The in vivo assessment of thoracic vertebral shape from MRI data using a shape model

Structured Abstract

Study design

Feasibility study on characterising thoracic vertebral shape from magnetic resonance images using a shape model.

Objectives

Assess the reliability of characterising thoracic vertebral shape from magnetic resonance images and estimate the normal variation in vertebral shape using a shape model.

Summary of background data

The characterisation of thoracic vertebrae shape is important for understanding the initiation and progression of deformity and in developing surgical methods. Methods for characterising shape need to be comprehensive, reliable and suitable for use in vivo.

Methods

Magnetic resonance images of the thoracic vertebrae were acquired from 20 adults. Repeat scans were acquired, after repositioning the participants, for T4, T8 and T12. Landmark points were placed around the vertebra on the images and used to create a shape model. The reliability was assessed using relative error (E%) and intra-class correlation (ICC). The effect of vertebral level, sex and age on vertebral shape was assessed using repeated measures analysis of variance.

Results

Five modes of variation were retained from the shape model. Reliability was excellent for the first two modes (mode 1: E% = 7, ICC = 0.98; mode 2: E% = 11, ICC = 0.96). These modes described variation in the vertebral bodies, the pedicle width and orientation, and the facet joint position and orientation with respect to the pedicle axis. Variation in vertebral shape was found along the thoracic spine and between individuals, but there was little effect of age and sex.

Conclusions

Magnetic resonance images and shape modelling provides a reliable method for characterising vertebral shape in vivo. The method is able to identify differences between vertebral levels and between individuals. The use of these methods may be advantageous for performing repeated measurements in longitudinal studies.

Level of Evidence

N/A

Key Words

Thoracic vertebrae

Magnetic resonance imaging

Statistical shape model

Reliability of results

Anatomy

Introduction

The characterisation of thoracic vertebral shape is important for helping us understand the aetiology and pathogenesis of spinal deformity and for developing optimal treatments. Many previous studies have characterised the shape of the thoracic vertebrae and shown it to exhibit considerable variation within the normal population and in the presence of pathology such as scoliosis [1] but these studies have mostly assessed discrete anatomical features using in vitro data [2-13]. Being able to comprehensively characterise thoracic vertebral shape in vivo is essential for further research to improve our understanding of how spinal deformity initiates and progresses and for determining information that can be used to improve surgical techniques such as the placement of pedicle screws.

In vivo measurements of vertebral shape can be achieved using medical imaging data. A few studies have assessed thoracic vertebral shape in vivo using radiographs [14] or CT data [10, 15]. These imaging modalities, however, incur a dose of ionising radiation and may not be suitable for all research studies, particularly longitudinal studies involving children or healthy control groups. Magnetic resonance image (MRI) data is an attractive alternative that avoids the use of ionising radiation, but the feasibility of using this imaging modality to reliably assess vertebral shape has not been established.

The shape of the vertebrae can be characterised using a number of different methods. Previous studies have tended to characterise shape by measuring individual dimensions and angles [2, 4, 16]. This approach, however, makes it difficult to establish relationships between anatomical features and to separate variation in shape from variation in size. Shape modelling, which uses statistical data analysis methods, provides a way of comprehensively characterising complex shapes, independently of size, using a small number of variables (modes of variation) where features that co-vary are included in the same mode of variation [17, 18]. Shape modelling has been used in a number of studies related to the spine [7, 19-22], and shown to be reliable [19], precise [19] and accurate [23], but has not been applied to characterising thoracic vertebrae.

In this feasibility study, the primary aim was therefore to assess the reliability of characterising thoracic vertebral shape from MRI data using a shape model. The secondary aim was to estimate the amount of variation in thoracic vertebral shape in heathy volunteers and identify the factors that contribute to the variability.

Material and Methods

Participants

Twenty adult participants were recruited; the participants (12 female and 8 male) were aged 20 to 53 years (median = 28 years). Ethical approval for the study was given by an ethics committee and written informed consent was obtained from all participants. Exclusion criteria were known deformity, arthritis, low bone density, previous injury, or surgery to the thoracic spine.

Imaging

Images of the participants' thoracic vertebrae were acquired using a 1.5 T Magnetic Resonance scanner (Intera, Philips, Amsterdam, The Netherlands) with a receive-only spine coil (Synergy, Philips, Amsterdam, The Netherlands). A T1-weighted turbo spin echo sequence was used (repetition time = 295 ms; echo time = 8 ms; number of signal averages = 3) that produced images with an in-plane pixel size of 0.5 mm x 0.5 mm, a slice thickness of 1.9 mm and slice gap of 1.63 mm. A stack of 27 slices was acquired at each vertebral level, orientated parallel to the mid-transverse plane of the vertebral body. During scanning the participants were positioned supine. Each vertebral scan took just under 2.5 minutes and the time taken to set-up and complete scanning of the twelve vertebrae was approximately 40 minutes. After scanning, the participants were removed from the scanner, allowed to stretch and walk around for a few minutes, and then repositioned. Repeat scanning was performed at the levels of T4, T8 and T12; in four cases the repeat scan was performed one level below or above. Full data was collected for most participants (296 out of 300 datasets); the four missing datasets were due to scan errors.

Image annotation

Each stack of 27 slices was visually inspected to find the slices that most clearly visualised the inferior facets, the spinous process, the pedicles, the vertebral body, the transverse processes, and the superior facets. This resulted in three to six slices being selected for each vertebra. These slices were then annotated by one observer (SJH) who manually placed landmark points using custom-written software tools in MATLAB [24]. The locations of the landmark points (Figure 1) were chosen to capture the anatomical features of the vertebral body and canal, the pedicles, the transverse and spinous processes, and the inferior and superior facets. A total of 77 landmark points were used for each vertebra.

Shape model

The landmark points were used to create a shape model using software tools written in MATLAB [24]. The 296 sets of landmark points were aligned into a common reference frame using Procrustes analysis; this removed differences in the location, orientation and size of the vertebrae. The mean shape was determined and principle component analysis performed to identify modes of variation. The number of modes retained for analysis was determined using the broken-stick method which retains the modes that account for more variance than would be expected from a random model [25].

Scores were given to each vertebra to describe its shape in terms of the retained modes of variation. The mean score, averaged across the 20 participants, at each vertebral level was then used to reconstruct the shape of the vertebrae at that level, *Shape(T)*, using equation 1.

$$Shape(T) = Shape(mean) + \sum_{m=1}^{N} S(T,m)Shape(m) \qquad \text{Equation 1}$$

where *Shape(mean)* is the overall mean shape,

S(T,m) is the mean score for mode *m* at vertebral level *T*,

Shape(m) is the shape described by mode *m*.

and *N* is the number of retained modes.

Statistical analysis

Statistical analysis was performed using SPSS [26] and a probability of 0.05 or less was taken to indicate statistical significance. The reliability of the mode scores was determined using the repeat data for T4, T8 and T12 (where a lower or higher level had been imaged it was matched to its corresponding level in the initial data). Reliability was assessed using one-way analysis of variation to calculate the within-subject standard deviation of the repeated results. The three vertebral levels were treated separately to assess whether reliability varied along the spine and then pooled together to obtain an overall measurement error. The relative error was determined by multiplying the overall within subject standard deviation by 2.77 and expressing it as a percentage of the full range of values for the mode of variation being considered. Single measures intra-class correlation coefficients (ICC) were determined for the overall data using a one-way random model. ICCs were classed as being poor (0<ICC<0.4), fair (0.4<ICC<0.59), good (0.60<ICC<0.74), or excellent (0.75<ICC<1) [27].

The variability in the thoracic vertebrae shape and the effect of vertebral level, sex and age was assessed using repeated measures analysis of variance (full model with vertebral level as a within-subject factor, sex as a between-subject factor, and age as a covariate). The assumptions of sphericity were tested using Mauchly's sphericity test and, where these assumptions were violated, the Greenhouse-Geisser correction was used. Main effects were compared with a Sidak adjustment for multiple comparisons. Missing data for T1 from one participant was replaced by the mean of the other 19 participants so that this participant's data could be included in the repeated measures analysis of variance.

Results

Modes of variation

Five modes of variation (Figure 2) were retained from the shape model and accounted for 73 % of the total variance. Individually the modes accounted for 44 % (Mode 1), 19 % (Mode 2), 4 %

(Mode 3), 3 % (Mode 4), and 3 % (Mode 5) of the total variance. Visual inspection indicated that the first mode related to variation in the size of the vertebral bodies, the width and orientation of the pedicles, and the position and orientation of the processes and facet points. The second mode related to the size of the transverse processes and the ratio of the anteroposterior to lateral vertebral body diameter. The third mode related to the variation in the articular and costal facets and the relative size of the vertebral canal. The forth mode related to curvature of the transverse processes and articular facets. The fifth mode related to variation in the location of the inferior and superior facets.

Reliability

The reliability of the mode scores increased slightly from T4 to T12 (Table 1) but the increase was small and the overlap of the 95 % confidence intervals (with the exception of those of T4 and T8 for mode 4) indicated that it was not significant. The overall error was therefore taken as representative for all vertebrae. The relative error and intra-class correlations showed that whilst modes 1 and 2 had excellent reliability, modes 3, 4 and 5 ranged from fair to good with a relative error up to 20 % of the data range.

Vertebral shape

The mean mode scores (averaged across the 20 participants) demonstrated systematic trends along the thoracic spine (Figure 3) with scores decreasing monotonically from T1 to T12 for mode 1 and displaying a U-shaped variation for mode 2. For modes 3, 4 and 5 there was a less clearly defined pattern to the variation along the spine. The reconstructed vertebral shapes (Figure 4) reflect the variation demonstrated in Figure 3 with, for example, T1 having a high score for both modes 1 and 2 that corresponds to a low anteroposterior to lateral diameter ratio and long transverse processes.

There was a significant effect of vertebral level on modes 1, 2 and 5 (Table 2). Pairwise comparisons (Figure 5) indicated that mode 1 differed significantly between nearly all pairs of vertebral levels and mode 2 differed significantly between most pairs of vertebrae except adjacent vertebrae in the middle of the spine and those at opposite ends of the spine. For mode 5 there were few significant differences between vertebral levels. The differences in the mode scores between male and female vertebrae were small (Figure 3) and the only significant for mode 3 (Table 2). There were no significant effects of age (Table 2).

Discussion

The primary aim of this study was to assess the reliability of using a shape model to characterise thoracic vertebral shape from MRI data acquired in vivo. Shape modelling is data analysis technique that is increasingly used to characterise the complex shape of anatomy. A particular advantage of shape modelling, over methods that involve making separate measurements of every individual anatomical feature of interest, is that it combines all correlated features into independent modes of variation. This makes the description of shape very efficient (using a small number of variables) and makes it easier to evaluate changes in shape due to the presence or progression of pathology. A recent example of this is the identification of changes in hip shape that may be related to the pathogenesis of hip osteoarthritis [28].

Shape modelling may be performed to characterise the three or two dimensional shape of anatomy. In our study, although 3D data was acquired, it was analysed as if it were projected 2D data in the plane parallel to the mid-transverse plane of the vertebral body. This was done because a full 3D analysis would involve more landmark points and would require a larger sample of participants. The manual placement of landmark points can be time-consuming for large scale studies; however, methods of automatic landmark placement have been developed for studies using CT data [29] and progress is being made in being able to do the same using MRI data [30].

Our results show the use of a shape model on MRI data to be reliable with low relative error and high intra-class correlation. In this study repeated measurements were taken from two sets of image data, the second of which was acquired after repositioning the participant. This was done to simulate data acquired at multiple time-points, which would be the case in a longitudinal study that aimed to assess changes in vertebral shape over time. All the images were processed once by one observer which means that we cannot determine whether the main source of the error in our results of vertebral shape is the observer error in placing landmark points on the images or whether it is due to the images being slightly different after repositioning. Our previous work on the intra-observer and inter-observer reliability of placing landmark points on a single set of images, however, has found ICCs over 0.98 for the first two shape modes [19, 23] suggesting that repositioning did not have a great effect.

This study has also demonstrated, for the first time, the feasibility of using MRI data to characterise vertebral shape in vivo. A major advantage of MRI, over imaging modalities such as

CT, is the lack of ionising radiation. This makes it preferable, from a safety point of view, for use in healthy volunteers and also for repeated measurements in longitudinal studies, particularly those involving children who are particularly vulnerable to the effects of ionising radiation. MRI has not previously been used to characterise vertebral shape and this may stem from concerns that MRI data does not have sufficient quality for this type of study. Improvements in MRI technology over recent years, however, mean that image resolution can be as good as or even better than other modalities such as CT and issues such as low contrast between the bone and the surrounding tissue can be mitigated through the use of imaging sequences that enhance the contrast (although in our study we used standard T1-weighted imaging sequences and still achieved high reliability in our measurements). Finally, although MRI data can suffer from geometric distortion due to inhomogeneity in the MRI field gradients, this is predominantly a problem for data acquired using gradient-echo sequences. If non-gradient echo sequences are used (in our study we used spin-echo sequences) then it is likely that the data has a geometrical accuracy close to that of CT [31]. Other studies on the accuracy of using MRI data for determining bony anatomy in bones other than vertebrae have also concluded that it is comparable to CT [32, 33].

The secondary aim of our study was to estimate the variation in thoracic vertebral shape in heathy volunteers and identify the factors that contribute to the variability. The shape of the vertebra, and the variation in this shape along the thoracic spine, was found to be consistent with anatomical measurements reported in the literature. These include the anteroposterior diameter of the vertebral body increasing from T1 to T12 [4, 5]; the lateral diameter of the vertebral body decreasing from T1 to T3 or T4 followed by an increase to T12 [5]; the lateral width of the vertebral canal decreasing from T1 to T5 followed by an increase to T12 [4, 13]; the pedicle width decreasing from T1 to T4 followed by little variation until T8 where it increases to T12 [8-11]; the pedicle angle decreasing from T1 to T12 [8, 9]; the transverse process changing from a more lateral orientation at T1 to a more posterior orientation T12 [12, 15]; and the length of transverse processes increasing slightly from T1 to the mid-thoracic region and then decreasing towards T12 [12]. The effect of vertebral level on the shape was found to be significant.

The shape of the vertebrae was very similar in males and females and although there were differences in the scores for modes 3 and 4, only mode 3 reached statistical significance. Nevertheless, the differences in these modes describe variation in shape that is consistent with results that have found the transverse processes to be more dorsally orientated, and the neural canal to be smaller, in males compared to females [7]. Previous studies that have identified large differences between male and female vertebrae have assessed absolute measurements but these reflect the larger size of the male vertebrae [4] which was not considered in the current study due to scale being removed from the model. Age was not found to have a relationship with vertebral shape in. A previous study has found changes in the relative dimensions of the thoracic vertebrae with age [34] but these were based on measurements in the sagittal plane which were not considered in the current study.

Our study has demonstrated that the shape of the thoracic vertebra can be characterised comprehensively and reliability from MR data using a statistical shape model. This suggests that the methods would be useful for future longitudinal studies; however, as our sample comprised twenty healthy volunteers, subsequent studies should independently repeat the assessment of reliability since our values, particularly those of the ICC which depend on sample heterogeneity, are unlikely to be generalizable to all samples. The correspondence between the results of our study and measurements reported in the literature demonstrates that the shape model is able to correctly characterise known variation in vertebral shape along the thoracic spine. This suggests that the technique may be powerful enough to detect differences between normal and pathological vertebrae. The differences found between male and female, although small, suggest it is important to conduct future studies on single sexes or include sex as an additional factor.

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Table 1. Reliability of the mode scores. The within-subject standard deviation (95 % confidence interval) is shown individually for the three vertebral levels and overall. The relative error indicates the measurement error as a percentage of the range.

Mode	T4	T8	T12	Overall	Relative overall	ICC
1	0.11 (0.07 - 0.15)	0.13 (0.08 - 0.17)	0.16 (0.1 - 0.21)	0.13 (0.11 - 0.16)	7%	0.98 (0.97 - 0.99)
2	0.15 (0.10 - 0.20)	0.17 (0.12 - 0.23)	0.24 (0.16 - 0.32)	0.19 (0.15 - 0.22)	11%	0.96 (0.94 - 0.98)
3	0.49 (0.32 - 0.65)	0.51 (0.34 - 0.68)	0.73 (0.48 - 0.99)	0.58 (0.47 - 0.69)	27%	0.70 (0.54 - 0.81)
4	0.32 (0.21 - 0.42)	0.71 (0.47 - 0.94)	0.72 (0.47 - 0.97)	0.61 (0.50 - 0.72)	21%	0.57 (0.37 - 0.73)
5	0.59 (0.39 - 0.80)	0.42 (0.28 - 0.56)	0.40 (0.26 - 0.54)	0.48 (0.39 - 0.57)	16%	0.68 (0.52 - 0.80)

Table 2. The effect of vertebral level, sex and age on the mode scores, assessed using repeated measures analysis of variance.

	Vertebral level		**Sex**		**Age**	
	F-statistic	P value	F-statistic	P value	F-statistic	P value
Mode 1	23	< 0.001	1.0	0.34	2.7	0.12
Mode 2	14	< 0.001	0.7	0.40	0.1	0.77
Mode 3	1.0	0.41	7.7	0.01	0.02	0.89
Mode 4	1.8	0.11	3.2	0.09	0.1	0.76
Mode 5	2.6	0.03	0.03	0.87	3.4	0.08

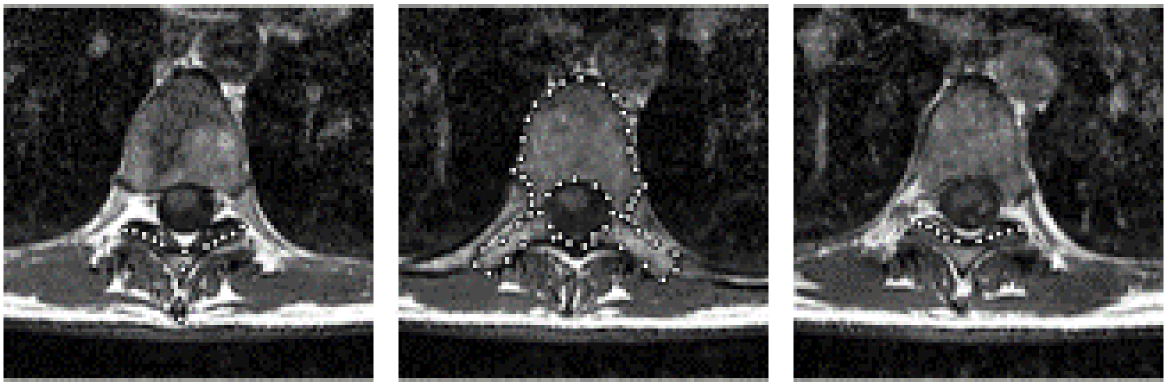

Figure 1. Three slices from a vertebra stack showing the placement of the 77 landmark points.

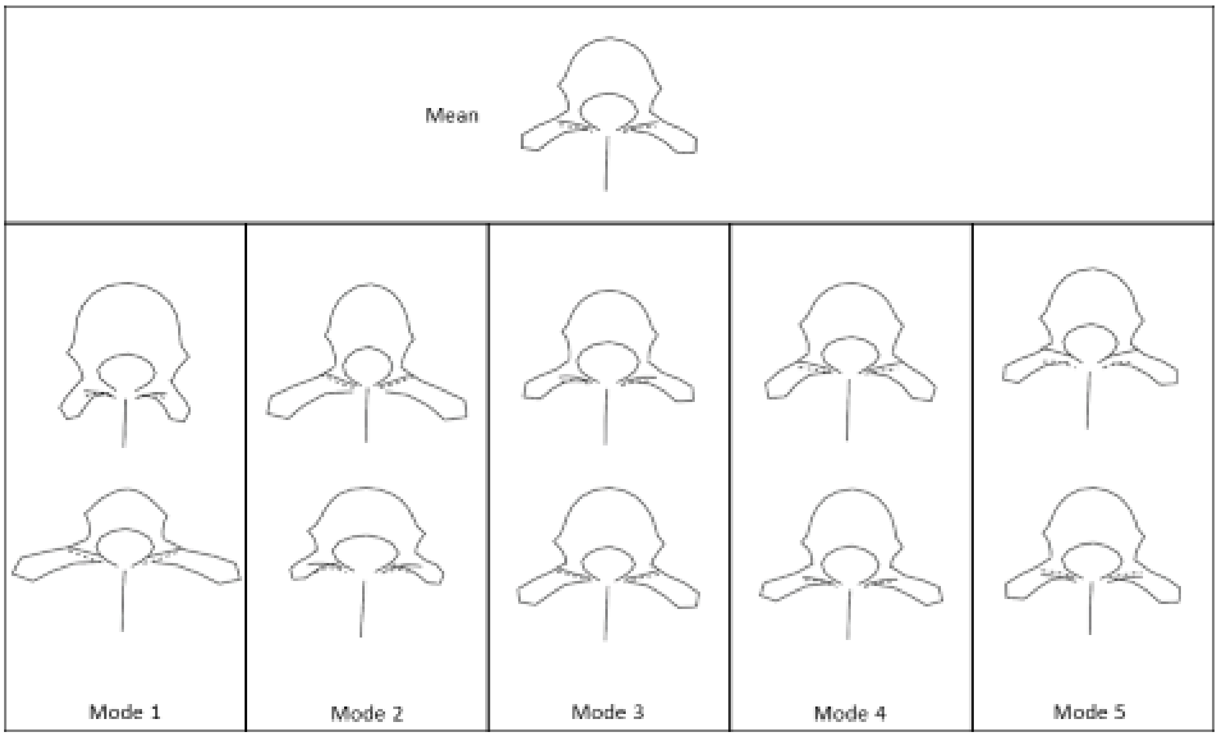

Figure 2. Mean shape and first five modes of variation. For each mode the upper image shows +2 standard deviations, and the lower image -2 standard deviations, from the mean shape. The superior facet is shown as a solid line and the inferior facet as a dashed line.

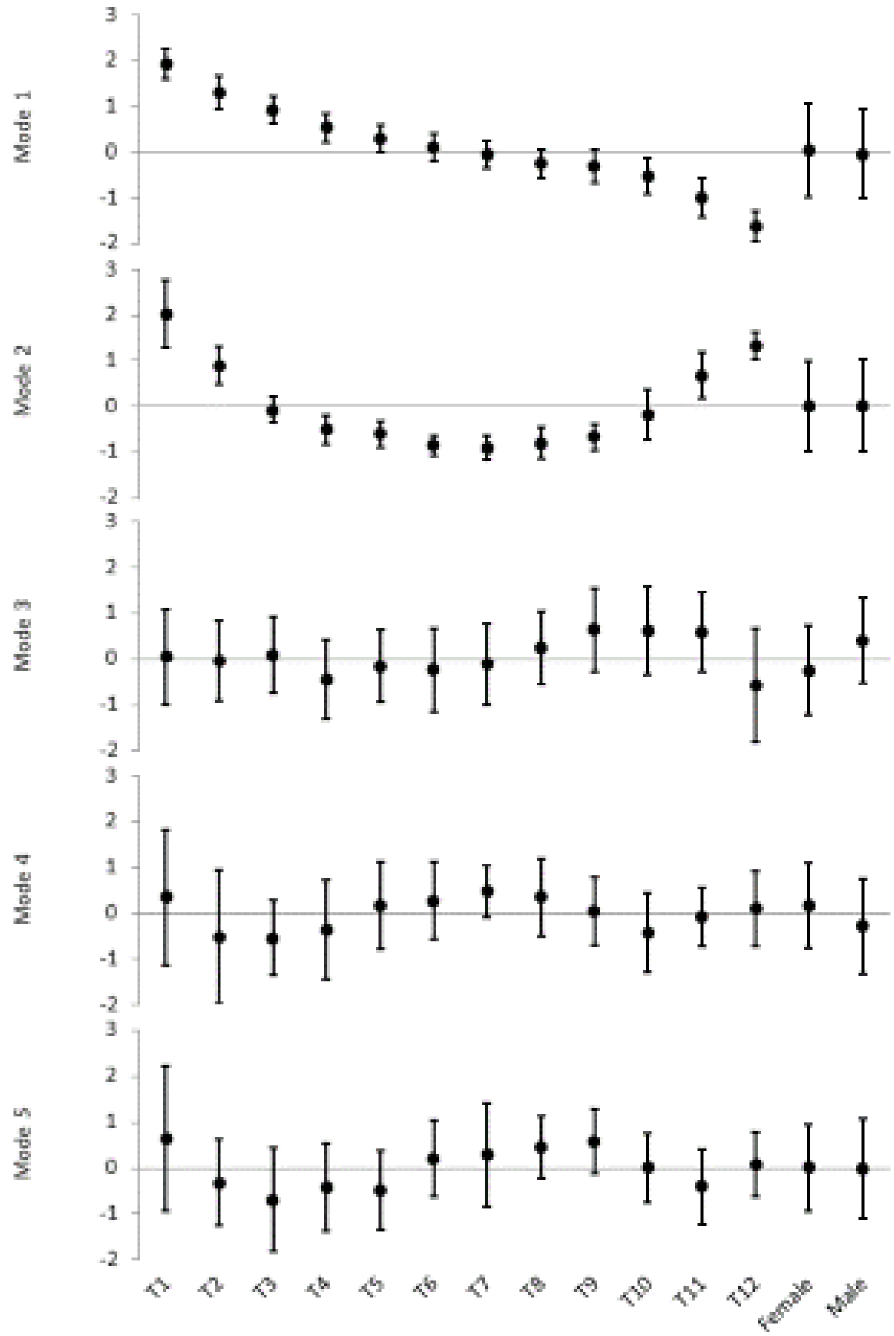

Figure 3. Mode scores along the thoracic spine (T1-T12) and for males and females. Data points indicate the mean values (n = 20 (T1-T12), 8 (male), 12 (female)) with error bars showing 1 standard deviation.

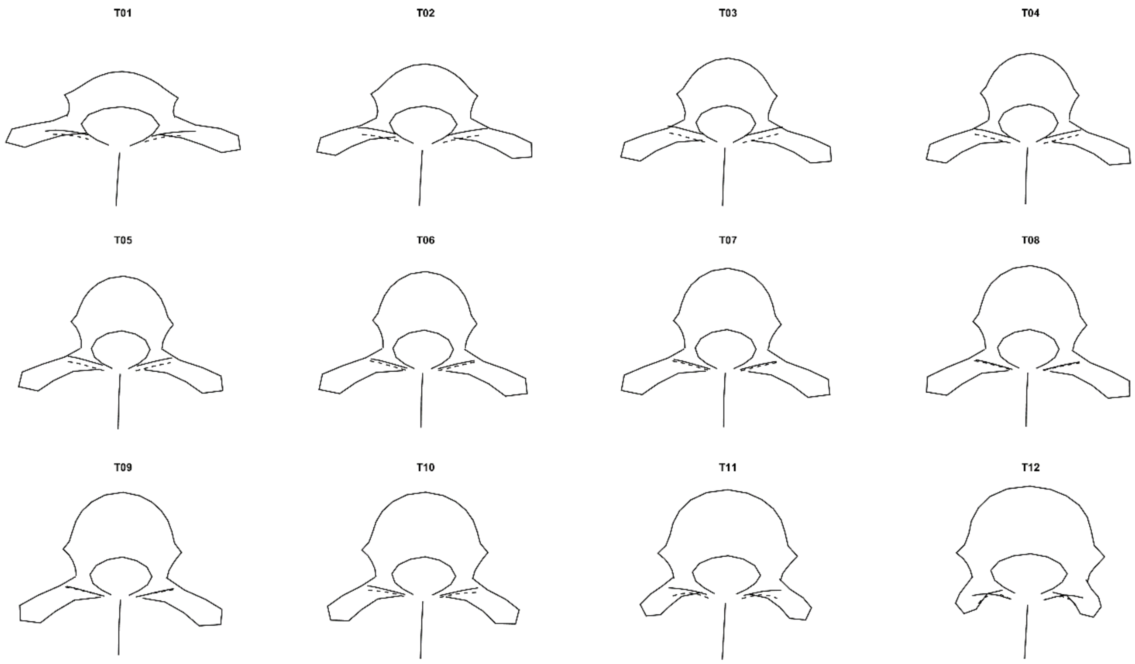

Figure 4. Mean thoracic vertebral shape. The shape of each vertebra represents the mean of the 20 participants and was reconstructed from the first 5 modes. The superior facet is shown as a solid line and the inferior facet as a dashed line.

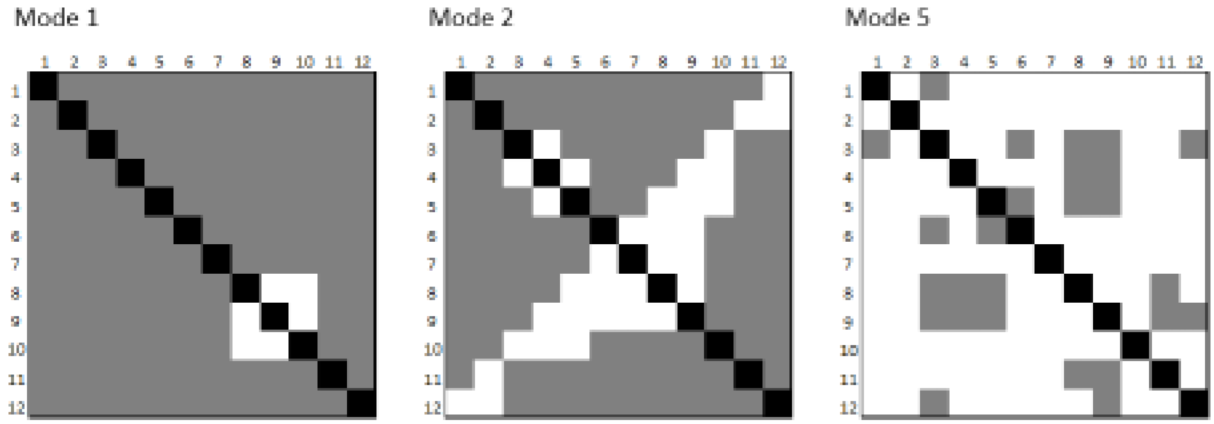

Figure 5. Visualisation of the results of the pairwise comparisons between vertebrae mode scores. Grey: significantly different ($p < 0.05$), white: not significantly different ($p > 0.05$), black: not applicable.