CHARACTERISING THE SHAPE OF THE LUMBAR SPINE USING AN ACTIVE SHAPE MODEL: RELIABILITY AND PRECISION OF THE METHOD.

Judith R Meakin, PhD [1,2], Jennifer S Gregory, PhD [2], Francis W Smith, MD [1], Fiona J Gilbert, FRCR [1], Richard M Aspden, DSc [2]

Department of Radiology[1] and Department of Orthopaedics[2], University of Aberdeen, Foresterhill, Aberdeen, AB25 2ZD, UK.

Corresponding author:

Dr Judith R Meakin, Room 2.26 IMS Building, University of Aberdeen, Foresterhill, Aberdeen, AB25 2ZD, UK.

Tel. +44 (0)1224 553555

Fax. +44 (0)1224 559533

email j.meakin@abdn.ac.uk

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Structured Abstract

Study Design

Analysis of positional magnetic resonance images of normal volunteers.

Objectives

To compare the reliability and precision of an active shape model to that of conventional lordosis measurements/

Summary of Background Data

Characterisation of lumbar lordosis commonly relies on measurement of angles; these have been found to have errors of around 10^o.

Methods

T2 weighted sagittal images of the lumbar spines of 24 male volunteers in the standing posture were acquired using a positional MR scanner. An active shape model of the vertebral bodies from S1 to L1 was created. Lumbar lordosis was also determined by measuring the angles of the superior end-plates. All measurements were performed twice by one observer and once by a second observer.

Results

The shape model identified two modes of variation to describe the shape of the lumbar spine (mode 1 described curvature and mode 2 described evenness of curvature). Significant correlations were found between mode 1 and total lordosis ($R = 0.97$, $P < 0.001$) and between mode 2 and mean absolute deviation of segmental lordosis ($R = 0.80$, $P < 0.001$). Intra- and inter-observer reliability was higher for the shape model (ICCs 0.98 – 1.00) than for the lordosis angle measurements (ICCs 0.68 – 0.99). The relative error of the shape model (mode 1 = 4 %; mode 2 = 9 %) was lower than the conventional measurements (total lordosis = 10 %).

Conclusions

The shape of the lumbar spine in the sagittal plane can be comprehensively characterised using a shape model. The results are more reliable and precise than measurements of lordosis calculated from end-plate angles.

Key words

Lumbar spine; lordosis; positional MRI; Active Shape Model

Mini Abstract

An active shape model was used to characterize the shape of the lumbar spine from positional MRI images of 24 male volunteers in the standing posture. The results of the model were more reliable and precise than the conventional method that uses end-plate angle measurements to characterize the lumbar lordosis.

Introduction

Characterising the natural curvature of the lumbar spine in the sagittal plane (the lumbar lordosis) is of interest for a variety of clinical, biomechanical and ergonomic reasons. The spinal shape influences design of seating in the workplace, in transport and in assessing posture in an attempt to prevent low back pain. A variety of methods have been proposed for characterising the internal curved shape from radiographs and MR images (1-4). The ones that are most commonly used involve determining the angles between lines placed tangentially to the vertebral body end-plates. A measure of the total lordosis, for example, may be determined from the angle of the superior end-plate of the most cephalad lumbar vertebra (L1) with respect to that of the superior end-plate of the sacrum (S1). A measure of how the total lordosis is distributed may be estimated from the superior end-plate angle of the other lumbar vertebrae (L2 – L5) with respect to S1 or with respect to the superior end-plate of neighbouring vertebrae (Figure 1). Variations on this method involve determining the angles made by lines connecting the vertebral body centroids (4) or placed tangentially to the lateral surfaces of the vertebral bodies (3). A number of studies have assessed the methods that involve angle measurements and found them all to have good inter- and intra-observer reliability (5-8). The precision has also been investigated, suggesting that the measurement error is up to 10^o (5-8). Although this may be acceptable when measuring the total lordosis, it is large compared to the changes in segmental lordosis observed when, for example, changing posture (9). The magnitude of the error stems from the fact that the methods rely on a relatively small amount of information to measure lordosis. A line placed tangentially to the end-plate, for example, utilises only two points. The uncertainty in selecting these points is further increased when the normal end-plate architecture is disrupted or obscured (5-6).

One way of avoiding this, and utilising much more of the information in the image, is to use a method of describing morphology that does not depend on measurement of angles, such as Active Shape Modelling (ASM). ASM and, more recently, Active Appearance Modelling (AAM), are image processing methods used to locate and characterise particular objects in a set of images (10). Each image in the set is marked with a number of landmark points, placed around the object of interest. The points are then aligned into a common co-ordinate frame by scaling, translating and rotating; this means that size differences and rigid body translations are removed. Principal component analysis is then used to determine how the position of the points varies; separating the overall variation in the shape of the object into distinct, statistically independent, ‘modes of variation’. Once the model has been created it can be used to characterise the shape of the object in each image in terms of these modes. The images are assigned a score for each mode describing how many standard deviations they lie from the mean of all the images. The model may also be used to locate and characterise similar objects in new images (11-12). The purpose of the current study was to create a shape model of the lumbar spine in the sagittal plane to characterize the lordosis and to compare the reliability and precision of the model with that of conventional lordosis measurements.

Materials and Methods

Subjects

Magnetic resonance (MR) images of the lumbar spine from 24 male volunteers in a standing posture were used for this study. The images were part of a dataset that had been acquired for a previous study (13). Approval from a local Research Ethics Committee had been obtained and all subjects had given their informed consent. None of the subjects reported any symptoms of low back pain and had only minor or no degenerative changes in their lumbar discs. The median age of the subjects was 26 years (range 20 – 55 years).

MR imaging

The subjects were imaged using a Fonar 0.6 T Upright ^{TM} positional MRI scanner (Fonar Corporation, Melville, New York). T2 weighted para-sagittal images were acquired using the following parameters: TR = 3262 ms, TE = 140 ms, N = 2. Eleven slices were obtained; each with a thickness of 4.5 mm and a gap of 0.5 mm. A 30 cm field of view was used with an acquisition matrix of 256 x 200. The data were subsequently reformatted onto a 256 x 256 matrix for image processing. The MRI slice closest to the mid-sagittal plane of the spine (as defined by observing the spinal canal to be wider than in adjacent slices) was selected and converted to JPG format.

Shape modelling

An active shape model of the lumbar spine was created using the Active Appearance Modelling software tools from the University of Manchester UK (14). The model first requires the user to identify landmark points describing the object of interest and these comprised 28 points placed around the periphery of each vertebral body from S1 to L1 (Figure 2). The same number of landmark points (168 in total) was used for each image and each point always referred to the same feature (e.g. the mid-point of the superior end-plate of a given vertebral body). Three sets of points were created for each image; two sets by one observer and one set by a second observer. Both observers were experienced in annotating images for the purposes of shape modelling. The points were then used by the software to create the model for the shape of the lumbar spine. The total amount of variation to be accounted for by the model was set at 90 %. After the first few images were input the model was able to semi-automatically place the landmark points with correction by the observer if necessary. When all the images had been input, the model determined the modes of variation and assigned values for each mode to each of the images.

End-plate angles

The total and inter-segmental lordosis angles were determined from the images using ImageJ software (version 1.34s, NIH, USA). The images were magnified by 300 % and contrast enhanced using histogram equalization and normalization. The angle of the superior end-plate of the vertebral bodies from S1 to L1 was measured. The angles were used to calculate the total lordosis (L1-S1) and the segmental lordosis angles (L1-L2, L2-L3, L3-L4, L4-L5, L5-S1). The mean absolute deviation of the segmental lordosis angles was also calculated for each spine (this is the average absolute deviation from the mean segmental angle and is a measure of the statistical dispersion). All the measurements were performed twice by one observer and once by a second observer.

Statistical analysis

Intra-class correlation coefficients (ICCs) were calculated to determine the intra- and inter-observer reliabilities. Relationships between variables were assessed using the Pearson correlation coefficient. The measurement error was calculated as 2.77 times the within-subject standard deviation (15) as determined using one-way analysis of variance.

Results

Shape model

Five modes of variation were identified which together accounted for 91 % of the total variance in the model. Individually, each mode accounted for 74 % (mode 1), 8 % (mode 2), 4 % (mode 3), 3 % (mode 4), and 2 % (mode 5). Figure 3 shows the shapes described by varying each mode by ± 2 standard deviations (sd) about the mean shape from all the images. To assist in interpreting these five modes, the centroids of the vertebral bodies shown in Figure 3 were determined and used to calculate the angle made between lines connecting the centroids (the vertebral body centroid angles (4)). The vertebral body centroid angles of the mean shape, and the shapes produced by each mode by ± 2 sd, are given in Table 1. This demonstrated that mode 1 described the variation in the total curvature of the lumbar spine and mode 2 described the variation in how evenly the lumbar curvature was distributed. A 2 sd reduction in mode 1 denotes a 25^o increase in total curvature (with respect to the mean shape) where the increase at each level is fairly equal. For mode 2, a 2 sd reduction denotes that the curvature is reduced at the lower lumbar levels and increased at the upper levels; this results in a more even distribution to the total curvature but with very little change in its magnitude. The effect of the other three modes on the curvature was found to be minimal and may reflect variation in, for example, the aspect ratio or wedging of the vertebral bodies.

End-plate angles

The total and segmental lordosis angles, calculated from the measurements of the end-plates, are shown in Table 2. The total lordosis angle was highly correlated ($R = 0.97$, $P < 0.001$) with the mode 1 values from the shape model (Figure 4). The mean absolute deviation of the segmental lordosis angles was found to be highly correlated ($R = 0.80$, $P < 0.001$) with the mode 2 values (Figure 5).

Reliability and measurement error

The intra-observer reliability (Figure 6) of both methods was found to be excellent ($ICC > 0.75$). This was also true for the inter-observer reliability, with the exception of the lordosis angle measurement at L1-L2. In comparing the two methods, the results from the shape model were more reliable than the lordosis measurements; the difference was marginal for the mode 1 value compared with the total lordosis measurement, but more pronounced for the mode 2 value compared with the segmental lordosis measurements.

The measurement error on the shape model (calculated from the three sets of observations) was 0.17 sd for mode 1 and 0.34 sd for mode 2. The measurement error on the lordosis angles (pooled for the segmental and total measurements) was 5^{o}. The relative errors (error expressed as a percentage of full range) were 4 % (mode 1), 9 % (mode 2), 10 % (total lordosis angle).

Discussion

A shape model of the lumbar spine was created using MR images of 24 male volunteers in the upright standing posture. The model identified two modes of variation which were associated with the curvature of the spine; the first described the variation in the total curvature, and the second described the variation in how evenly the curvature was distributed. The images were also analysed using a conventional method where the total and segmental lordosis angles were calculated from measurements of the end-plate angles.

The results from the two methods for the total curvature of the lumbar spine (mode 1 and total lordosis angle) were found to be in good agreement. Comparing the results for the distribution of the curvature was more difficult since the conventional method uses five variables (the lordosis at each lumbar level) whereas the shape model uses one. However, the mean absolute deviation of the segmental lordosis angles was found to be in agreement with mode 2. Mean absolute deviation provides an indication of whether the curvature is even or not (with a value of zero corresponding to the five segmental angles being identical) but is not able to describe where the curve is uneven.

The intra- and inter-observer reliability (expressed as the intra-class correlation coefficient) and precision of the conventional method used in our study were similar to those found by other studies (5,7-8). When comparing the two methods for total lumbar curvature, we found that the shape model was more reliable and had less measurement error (4 % compared to 10 %) than the conventional method. Again, it was difficult to compare the methods for the evenness of curvature. However, the reliability of mode 2 was better than that of any of the segmental lordosis angles measured using the conventional method.

The better reliability and lower measurement error in the shape model may be, in part, due to the fact that substantially more information from the image is used to develop the shape model, and errors induced in the position of a few points are filtered out to the less important modes of variation. This is means that the model is less likely to be affected by things such as differences in end-plate architecture (5) or where part of an image has been obscured (6). The reliability investigated in our study essentially looked at the consistency between measurements made either by one observer on two different occasions or by two different observers. This is an important measure of reliability since observer subjectivity is a major cause of error in analyses of image data. Another issue for the reliability of spinal shape measurement is the consistency of the lumbar spine shape of an individual on two different occasions. There may be a number of factors that affect this, such as time of day or muscle fatigue. The extent to which this will affect the reliability it not clear; repeated measurements of lordosis using end-plate angles have concluded that longitudinal variation is small (16), but it would be interesting to investigate if similar results were found using shape modelling.

For certain applications, conventional end-plate measurements are very useful. If a simple measure of total lumbar lordosis is required, for example, then measuring just two end-plate angles provides a quick and easy method; using a more sophisticated method such as an active shape model in this case is unlikely to be beneficial. However, existing methods may not be adequate for all applications. Investigations on the effects of posture, load-bearing, or surgery, for example, deal with changes in segmental lordosis that are less than the typical measurement error of an end-plate angle. This suggests that, for some applications, it is worth pursuing new methods that provide greater measurement reliability and precision.

In addition to the better reliability and precision, an advantage of shape modelling is its ability to classify spinal shape in a comprehensive and quantifiable manner with just a small number of independent variables. Achieving this using measurements of segmental lordosis can be much more difficult since the amount of data required to fully describe the spinal curvature (5 angles for the lumbar spine, more when higher levels are included), combined with the large variation in spinal shape in the normal population, makes it difficult to see consistent similarities or differences between individuals. Researchers investigating the association of pathology to spinal shape, for example, have resorted to defining their own classification schemes but comment that it can be difficult to assign everyone into a class (17). Using a shape model should make it easier to evaluate differences in spinal shape between subjects (due to pathology, age etc.) and within subjects (due to posture, disease progression etc); we have recently used such a model to investigate the subtle effects of load-carriage on the spine (18). In the hip, active shape modelling has been found to provide a method for predicting fracture risk which is as good as bone mineral density measurements, and better than geometric measurements (19); applying the method to the spine may therefore help to throw new light on how spinal shape is related to pathology and back pain.

The statistical nature of the shape model should also facilitate the development of biomechanical models that aim to incorporate the effects of natural subject variability into their analyses (20-21). This is important since the results of such models can be more sensitive to differences in geometry than other factors (22).

Another advantage of the shape model is its potential time saving for analysing large numbers of images. Although the main focus of our study was to characterise shape, a trained active shape model may be used to automatically locate an object in an image (11-12). This would be particularly beneficial for analysing a time series of images, such as obtained using dynamic magnetic resonance imaging or fluoroscopy, where measuring all the end-plate angles would be very labour intensive. As yet, the method has not been used to analyse the dynamic behaviour of the spine, but it has been successfully applied to cardiac motion (23).

One of the limitations of using a shape model is that the results (i.e. the values assigned to the modes) are not directly comparable with the existing conventional measurements reported in the literature (i.e. angles). Furthermore, the results from one model can not be directly compared to those from another model generated using a different set of images. This is because the values assigned to each mode refer to variation about the mean of that particular set of images. This limitation may be overcome by determining the end-plate angles or, as in the current study, the vertebral body centroid angles of the shapes described by each mode. In practice, however, for many of the applications described above, this would not be necessary since the purpose of the model would be to characterise the shape of the spine, and the effects of various factors, in a given set of subjects.

A further limitation is that shape model requires medical imaging to be performed to visualise the internal shape of the lumbar spine. Although other studies have sought to relate the position of the vertebral bodies to the surface of the back, there is likely to be considerable differences between individuals which would render these relationships inaccurate. However, this drawback is not unique to the shape modeling method, but to all methods that aim to investigate internal lumbar shape.

In conclusion, a shape model may be used to characterise the shape of the lumbar spine in the sagittal plane using just two variables. The results of the shape model are more reliable and precise than conventional measurements of lordosis which utilise end-plate angles.

Key points

- Active shape modelling provides a method for comprehensively describing the shape of the lumbar spine in the sagittal plane.
- The shape of the lumbar spine can be described by the total curvature and the evenness of curvature.
- The results from the shape model are more reliable and precise than measurements of the angles between the end-plates from the lumbar vertebrae.

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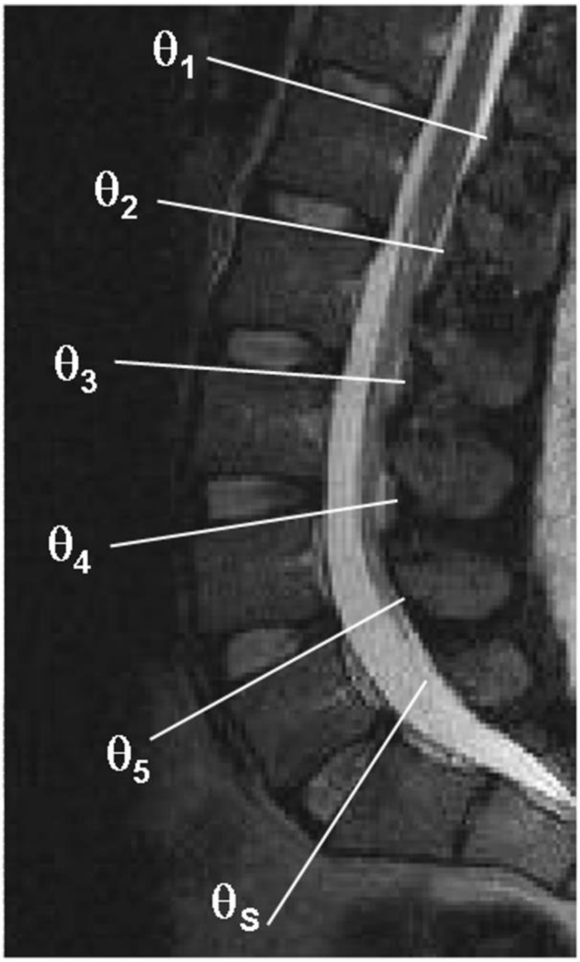

Figure 1. Determination of the total and segmental lordosis via end-plate angles. Total lordosis is calculated as θ_1-θ_S. Segmental lordosis may be determined with respect to the sacrum (θ_i-θ_S) or the neighbouring vertebrae (θ_i-θ_{i+1}).

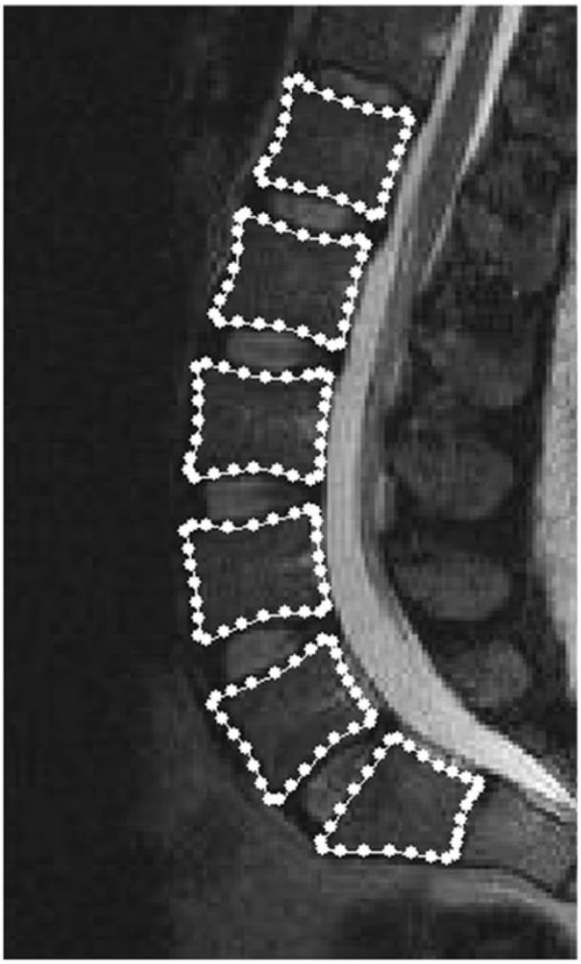

Figure 2. Shape model of the lumbar spine. A total of 168 landmark points were placed around the periphery of the vertebral bodies from S1 to L1.

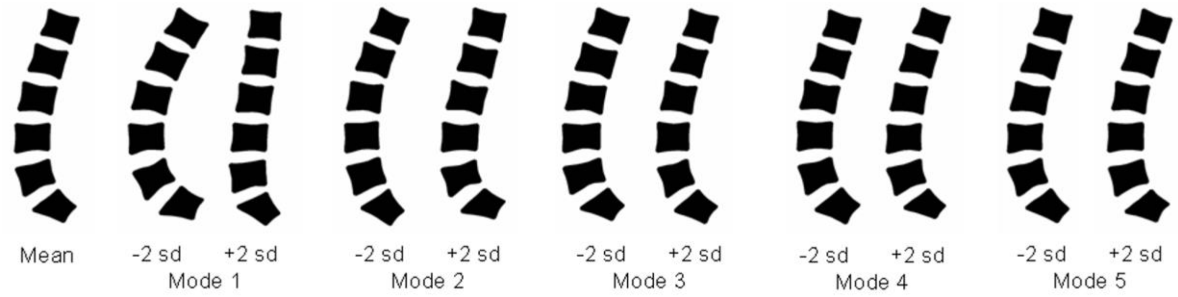

Figure 3. The mean lumbar spine shape and the first five modes of variation identified by the shape model. Each mode was varied by ± 2 sd about the mean whilst keeping the other modes at zero.

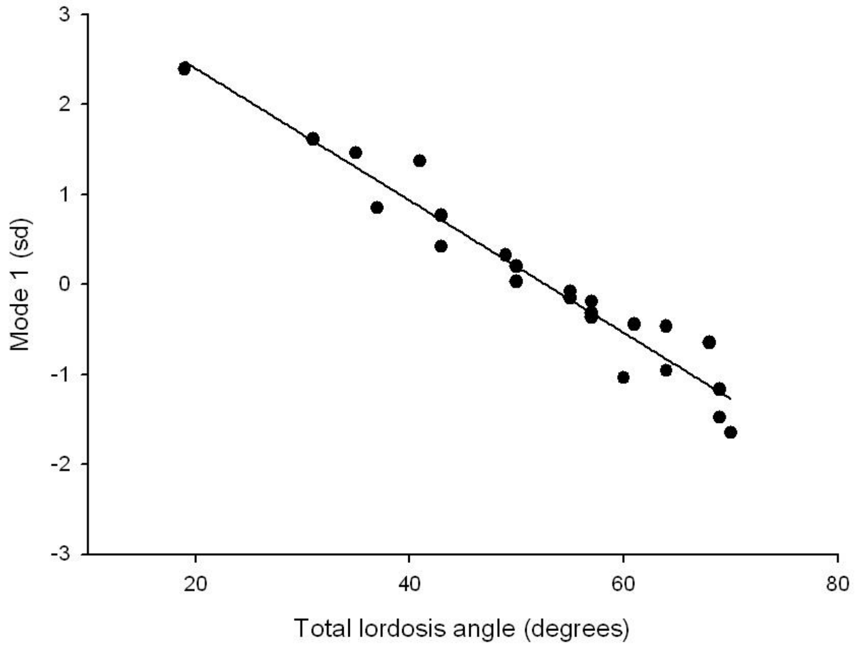

Figure 4. Scatter plot comparing mode 1 scores with the total lordosis angle.

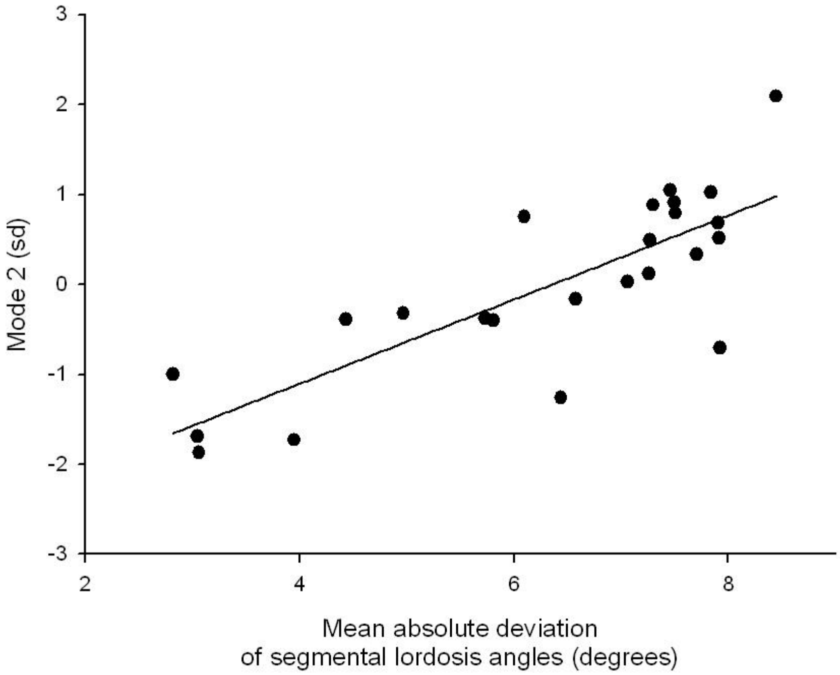

Figure 5. Scatter plot comparing mode 2 scores with the mean absolute deviation of the segmental lordosis angles.

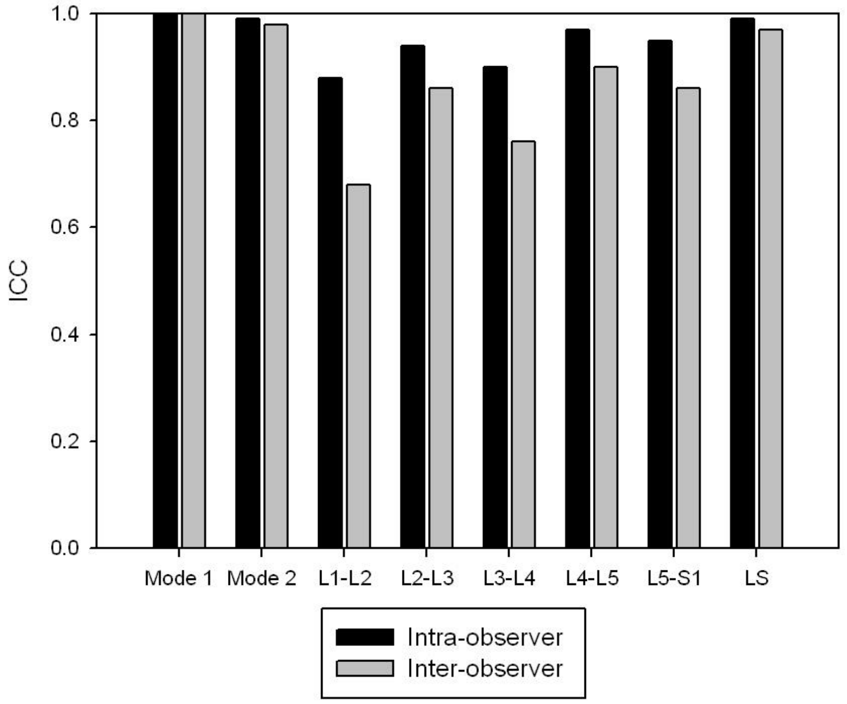

Figure 6. Intra-class correlation coefficients within and between observers for the shape model modes of variation and the total (LS) and segmental lordosis angles.