The accuracy of active shape modelling and end-plate measurements for characterising the shape of the lumbar spine in the sagittal plane.

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The two-dimensional shape of the lumbar spine in the sagittal plane can be determined from lordosis angles measured between corresponding end-plates of the vertebral bodies or by using an active shape model (ASM) of the vertebral body outline. The ASM has previously been shown to be a more efficient and reliable method but, its accuracy has not been assessed. The aim of this study was to determine the accuracy of an ASM for characterising lumbar spine shape and compare this to conventional measurements. Images of twenty five different lumbar spine shapes were generated and measured, using both methods, by three independent observers. The accuracy of the ASM, determined from lordosis angles predicted by the model, was found to be better than conventional measurements.

Keywords: active shape model; lumbar spine; lordosis; end plate angles

1. Introduction

Reliable and accurate determination of the two dimensional shape of the lumbar spine in the sagittal plane is important for a number of reasons. Biomechanically it is important for understanding how the normal healthy spine works (Meakin, Smith, et al. 2008, Meakin et al. 2009), for providing data for computer simulations (Keller et al. 2005), for understanding how certain aspects of spinal shape may lead to the development and progression of pathology (Roussouly et al. 2006), and for assessing the effect of surgical interventions and medical devices on spinal curvature (Crawford et al. 2009) and range of motion (Beastall 2007).

A number of methods have been proposed for characterising lumbar spine shape (Harvey et al. 1998; Vrtovec et al. 2009); the most commonly used being to measure angles made at the intersection of lines placed tangentially to the end-plates of the vertebral bodies observed on two-dimensional sagittal images acquired using X-rays, DXA, CT or MRI. Using this method, which is simple to understand and implement, the total lordosis (curvature) can be determined from the end-plates of the vertebrae at the extremes of the lumbar spine and the segmental lordosis can be determined from the end-plates of the intervening vertebrae. Some of the drawbacks of the method are that six variables (one total and five segmental lordosis angles) are required to fully describe the lumbar shape in terms of total curvature and curvature distribution, the variables are correlated, making analysis difficult, and precision can be relatively low.

We have recently proposed the use of active shape modelling for the characterisation of lumbar spine shape (Meakin, Gregory, et al. 2008). Active shape modelling (Cootes and Taylor 2004) represents the shape of an object in an image by a set of points which are constrained by a point distribution model. Procrustes analysis is used to align and scale the points and principal component analysis is used to determine correlated patterns in variation of the position of the points (modes of variation). Due to the nature of principal components analysis, the modes of variation are linearly uncorrelated, making their analysis easier.

Our previous work has found that the lumbar spine can be described well using two modes of variation, making it a very efficient method, and that, compared to conventional measurements of total and segmental lordosis, it is more reliable and precise (Meakin, Gregory, et al. 2008). The accuracy of using a small number of modes from an active shape model, compared to the accuracy of end-plate measurements, could not be determined however, since the true shape of the subject's lumbar spine in the images used was not known.

The aim of this study was, therefore, to determine the accuracy of the active shape modelling method for characterising the shape of the lumbar spine and compare this to the accuracy of conventional lordosis measurements. To achieve this aim, simulated images of the lumbar spine in the sagittal plane were created with a variety of known total and segmental lordosis angles.

2. Methods

2.1 Generation of simulated spine images

Our previous work has used sagittal images of the lumbar spine acquired using a positional MRI scanner (Meakin, Gregory, et al., 2008, Meakin, Smith et al., 2008, Meakin et al., 2009). The images created for the study reported here were therefore designed to simulate two of the characteristics of typical MRI images: the image resolution and noise. The images (Figure 1) were created using a two step process.

Firstly, MATLAB (The MathWorks, Inc.) code was created to generate twenty-five PostScript command files to draw spines with various total and segmental lordosis angles. The spines were represented by the outline of the five vertebral bodies of the lumbar spine (L1 to L5) plus the top of the sacrum (S1). The vertebral body shape was idealised and assumed to be the same at each vertebral level.

The total lordosis was allowed to vary from 26^{o} to 79^{o}. The proportion of lordosis at each intervertebral level was specified to be distributed linearly along the lumbar spine. This linear distribution was allowed to vary from being completely even (20% at each level) to being uneven (0% at L1L2, 10% at L2L3, 20% at L3L4, 30% at L4L5 and 40% at L5S1). The orientation of the sacrum, S1, was also allowed to vary from 30^{o} to 46^{o}. Although this variable was not part of the study, it was included to represent the natural variation in pelvic morphology and orientation. The values for the total lordosis and curvature distribution were based on our previous measurements of real lumbar spines (Meakin, Gregory, et al. 2008).

One of the spine shapes was prescribed to have the mean value for lordosis and lordosis distribution derived from our previous study, four shapes were prescribed to have combinations of the extreme values, and the remaining twenty shapes were created with values taken randomly from the specified ranges. The rotation angle of each vertebral body, with respect to the one below it, was written to the PostScript file but was not known to the observers until after all measurements had been made. The PostScript files were also randomly assigned a filename so that the observers could not know which files contained the five preset value images.

In the second stage a script was written for GIMP software (www.gimp.org) which opened the PostScript files, applied a scaling transform to pixelate the images, added noise, and saved them in bitmap format. The pixelation used a pixel size which, relative to the width of the vertebral bodies, was similar to that of the MR images used in our previous study (Meakin, Gregory, et al. 2008, Meakin et al. 2009). The noise was added using the Scatter RGB filter in the GIMP software. This filter adds noise to the image using a Gaussian distribution with a standard deviation set by the user between 0 and 1; in our case we used a value of 0.1. An example of one of the created images is shown in Figure 1 alongside a typical MR image of the lumbar spine for comparison.

2.2 Measurement of lordosis angles from end-plate measurements

ImageJ software (NIH, USA) was used to measure the angle of the superior end-plate of each vertebral body. The images were first magnified to 300% and then the angle of a line placed tangential to the superior end-plate was recorded (Figure 2a). These angles were used to determine the segmental lordosis angle between subsequent vertebral bodies (θ_{L1L2}, θ_{L2L3}, θ_{L3L4}, θ_{L4L5}, θ_{L5S1}) and the total lordosis angle between L1 and S1 (θ_{LS}). Each of the 25 images was measured once by three independent observers and the values from the three observers averaged.

2.3 Active shape modelling

An Active Shape Model (ASM) of the simulated spines was created using the Active Appearance Modelling software tools from the University of Manchester UK (http://www.isbe.man.ac.uk/~bim/software/am_tools_doc/index.html). The model, which was the same as that used in our previous work on the lumbar spine (Meakin, Gregory, et al. 2008, Meakin et al. 2009), was defined by placing 28 landmark points around the periphery of each vertebral body, a total of 168 points per image, as shown in Figure 2b. Each of the 25 images was analysed once by the three independent observers. Since one of the features of the software is that, after a number of images have been analysed, it is able to search and locate a shape in an image, the placement of the points was adjusted manually, if required, after the software had identified their approximate position. The ASM software then processed the 75 sets of points to align them into a common co-ordinate frame by scaling, translating and rotating. The software calculated the average position of the points, giving the mean shape, and determined the eigenvectors and eigenvalues of the covariance matrix of the data. The eigenvectors describe independent correlated patterns in the variation of the position of the points; in the ASM, these new variables are called ‘modes of variation’ and are ordered such that the first describes the largest proportion of variance in shape, and the second, and subsequent, modes account for decreasing proportions of variance. Each image was assigned a series of values relating to the coefficients of the modes of variation; these were standardised such that each mode of variation had a mean of zero and a unit standard deviation. The values for each image from the three observers were averaged. The ASM software also allows the modes of variation to be visualised; images of the mean shape and the shapes corresponding to two standard deviations either side of the mean, which were generated by the software, were saved for subsequent analysis (these are shown in Figure 3).

2.4 Data and statistical analysis

The accuracy of the segmental and total lordosis angles determined from end-plate measurements was assessed by determining the agreement, using methods described by Bland and Altman (1986), with the true angles defined by the relative vertebral body rotation angles used to create the simulated images. The statistical analyses were performed using SPSS software (version 17) and the Kolmogorov-Smirnov test was used to assess whether data followed the normal distribution.

The form of the output from the ASM, in terms of variation from a mean shape, meant its accuracy could not be directly assessed. Instead, the output was used to predict lordosis angles which were then compared to the true angles. These predicted angles were calculated using the mean shape, and shapes described by plus and minus two standard deviations of each mode of variation, produced by the ASM software. Similarly to the analysis of the images described above (section 2.2), ImageJ was used to measure the angle of the superior end-plates of the vertebral bodies in these ASM generated shapes so that the segmental and total lordosis angles could be calculated. This measurement was performed by one observer. The effect of each mode of variation on the lordosis angles, with respect to those of the mean shape, was thus calculated and used, together with the standardised coefficients of variation assigned to each image, to predict the lordosis angles of the spine in each image.

3. Results

3.1 Shape model output

The first three modes identified by the shape model accounted for 87%, 7%, and 2% of the total variation in shape. The mean shape and the shapes described by these three modes are shown in Figure 3 and the segmental and total lordosis angles of each shape are given in Table 1. These showed that the first mode, M1, described differences in total curvature and the second mode, M2, described differences in the distribution in the curvature, with some slight differences in total curvature. The third mode, M3, was unrelated to spinal curvature and described differences in sharpness of the corners of the vertebral bodies. Since each vertebral body in the simulated images was identical, this mode corresponds to differences in the way the observers placed the landmark points at the corners. The third and higher modes were therefore ignored from subsequent analyses and only the first two modes were used for predicting lordosis angles.

3.2 Accuracy of predicted and measured lordosis angles

The agreement between the true lordosis angles and those determined from end-plate measurements (measured angles) or predicted from the shape model (predicted angles) are shown in Figure 4. The mean difference was found to be less than 1 degree in all cases, indicating that there was little overall bias to either method. The limits of agreement, shown as error bars in Figure 4, show that the predicted angles were, in most cases, more accurate than the measured angles. When the data were pooled (total and segmental angles) the limits of agreement were -1.8 to 1.8 degrees for the measured angles and -1.4 to 1.3 degrees for the predicted angle.

These limits of agreement, particularly for the predicted angles, are likely to be conservative estimates since their calculation assumes that the difference from the true angles does not vary systematically across the range of values. In our data, difference from the true angles was found to be significantly related to the average magnitude of the angle in a number of cases. This is shown in Figure 5 for the total lordosis, θ_{LS}, where a significant correlation was found for both the measured ($R = 0.43$, $P = 0.03$) and the predicted angles ($R = 0.86$, $P < 0.001$). Similar relationships were found for the predicted segmental angles ($R > 0.49$, $P < 0.015$) with the exception of θ_{L4L5} ($R = 0.35$, $P = 0.09$). The recommendation that a logarithmic transformation be applied to the data (Bland and Altman, 1986) did not remove this relationship and so the limits were calculated for the untransformed data.

4. Discussion

The results from our study demonstrate that an active shape model provides an accurate method for characterising lumbar spine shape from a two-dimensional image of the lumbar spine. Overall, the accuracy of the angles predicted from the model was found to be better than that of angles measured directly from the images, but not by a large amount. The pooled data (total and segmental combined) suggested that a lordosis angle could be measured, with 95% confidence, to within 1.8 degrees and predicted to within 1.4 degrees. As far as we are aware, this is the first time that the accuracy of such measurements has been determined.

Accuracy, in the context of the study, was concerned with how well the angles, measured directly from vertebral body end-plates, or predicted from the active shape model data, matched the known rotation angles of the vertebral bodies in a set of two-dimensional simulated images. Essentially, our assessment of accuracy dealt with the errors that occur due to the image acquisition process (resolution and noise). When determining the lordosis angles of a real subject there are additional errors that are induced such as curvature or movement of the lumbar spine out of the sagittal plane or about the vertical axis of the body; this is true irrespective of whether the image is acquired using MRI, CT, x-rays or DEXA. To resolve these errors fully would require a full three-dimensional reconstruction of the lumbar spine shape. For many purposes, however, 2D images are considered more practical and our study suggests that for these, the active shape model is more accurate.

The number of modes of variation that were required to achieve the accuracy demonstrated in the current study may not be the same for all active shape models of the lumbar spine. In the current study it was identified that only the first two modes, accounting for 94 % of the total shape variation, were relevant to spinal curvature. These were, therefore, the only modes used to predict lordosis angles. In our previous work the first two modes accounted for 82% (Meakin, Gregory, et al. 2008) and 91 % (Meakin et al. 2009) of the total variation. In these studies, more modes may have been required to achieve the same accuracy; this could be easily ascertained from the measurements of the modes shapes such as are given in Table 1.

The relationship found for the agreement between the true and the predicted angles may be due to inadequacy of the shape model to pick up non linear variation in the position of the landmark points. The active shape model assumes that landmark points only move along straight lines and uses linear statistics. In the spine, the changes in lordosis result in rotation of the vertebral bodies in the sagittal plane, particularly at the ends of the spine. Rotation of the landmark points about a central axis causes incorrect shapes to be generated by the model (Heap and Hogg 1996). The effect of this can be observed in Figure 6 which shows clearly that when mode 1 is varied to three standard deviations above the mean, the size of vertebral body S1 appears to have increased. Solutions to this problem include using a hybrid point distribution model which utilises polar coordinates as described by Heap and Hogg (1996). Using such a model might lead to improvements in the accuracy of the angle predictions from the model. However, despite this, the results of our study suggest that even the linear model is able to predict lordosis angles as accurately as, and more reliably than, conventional measurements.

The images generated for this study were simpler than the real MR images of the lumbar spine that we used in our previous work (Figure 1), with an idealised vertebral body shape, greater contrast between the outline of the vertebral bodies and their surroundings, and no additional anatomical details such as the intervertebral disc. The model used to add noise to the images was also simpler than that of real MR images (Aja-Fernández et al., 2009). The main purpose of the study, however, was not to create realistic MR images, but to compare the ability of two different methods to deal with two characteristics of images (resolution and noise) which contribute to measurement uncertainty. These characteristically affect all imaging methods to a greater or lesser extent. The similarity between the intra-class correlation coefficients (data not shown) and the observer measurement errors determined in this and a previous study using real MR images (Meakin, Gregory, et al. 2008) suggests that the simulated images provided a reasonable test for the study.

The effort required to place all the landmark points on the images is greater than that required to measure the end-plate angles and, for some applications, may not be worthwhile. However, one of the advantages of the shape model is that it is able to comprehensively describe the lumbar spine curvature using a minimum of variables. In addition, once the first images have been marked manually, the semi-automated search algorithm within the software simplifies subsequent point placement. Active shape models and active appearance models (where the texture of the image is incorporated into the model) of the spine have been shown to provide a powerful method for semi-automatic detection of vertebral fractures from DXA images (Roberts et al., 2006).

In the current study, the segmental lordosis was prescribed to vary linearly along the lumbar spine and could be sensibly characterised using a measure such as absolute deviation (Meakin, Gregory, et al. 2008). In real lumbar spines, however, segmental lordosis is not linearly distributed and cannot be adequately described using this measure. Active shape modelling is not limited by this and can fully describe more complicated morphologies. In addition to the characterisation of sagittal curvature dealt with in this study, the method can be used to elucidate the shape of the vertebral bodies and information about the disc spacing, which may be useful for further biomechanical analysis.

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Table 1. Segmental and total lordosis angles (in degrees) of the mean shape and first three modes of variation of the shape model corresponding to the images shown in Figure 1.

	Mean	M1		M2		M3	
		-2 sd	+2 sd	-2 sd	+2 sd	-2 sd	+2 sd
θ_{L1L2}	6	2	11	-1	14	6	6
θ_{L2L3}	8	2	14	5	11	9	8
θ_{L3L4}	11	4	17	10	12	11	11
θ_{L4L5}	14	6	22	17	11	14	14
θ_{L5S1}	17	8	25	23	11	16	17
θ_{LS}	56	21	89	53	59	56	56

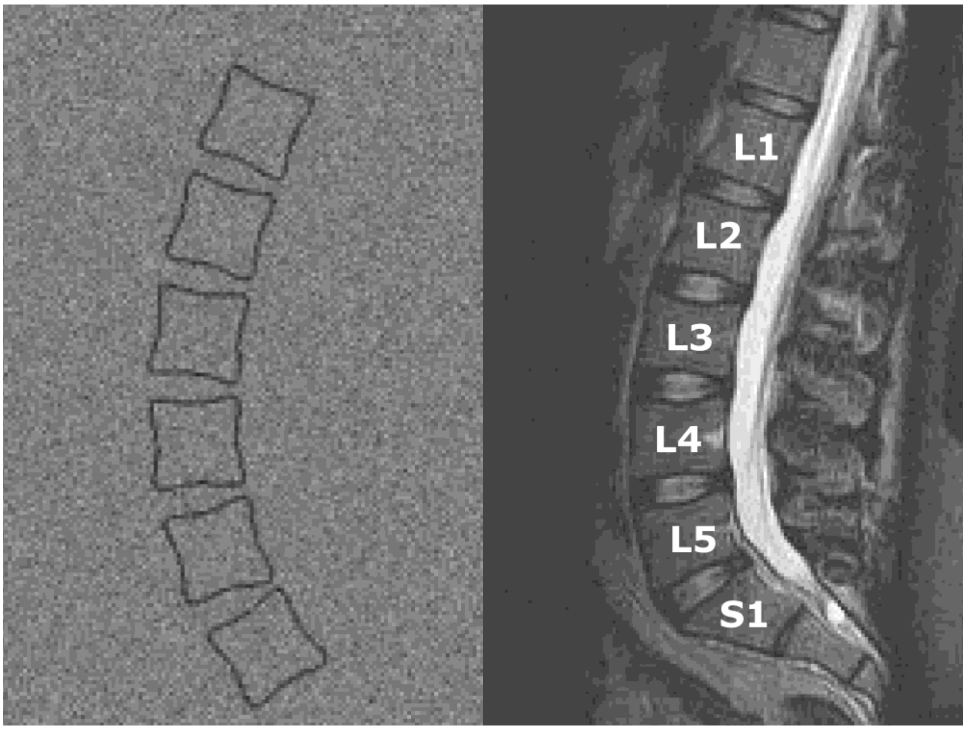

Figure 1. An example of one of the twenty-five simulated spine images (a) shown alongside a real MRI image of the lumbar spine (b). The vertebral bodies L1 to S1, which were represented in the simulated images, are marked on the MR image.

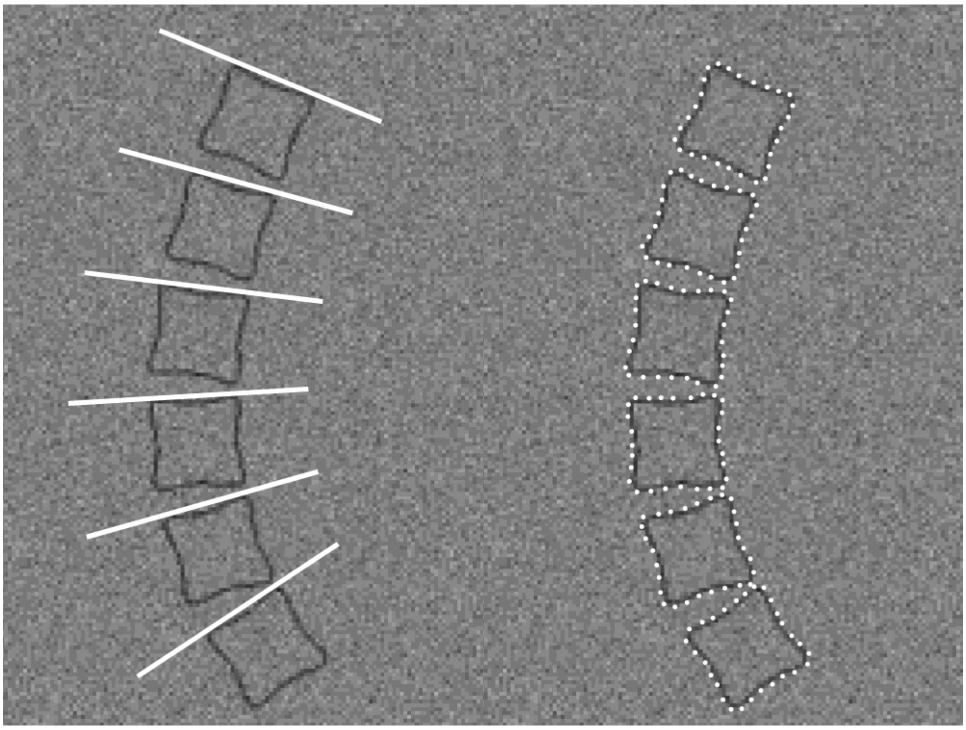

Figure 2. The measurement of the angle of the superior end-plates (a) and the landmark points used in the active shape model (b). The difference between the end-plate angle of the top (L1) and bottom (S1) vertebral body was used to determine total lordosis (θ_{LS}) and that of adjacent vertebrae was used to calculate segmental lordosis (θ_{LnLm}).

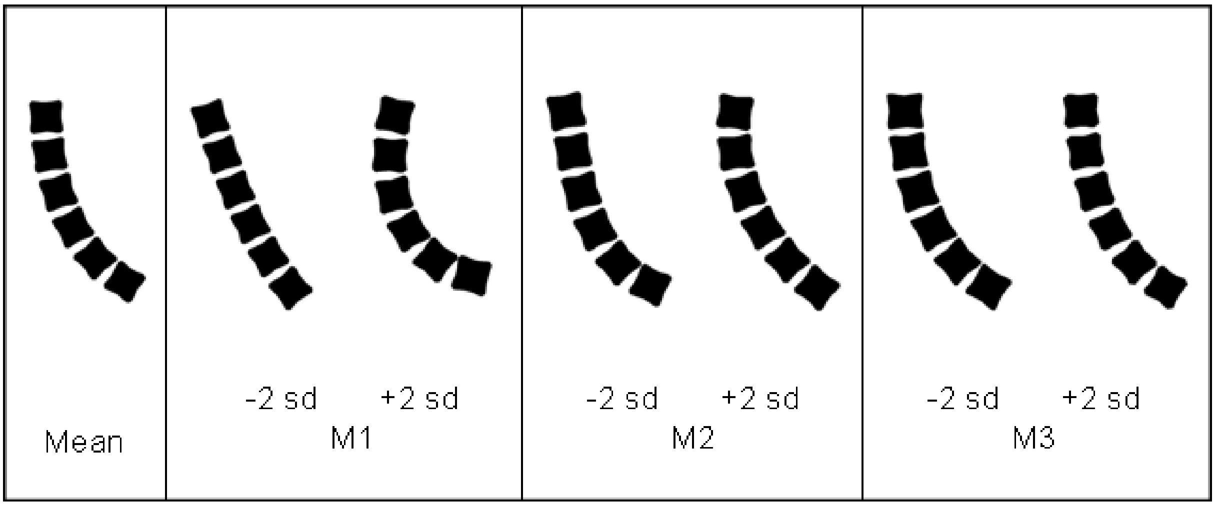

Figure 3. The first three modes of variation (M1, M2, M3) identified by the shape model. The mean shape is shown together with the shape that is obtained by varying each mode by 2 standard deviations, whilst holding the other modes constant. The lordosis angles for each of the shapes shown here are given in Table 1.

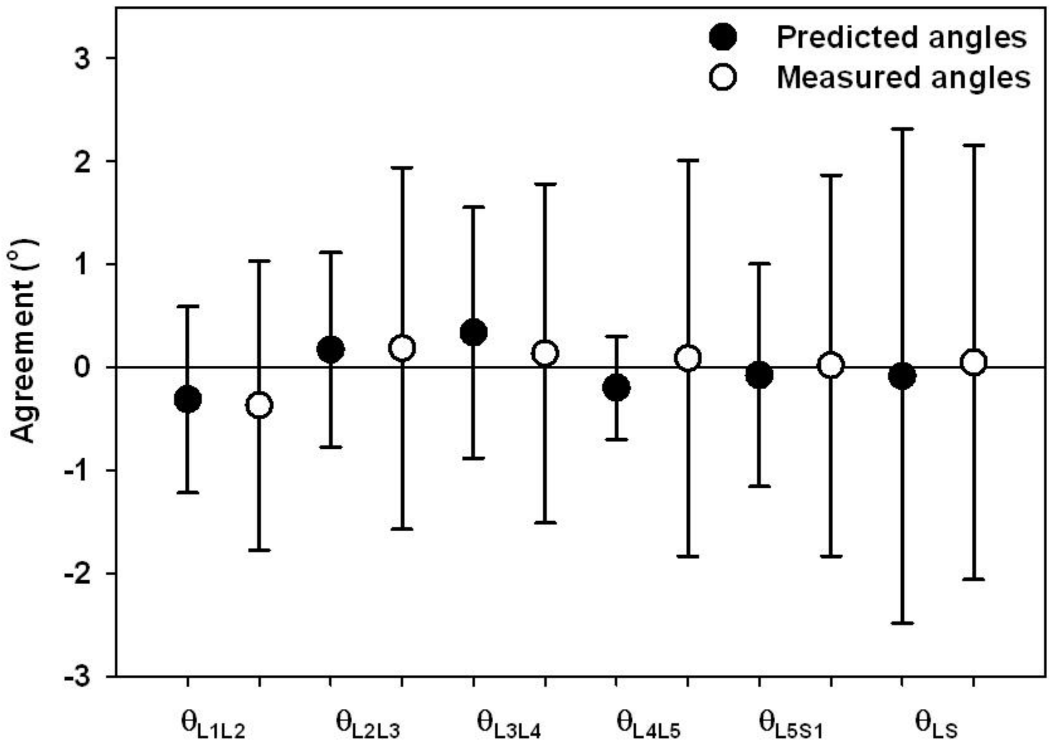

Figure 4. Limits of agreement between the true values of the segmental (θ_{LnLm}) and total (θ_{LS}) lordosis angles and those determined from end-plate measurements or predicted from the shape model. The plot shows the mean difference with error bars corresponding to 1.96 standard deviations.

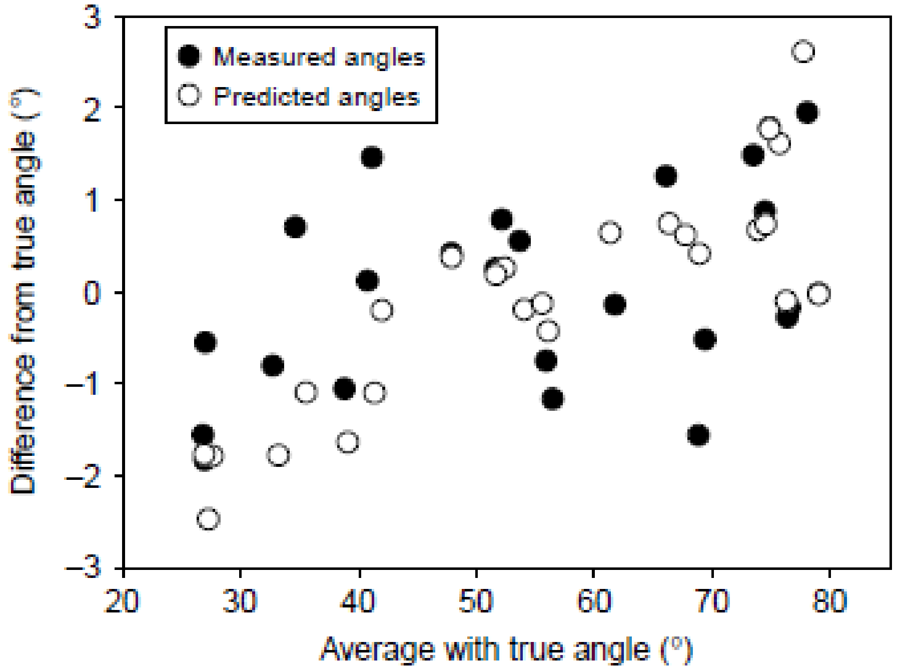

Figure 5. Plot of difference against the average for the true total (θ_{LS}) lordosis angles and those determined from end-plate measurements or predicted from the shape model.

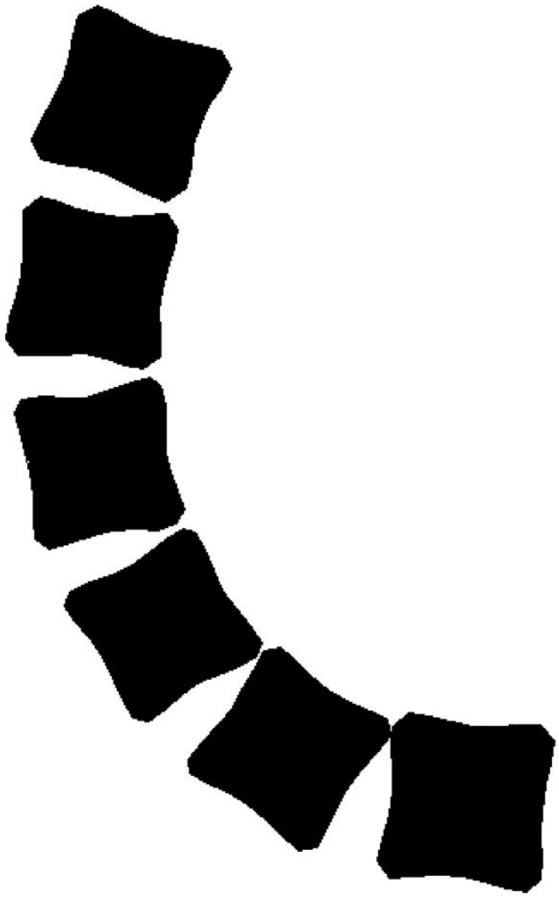

Figure 6. Mode 1 at + 3 standard deviation showing the artefact of different sizes in vertebral body size, particularly for S1.