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Changes in the shape of the lumbar curve during growth

a geometric morphometric approach

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Correspondence should be sent to Prof. Hila May
mayhila@tauex.tau.ac.il

R. Pelleg-Kallevag,[1,2] S. Borgel,[2,3] E. Kedar,[2,3] N. Peled,[4,5] H. May[2,3]

[1]Department of Physical Therapy, Zefat Academic College, Zefat, Israel
[2]Department of Anatomy and Anthropology, School of Medicine, Faculty of Medical and Health Sciences, Tel Aviv University, Tel Aviv, Israel
[3]The Shmunis Family Anthropology Institute, the Dan David Center for Human Evolution and Biohistory Research, School of Medicine, Faculty of Medical and Health Sciences, Tel Aviv University, Tel Aviv, Israel
[4]Department of Radiology, Elisha Hospital, Haifa, Israel
[5]Radiology Department, Carmel Medical Center, Haifa, Israel

Aims
The development of lumbar lordosis has been traditionally examined using angular measurements of the spine to reflect its shape. While studies agree regarding the increase in the angles during growth, the growth rate is understudied, and sexual dimorphism is debated. In this study, we used a novel method to estimate the shape of the lumbar curve (LC) using the landmark-based geometric morphometric method to explore changes in LC during growth, examine the effect of size and sex on LC shape, and examine the associations between angular measurements and shape.

Methods
The study population included 258 children aged between 0 and 20 years (divided into five age groups) who underwent a CT scan between the years 2009 and 2019. The landmark-based geometric morphometric method was used to capture the LC shape in a sagittal view. Additionally, the lordosis was measured via Cobb and sacral slope angles. Multivariate and univariate statistical analyses were carried out to examine differences in shape between males and females and between the age groups.

Results
The overall shape of the LC overlapped between males and females in most age groups, except for the nine- to 12-year age group. However, size did not affect LC shape. LC shape changed significantly during growth from straight to curved, reaching its mature shape earlier in females. This corresponded with the results obtained by the lordosis and sacral slope angles. A significant positive correlation was found between the LC shape and angles, although the angles demonstrated poor distinction between age groups, as opposed to the LC shape.

Conclusion
New insights into LC shape development were achieved using the geometric morphometric method. The LC shape was sex-independent in most age groups. However, the LC reached its mature shape earlier in females than males. The method and data of this study are beneficial for future studies examining aetiological factors for spinal pathologies and maldevelopment.

Article focus

- To follow the change in lumbar curve shape during growth using the landmark-based geometric morphometric method.
- To explore the presence of allometry and sexual dimorphism within the lumbar curve shape.
- To examine the correspondence between changes in angular measurements of the lumbar spine and its shape during development.

Key messages

- The lumbar curve shape changed with growth from a nearly straight spine to a curved shape in both sexes. However, females demonstrated an earlier and faster rate of curve development.
- Size does not affect the shape of the lumbar curve.
- Shape analysis of the lumbar spine demonstrated better changes in the growing spine than angles.

Strengths and limitations

- This is the first study to demonstrate the development of the lumbar curve shape during the entire growth period in males and females.
- The main limitation of this study is the relatively small sample size of the youngest age group in females.

Introduction

Spinal disorders are among the most common pathologies in the modern population due to maldevelopment of the spine during growth or other factors appearing later in life.[1] Adolescent spinal pain is a major health concern and is associated with sex and pubertal status; its prevalence increases with age, approximating that of adults by late teen years.[2-5] It has been suggested that some pathologies are related to bipedal locomotion and posture adaptations, which involve the development of spinal curves.[6,7] These curves are unique to humans and play a fundamental role in maintaining an upright posture and efficient shock absorption.[8,9]

The key to understanding the formation of lumbar lordosis (LL) is the developmental process during growth. While many studies have been carried out to understand the unique characteristics of the human spine and curves,[8-14] only a few have studied their developmental process.[15,16] Hence, information on these changes remains limited due to either small sample sizes or methodological limitations. Nevertheless, revealing the impact of acquiring bipedalism and growth on human spine morphology, as well as the sexual dimorphism related to it, is essential for understanding the normal variation of the adult human spine. Specifically, advancing our knowledge about the developing LL may shed light on the aetiology of spinal pathologies during growth and later in life. Additionally, spinal deformities that appear during the various stages of development (i.e. infantile, juvenile, or adolescent scoliosis) are sex-dependent.[17] Therefore, a better understanding of growth pattern and cessation in males and females may improve the management of these deformities.[18]

Various methods are used to capture the sagittal profile of the lumbar spine, usually measuring the angle of the LL using the 'modified Cobb method'.[8,11-1419-22] However, this method is limited due to its inability to capture the shape of the curve in the sagittal and coronal planes, and is insensitive to segmental changes.[23-25] Accordingly, individuals with the same Cobb angle can have different curve shapes.[23]

Studies relying on this method found inconsistent results regarding sexual dimorphism in LL angle during growth.[12–14,19,26,27] Several studies demonstrated a more pronounced LL in females than males;[11,28,29] others suggested a difference only at a young age, which disappeared after age 15 years,[13,27] and some did not find differences between the sexes.[12,19,30] Nevertheless, a consensus exists regarding the increase in LL angle during growth, ranging from 22° to 60°. However, they failed to capture the exact change in curve shape. The landmark-based geometric morphometric method (GMM) can overcome these limitations and quantify the shape of the spinal curve in either 2D images or 3D models.[31] The advantage of the GMM over traditional linear and angular measurements lies in its ability to preserve the geometry of the landmark configuration throughout the analysis, and allows assessing developmental (and evolutionary) trajectories.[31,32]

To date, few studies have used GMM to explore the shape of the lumbar spine, one of which was during growth.[33,34] Thus, there is a lack of data on the shape of the growing spine.

An additional important aspect of studying changes in the morphology of bones during growth and development is allometry, defined as a size-related change in shape or morphological traits. While this has been examined on other skeletal elements, such as the mandible[35] and cervical spine,[36] it has not been examined on the lumbar spine.

In this study, we aimed to reveal changes in LC shape during growth using the landmark-based GMM on midsagittal images obtained from CT scans of children, and examine which factors affect its shape (e.g. sex and allometry). Furthermore, we aimed to test the correlation between LL and sacral slope (SS) angular measurements and the LC shape.

Methods

Materials

The study population included 315 children aged between zero and 20 years, divided into five age groups. All children had an abdominal, spinal, or pelvic CT scan between 2009 and 2019 (Table I). This study was approved by the

Table I. Mean age of the sample included in the study by age group and sex (n = 258).

	Males		Females	
Age group, yrs	N	Mean age, yrs (SD)	N	Mean age, yrs (SD)
0 to 4	25	2.8 (1.1)	16	2.7 (0.7)
5 to 8	29	6.7 (1.0)	17	6.6 (1.2)
9 to 12	30	10.4 (1.1)	28	10.5 (1.2)
13 to 15	28	14.0 (0.8)	26	14.2 (0.8)
16 to 20	29	17.9 (1.4)	30	18.3 (1.3)
Total	141		117	

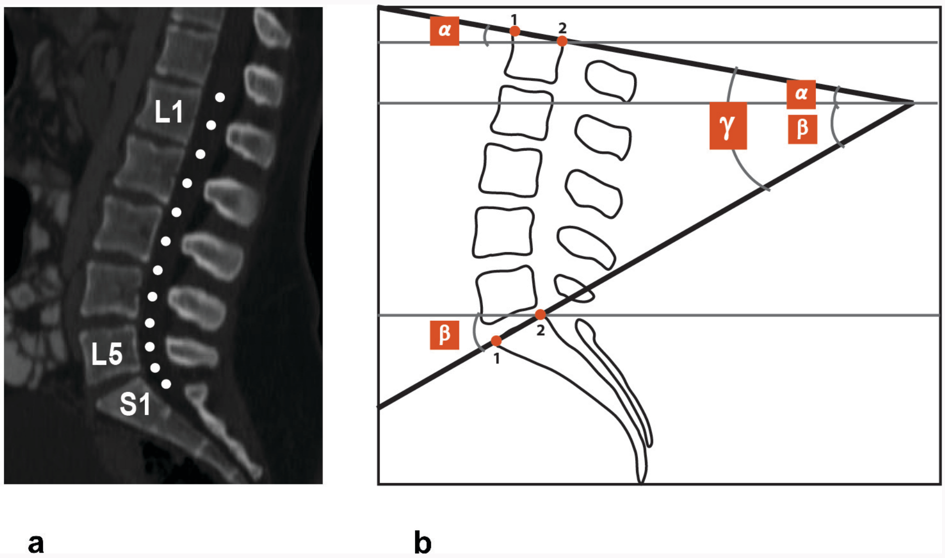


Fig. 1
Measurements of the lumbar curve. a) Landmarks' position for the lumbar curve. The first landmark was placed at the level of the superior endplate of L1; the following landmarks were marked at the level of the mid-height of the vertebra (starting at L1) and mid-height of the corresponding intervertebral disc space. The last landmark was placed at the mid-height of S1. b) Angular measurements of the lumbar lordosis; the coordinates from landmarks 1 and 2 on the superior endplates of L1 and S1 were used to calculate the lumbar lordosis and sacral slope (Supplementary Table i).

ethics committee of Tel Aviv University and the ethical board of Carmel Medical Centre (Haifa, Israel), and followed their guidelines.

Individuals with inadequate scans, spinal pathology or deformity, and those with a neurologic, metabolic, or chronic illness that can potentially affect normal development (e.g. cerebral palsy, endocrine disease) were excluded from the study. While the individuals included in the study did not show signs of maldevelopment, we had no information regarding post-scan maldevelopment onset. Consequently, 57 individuals were excluded from the study.

2D landmark-based GMM protocol

The shape of the LC was captured in 2D using the landmark-based GMM (Supplementary Material). An image of the midsagittal section of the lumbar spine was created using the planar mode in the Philips portal (Brilliance 64, Philips Medical System, USA; slice thickness 0.3 to 3.0 mm, 100 to 120 kV, 250 to 500 mAs, and Matrix 512*512). Then, 12 landmarks were placed in the middle of the spinal canal in ImageJ software (v. 1.51; National Institutes of Health, USA) (Figure 1a).

Angular measures

LL and SS angles were calculated from landmarks placed on the superior endplate of L1 and S1 vertebral bodies on the midsagittal image (Figure 1b, Supplementary Table i).

Statistical analysis

Descriptive statistics and statistical analyses were carried out using SPSS (v. 21.0; IBM, USA), RStudio (v. 4.1.2; USA),[37] and PAST software (v. 3.15).[38] Statistical significance was set at $p < 0.05$. The Kolmogorov-Smirnov test was carried out to examine the normality of the distribution of the linear variables.

To test the GMM protocol reliability, i.e. landmark placement, we used seven randomly selected subjects. For intraobserver reliability, the landmarks were positioned twice by the main investigator (RPK) with a week interval between landmarking sessions. For the interobserver reliability test, an additional researcher (EK) placed the landmarks blindly. Then, principal component analysis (PCA) was carried out following a general Procrustes analysis (GPA).[32] The significance of Procrustes distances within and between specimens and researchers was examined via multiple pairwise comparisons. In order to test intra- and interobserver variations of the angular measurements, the main investigator measured a subsample of 20 randomly selected individuals with a one-week interval between measuring sessions; then, an additional researcher (see Acknowledgements) measured the same individuals. Intraclass correlation coefficient (ICC) analyses were carried out to examine the reproducibility of these measurements.[39]

Cartesian coordinates were converted into shape variables using GPA followed by PCA to examine LC shape variance in males and females and among age groups. Procrustes analysis of variance (ANOVA) was carried out to assess whether allometry (shape~ group*log Centroid size) had a significant effect on the shape of the LC and visualized using plotAllometry function in R (Geomorph library). Multiple pairwise comparisons using Bonferroni correction were carried out following permutational multivariate ANOVA (PERMANOVA) to examine differences in shape between males and females and between the age groups. Two-block partial least square analyses were carried out to reveal associations between the LC shape and the angular measurements. Spearman correlations were calculated between the first singular wraps (SW1) of each block and between the first principle component (PC1) of the LC shape and age.

The Mann-Whitney U test and Kruskal Wallis test, with multiple pairwise comparisons using Bonferroni correction, were carried out to examine differences between males and females and between the age groups for the angular

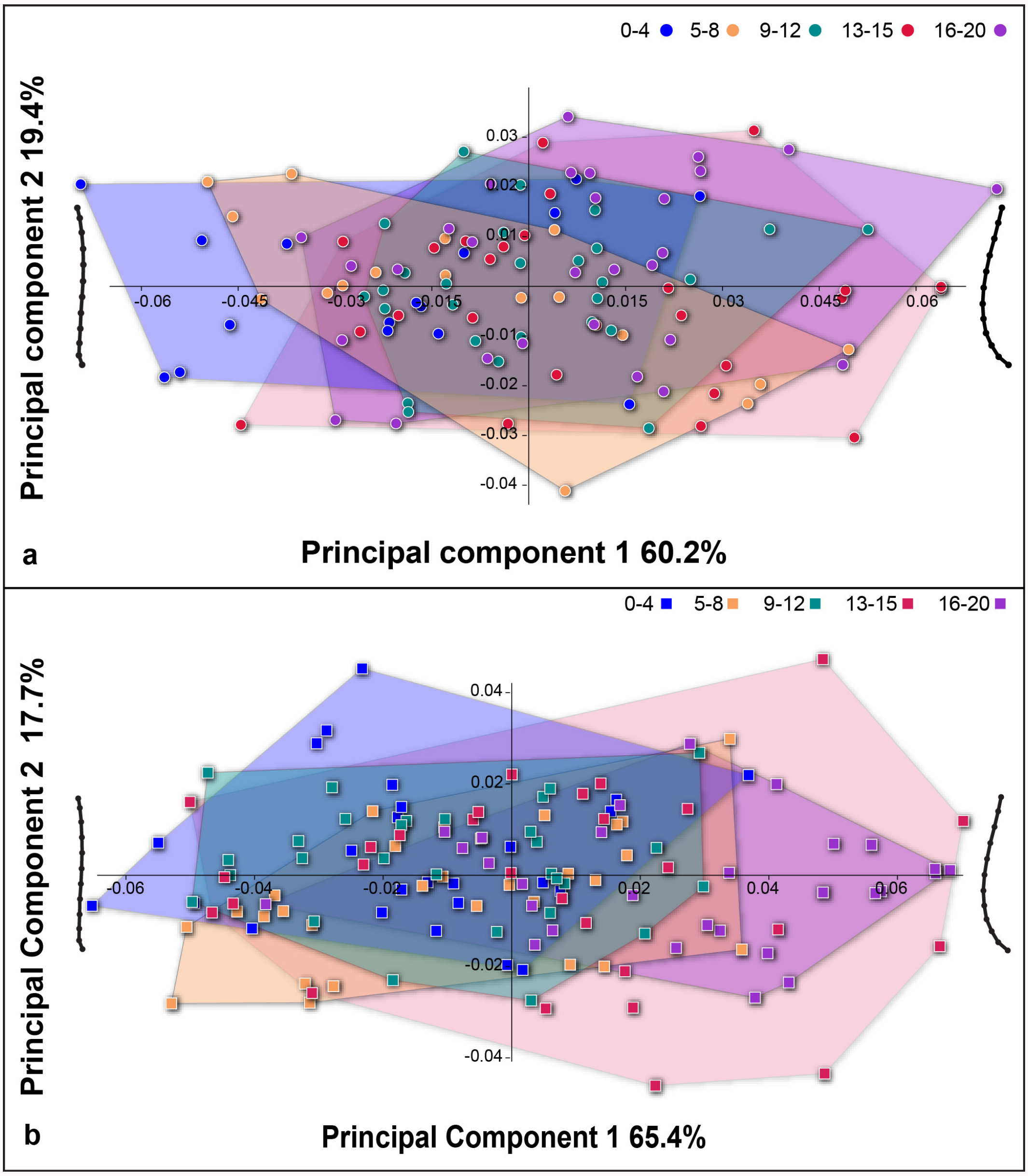


Fig. 2
Principal component analysis plot in space shape for the lumbar curve by age group in a) females and b) males. Pairwise comparisons between age groups are presented in Table II.

measurements. Spearman correlations were carried out between age and LL and SS angles.

Results

Reliability

The GMM protocol demonstrated high intra- and inter-observer reliability. Permutation tests of PC scores indicated that differences in shape between specimens were significantly greater than those within specimens when landmarks were placed by the same researcher (RPK) ($p < 0.001$, pairwise comparisons following Kruskal Wallis test). Furthermore, no significant differences were found between researchers ($p = 0.645$, pairwise comparisons following Kruskal Wallis test) (Supplementary Figure a). Intra- and interobserver variations for LL and SS angular measurements were excellent (ICC = 0.936 and ICC = 0.945, respectively) (Supplementary Table ii).

LC shape

The LC shape changed significantly during growth, from a nearly straight spine above the lumbosacral angle for the youngest age group to a curved lumbar spine for the older age group (Figure 2). Along PC1, an increase in curvature of the spine was observed during growth, explaining 65.4% and 60.2% of variance in shape for males and females, respectively (Figure 2). A significant correlation was found between PC1 scores and age, with males manifesting a stronger correlation than females (Spearman correlation: $r = 0.457$, $p < 0.001$; and $r = 0.286$, $p = 0.002$, respectively). Furthermore, significant differences between males and females were found in PC1 scores, with females manifesting, on average, a significantly more curved lumbar spine ($p = 0.032$, Mann-Whitney U test). However, further analyses by age group and sex highlighted the changes during growth and the differences between the sexes. In most age groups, no significant differences in LC

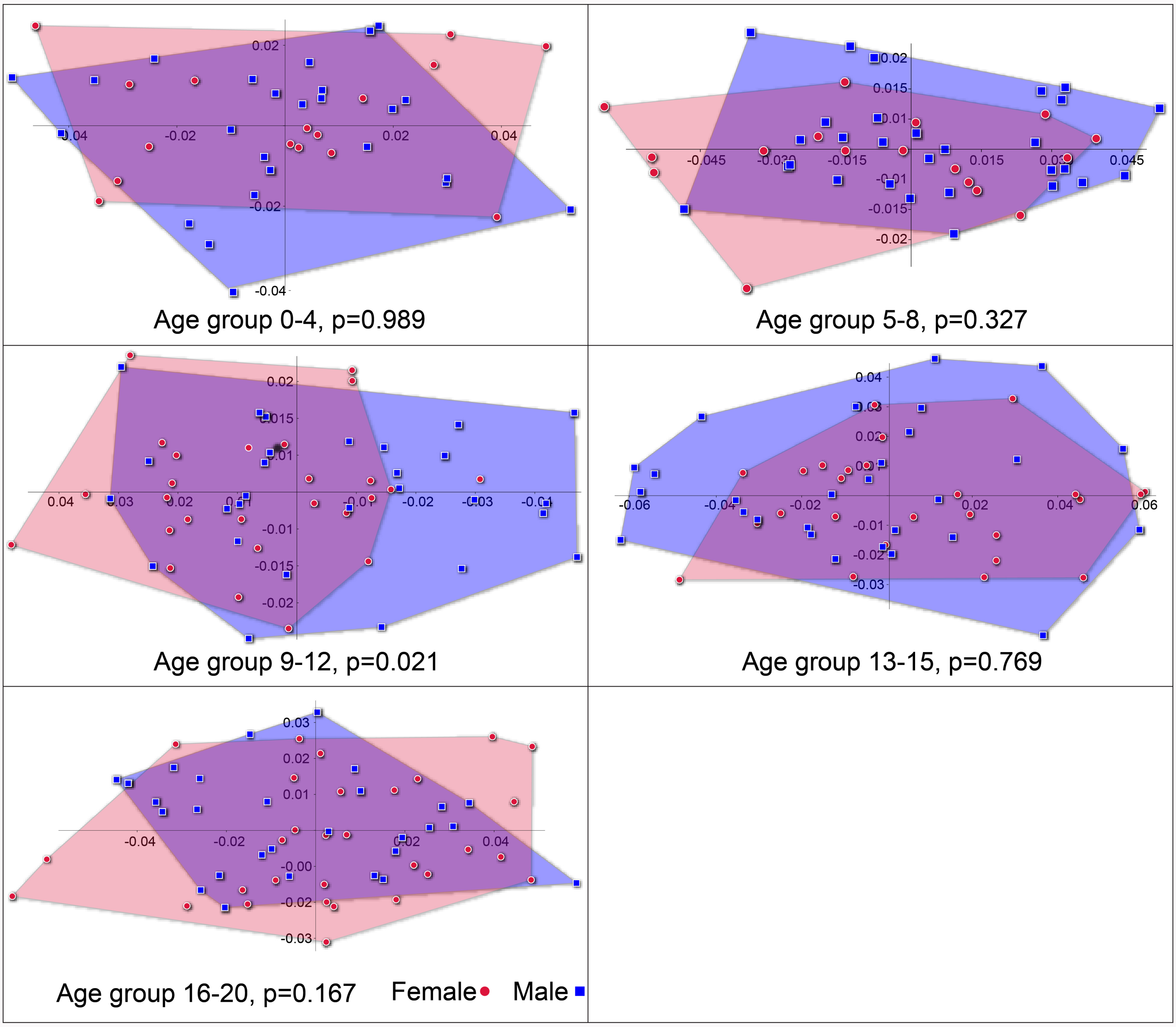


Fig. 3
Principal component analysis plot in shape space for the lumbar curve in males (blue) and females (pink) by age group.

shape were found between males and females, except for age group 9 to 12 years (p = 0.013, PERMANOVA) (Figure 3).

In females, the increased curvature in the LC shape was evident at a younger age group, and stabilized earlier, whereas in males it continued into adulthood (Figure 4, Table II). In females, significant differences were found between the youngest age group and the three oldest ones (9 to 12, 13 to 15, and 16 to 20 years) (Figure 2a, Table II), whereas in males, significant differences were found between the three young age groups (0 to 4, 5 to 8, and 9 to 12 years) and the oldest one (Figure 2b, Table II). The LC shape of males continued to increase after the age group of 13 to 15 years, whereas in females it remained similar after this age group (Figure 4).

A significant interaction between sex and size was found in age groups nine to 12 years and 13 to 15 years (Table III). Nevertheless, males and females did not share a common allometric trajectory, meaning that the difference in size between the sexes did not dictate the LC shape (Figure 5).

Angular measurements

Significant positive weak correlations were found between age and LL and SS angles (r = 0.316 and 0.225, p < 0.001). In general, the LL angle in females was significantly larger than in males (41.6 vs 38.5, p = 0.008, Mann-Whitney U test), with a similar SS angle (35.2 vs 34.2, p = 0.315, Mann-Whitney U test). When examined by age group, a significant difference in LL angle was found between the youngest and oldest age groups in females (p = 0.014, Kruskal Wallis test). Yet, in males, they were found between the three young age groups and the oldest one for both LL and SS (Table IV).

In the youngest age group, the angles were similar between the sexes, yet in the nine- to 12-year age group, females had significantly greater LL and SS angles than males, and in the 16- to 20-year age group, males had larger angles (Figure 6). Accordingly, the pattern of increase in LL and SS angles during growth differed between the sexes. In females, the angles increased up to the nine- to 12-year age group, whereas in males, a sharp increase in LL and SS angles

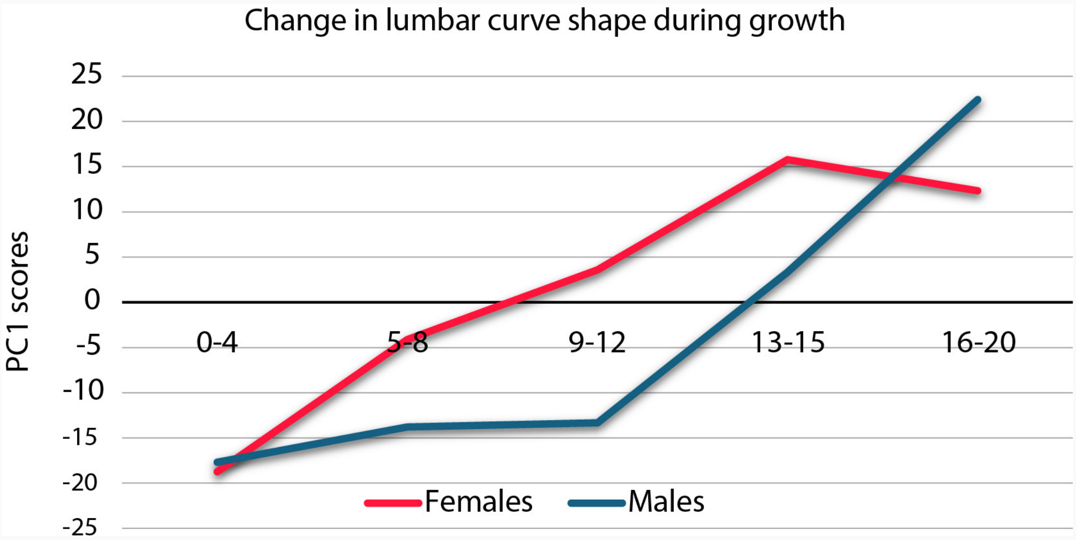


Fig. 4
Change in the first principal component (PC1) during growth for males and females.

Table II. Significance values for multiple pairwise comparisons (with Bonferroni correction) following permutation multivariate analysis of variance for differences in lumbar curve shape between age groups.

Age groups	Females				Males			
	0 to 4 yrs	5 to 8 yrs	9 to 12 yrs	13 to 15 yrs	0 to 4 yrs	5 to 8 yrs	9 to 12 yrs	13 to 15 yrs
5 to 8 yrs	1				1			
9 to 12 yrs	0.020	1			1	1		
13 to 15 yrs	0.010	0.260	0.949		0.080	0.270	0.490	
16 to 20 yrs	0.010	0.180	1	1	0.010	0.010	0.010	1

Table III. Results of Procrustes analysis of variance for the effect of allometry on lumbar curve shape (i.e. the interaction between sex and log of centroid size) by age group.

Age group, yrs	Df	SS	MS	Rsq	F	Pr (> F)
0 to 4	1	0.001	0.001	0.03	1.244	0.278
5 to 8	1	0.001	0.001	0.011	0.599	0.512
9 to 12	1	0.003	0.003	0.057	3.569	0.027
13 to 15	1	0.007	0.007	0.082	4.783	0.009
16 to 20	1	0.001	0.001	0.012	0.777	0.446

Df, degrees of freedom; F, F ratio; MS, mean squares; Pr, probability; Rsq, R-squared; SS, sum of squares.

occurred only from the nine- to 12-year age group onwards. After this age, while tempering in females, the LL and SS angles continued to increase in males, exceeding those of females in the oldest age group (Figure 6).

Association between LC shape and angular measurements
Two-block partial least squares analysis revealed a significant strong correlation between the SW1 of the LC shape and the SW1 of LL and SS angles for both males and females (r = 0.818 and r = 0.782, respectively; $p < 0.001$) (Figure 7). As the angles' scores increased, the LC changed from straight to more curved in both males and females. However, a better distinction between the age groups was observed along the SW1 of the LC shape than the SW1 of the angles (Figure 7).

Discussion

This study is the first to show the development of the LC shape using the landmark-based GMM in children from infancy to adulthood. Among the known factors affecting LC development is the acquisition of bipedal locomotion during growth.[15,40] The spine increases in length at an accelerated rate during adolescence, occurring earlier in females than males.[16,41] However, we demonstrated that size did not affect the changes in shape. Our study corresponds with previous studies demonstrating an increase in lumbar spine curve during growth.[11–14,29,42] The main advantages of this study are the combination of the method used and the wide age range (from birth to adulthood), which enabled us to identify changes in LC shape during growth, as well as differences in growing patterns and timing between males and females.

Our results suggest that the LC shape changes from straight to curved during growth, regardless of sex. This corresponds with Peters et al,[34] who did not find sexual dimorphism in the lumbar spine shape measured by the vertebral centroid location and vertebral orientation. However, we found an earlier LC development in females than males until the nine- to 12-year age group, with no significant change after the 13- to 15-year age group. In males, LC shape changed after the nine- to 12-year age group and continued up to at least the 16- to 20-year age group. Nevertheless, significant sexual dimorphism in LC shape was apparent in

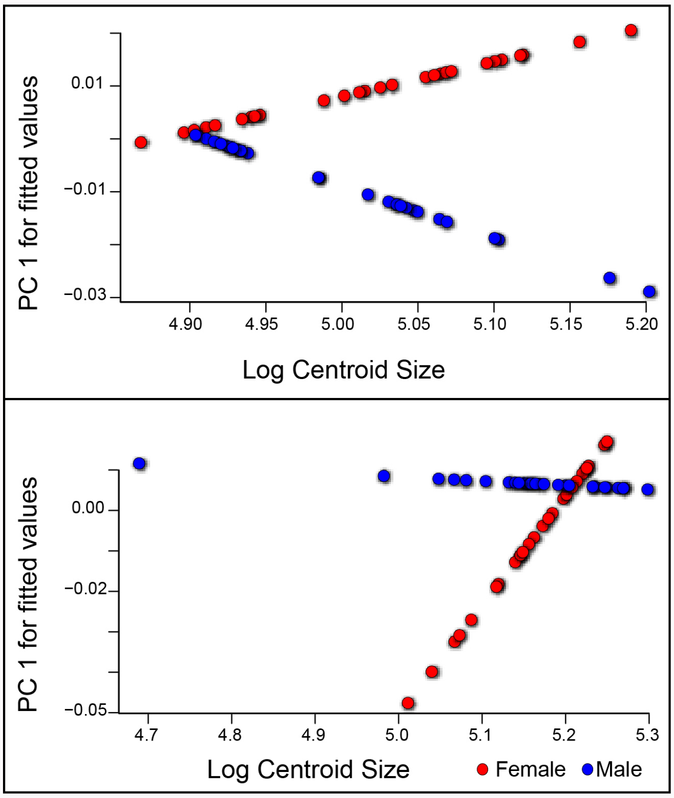
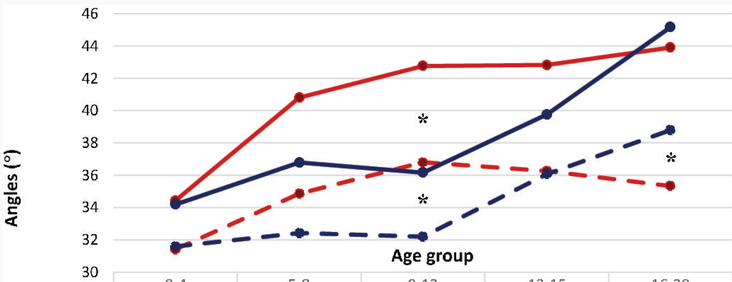


Fig. 5

Plot of predicted shapes against the logarithm of the centroid size for the lumbar curve by sex, and age groups of 9 to 12 years (top) and 13 to 15 years (bottom). Results of Procrustes analysis of variance for these age groups yielded significant results (p = 0.027 and p = 0.009, respectively). PC, principal component.



	0-4	5-8	9-12	13-15	16-20
LL-F	34.4	40.8	42.8	42.8	43.9
SS-F	31.4	34.9	36.8	36.3	35.3
LL-M	34.2	36.8	36.2	39.8	45.2
SS-M	31.6	32.4	32.2	36.1	38.8

Fig. 6

Lumbar lordosis and sacral slope angles for males and females by age group. LL-F/LL-M, lumbar lordosis females/males. SS-F/SS-M, sacral slope females/males. *p = 0.004 for lumbar lordosis at age group 9 to 12 years; and p = 0.010 and p = 0.043 for sacral slope at age groups 9 to 12 years and 16 to 20 years, respectively.

the nine- to 12-year age group. This corresponds with the age when the growth rate of females decreases, whereas in males, growth continues for approximately two more years.[16,43] In contrast to other studies,[33,44] we did not identify sexual dimorphism in curve-peak location. This discrepancy is probably due to differences in age distribution between the studies, as they examined only adults.

We examined whether angular measures used in previous studies adequately represent the changes in LC shape during growth.[12–14,19,20,22,42] Generally, the two methods showed a similar pattern during growth and were highly correlated (r ≈ 0.8). However, for the angular measures, significance was reached in females only between the youngest and oldest age groups, probably due to the large SD. Nevertheless, similar to LC shape analysis, the LL and SS angles captured the differences between the sexes in the timing of LC development. Yet, the shape analysis differentiated better between the age groups.

Our LL values corresponded with those of some previous studies. For example, Shefi et al[14] had similar results,

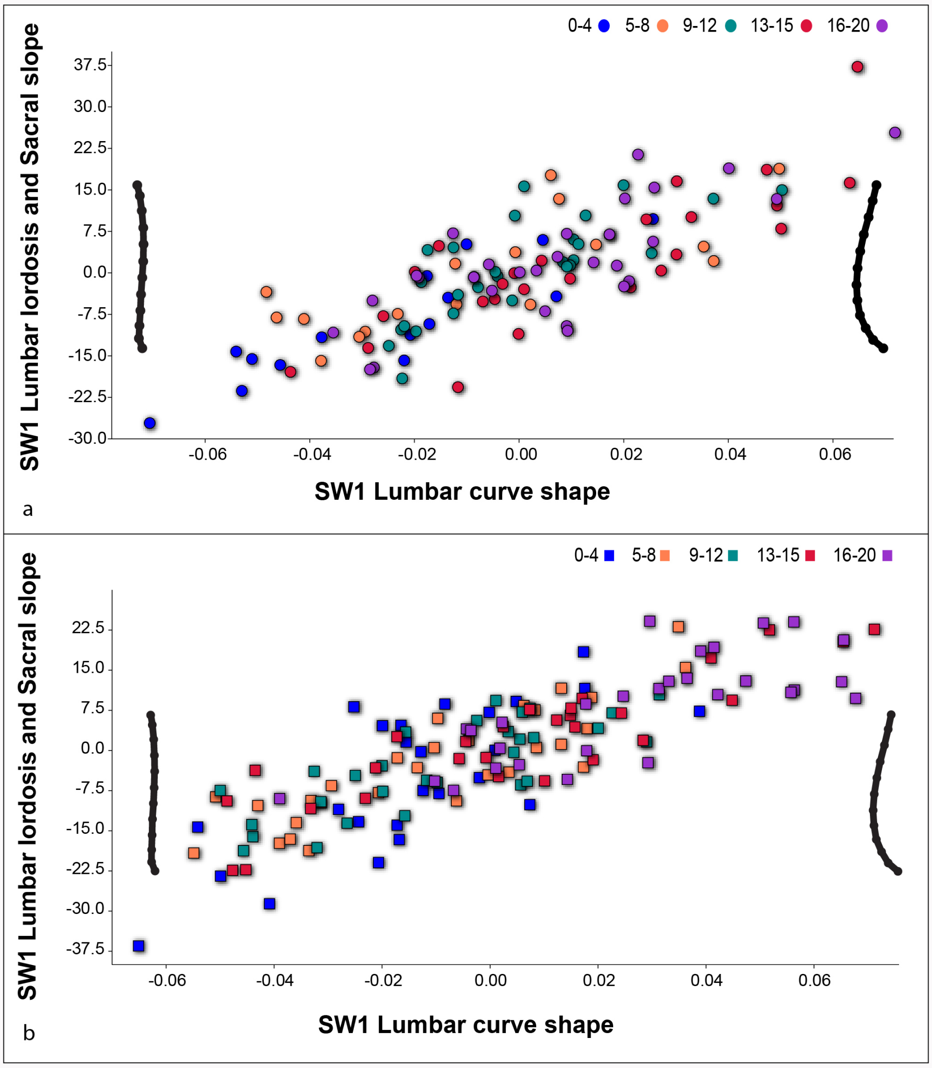


Fig. 7
Plot of the first singular wrap (SW1) of lumbar curve shape variables against the SW1 of lumbar lordosis and sacral slope angles from a two-block partial least squares analysis for a) females and b) males ($r = 0.782$ and $r = 0.818$, respectively; $p < 0.001$).

Table IV. Significance values of multiple pairwise comparisons (with Bonferroni correction) following Kruskal-Wallis tests for the differences in lumbar lordosis and sacral slope between the age groups by sex.

Age group, yrs		LL-males	SS-males	LL-females	SS-females
	5 to 8	1	1	0.655	
	9 to 12	1	1	0.059	
	13 to 15	0.537	0.473	0.109	
0 to 4	16 to 20	0.001	0.012	0.014	
	9 to 12	1	1	1	0.180
	13 to 15	1	0.323	1	
5 to 8	16 to 20	0.006	0.006	1	
	13 to 15	1	0.260	1	
9 to 12	16 to 20	0.002	0.004	1	
13 to 15	16 to 20	0.354	1	1	

LL, lumbar lordosis; SS, sacral slope.

demonstrating a gradual increase in LL angle with significant differences between non-adjacent age groups. Bailey et al[22] divided their sample into different age categories than our study or those of Shefi et al;[14] nevertheless, their LL values were similar to both. Several studies reported higher LL and SS angles than we did,[12,19,27] yet with a similar trend of increase during growth. Voutsinas and MacEwen[27] also reported an earlier cessation of development in females than in males, as we did. The discrepancies in the value of LL and SS angles between these studies and ours could be related to the manner of image acquisition, i.e. standing versus supine position. Finally, our study and others found stabilization in lumbar spine curve development after maturation,[14,22] although other studies suggested that it continued to change thereafter.[45]

Furthermore, we found that the LL and SS angles reflect sexual dimorphism similar to that found in LC shape, i.e. in the nine- to 12-year age group for both angles. Our results also corresponded with several other studies regarding sexual dimorphism in LL.[13,19,27] Masharawi et al[13] examined LL and SS before and after the onset of puberty (age 12 to 13 years and 15 to 16 years, respectively). They demonstrated greater LL and SS angles in females than males at age 12 to 13 years, whereas at age 15 to 16 years, the LL became sex-independent, and the SS more pronounced in males. The results of Voutsinas and MacEwen[27] also supported this trend, whereby females displayed LL and SS that were greater up to age 15 years, with the LL becoming similar to that of males and the SS more pronounced in males thereafter. Gardner et al,[29] in a longitudinal study, also demonstrated greater LL in females than males between the ages of nine and 16 years, however they used an integrated shape imaging system that measured the LL based on surface markings, which may explain the lower values in LL angle they reported. The studies by Mac-Thiong et al[19] and Cil et al,[12] which were also carried out in a standing position, did not find sexual dimorphism in LL. To summarize, while the angular methods demonstrated mixed tendencies, the shape analysis at large suggested that LC is sex-independent except for the nine- to 12-year age group. Nevertheless, it highlighted the difference in the timing of LC development between the sexes.

The magnitude of spinal curves and pelvic parameters have been related to spinal pathologies that occur later in life.[46,47] For example, increased LL has been linked to spondylolysis/lysthesis, facet joint osteoarthritis, and possibly increased risk of hip arthroplasty instability.[1,48,49] A less pronounced LL was associated with disc herniation or degeneration.[49,50] Thus, early detection of those at risk of developing spinal pathology would allow for the implementation of preventive measures.[51] Additionally, the onset of some spinal pathologies, such as adolescent idiopathic scoliosis, is typical in adolescent years and is sex-dependent (more common in females).[17] It might be that the earlier and faster LC shape development of females, and their greater flexibility, increases their vulnerability to spine maldevelopment.[52,53] Adequate management requires a thorough understanding of spine development, growth rate, and cessation of growth. Identifying the growth spurt of the spine or peak height velocity may help to predict curve development and optimize the outcome of treatment.[18,54] This might overcome the limitations of the commonly used Risser sign for predicting spinal growth cessation or curve progression.[18] Further research is needed to examine how the differences in LC shape development between the sexes affect the risk of maldevelopment and the applicability of this method for risk management of different spine pathologies.

This study has several limitations, mainly due to the effort to study children. The study included a relatively small sample size in the two younger age groups (0 to 4 and 5 to 8) due to the unavailability of scans of young females. The design of the study was retrospective cross-sectional, limiting our ability to follow LC shape development as it occurred. However, this is the next best solution for imaging-based studies, as no ethical committee would approve a longitudinal CT-based study of children.[29] The supine position of the children could also be considered a limitation, as it influences the degree of curvature.[12-1419,22,,27] However, since all children included in the study were scanned in the same position, we could still trace the trend of change in LC shape during growth and between the sexes. Additionally, information on factors impacting spinal growth, such as height, weight, puberty status,[16,18] and physical activity level was limited;[55,56] therefore, concluding their effect on LC shape was impossible.

The current study explored the changes in lumbar spine morphology in children to shed light on the normal developmental process during growth and differences between the sexes. The LC changed from a nearly straight to a curved lumbar spine during growth, developing faster and earlier in females. Furthermore, size does not dictate the change in shape of the LC. Finally, we suggest a more sensitive method to capture differences in LC shape that could not be captured by the angular measurements.

Supplementary material

A brief description of the geometric morphometric method, lumbar lordosis/sacral slope calculation, and reliability figure and table.

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Author information

R. Pelleg-Kallevag, BPT, Diploma Sports PT, PhD, Lecturer,
Department of Physical Therapy, Zefat Academic College, Zefat, Israel;
Department of Anatomy and Anthropology, School of Medicine, Faculty of Medical and Health Sciences, Tel Aviv University, Tel Aviv, Israel.

S. Borgel, MSc, PhD Candidate
E. Kedar, MSc, PhD Candidate
H. May, PhD, Principal Investigator, Head of Department, Head of the Dan David Center
Department of Anatomy and Anthropology, School of Medicine, Faculty of Medical and Health Sciences, Tel Aviv University, Tel Aviv, Israel; The Shmunis Family Anthropology Institute, the Dan David Center for Human Evolution and Biohistory Research, School of Medicine, Faculty of Medical and Health Sciences, Tel Aviv University, Tel Aviv, Israel.

N. Peled, MD, Head of Department, Associate Professor of Radiology, Department of Radiology, Elisha Hospital, Haifa, Israel; Radiology Department, Carmel Medical Center, Haifa, Israel.

Author contributions

R. Pelleg-Kallevag: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing.
S. Borgel: Writing – review & editing.
E. Kedar: Writing – review & editing, Investigation.
N. Peled: Writing – review & editing, Investigation.

H. May: Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing.

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