Wallis test from the nonparametric methods.

Discriminant analysis: I used discriminant analysis to establish degeneration classes for lumbar intervertebral discs and to indicate these classes. The Pfirrmann grading system was used for the classification of lumbar intervertebral disc degeneration. To design the degeneration classes I also examined the possibility of using the median and the average of the five degeneration values. I used the SPSS Visual Binning modeler to create the classes. In the analysis of the established degeneration classes I analysed the descriptive statistical data and I used the Levene test to examine the homogeneity of the standard deviation. I used analysis of variance (ANOVA) to detect differences between classes, furthermore I used the conservative Scheffe test from the post hoc tests for pairwise comparison. To confirm my results I also performed the Kruskal-Wallis test from the nonparametric methods.

RESULTS

A novel mathematical approximation of lumbar lordosis: To evaluate the lumbar lordosis I used interpolation in the novel mathematical method because my aim was to give a more accurate approximation of the spine besides the methods known so far. Interpolation is a mathematical approximation method where an approximation is given to the unknown values of a function based on the known values. In the novel mathematical method I used Lagrange interpolation because this procedure proved to be the most suitably and feasibly considering the properties of the spine and this was also confirmed by the medical expert opinion. In the novel method firstly the user has to select the lower and upper corners of the last thoracic vertebra (Th12 vertebra) and the five lumbar vertebrae (L1, L2, L3, L4 and L5 vertebrae) and the upper corners of the first sacral vertebra (S1 vertebra) in the new software. These selected points define six vertebral centers and one upper midpoint.

After this, the steps of the novel mathematical method are as follows:

1. Let point $P_0(x_0, y_0) = P_0(0,0)$ be the measured center of the last thoracic vertebra (Th12 vertebra) where both the first and the second coordinates are zero. (So the point $P_0(0,0)$ is the origin.)
2. Let point $P_i(x_i, y_i)$ be the measured center of the L*i* lumbar vertebrae where $i = 1,2,3,4,5$.
3. Let point $P_6(x_6, y_6) = P_6(x_6, 0)$ be the measured midpoint of the first sacral vertebra (S1 vertebra) where the second coordinates are zero. (So the x-axis is defined by point $P_0(0,0)$ and point $P_6(x_6, 0)$.)
4. The spine is located above the x-axis.
5. Let the interpolation polynomial in the interval $[x_0, x_6]$ be the

$$p(x) = \sum_{i=0}^{6} y_i \cdot L_i(x)$$

function where the functions of the Lagrange interpolation are the

$$L_i(x) = \prod_{\substack{k=0 \\ k \neq i}}^{6} \frac{x - x_k}{x_i - x_k}$$

functions.

With Lagrange interpolation just one interpolation polynomial can be aligned on the spine line, therefore the polynomial $p(x)$ is unique. In addition, this polynomial is a continuous, differentiable and integrable function, and at the examined interval $[x_0, x_6]$ the function takes up the maximum and the minimum.

The essence of the novel method is that the centers defined by the measurement points can be used to approximate the shape of the spine with a unique polynomial (Figure 1) which gives a much more accurate approximation than a simple circular arc or an ellipse. The name of the introduced novel mathematical method is *SRD-method*. In the *SRD-method* a polynomial can be clearly fitted to the lumbar spine with the help of the centers of the vertebrae whose the favorable mathematical properties can be used to further investigation of the distribution of lumbar lordosis.

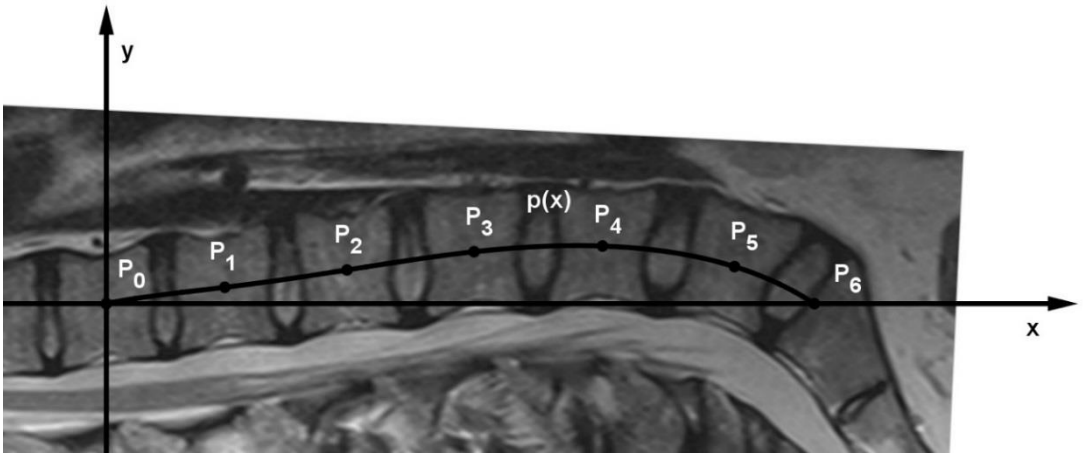

Figure 1: The evaluation of lumbar lordosis with the novel *SRD-method*.

New characterization of the distribution of lumbar lordosis: In addition to the novel approximation of lumbar lordosis my further aim was to develop a new quantitative parameter based on the introduced novel mathematical method which characterizes the distribution of lumbar lordosis and can be related to the lumbar intervertebral disc degeneration. The unique interpolation polynomial introduced in the *SRD-method* has favorable mathematical properties because this polynomial is a continuous, differentiable and integrable function, and at the examined interval $[x_0, x_6]$ the function takes up the maximum and the minimum. Utilizing these favorable properties I introduced some new morphological parameters to characterize the local behaviour of lumbar lordosis. During introduction of the new morphological

parameters, in line with and supported by medical expert opinion, my aim was to develop parameters to measure abdominal deflection of the lumbar spine, to measure the concentration of curvature of the lumbar spine and to characterize the local distribution of global lumbar lordosis.

The introduced new morphological parameters are as follows:

1. *Rho-angle* (ρ): (Figure 2)

   Let point $S(x_S, y_S)$ be the maximum of the interpolation polynomial $p(x)$ on the interval $[x_0, x_6]$. (According to the theory the polynomial could take up its maximum several times in a given interval but in practice it takes up only exactly once due to the properties of the shape of the spine, so this point is unique.) Let point $Z(x_S, 0)$ be the orthogonal projection of the point S onto the x-axis. Let *Rho-angle* be the angle ZP_0S in the right-angled triangle P_0SZ.

2. *Digression percentage* (*K*): (Figure 2)

   Let *Digression percentage* be the

   $$K = \frac{x_S}{x_6} \cdot 100$$

   value.

3. *Expansion percentages* (A_1, A_2, A_3, A_4, A_5, A_6): (Figure 3)

   Let *Expansion percentages* be the

   $$A_i = \frac{T_i}{T}$$

   values where $i = 1,2,3,4,5,6$ and

   $$T_i = \int_{x_{i-1}}^{x_i} p(x)dx \qquad \text{és} \qquad T = \int_{x_0}^{x_6} p(x)dx\,.$$

The *Rho-angle*, expressed in degree, gives the maximum deflection of the lumbar lordosis from the line defined by the Th12 vertebra and the S1 vertebra. The larger this angle value the greater the shift in the breaking point of the maximum deflection of the lumbar lordosis is towards the abdomen. Related to this, the *Digression percentage* (*K*) gives the location of the maximum deflection of the lumbar lordosis. The higher this percentage the closer the breaking point of maximum deflection is to the S1 vertebra. For example if *K* is 50%, the lumbar spine forms a “D” shape while at 75%, it forms a

"J" shape. This quantitative parameter distinguishes the possible forms of lumbar lordosis thus also characterizing its distribution. The *Expansion percentages* give the magnitude of the local expansions of lumbar lordosis relative to its global expansion. The six values can be used to examine the local behaviours of lumbar lordosis and to investigate the distribution of the curve in terms of which parts and how to contribute to the global curvature.

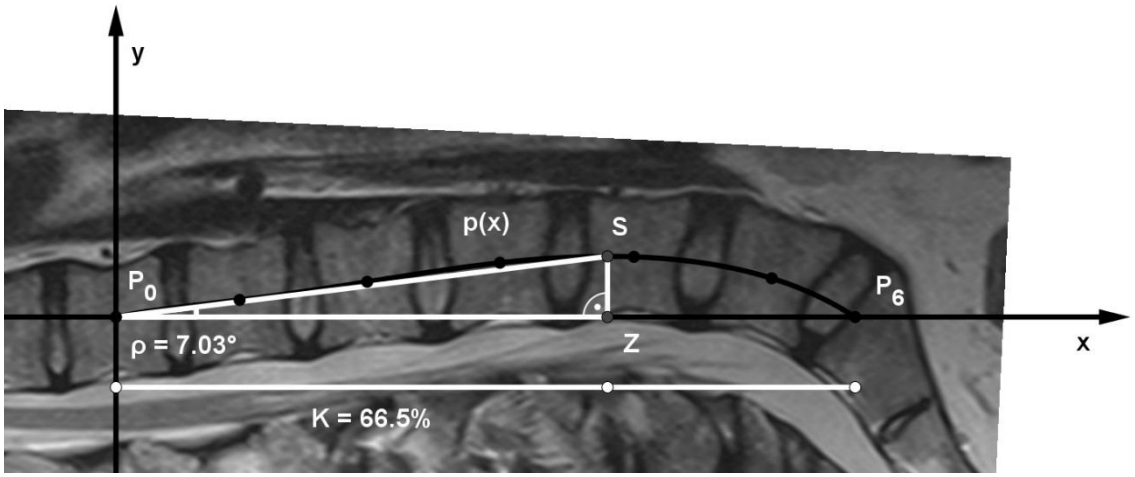

Figure 2: The determination of *Rho-angle* (ρ) and *Digression percentage* (K).

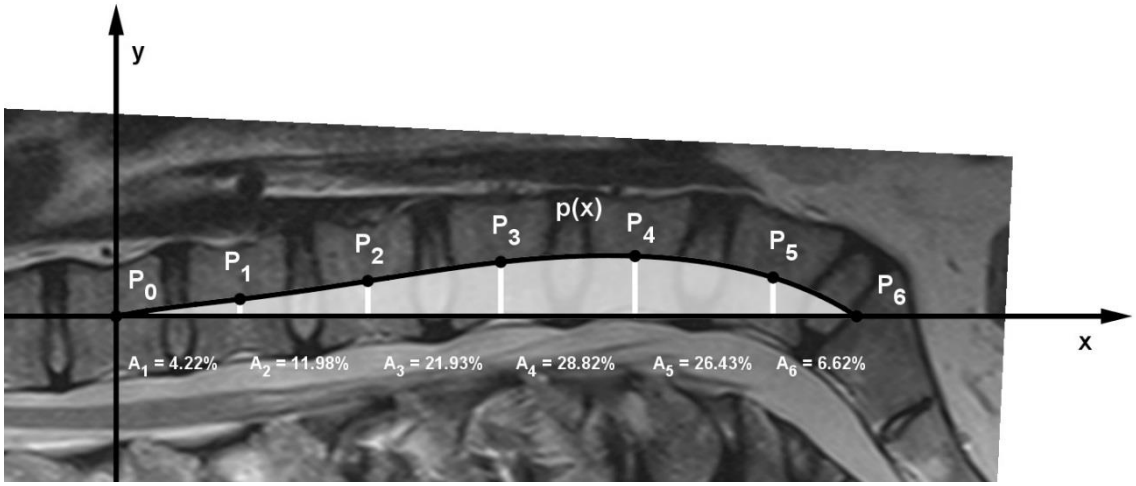

Figure 3: The determination of *Expansion percentages* (A_1, A_2, A_3, A_4, A_5, A_6).

Descriptive statistics results of the sample: The research included 60 patients which contains 39 female (65%) and 21 male (35%). Basic physiological data of the patients were recorded: age (44.2 ± 14.3 year), body height (170.9 ± 10.2 cm), body weight (73.7 ± 14.3 kg). From these data the BMI, the body mass index (25.2 ± 4.4

kg/m^2), could be determined. Significant differences were found only in body height ($p < 0{,}001$ and Cohen's $d = 1{,}73$) and body weight ($p < 0{,}001$ and Cohen's $d = 1{,}53$) while there was no significant gender difference in age ($p = 0{,}273$) and BMI ($p = 0{,}092$).

Description of the self-developed *Spinalyze Software*: In order to implement the novel *SRD-method* and the new morphological parameters in practice I have developed a new informatic software. The new self-developed software is called *Spinalyze Software* whose fantasy name is made up of the English words "spine" and "analyze", and the self-developed logo is shown in Figure 4.

Figure 4: The logo of the self-developed *Spinalyze Software*.

The software framework is a dynamically evolving mathematical program, written in the Java and HTML5 programming languages, called GeoGebra. *Spinalyze Software* is available free of charge on any devices (e.g. desktop computer, laptop, tablet, smartphone) with any operating systems (e.g. Windows, macOS, Linux) and with Internet using any browsers (e.g. Google Chrome, Firefox, Internet Explorer) at each of the following two addresses:

https://www.spinalyze-software.com

https://www.spinalyzesoftware.com

Each address contains one redirect which redirects the user to the GeoGebraTube website. On this website, after a brief introduction to the technical text, you will find the *Spinalyze Software*, anonymous MRIs for trial measurements, a User Guide video and a feedback interface for gathering opinions. All available contents are in English.

The operating steps of *Spinalyze Software* are as follows:

- The first step is uploading the MRI into the *Spinalyze Software*.
- The user has to select the lower and upper corners of the last thoracic vertebra (Th12 vertebra) and the five lumbar vertebrae (L1, L2, L3, L4 and L5 vertebrae) and the upper corners of the first sacral vertebra (S1 vertebra).
- The software uses the selected vertebral corners to determine the required centers and the interpolation polynomial fitted to the spine.

- The software provides the morphological parameters of the measurement (Cobb-angle, *Rho-angle* (ρ), *Digression percentage* (K), *Expansion percentages* (A_1, A_2, A_3, A_4, A_5, A_6)) which can be saved in tabular form at the end of the measurement.
- In the last step, by uploading the gender and age associated with the MRI, the software provides the degeneration class of the patient as a result of the discriminant analysis.

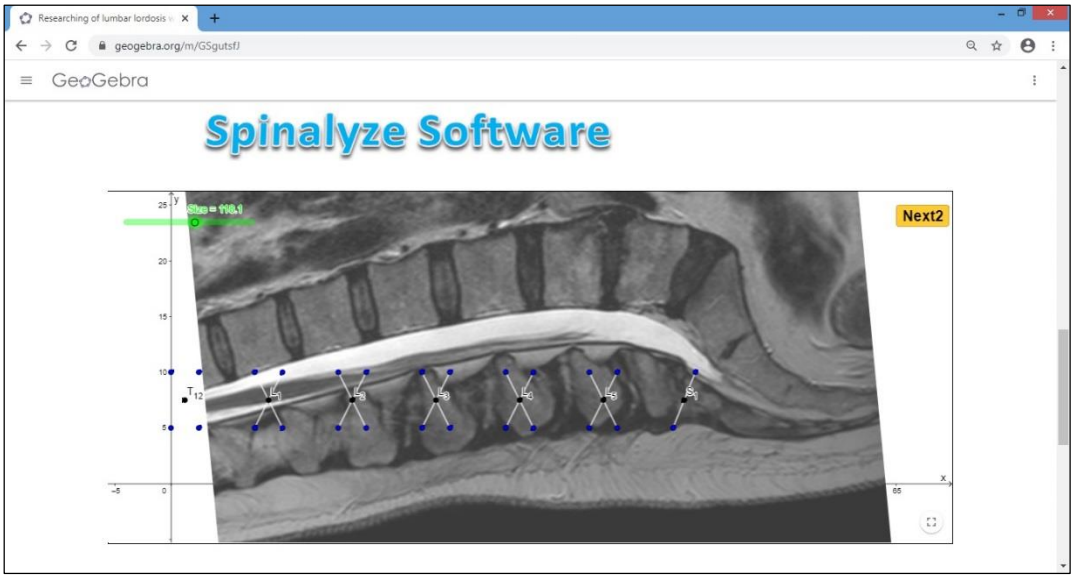

Figure 5: The measurement points waiting to be selected in the software.

Results of the reliability analyses: In my first reliability analysis I examined the reliability of the developed software where for both the first and the second observers each ICC value for the coordinates at each measurement point belongs to the excellent category (ICC > 0.90). This means that each observer was in line with itself excellently so the measurement made with *Spinalyze Software* can be safely repeated by the same person because it will be reliable. Furthermore, for both the first and the second measurements each Pearson's r coefficient for the coordinates at each measurement point belongs to the very strong category (r > 0.80). This means that, based on both the first and the second measurements, the two independent observers were very strongly in agreement with each other so the measurement made with *Spinalyze Software* can be safely repeated by different people because it will be reliable. Thus, based on the measurements supported by reliability analyses, it can be concluded that with the using

of *Spinalyze Software* the determination of measurement points can be performed easily and repeatedly, therefore *Spinalyze Software* is reliable and the parameters obtained from calculations based on it will also be reliable. In my second reliability analysis I examined the reliability of the performed intervertebral disc degeneration test where the agreement between observers is 88.33% and the Cohen's kappa value is 0.84 which falls into the excellent agreement category (kappa > 0.81). This means that, based on the measurement, the two independent observers were in excellent agreement with each other so the performed intervertebral disc degeneration test is reliable.

Descriptive statistics results of the morphological parameters: To get to know the behaviour of the introduced new morphological parameters I performed the descriptive statistical values of the measurement attached to the sample. From the parameters examined only the Cobb-angle, *Rho-angle*, and A_6 value were normally distributed. The gold standard Cobb-angle shows no significant difference between the genders and its average is 33.43° with a relatively larger standard deviation of 12.12°. None of the new morphological parameters show a significant difference between the genders so the parameters can be examined regardless of gender based on the measurements. The *Rho-angle* has a low average angle value (7.80°) and also a small standard deviation (2,97°). Thus, in the case of the sample, the breaking point of the maximum deflection of the lumbar lordosis shifts only slightly towards the abdomen. The *Digression percentage* is on average 62.68% and the standard deviation is 4.36% so based on the data, it can be said that the breaking point of the maximum deflection is not in the middle (which would be represented by K = 50%), however, on average closer to the S1 vertebra. From the *Expansion percentages* the A_5 value has the highest variability and A_6 value has the lowest variability. Examining the averages the spine section belonging to the A_4 value contributes to the global curvature mostly.

Results of the relationships analyses: I performed my first correlation analysis to investigate the relationships among the morphological parameters where the Cobb-angle has a very strong positive linear relationship with the *Rho-angle* (p = 0.937) which means that as the Cobb-angle increases the *Rho-angle* as well. Thus, in the case of a greater lumbar lordosis the spine is more bended towards the abdomen. Based on the measurements the breaking point of the maximum deflection of the lumbar lordosis may be different at the same Cobb-angle. The results show that the *Digression*

percentage is not statistically related to the Cobb-angle and the *Digression percentage* is a more precise parameter to characterize the shape of the lumbar lordosis. The sum of the average of the A_4, A_5 and A_6 *Expansion percentages* is 58.79% which indicates that the expansion of lumbar lordosis is focused between the L3 vertebra and the S1 vertebra. The Cobb-angle has a positive correlation with A_1, A_2, A_3 values and a negative correlation with A_5, A_6 values while A_4 value has no correlation. Based on these, it can be seen that the turning point occurs at the value of A_4 value. Thus, as the Cobb-angle increases the A_1, A_2, A_3 values increase and the A_5, A_6 values decrease while the A_4 value shows no statistical relationship with the Cobb-angle. The *Rho-angle* shows a weaker correlation with the *Digression percentage*. Furthermore, the *Rho-angle* has a positive correlation with A_1, A_2, A_3 values and a negative correlation with A_5, A_6 values while A_4 value has no correlation. This is consistent with the relationship between the Cobb-angle and the *Expansion percentages* which is consistent with the fact that the Cobb-angle has a very strong positive linear relationship with the *Rho-angle*. The *Digression percentage* has a significant or strong correlation with each *Expansion percentage* which indicates that a downward shift in the shape of the curvature toward the S1 vertebrae has a large effect on the magnitude of the local expansions of the lumbar lordosis. The *Digression percentage* has a negative correlation with A_1, A_2, A_3 values and a positive correlation with A_4, A_5, A_6 values. Thus, as the *Digression percentage* increases the expansion decreases at the top of the curvature while it increases at the bottom. Fifteen correlations among *Expansion percentages* can be examined (Table 1). Based on the results the correlation between two parameters is strong in six of the fifteen cases and very strong in five cases. The A_4 value is responsible for the four cases that does not belong to these because A_4 value has a significant correlation with A_1 value, (barely a strong correlation with A_2 value), a weaker correlation with A_3 value, also a weaker correlation with A_5 value and no correlation with A_6 value. Furthermore, it should be noted that the A_5 value has a very strong correlation with all values except the A_4 value. Based on these results, it can be said that the *Expansion percentages* are closely related to each other, so a change in one value strongly influences the other values as well which indicates a high degree of interactions among the local sections of lumbar lordosis. The results of the correlation analysis show that the A_4 value behaves abnormally compared with the other parameters

because in several cases it does not correlate with certain parameters and in each case at this value the direction of the correlation changes (from positive to negative or vice versa). Consequently, analysing the developed new parameters it can be concluded that there are spines with the same Cobb-angle with different local lumbar lordosis shape and distribution, furthermore the distribution of global lumbar lordosis is uneven because the curvature shape shifts downward toward the S1 vertebra and centralizes around the L4 vertebra.

Table 1: The correlation values among the developed new parameters.
Notes: The correlation matrix is symmetric to the main diagonal so it is sufficient to display the values of the lower triangle. The * indicates the significant result.

Spearman correlation (rϱ)								
Vari-ables	**Rho-angle**	**K**	**A_1**	**A_2**	**A_3**	**A_4**	**A_5**	**A_6**
Rho-angle	1,000							
K	-0,315*	1,000						
A_1	0,340*	-0,605*	1,000					
A_2	0,446*	-0,713*	0,711*	1,000				
A_3	0,572*	-0,690*	0,729*	0,786*	1,000			
A_4	-0,157	0,586*	-0,570*	-0,603*	-0,350*	1,000		
A_5	-0,530*	0,674*	-0,825*	-0,832*	-0,954*	0,367*	1,000	
A_6	-0,490*	0,487*	-0,630*	-0,762*	-0,840*	0,136	0,852*	1,000

In my second correlation analysis I investigated the relationships between the morphological parameters and the intervertebral disc degeneration where based on the measurements both the Cobb-angle (rϱ = 0,283) and the *Rho-angle* (rϱ = 0,388) have a weaker correlation only with the degeneration categories of the L4-L5 intervertebral disc. These results indicate that neither the Cobb-angle nor the *Rho-angle* are sufficiently sensitive parameters to determine the degree of intervertebral disc degeneration. However, the *Digression percentage* shows a significant negative correlation with the degeneration categories of all lumbar intervertebral discs with decreasing Spearman's correlation rϱ values (Figure 6). Based on the results this means

that the smaller the value of *Digression percentage* (*K*) the more the number of degenerated discs is in the lower lumbar sections. These results indicate that the more the total lordosis is concentrated in the lower segments the fewer the number of the degenerated discs is in the lumbar spine. According to the analysis the *Expansion percentages* showed no association with the degeneration categories of lumbar intervertebral discs. Consequently, the *Digression percentage* shows a clear relationship with lumbar intervertebral disc degeneration, furthermore based on the results, proves to be a much more sensitive parameter in determining the degree of intervertebral disc degeneration than the Cobb-angle, *Rho-angle* or *Expansion percentages*.

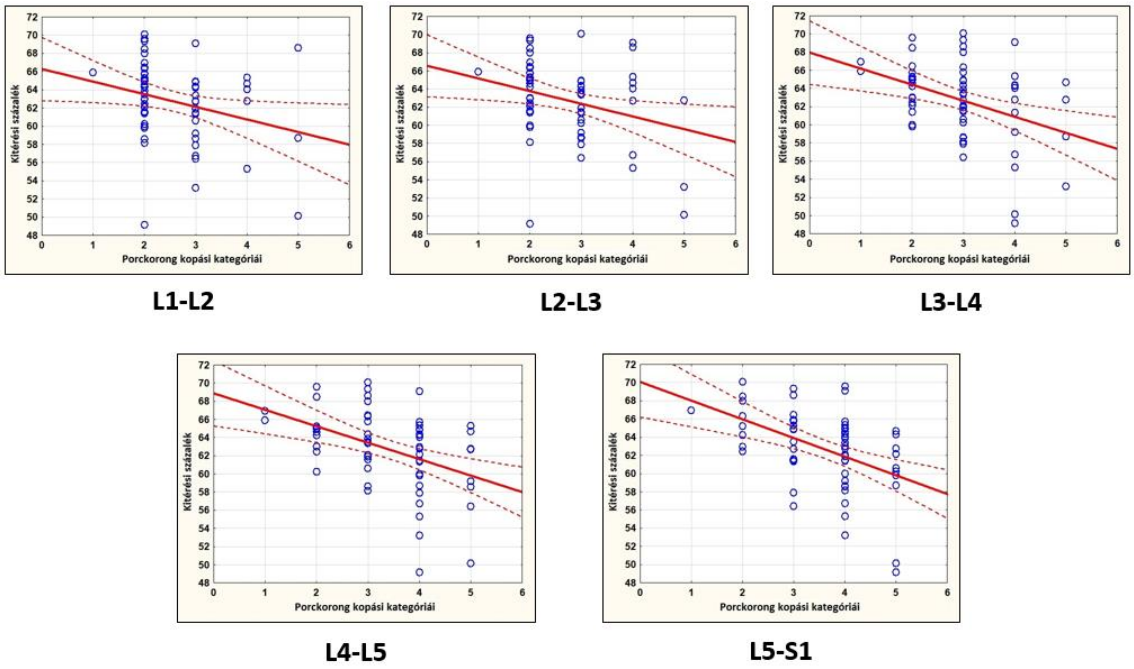

Figure 6: The relationship between the degeneration categories of lumbar intervertebral discs and *Digression percentage*.

Results of the comparison with control groups: Considering the results of the correlation analyses I performed a control group comparative analysis only regarding the *Digression percentage* (*K*) because only this parameter among the new morphological parameters was linked to the intervertebral disc degeneration. The creation of the control group was not based on the presence or type of low back pain but based on the degree of disc degeneration because my aim was a further investigation of

the relationship between the *Digression percentage* and lumbar intervertebral disc degeneration. Based on the results, the difference of the *Digression percentage* between the ill group and the healthy control group is significant ($p < 0.001$). In the healthy control group the average of the *Digression percentage* is 67.12% (with a standard deviation of 3.73%) while in the ill group the average is 61.66% (with a standard deviation of 4.30%). Thus, based on the results, the *Digression percentage* values are significantly different in the ill group compared with the healthy control group and *Digression percentage* has a smaller average value in the ill group. These results also confirm the results obtained in the correlation analyses that the *Digression percentage* shows a clear relationship with lumbar intervertebral disc degeneration and proves to be a sensitive parameter in determining the degree of intervertebral disc degeneration.

Results of the discriminant analysis: Considering the results of the correlation analyses I performed a discriminant analysis only regarding the *Digression percentage* (*K*) to establish degeneration classes for lumbar intervertebral discs and to indicate these classes. To design the degeneration classes I also examined the possibility of using the median and the average of the five degeneration values. There is a significant difference between the median and the average of the degeneration values ($p = 0.005$). To sum up, the analyses performed in the design of median classes and in discrimination showed that the formed classes are mixed and the discriminant functions do not separate the classes well, so the median is not suitable for discrimination. While designing the classes with the average I determined a suitable classification with the help of the analyses where the difference among the degeneration classes is significant ($p < 0.001$). This classification includes three classes: the Healthy, the Moderate and the Serious class. Consistent with the results of the correlation analyses and the control group comparative analysis the *Digression percentage* has the smaller average value in the Serious class (60.18%). Based on the results the average is suitable for discrimination and the following introduced degeneration classes were adequate to perform further analyses.

Healthy class:	$1 \leq$ average degeneration value $< 2{,}8$
Moderate class:	$2{,}8 \leq$ average degeneration value $< 3{,}8$
Serious class:	$3{,}8 \leq$ average degeneration value ≤ 5

Three independent variables showed significant results in the classification into the introduced degeneration classes: the Gender ($p = 0.030$), the Age ($p < 0.001$) and the *Digression percentage* (*K*) ($p < 0.001$), but not the gold standard Cobb-angle. Thus, these three parameters (Gender, Age, *Digression percentage*) and the following discriminant functions can be used to determine the degeneration class, furthermore the introduced degeneration classes are well-separated by the discriminant functions.

$$y_{Healthy} = -151{,}894 + 8{,}603 \cdot Gender + 0{,}120 \cdot Age + 4{,}244 \cdot K$$

$$y_{Moderate} = -134{,}694 + 9{,}428 \cdot Gender + 0{,}230 \cdot Age + 3{,}887 \cdot K$$

$$y_{Serious} = -137{,}532 + 11{,}088 \cdot Gender + 0{,}440 \cdot Age + 3{,}684 \cdot K$$

After performing the discriminant analysis the total correct classification value of the whole sample is 80.4% (Table 2) and this value is 75.0% from the test of the model validity which can be considered good.

Table 2: The classification results of the whole sample.

		Model classification			
	Class	**Healthy**	**Moderate**	**Serious**	**Total**
Original classification	**Healthy**	40	5	0	45
	Moderate	9	24	2	35
	Serious	1	1	10	12
	Total	50	30	12	92

As an opportunity to improve the result I also performed the analysis by merging the Moderate and Serious classes, so using two classes, but the analyses did not give a better classification, therefore it is worth using the three introduced classes. In summary, based on the results of the analysis, in indirect way (based on the Gender, the Age and the *Digression percentage* (*K*)) the model statistically reliable classifies patients into the Healthy, Moderate, or Serious degeneration classes. Thus, the values of Gender, Age, and *K* give the degeneration class, as opposed to the conventional direct way where you have to determine individually the degree of lumbar intervertebral discs

according to the Pfirrmann grading system, then you have to average and determine the class. These results also confirm the results obtained in the correlation analyses and in the control group comparative analysis that the *Digression percentage* shows a clear relationship with lumbar intervertebral disc degeneration and proves to be a sensitive parameter in determining the degree of intervertebral disc degeneration.

CONCLUSIONS

Based on my research and results, in line with my objectives, my new scientific findings are as follows:

1. I have developed a new examination method, using a novel mathematical method, which approximates the curve of the lumbar lordosis more precisely. The new developed method is called *SRD-method*.
2. I have defined a new quantitative parameter which assesses the distribution of the lumbar lordosis. The new developed parameter is called *Digression percentage* (*K*).
3. I have discovered a relationship between the distribution of the lumbar lordosis and the degeneration of the lumbar intervertebral discs by the new quantitative parameter.
    - According to the correlation analyses based on the results I have discovered that the smaller the value of *Digression percentage* the more the number of degenerated discs is in the lower lumbar sections. These results indicate that the more the total lordosis is concentrated in the lower segments the fewer the number of the degenerated discs is in the lumbar spine.
    - According to the control group comparative analysis based on the results I have discovered that there is a significant difference between the healthy control group and the ill group, and the average of the *Digression percentage* is smaller in the ill group.
    - According to the discriminant analysis based on the results I have discovered that the *Digression percentage* shows a significant effect by the classification into the lumbar intervertebral disc degeneration classes.
4. I have developed a new informatic software, based on the new method, which makes the results of the research available for using in clinical practice. The new developed software is called *Spinalyze Software*.

LIST OF OWN PUBLICATIONS

Publications related to the thesis

1. **Sándor Z**, Ráthonyi GK, Dinya E. A gerinc morfológiai elváltozásainak és geometriai jellemzőinek matematikai vizsgálata. In: Bari F, Almási L (szerk.), Orvosi Informatika 2014: A XXVII. Neumann Kollokvium konferencia-kiadványa. Pannon Egyetem, Veszprém, 2014: 21-24.
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   Impact factor: 1,770
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