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Body Mass Index and sagittal lumbar balance. A geometric morphometrics approach

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SUMMARY

Geometric Morphometrics (GM) offers a new and interactive way for shape analysis, rarely used in spine morphology study. We used GM to investigate the relationships between being overweight and lumbar sagittal configuration. Age, sex, weight, height and BMI of 152 consecutive spine MRI were retrospectively collected. 66 landmarks were digitized on each midsagittal T2-weighted images. Procrustes superimpositions, Principal Component analysis (PCA), Canonical Variate analysis (CVA), and other multivariate techniques were used to find mean shape consensus and possible shape-BMI covariations.

A strong correlation between sagittal lumbar shape and BMI was found. Morphological changes such as telescoping, lordosis and variations in vertebral-disk shape were found to be related with BMI, as well as other common variables such as sex and age. GM helps understand the way in which being overweight influences the lumbar shape. These techniques offer a powerful, reproducible and dynamically interactive method to explore spine shape, with diagnostic, therapeutic and preventive implications. A more extensive use of Geometric Morphometrics in spine shape investigation is proposed.

Key words: Lumbar – Spine – Sagittal balance – Geometric morphometrics – Procrustes superimposition – Body Mass Index

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INTRODUCTION

The influence of Body Mass Index (BMI) on spine morphology remains a matter of discussion. Some studies found a significant effect (Romero-Vargas et al., 2013), but others did not (González-Sánchez et al., 2014). Nevertheless, the clarification of possible mutual interactions between these two variables could be of clinical and anatomical interest. Clinically, knowledge of the precise effects of obesity on spine morphology could lead, for instance, to the design of more effective ways to improve spine statics. Anatomically, the relationship between BMI and spine shape could help to reconstruct soft tissue conformation from vertebrae shape.

So far, the Euclidean approach (using distances, angles and indices) has been mostly used to study spine morphology and is well documented across the literature (Morales-Avalos et al., 2014; Watts, 2013; Bisćević et al., 2012; Santiago et al., 2001).

In recent years, a new approach to shape analysis, Geometric Morphometrics (GM), has changed morphological investigation in Biology. It could be defined as the study of form in two or three dimensional spaces allowing in-depth investigation of morphological changes (Bookstein, 1982).

It has been used extensively in Anthropology, mainly for sex dimorphisms and evolutive cephalometrics (Badawi-Fayad and Cabanis, 2007; Wellens et al., 2013). Clinical applications are relatively rare to date (Maier et al., 2012; Mayer et al.,

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2017).

GM is not based on Euclidean dimensions measurements but on the study of the shape as a whole. The procedure computes a mean shape of the specimens (called consensus), using a superimposition method (Generalized Procrustes Analysis). Afterwards, powerful multivariate statistical analysis tests are used to calculate the variability of the specimens from the consensus, trying to offer an explanation for the variation.

The main advantage of GM techniques is their ability to include shape variables in the statistical analysis along with other parameters like BMI, genetic traits, age, sex, spinal degeneration and others. In consequence, both shape and clinical variables can be investigated together, thereby providing a powerful new way to identify covariation between them.

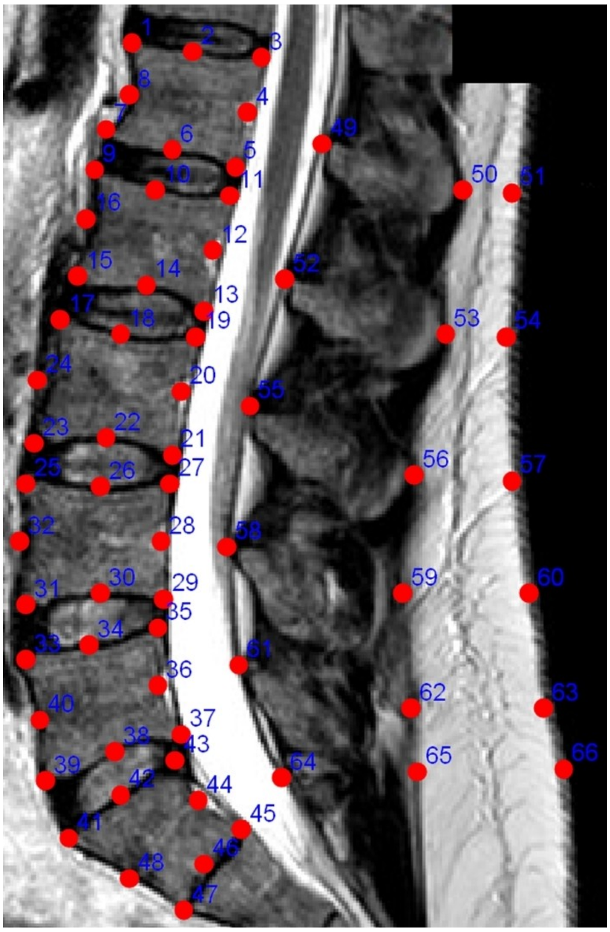

Fig 1. Magnetic resonance on midsagittal T2-weighted imaging, based on 66 anatomical landmarks positioned using TpsDig2 software, as described in Table 2.

Unlike other works, which used traditional Euclidean morphometric methods, our study was based on GM. The objective was to investigate the usefulness of these techniques in testing how the shape of the lumbar region is influenced by BMI.

The study's hypothesis was that the BMI is related to lumbar sagittal balance, and the characteristics of this relationship could be established by using GM, provided the powerful estimation of covariations that this procedure offers. In addition, we studied other possible influences on shape, such as age or sex.

The observed increase in obesity in western countries should affect the spine not only due to overload reasons but to other factors, such as changes in static or curvatures linked to soft tissue transformations, intervertebral disc nutritional changes, modification of vertebral bone shape related to osteoporosis, and others. Overweight, disc degeneration and osteoporosis are prevalent health problems and could all be interrelated, with lumbar shape being a biomarker of such conditions. Therefore, the hypothesized BMI influence on the spinal shape could help understand the degree and meaning of these changes, providing a way to correct some of them.

Along with shape variability, the consensus could also be an important finding, because it represents a "normality" reference in each group, providing useful patterns in therapy and prevention.

MATERIALS AND METHODS

Our work is a retrospective, population-based, analytical study of 153 patients treated for lumbar pain over a 3-year period.

1. Patients

MRI studies of patients with lumbar pain over a 3 -year period in our Institution were retrospectively reviewed. Cases presenting fractures, infections and tumors were excluded, as were cases with spinal surgery or severe scoliosis. Genetic disorders (one case of Down syndrome) and severe systemic conditions (systemic rheumatisms such as ankylosing spondylitis and rheumatoid arthritis) were not included. The reasons for these exclusions were that they could all affect the spinal shape through factors different from BMI. Patients under BMI=16 were excluded. Clinical variables included age, sex, weight, height and BMI. Cut-off

Table 1. Sample characteristics

		Age				Weight		Height		BMI	
Sex	**N**	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
MALE	103.00	46.72	12.63	25.00	80.00	84.61	12.32	173.87	7.03	28.03	4.04
FEMALE	49.00	50.02	13.97	27.00	79.00	68.95	10.63	160.72	7.73	26.74	3.99
Total	**152.00**	**47.78**	**13.12**	**25.00**	**80.00**	**79.56**	**13.87**	**169.63**	**9.51**	**27.62**	**4.06**

values for BMI categories were: underweight < 18.5; normal weight 18.5-24.9; overweight 25.0-29.9; obesity >30.0. The sample consisted of 103 males and 49 females. Main sample data are shown in Table 1.

2. Procedure

66 landmarks were digitized on the midsagittal T2-weighted imaging of each of the 152 patients, using the tpsDig2w32 package (2.26 version) (Rohlf, 2015). These markers were placed on spine and skin as shown in Fig. 1 and described in Table 2. The calibration factors were stored in each file. The landmarks were placed by two investigators, independently (Neurosurgeon and Radiologist).

Differences between linear distances of digitized point were reviewed by two investigators. No differences above 3% of the distances were found, according to Corner indications (Corner et al., 1992). In the case of discrepancy, the average of repeated measurements was used.

The data were analyzed using MorphoJ (Version 1.06d) (Klingenberg, 2011) and PAST (Version 2.12) (Hammer, 2001).

Although the dimensions cannot be analyzed after Procrustes superimposition, angles remain inalterable. We measured the lumbosacral, sacral inclination and lumbar lordosis angles of the respective consensus (males, females, overweight and non-overweight groups).

3. Statistical analyses

Generalized Procrustes Analysis (GPA) (Badawi-Fayad, 2007; Rohlf and Bookstein, 1990) is a superimposition method that calculates an average (called consensus) of the shapes (Fig. 2). Once the consensus is computed, individual type and amounts of deviation are calculated using multivariate statistical techniques. These included Principal Component Analysis (PCA), Canonical Variate Analysis (CVA), Discriminant Function Analysis (DFA) and multivariate regression (MVR).

GM procedures find the similarity and difference between shapes. Morphometric distances are the primary measures of difference. The Procrustes distance is the distance between shapes after they have been superimposed. Mahalanobis Distance (or quadratic distance) is the distance between a data point and the mean point in the multidimensional space of coordinates.

PCA are used to identify the shape deviations from the consensus and to find their relationships

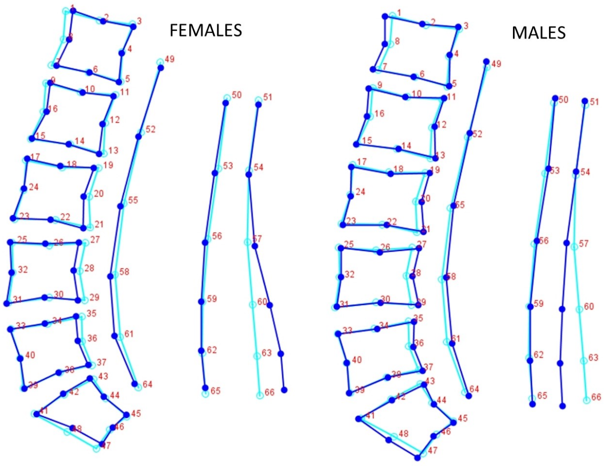

Fig 2. Principal components analysis showing the shape variation of spine, soft tissues, and skin in men and women: The consensus shape of each sex is indicated in light blue and the differences in shape relative to the consensus is indicated in dark blue The main differences are associated with the distribution of fat tissue, relative vertebral body sagittal width, and canal dimensions at L3 -L4 and L4-L5.

Table 2. Description of landmarks on the MRI midsagittal plane.

Number	Placement
1	Most anterior and upper point on superior vertebral plate
2	Middle point of superior vertebral plate
3	Most posterior and upper point on superior vertebral plate
4	Middle point of vertebral body posterior wall
5	Most posterior and inferior point on inferior vertebral plate
6	Middle point of inferior vertebral plate
7	Most anterior and inferior point on inferior vertebral plate
8	Middle point of vertebral body anterior wall
Landmarks 1 to 8 capture the middle-sagittal vertebral body from L1 to S1 (total of 48 landmarks, the last one corresponding to the	
49	More anterior, superior and medial aspect of midline spinal canal of each vertebrae
50	Surface of Supraspinous ligament at the tip of spinous process
51	Skin immediately above landmark 50
Landmarks 49, 50, 51 capture the canal and midline soft tissues. This triplet was repeated at each lumbar level, accounting for a total of 60 landmarks (49 to 60).	

with variables (e.g. age, sex, BMI). PCA can reduce data multidimensionality, simplifying the interpretation of relationships between shape and variables.

CVA is used to identify the shape features that best discriminate among groups of specimens. Unlike CVA, in DFA just two groups are used.

To evaluate skin-spine covariation, we used Partial Least Squares Analysis (PLS). PLS finds the main components of shape variation between subsets of landmarks. The RV coefficient (Escoufier, 1973) is used to quantify the covariation (Klingenberg, 2011).

SPSS for Windows (IBM Corp. Released, 2010) was used for conventional statistical tests (e.g., ANOVA, normality tests, regression).

RESULTS

The analysis included 152 patients, 103 (67.76%) men and 49 (32.24%) women. Mean age was 47.8 (range = 25 - 80). Mean BMI was 27.6 (range=19.0 - 39.1). Forty-three (28.29%) of the patients had a BMI that was normal, 68 (44.74%) were overweight and 41 (26.97%) were obese. A higher proportion of the males (36.73%; n=18) than of the females (24.27%; n=25) had a high BMI.

1. Variation in overall shape

1.1. Spine, soft tissues and skin profile

The overall shape average (consensus) after GPA is shown in Fig. 2.

Three principal components explained almost 70% of the variance (Table 3). The main one (PC1), which explained 41.3% of the variance, included fat tissue widening vs. stretching, in particular, at L5-S1, slight lordosis vs. back flattening, and variability in skin profile (increasing vs. decreasing spine lordosis and flat vs. “S” skin shape) (Fig. 3).

The second component (PC2), which explained 17.5% of the variance, identified back flattening associated with an increase in fat tissue thickness and lordosis associated with thin fat tissue (Fig. 3). The third component (PC3), which explained 8.4% of the variance, captured differences at the top and bottom. Positive values indicated sacral horizontalization and widening of caudal soft tissue. Negative values indicated stretching of caudal soft tissue and tended to render a vertical sacrum (Fig. 3).

Table 3. Principal component analysis of spine with soft tissues and spine alone

PC	Eigenvalue	% of variance explained	% Accumulative
Spine and soft tissues			
PC 1	0.00229152	41.348	41.348
PC 2	0.000972052	17.54	58.888
PC 3	0.000464283	8.3774	67.2654
Spine alone			
PC 1	0.00131845	47.073	47.073
PC 2	0.00033181	11.847	58.919
PC 3	0.00017847	6.372	65.291

1.2. Spine alone

PCA identified three principal components based on spine alone. PC1, which explained 47.1% of the variance, corresponded to changes in curvature (lordosis vs. flat back). PC2, which explained 11.8% of the variance, showed telescoping and widening vs. stretching of vertebral bodies in the sagittal plane. PC3, which explained 6.4% of the variance, identified differences in top and end vertebral configurations (Fig. 4).

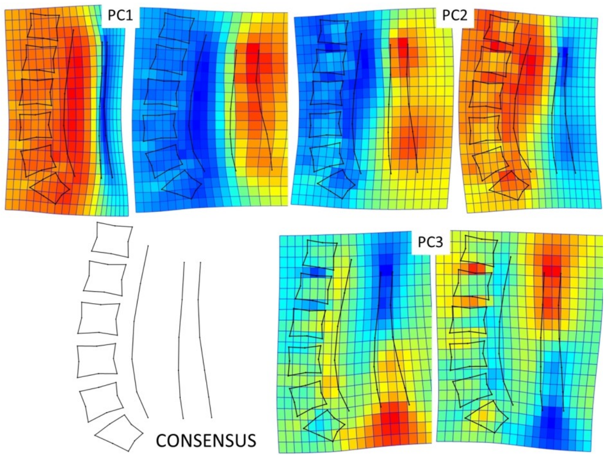

Fig 3. Principal components analysis and main shape variations in spine and soft tissues PC1 (41,34%): indicated fat tissue widening associated with hyperlordosis, particularly, at L5-S1. Fat tissue stretching was correlated with flat back PC2 (17,54%): identified the opposite effect to that indicated in PC1 PC3 (8,27%) captured top and bottom changes. Positive values (left) indicated a sacral horizontallization and widening of caudal soft tissue. Negative values (right) indicated stretched caudal soft tissue and tended to reflect a vertical sacrum.

Table 4. Canonical variate analysis of sex

Sex	Sample size
Male	103
Female	49
Mahalanobis distances among groups	4.3461
P <0.0001*	
Procrustes distances among groups	0.0232
P=0.0005*	

(*)P-values from permutation tests (10000 iterations) for Procrustes distances among groups

2. Sex-based differences

2.1. Spine, soft tissues and skin

The CVA distinguished between males and females (Table 4). The primary difference was fat tissue, especially, in the lower region. In males, the skin tended to be flat; however, in females, an italic “S” shape in the lower portion of the spine was observed (Table 4). Significant differences were observed among groups in Procrustes and Mahalanobis distances: p=0.0005 and p<0.0001, respectively).

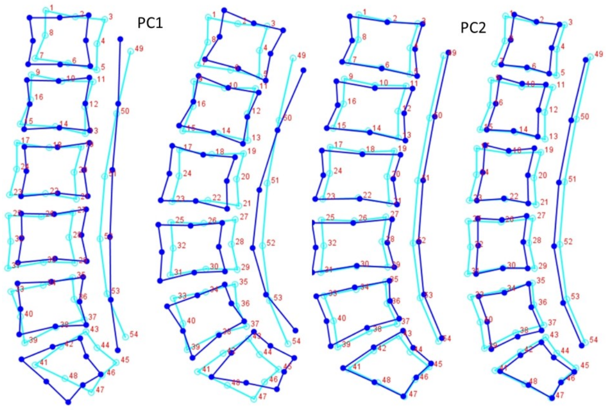

Fig 4. Principal components analysis and shape variation of isolated spine. The consensus shape is indicated in light blue and the differences in shape relative to the consensus are indicated in dark blue. CP1 distinguished between lordosis and flat back. CP2 captured telescoping and distinguished between the widening of sagittal vertebral bodies and stretching.

2.2. Spine alone

CVA detected significant differences in the shapes of males and females (Table 4). Males had a less pronounced curvature, slightly narrower canals, and wider vertebrae size in sagittal plane than did females (Fig. 2).

3. BMI and spine shape

3.1. Spine, soft tissues and skin

CVA identified a correlation between BMI and shape, both when the CVA was based on spine and fat tissue and when it was based on spine alone, (Fig. 5 and Table 5). CV1 (77.1% of the variance) corresponded to fat tissue thickness. Patients with higher BMI exhibited an “S-shaped” skin deformation and some degree of telescoping. CV2 (22.9% of the variance) showed widening of sagittal bodies, hyperlordosis and a tendency toward L4 -L5 stenosis, associated to high BMI.

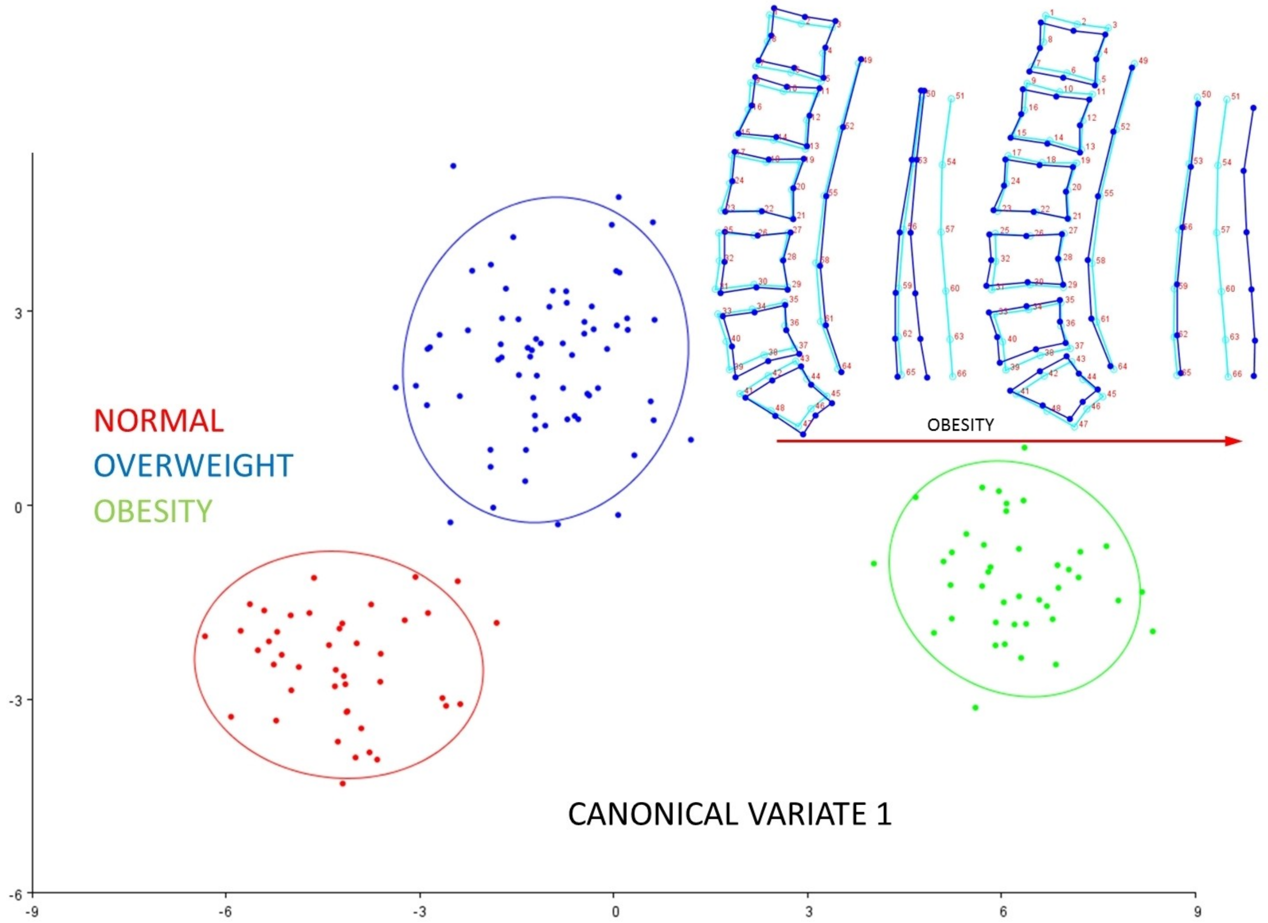

Fig 5. Canonical Variate Analysis CV1, which explained 100% of variance, clearly distinguished normal from the overweight and the obese groups. Telescoping, soft tissue enlargement, increased lordosis, and stenosis at the L4-L5 level were the main shape changes associated with an increase in BMI.

In particular, BMI increase correlated with the sagittal widening of vertebral bodies, anterior wedging bodies, reduction in posterior disc height, tendency toward L3-L4 and L4-L5 retro-listesis, reduction in canal diameter, and higher degree of telescoping. CV1 clearly distinguished between the obese and non-obese groups (Fig. 5).

3.2. Spine alone

We found no correlation between BMI and centroid size, which suggests that individual size was not correlated with BMI and was not associated with changes in lumbar shape.

Vertebral bodies and disks were subtly affected in patients with high BMI. In particular, telescoping and sagittal widening were observed. Sagittal canal size tended to be reduced in high BMI, in particular, at the L4-L5 level (CV1) (Fig. 6).

In patients with high BMI, vertebral bodies tended to squaring and anterior wedge-shaping, and exhibit a tendency to L3 and L4 retrolistesis. In addition, CV2 indicated hyperlordosis and L3-L4 stenosis (Fig. 6).

4. Skin-spine shape correlation

Spine shape and skin profile were strongly correlated (Fig. 7). Skin significantly co-varied with spine (PLS: Coef. Correlation= 0.772; p <.0001). The RV coefficient, which reflects the strength of the association between blocks, was 0.51. Skin does not encompass the exact shape of spine deformation; rather, it is deformed in a manner that

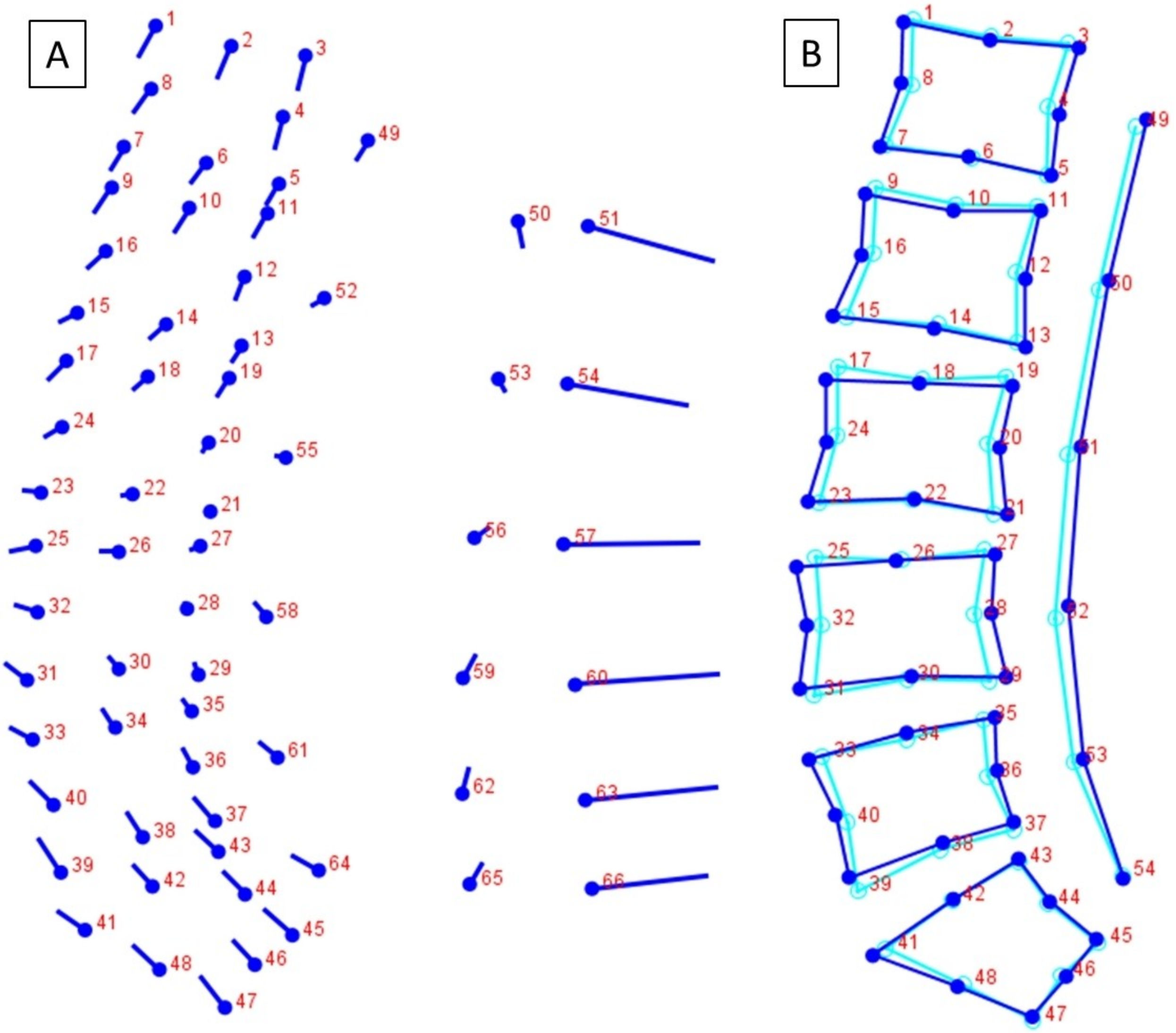

Fig 6. Canonical Variate Analysis of the effects of overweight based on (**A**) spine and soft tissues, and (**B**) spine alone. In (A), changes associated with being overweight are represented as vectors that deform the consensus toward obesity. As weight increases, the skin profile is pushed backwards, telescoping vectors causing both spine tops to be approximated Central lumbar spine (L3-L4 and, to a lesser extent, the remaining spine) is pushed forward. It resembles what might be expected if axial loadings were increasing in a curved column, and the deformations that occur resemble a drawn bowstring. In (B), the main differences included sagittal body widening and squaring, lordosis, and stenosis L4 -L5.

differs from that of the spine. As the spine is lordotized and telescoped, the skin adopts an S-shaped deformation and exhibits a degree of cephalic-caudal collapse. Hence, it might be difficult to infer the shape or degree of lordosis based on the skin profile, in particular in obese patients.

5. Spine angles

Angles can be readily measured on the consensus because they are influenced by shape not by distances. Sex and BMI were strongly correlated with the angles (Table 6). Angles tended to be wider in females than in males. In addition, overweight patients had the widest angles. The statistical significance of those differences could not be quantified because the individual angles were not measured.

6. Age

Spine shape differed significantly between those < 50 yr and those > 50 yr (Table 7). Telescoping, vertebral body-squaring and height loss were the most common findings (Fig. 8) (Mahanobis Distance after 1000 permutations: $p<.0001$; Procrustes Distances: $p=0.0032$). Changes were similar to those observed in the overweight group. However, age and BMI were not correlated.

DISCUSSION

Most studies of spine morphometrics are based on Euclidean methods (Iyer et al., 2016; Onyemaechi et al., 2016). To our knowledge, only one study has used GM procedures to study spine morphology "*in vivo*" (Aso Escario et al., 2014). GM has not been used to investigate the possible relationship between BMI and spinal shape.

1. Model of inter-individual shape variability

The deviations from the consensus in the entire sample followed an "aiming-bow" model. PC1 represents the skin as if it were a drawn bowstring. As the skin separates from the spine, lordosis of the lumbar column increases, causing the top and bottom to be translated posteriorly and inferiorly. A slight degree of telescoping (spine shortening) accompanies these changes. On the contrary, as the skin becomes closer to the spine, its profile tends

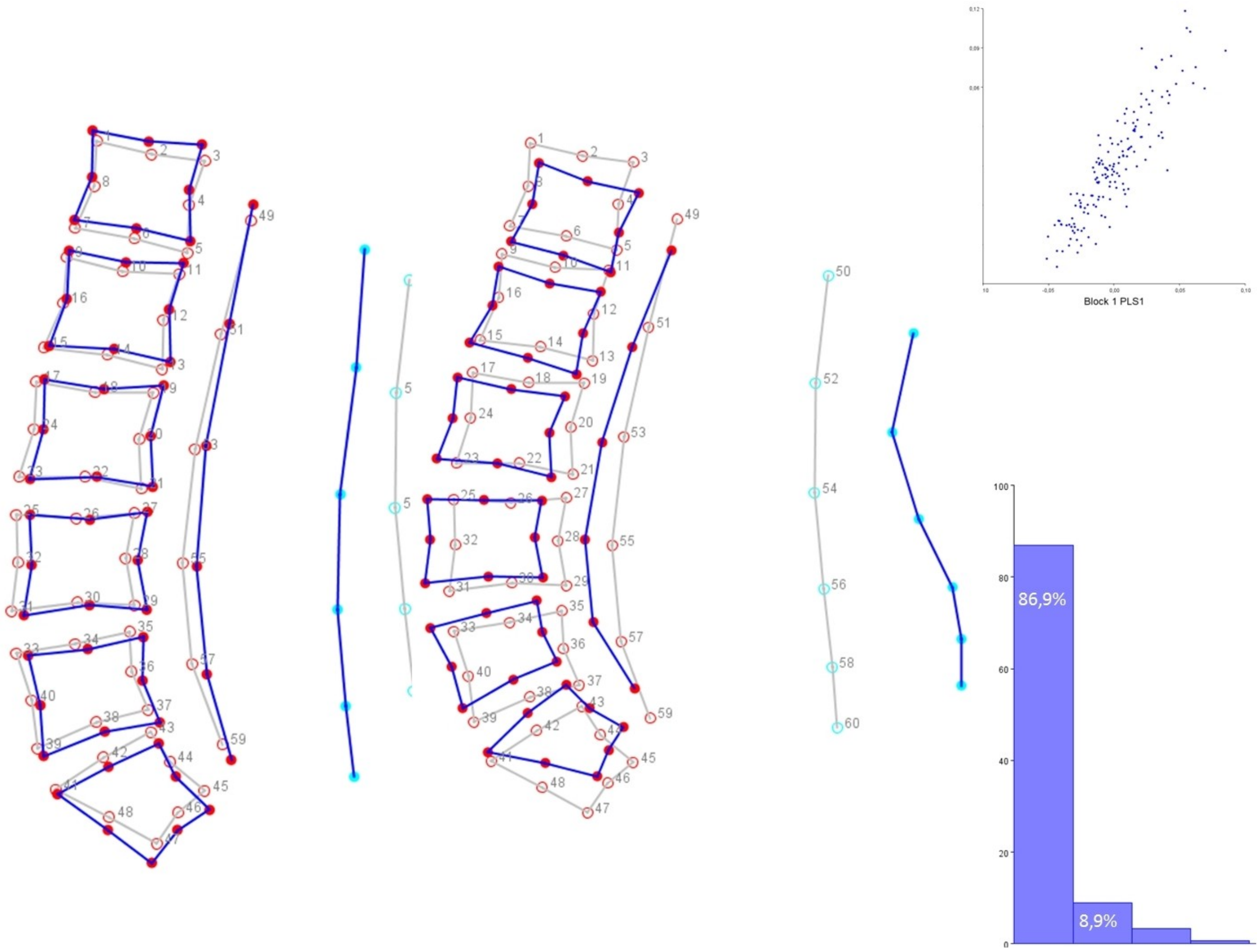

Fig 7. Partial Least Squares Analysis (PLS) of skin and spine configurations PLS1, which explained 86,9% of the co-variation, revealed a strong skin-spine shape correlation, which was non-linear, particularly, in obese patients, and the results were strongly sex-dependent Therefore, any assessment of spine shape based on skin profile should be interpolated within the non-linear correlation, particularly, in obese patients.

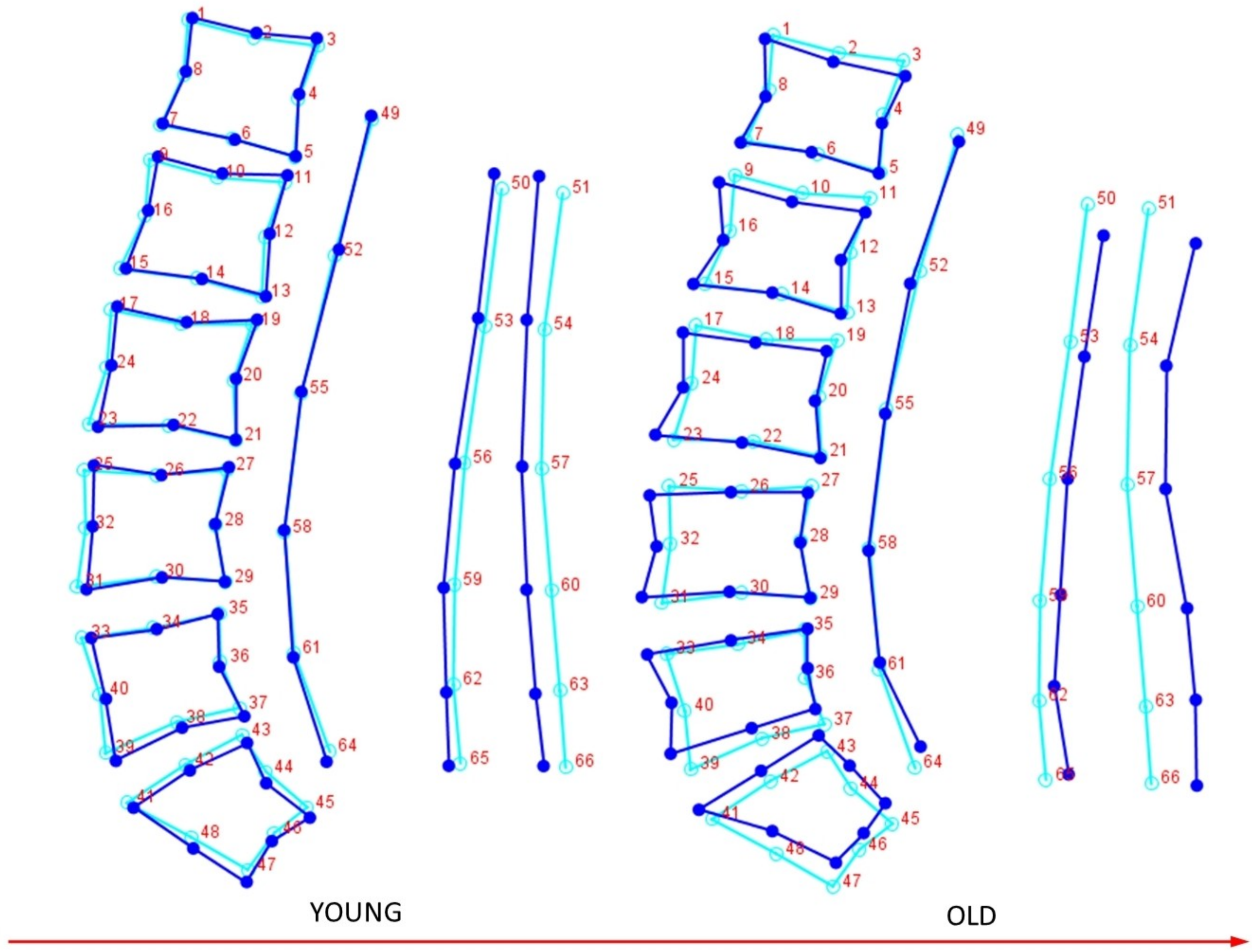

Fig 8. Canonical Variate Analysis. Age-related changes in spine shape. Telescoping, body squaring, and height loss were the main features. A tendency toward a trapezoid body morphology was observed.

to a straighter shape and spine lordosis results progressively reduced.

This model helps to understand how a person's spine configuration is, or should be, according to his/her particular skin, spine and soft tissues.

2. Origin and causes of variation

2.1. Sex

If we consider soft tissue changes, CVA finds a strong dimorphism between males and females (CVA. Hotelling's p value with Bonferroni correction =0.0003). Females showed greater lumbar lordosis, wider fat tissue (in particular over the sacrum), and shorter and higher vertebral bodies. A study found that the female spine exhibits a greater curvature, a caudally located lordotic peak, and greater cranial peak height. The amount of inward curving (lordosis) is found to be sex-independent (Hay et al., 2015). The paper takes into account only lumbar curvature, but not soft tissue and skin as in our investigation.

We did find that the spine alone of males had a less pronounced curvature, slightly narrower canals and wider vertebrae size in sagittal plane than did females. But these findings did not reach statistical signification (CVA. Hotelling's p value with Bonferroni correction=0.87). Perhaps the small number of women in our sample is behind this result.

But when soft tissues morphology is considered, sexual dimorphism is strong and clearly significant.

2.2. Muscles

Muscles play a role in spinal curvature (Jun et al., 2016; Meakin et al., 2013). Erector spinae and multifidus muscle influence the loss of lordosis (Snijders et al., 2008). Multifidus and psoas influence sagittal spine alignment (Yagi et al., 2016). Psoas major thickness and echo intensity of multifidus are significant determinants of the sacral anterior inclination angle (Masaki et al., 2015). Various muscle forces or tonus might possibly cause the inter-individual variation observed in our study. The inter-individual variation depending on sex could also be explained by different male-female muscular forces and tonicity, in particular in supine position, where a more relaxed status is expected to occur.

Table 5. Canonical variate analysis of BMI and Shape, including soft tissues.

Group	**Sample size**	
NON-OVERWEIGHT	43	
OVERWEIGHT	109	
Variation among groups, scaled by the inverse of the within-group variation		
Eigenvalues	% Variance	Cumulative %
6.82102961	100.000	100.000
Mahalanobis distances among groups:		
	NON-OVERWEIGHT	
OVERWEIGHT	5.7603	
P-values from permutation tests (10000 iterations) for Mahalanobis distances among groups:		
	NON-OVERWEIGHT	
OVERWEIGHT	<.0001	
Procrustes distances among groups:		
	NON-OVERWEIGHT	
OVERWEIGHT	0.0432	
P-values from permutation tests (10000 iterations) for Procrustes distances among groups:		
	NON-OVERWEIGHT	
OVERWEIGHT	<.0001	

Table 6. Spine angles.

	LSA	SIA	LLA
General Consensus	30.34°	41.42°	12.09°
Consensus Females	33.16°	45°	14.38°
Consensus Males	27.57°	38.25°	11.47°
Consensus Non-Overweight	29.29°	39.81°	10.21°
Consensus Overweight	31.26°	43.19°	15.01°

2.3. Position

Lumbar lordosis decreases from standing to laying (Tarantino et al., 2013; Lee et al., 2014). The Minimum Energy Hypothesis states that the spine will assume an optimal minimum energy configuration if the constraints preventing it from doing so are removed. Hypothetical constraints are joint fixations caused by inflammation or other causes (muscle spasms, fibro-adipose scar tissue and, ultimately, degeneration). In the supine position, muscle tonus is minimized (Evans et al., 2002).

Thus, when all our patients are supine, inter-individual shape variability must depend on other factors than gravity linked to the position. One of them could be the degeneration preventing the lumbar spine from resting in a minimal energy status. Another could be the basal muscle tonus, which is relaxed in supine (Evans et al., 2002). Another could be pain.

2.4. Age

Recent works have suggested that lumbar lordosis decreases with age (Iyer et al., 2016).We did not find age to be related with lordosis. Instead, we did find telescoping and vertebral body height loss as the more common age-related features.

2.5. BMI

There are two potential effects of BMI on the lumbar spine: modification of curvatures and changes in vertebral bodies, canal or disc morphology.

Onyemaechi et al. (2016) found that high BMI is associated with higher lumbo-sacral angle. Salem et al. (2015) described three subgroups of patients based on lumbar profile according to their flexibility, torque, height, weight, waist and body mass.

Our findings showed that patients with the highest BMI exhibited the most lordosis, and individuals with normal or low BMI tended to be close to the consensus or to have a flat back. GM provides a continuous representation of the transitions between shapes. Hence, it might represent shape changes better than a categorical model, as described by Salem, does.

As all our patients lay supine, gravity might be expected to rectify lordosis. But our findings sug-

Table 7. Canonical variate analysis of Age

Age	Sample size	
0-50	92	
50--90	60	
Variation among groups, scaled by the inverse of the within-group variation		
Eigenvalues	% Variance	Cumulative %
10.52610992	100.000	100.000
Mahalanobis distances among groups:		
	0-50	
50--90	6.5937	
P-values from permutation tests (10000 iterations) for Mahalanobis distances among groups:		
	0-50	
50--90	<.0001	
Procrustes distances among groups:		
	0-50	
50--90	0.0243	
P-values from permutation tests (10000 iterations) for Procrustes distances among groups:		
	0-50	
50--90	0.0032	

gest that BMI excess acts as a structural deformity factor, independent of relaxation linked to laying supine.

From supine to the upright position, the compressive force on the disc increases (Alyas et al., 2008). This causes circumferential bulging of degenerative discs. These changes have been described as telescoping (Jinkins et al., 2003; Jinkins et al., 2005; Lee et al., 2003). Theoretically, in the supine position, telescoping should not occur.

Our findings indicate that there is an inter-individual position-independent telescoping, more evident in higher BMI patients. This effect is probably caused by chronic overloading of the spine. In other words, it seems that a high BMI might be responsible for a “basal, structural or non-dynamic telescoping”.

Overweight plays a role in spine degeneration and is a risk factor for lumbar radicular pain and sciatica (Shiri et al., 2014). Obesity is also a strong predictor of the recurrence of herniation (Meredith et al., 2010). In addition to gravity, an increase in spinal extension in the standing position has an effect on posterior disc herniation (Alyas et al., 2008). Loss of disc height in the obese individual in the transition from supine to sitting or standing positions can occur (Yar, 2008). Spontaneous disk herniation regressions following weight loss have been reported (Tokmak et al., 2015).

Although our study does not consider degeneration, it does suggest the morphological changes observed in obese patients are similar to those seen in disc degeneration. Future works using GM methods might find possible links between shape, obesity and disc degeneration.

The shape of the vertebrae varies not only with a person’s height but also weight (Caula et al., 2016). Our results clearly indicate that obesity is associated to telescoping, disc height reduction and changes in the shape of vertebral bodies (sagittal widening and reduction in height). Hypothetically, in women, because of a higher incidence of osteoporosis, loss of vertebral body height could be influenced by high BMI.

A consequence of lordosis increasing, especially when BMI is high, was a tendency to L3-L4 and L4-L5 retrolisthesis. In contrast, when the back is flat, a tendency to L5 retrolisthesis was found. Lumbar spines with spondilolysis and spondylolisthesis usually demonstrate high lumbar lordosis (Been et al., 2011). Perhaps more extensive studies on lordosis and listesis using GM techniques could clarify the relations between listesis and spinal curves, as our study suggests.

3. Skin-spine correspondence

Many devices capture the spinal shape by using the skin profile (Cloud et al., 2014). It is known that back and spine curvatures are significantly correlated (Guermazi et al., 2006; Stokes et al., 1987; Adams et al., 1986) except in obesity (Dreischarf et al., 2014).

Our findings indicate that overweight changes the skin profile, distorting the correspondence between shape-skin morphology.

Skin-spine correspondence is far more complex than a linear Euclidean relation (Fig. 7). In our study, patients with a flat spine had a flat skin profile at the bottom but convex at the top. In greatest lordosis, the skin adopted an “S” shape, highly inconsistent with the spine morphology. Telescoping weakens the linear skin-spine correspondence.

Our results could help in estimating spine shape from the skin by interpolating the back shape within the range of configurations, in particular in obese patients.

Study limitations

A shortcoming was including only patients with backache, rendering uncertain the extrapolation of the results to the general population. Future studies in asymptomatic subjects are required.

Another limitation was the supine position. Nevertheless, the modifications might affect the lumbar shape as a whole (mainly the curvatures) more than the vertebral bodies and discs. Future investigations with GM might provide a more accurate and flexible model of the correspondence between the shapes in both positions.

Although most works emphasizes the spino-pelvic relationship, the isolated lumbar spine remains a substantial source of investigation itself. Tang et al. (2016) underlines the MRI role (L3-S1) to establish a morphometric quantification of intervertebral discs and vertebral endplates. They suggest that crucial information could be obtained from lumbar MRI alone. The interest in the sagittal lumbar MRI to investigate disc and body changes has also been established (Lakshmanan et al., 2012; Volkov et al., 2015; Korez et al., 2014). The spine alone remains useful for investigating morphology changes depending upon variables such as BMI, as presented in this work.

Conclusions

Spine shape can readily be analyzed with GM techniques. BMI is a factor that clearly determines changes in lumbar shape, apart from other variables such as sex or age. Changes in curvature, soft tissue, telescoping and vertebral body shape were observed in the obese patients. These findings may be important in assessing the influence of BMI on spinal degeneration as well as to construct references of normality. Non-linear changes in skin can distort the skin-spine morphological correspondence, which renders some of the methods used to measure lumbar curvature inaccurate, in particular in the obese group and women. The widespread use of GM techniques in clinical spinal evaluations appears warranted.

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