A statistical approach to predict subject-specific morphometry of the human thoracic and lumbar spine from radiographic images

Cumulative Dissertation to Obtain the Doctoral Degree
of Human Biology (Dr. biol. hum.)
of the Medical Faculty of Ulm University

handed by Maria Elizete Kunkel
Fortaleza (Brazil)

2011
This thesis is dedicated to my parentes, Maria Ivonete S. Rodrigues and Joaquim R. Souza, that although they never had the chance to go to school they have given me the opportunity of an excellent education.

This thesis is also dedicated to my son Adrian Kunkel whose laughter and joy are the reason of my life.

Acting Dean: Prof. Dr. Thomas Wirth
1. Reviewer: Prof. Dr. Hans Joachim Wilke
2. Reviewer: Prof. Dr. Tobias M. Böckers

Date of Defense: January 20, 2012
"When you can measure what you are speaking about, and express it in numbers, you know something about it, when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts advanced to the stage of science."

William Thomson Kelvin
Contents

1. Introduction 1

2. Prediction equations for human thoracic and lumbar vertebral morphometry 8

3. Prediction of the human thoracic and lumbar articular facet joint morphometry from radiographic images 14

4. Morphometric analysis of the relationships between intervertebral disc and vertebral body heights: An anatomical and radiographic study of the human thoracic spine 19

5. Conclusion 25

6. Summary 27

7. References 29

A. Acknowledgements 39

B. Scientific Curriculum Vitae 40

C. Papers 41
Nomenclature

2D  two-dimensional
3D  three-dimensional
ADH  anterior disc height
AFJ  articular facet joints
AP  anterior-posterior
CT  computed tomography
CV  coefficient of variation
EPDI  end-plate depth inferior
EPDS  end-plate depth superior
EPII  end-plate inclination inferior
EPIS  end-plate inclination superior
EPWI  end-plate width inferior
EPWS  end-plate width superior
FE  finite element
FHIL  facet height inferior left
FHIR  facet height inferior right
FHSL  facet height superior left
FHSR  facet height superior right
FWIL  facet height inferior left
FWIR  facet height inferior right
FWSL  facet width superior left
FWSR  facet height superior right
IFHL  interfacet height left
IFHR  interfacet height right
IFWI  interfacet width inferior
IFWS  interfacet width superior
L1  1st lumbar vertebra
L2  2nd lumbar vertebra
L3  3rd lumbar vertebra
L4  4th lumbar vertebra
L5  5th lumbar vertebra
MDH  middle disc height
mm  millimetres
MRI magnetic resonance imaging
P  statistical significance level
PDH  posterior disc height
PHL  pedicle height left
PHR  pedicle height right
PSIL  pedicle sagittal inclination left
PSIR  pedicle sagittal inclination right
PTIL  pedicle transverse inclination left
PTIR  pedicle transverse inclination right
PWL  pedicle width left
PWR  sagittal width right
R²  correlation coefficient
SAIL  sagittal angle inferior left
SAIR  sagittal angle inferior right
SASL  sagittal angle superior left
SASR  sagittal angle superior right
SCD  sagittal canal depth
SCW  spinal canal width
SD  standard deviation
SE  standard error
SPL  spinous process length
T1  1st thoracal vertebra
T2  2nd thoracal vertebra
T3  3rd thoracal vertebra
T4  4th thoracal vertebra
T5  5th thoracal vertebra
T6  6th thoracal vertebra
T7  7th thoracal vertebra
T8  8th thoracal vertebra
T9  9th thoracal vertebra
T10  10th thoracal vertebra
T11  11th thoracal vertebra
T12  12th thoracal vertebra
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAIL</td>
<td>transverse angle inferior left</td>
</tr>
<tr>
<td>TAIR</td>
<td>transverse angle superior right</td>
</tr>
<tr>
<td>TASL</td>
<td>transverse angle superior left</td>
</tr>
<tr>
<td>TASR</td>
<td>transverse angle inferior right</td>
</tr>
<tr>
<td>TIVD</td>
<td>thoracic intervertebral disc</td>
</tr>
<tr>
<td>TPD</td>
<td>transverse process depth</td>
</tr>
<tr>
<td>TPW</td>
<td>transverse process width</td>
</tr>
<tr>
<td>VBD</td>
<td>vertebral body depth</td>
</tr>
<tr>
<td>VBHA</td>
<td>vertebral body height anterior</td>
</tr>
<tr>
<td>VBHP</td>
<td>vertebral body height posterior</td>
</tr>
<tr>
<td>VBW</td>
<td>vertebral body width</td>
</tr>
</tbody>
</table>
1. Introduction

During the last decade there have been considerable developments in new techniques of surgical treatments to stabilize and correct the human spine. Many approaches have been proposed for patient-specific modeling of the human spine to explore the correction of spinal deformities, such as scoliosis, by spinal instrumentation. The current increased interest in biomechanical models of the spine and spinal implants calls for a detailed knowledge of spine morphometry and relationships between geometrical dimensions of the vertebrae and the intervertebral discs. The malfunction of these structures due to spinal pathologies or accidents represents worldwide a high-cost for medical care (Hansson & Hansson 2000, Wenig et al. 2009). Accurate anatomical descriptions of the size, shape and orientation of the main structures of the human vertebrae and intervertebral discs are necessary for a variety of approaches and objectives:

(1) The identification of clinical situations that are related to the morphometry of the spine structures, such as the incidence of low-back pain related to the spinal canal size (Porter et al 1980); the incidence of disc herniation dependent on the shape of the lumbar vertebrae (Frederick et al. 2001); rotational coupling in the spine or disc failure due to the orientation of the articular facets (Farfan & Sullivan 1967; Adams & Hutton 1983; Duncan & Ahmed 1989; Abumi et al. 1990). (2) The development of anthropological and forensic approaches for the identification of human remains where precise information about quantitative aspects of vertebral and intervertebral disc morphometry is required (Jason & Taylor 1995; Kósa & Castellana 2005; Yu & Lee 2008). (3) The understanding of both the normal and abnormal morphology of the spine in cases of spine disorders such as scoliosis and kyphosis (Manns et al 1996; Parent et al. 2004). (4) The development and use of implantable devices for spinal instrumentation, e.g. design of transpedicular fixation devices based on the size and orientation of the pedicles (Krag et al 1986, 1988; Berry et al. 1987; Zindrick et al 1987; Scoles et al. 1988; Abuzayed et al. 2010); analysis of the vertebral morphometry in idiopathic scoliosis treated by pedicle screw instrumentation (Liljenqvist et al. 2000; Parent et al. 2004); development of artificial intervertebral discs (Aharinejad et al. 1990). (5) To compare morphometric similarities and differences of spinal structures of animals which are used as experimental models relative to the humane spine, e.g. vertebrae (Wilke et al. 1996, 1997a, 1997b; McLain & Yerby, 2002) and
intervertebral discs (O’Connell et al. 2007). (6) To build a base of anatomical data for the construction of accurate parameterized mathematical models of the human spine (Nissan & Gilad, 1984).

Several quantitative studies have investigated the external geometry of the vertebrae and intervertebral discs of different regions of the human spine. Morphometric measurements with cadaveric vertebrae have been taken directly from bony specimens or have been obtained from medical images (e.g. plain radiographs, computed tomography (CT) or magnetic resonance imaging (MRI)). However, these in vitro studies have focused on only a specific anatomical structure such as the vertebral body (Larsen 1985a, 1985b; Hall et al. 1998), spinal canal (Huizinga et al. 1952; Jones 1978; Eisenstein 1976, 1977, 1983; Postacchini et al. 1983), pedicle (Zindrick et al. 1987; Krag et al. 1988; Marchesi et al. 1988; Moran et al. 1989; Olsewski et al. 1990) and articular facet joints (van Schaik et al. 1985a; Cotterill et al. 1986; Berry et al. 1987; Scoles et al. 1988; Ahmed et al. 1990; Boszczyk 1997; Ebraheim et al. 1997; Laporte et al. 2000; Masharawi et al. 2004, 2005, 2007a, 2007b; Wang & Yang 2009), in a limited set of structures (Berry et al. 1987), in a limited segment of the spine such as thoracic (Cotterill et al. 1986; Scole et al. 1988; Aharinejad et al. 1990) or lumbar (Berry et al. 1987; Boszczyk 1997; Semaan et al. 2001), or in a specific population group such as South African negroes (Eisenstein, 1977), Italians (Postacchini et al. 1983), Japanese (Nojiri et al. 1990), Koreans (Lee et al. 1995) and Indians (Singh et al. 2011). The most complete collection of quantitative three-dimensional (3D) surface anatomy of the main vertebral parameters of the entire human spine was provided in Panjabi et al. (1991; 1992; 1993) (Figure 1). Since this dataset has been used in the current research, a detailed description of the measured parameters will be provided in the Chapters 2 and 3.

In vivo, accurate assessment of the geometry of the vertebrae has been typically obtained through segmentation and 3D reconstruction of CT data (e.g. van Schaik et al. 1985b) or MRI (e.g. Dai 2001). These techniques provide accurate geometrical assessment, but since this process cannot be totally automated, a long processing time and considerable computational power is required for the manual or semi-automatic segmentation of the images. Moreover, as well as besides being an expensive method, for CT imaging the subject has to be submitted to relatively high doses of ionizing radiation, and since it is performed
with the patient in a supine position, changing in the spine posture should be considered (Yazici et al. 2001).

**Figure 1**: Schematic representation of anatomical dimensions of the human thoracic vertebra. Tree orthogonal views, front (A), side (B), top (C), and an isometric view showing the coordinate system used to define these dimensions (D). (Panjabi et al. 1991).

Geometrical dimensions of the human lumbar intervertebral discs are found in several studies (e.g. Farfan et al. 1972; Nissan & Gilad, 1986; Amonno-Kuofi 1991; Eijkelkamp 2002; Shao et al. 2002; van der Houwen et al. 2010). However, the morphometry of the thoracic discs has received limited attention despite the thoracic spine being the most common site for spinal deformities such as kyphosis, lordosis and scoliosis. For example, accurate anatomical data on the disc heights including all levels of the thoracic spine of a representative adult population are very scarce. Few *ex vivo* studies have been carried out on the thoracic disc due to the difficulty in obtaining intact human specimens. Previous studies showed limitations either in accuracy, study population, parameters recorded, or disc level. Todd & Pyle (1928) measured only anterior heights of discs of male cadavers. Pooni et al. (1986) used only a few elderly cadavers, and the data were published
only as a percentage of the total spine height. Radiographic measurements by Goh et al. (1999) and Giles & Singer (2000) were performed for the investigation of thoracic kyphosis, but the anterior and posterior heights of the disc were not provided and only a segmental trend was reported. The measurements of thoracic disc heights by Pooni et al. (1986), Goh et al. (1999) and Giles & Singer (2000) were performed on plain radiographs. The repeatability of these measurements have been questioned due to a lack of the requisites needed to perform geometric measurements with relative accuracy such as the use of a standard vertebral position, control of the film-specimen-focus distances and optimal visualization of the bony landmarks (Pope et al. 1977; Andersson et al. 1981). Furthermore, in some of these investigations, errors due to radiographic magnification bias or inter- and intraobserver reliability of the radiographic measurements were not taken into account (Hurxthal 1968; Manns et al. 1986; Pooni et al. 1986). For example, Hurxthal (1968) and Manns et al. (1986) measured anterior disc height using radiographs of female patients but only a limited number of thoracic levels (from T5-6 to T11-12) were investigated.

Planar radiography is the technique frequently used in clinical diagnosis and for evaluation of spinal deformities (Dupuis et al. 1985; Carman et al. 1990). Due to this fact, some approaches were proposed in recent decades to extract geometrical information of the spine from radiographs (Gilad & Nissan, 1986). The main advantage of these approaches is that radiography enables capture of the entire bony structures of the spine while being much less invasive and expensive than CT. The disadvantage is that radiographs are two-dimensional (2D) projections and do not allow direct assessment of 3D information of the spine’s structures. Therefore, the main problem that arises is in determining the real dimensions of the structures captured by X-rays as well as to identify their shape, position and orientation in all planes. The stereo-radiographic approach is an alternative procedure that has been proposed for 3D reconstruction of the spinal structures (e.g. Dansereau & Stokes, 1988). In this case, one film plane is used, and two exposures are made with different positions of the X-ray source (Aubin et al. 1997; Petit et al. 1998; Cheriet et al. 1999a, 1999b; Dumas et al. 2003, 2004; Kadoury et al. 2007a, 2007b). It provides good parameterized information about the vertebrae, but it is also time-consuming (due to the long process of identification of numerous anatomical landmarks) and resource-consuming requiring specific software and hardware. The most accurate methods to provide
vertebral parameters using radiographs are still the semi-automatic approaches (Pomero et al. 2004; Dumas et al. 2008). Benameur et al. (2005) proposed an automatic approach but it was limited to the lower lumbar spine.

**Statistical approaches for prediction of the human spine morphometry**

Several alternative approaches have been used to provide accurate anatomical data related to the morphometry of the human spine. Previous studies have investigated whether vertebral relationships could be used to predict vertebral morphometry using the statistical correlations between anatomical dimensions of the human vertebral structures. A statistical approach based on these relationships could eliminate the need for preliminary processing of medical images such as CT to provide anatomical data on the human spine. However, statistical analyses performed using simple linear regressions between the main parameters of the vertebrae and intervertebral discs (e.g. Gilad & Nissan (1986); Scoles et al. (1988); Skalli et al. (1993); Maurel et al. (1997); Breglia (2006)) found low or no correlations for some important parameters, such as the dimensions of pedicles. Scoles et al. (1988) for example, described the posterior structures of the vertebrae as being highly variable and largely unpredictable. Some studies used multiple linear regression analyses (e.g. Lavaste et al. 1992; Laport et al. 2000) to provide methods for the reconstruction of the human vertebrae from two radiographs (anterior-posterior (AP) and lateral). They used statistical relationships between vertebral dimensions to generate vertebral data for parameterized models of the spine. However, the models based on the generated parameters have a very simplified geometry and the ability to predict vertebral parameters with this approach has been questioned because no validation using a second set of experimental measurements was provided (Lavaste et al. 1992; Laport et al. 2000).

In all the studies described above, linear regressions were used to find the correlation between the vertebral or intervertebral disc parameters. No study was conducted to investigate whether a non-linear regression (e.g. exponential, logarithmic or polynomial) could provide better results. Furthermore, the relationships between anatomical dimensions of the vertebrae and intervertebral discs including the thoracic and lumbar spine have never been investigated. To the author’s knowledge, to date no report has presented a statistical approach for
useful predictors of intervertebral disc dimensions based on the size of the vertebral bodies. Such quantitative analysis could provide anatomical data for patient-specific modelling of the spine from only one or a few initial vertebral dimensions.

Numerous studies have reported the impact of the use of the finite element (FE) method in conjunction with experimental studies to investigate the mechanical behaviour of the normal and pathological human spine (e.g. Gilbertson et al. 1995; Goel & Gilbertson, 1995). In FE modelling, an anatomical structure is divided into a finite number of elements that can interact with one another through their points of attachment. The important geometrical and material properties of this structure may be incorporated into the FE model and different types of structural analyses (e.g. static, dynamic) can be carried out by simulating a variety of clinical situations.

During the last decade, many biomechanical models have been proposed in order to simulate surgical correction of scoliosis supported by spinal instrumentation (Lafage et al. (2002, 2004); Duke et al. (2004); Dumas et al. (2005)). Scoliosis is a complex 3D structural deformity of the spine that involves morphological deformation of the vertebrae (e.g. asymmetrical pedicle length, spinous process deviation, facet joint asymmetry and intervertebral discs (Stokes, 1994)). Such biomechanical models have been considered as a way to overcome the limitation of the clinical investigations and laboratory experiments with cadavers and animals. Since the accuracy and reliability of the mathematical modelling of the human spine depends directly on the geometry of the spinal structures, reliable biomechanical simulations of the behaviour of the human spine require 3D modelling of the complex anatomy of the vertebrae and intervertebral discs (Robin, 1994).

Consider the articular facet joints, which are vertebral structures that play an important role in the biomechanics of the spine, because they transmit a significant percentage of the spinal loading, and provide translational, rotational and axial spinal stability (Lorenz et al. 1983; Adams & Hutton, 1993; Onan et al. 1998). The physiological motion of the spine is thus strongly dependent on the shape, position and orientation of the AFJ (Taylor & Twomey, 1986; White & Panjabi, 1990). This issue has been investigated in normal and pathological conditions through FE models of the spine created from 3D reconstruction of CT images (Shirazi-Adl 1991, 1994; Zander et al. 2003; Schmidt et al. 2008a, 2008b,
However, in cases of simulations of spinal deformities such as scoliosis, morphological changes in the anatomy of the AFJ such as facet height and width, and facet angles should be implemented in the computer models (Millner & Dickson, 1996; Maurel et al. 1997; Parent et al. 2002; Aebi, 2005). Since it is difficult to appropriately to modify the geometry obtained from CT reconstructions, FE models with a simple but parameterized geometry could be an alternative to these complex models. In parameterized models of the spine, different vertebral and disc geometries may be created merely by changing the input data or parameters that represent the anatomical dimensions (Maurel et al. 1997).

Using an adequate statistical approach, the initial measurements of only a few dimensions on radiographs of patients (e.g. vertebral body height) could be enough for a rapid prediction of other dimensions (e.g. articular facet size or orientation) by using the relationships between them. Most surgical procedures for spinal deformity corrections are based on the average values of vertebral dimensions of a healthy spine, without taking into account the fact that each patient has a specific morphometry. A statistical approach allowing rapid acquisition of geometrical parameters specific to a given subject could be used both for clinical evaluation and for parameterized subject-specific modelling of the spine for biomechanical research.

The objective of this cumulative PhD-thesis was to develop a statistical approach for the acquisition of subject-specific morphometry of the main thoracic and lumbar spinal dimensions from radiographic images. Some research questions related to spine morphometry that have not been sufficiently addressed in the previous studies have been formulated as hypotheses:

(i.) The main vertebral and intervertebral disc dimensions can be measured on lateral radiographs with ease and accuracy.

(ii.) There are unique vertebral dimensions that show good correlation between all other vertebral and intervertebral disc dimensions.

(iii.) The result of these correlations depends on the inclusion or exclusion of given spinal levels (e.g. the transition regions) or the consideration of only a particular region of the spine (e.g. thoracic or lumbar).

(iv.) A nonlinear regression would be able to better describe these correlations than a linear regression by means of an equation.

(v.) It is possible to predict accurately vertebral and disc morphometry of the thoracic and lumbar spine from only one initial dimension
(vi.) It is possible to predict linear and angular dimensions of the vertebrae and intervertebral discs that are not visible on lateral radiographs.

(vii.) It is possible to make specific predictions of the morphometry of the vertebrae and intervertebral discs for an individual using these equations.

(viii.) It is possible to validate these prediction equations.

In order to test these hypotheses, three studies concerned with the morphometry of the vertebrae and intervertebral discs of the thoracic and lumbar spine were carried out using a linear and nonlinear statistical approach. The results of these studies were published in three peer reviewed articles in the Journal of Anatomy being summarised in the following sections of this cumulative PhD-thesis (see the articles attached). In Chapter 2, a morphometric analysis performed with experimental vertebral data is described. Prediction equations were generated to estimate the main anatomical dimensions of the thoracic and lumbar vertebrae from the unique radiographic measurement of heights the vertebral bodies. A similar approach is presented in Chapter 3 to predict the articular facet joints morphometry taking into consideration the anatomical variation between the thoracic and lumbar vertebrae. Chapter 4 describes an ex vivo study for direct and radiographic measurements of the human thoracic intervertebral disc height. The radiological measurement error was calculated. Equations were generated for the prediction of the intervertebral disc height from measurement of the heights of vertebral bodies using a similar statistical approach.

2. Prediction equations for human thoracic and lumbar vertebral morphometry


Statistical correlations between anatomical dimensions of vertebral structures have indicated a potential that could be applied to provide geometric data for the development of simplified geometrical models of the spine while excluding the need for preliminary processing of medical images (e.g. Scoles et al. 1988; Lavaste et al. 1992; Laporte et al. 2000; Breglia, 2006). In this study, linear and
nonlinear regressions were performed for the generation of prediction equations for 20 vertebral parameters of the human thoracic and lumbar spine as a function of only one given vertebral parameter that could be measured from radiographs.

The complex geometry of the thoracic and lumbar vertebrae from the level T1 to L4 was simplified as 21 vertebral parameters related to the end-plate, vertebral body, pedicle, spinal canal, and spinous and transverse processes (Figure 2). The vertebral data were obtained from the cadaveric studies of Panjabi et al. (1991; 1992; 1993). This data set represents an average of a non pathological adult population including the means values of 15 linear and 6 angular parameters of 12 human cadavers. The mean age of the subjects was 46.3 years (range: 19 – 59 years), weight was 67.8 kg (range: 54 – 85 kg), height was 167.8 cm (range: 157 – 178 cm), and the male / female ratio was 8:4.

Figure 2: Schematic representation of the 21 vertebral parameters that were considered for linear and nonlinear regression analyses.
Each of these 21 vertebral parameter was considered and tested individually as a predictor variable. The parameters were individually regressed against the possible predictor variable by a least-squares estimation process. Based on the level of correlation with the other parameters and ease of measurement on lateral radiographs, the parameter VBHP was chosen and the statistical analyses described in this study are related to this parameter. Linear and nonlinear regression analyses were employed to find the best functions to fit each parameter in a prediction equation. The following hypotheses were tested: (i) a function could not fit the data significantly better than a horizontal line; (ii) a second-order equation could not fit the data significantly better than a linear equation; (iii) a third-order equation could not fit the data significantly better than a second-order equation, and so on.

The statistical procedure performed on each parameter corresponds to four-steps: Consider the parameters EPWS and VBHP (Figure 3): (1) Least-squares estimation was used to find equations to describe the relationship between EPWS and VBHP. Initially, a linear regression was performed, fitting an equation of the form $y = C_1 + C_2x$ to the data. The variance of the EPWS was determined by the $R^2$ value. A logarithmic and an exponential curve with equations of the form $y = C_1 + C_2\ln(x)$ and $y = C_1e^{C_2x}$, respectively, were then used to test the increase in $R^2$. Next, polynomial equations including more coefficients ($C_1$, $C_2$, $C_3$, $C_4$, etc.) were used to find the best fit. This was continued until adding another higher-order term did not significantly increase $R^2$. (2) An analysis of variance was performed to select the best prediction equation. High values of $R^2$ associated with a $P$-value $< 0.01$ indicated the third-order polynomial as the best-fitting equation. (3) It was evaluated how the selected nonlinear equation fits the EPWS data significantly better than a linear equation by superimposing experimental values. (4) The predictability of the best-fitting equation was evaluated using experimental data from two further datasets (Berry et al. (1987); Scoles et al. (1988)).
Figure 3: Description of the statistical procedure for the parameters EPWS and VBHP of the thoracic and lumbar spine. Set of prediction equations generated from linear, logarithmic, exponential and polynomial regression analyses (y is the value of EPWS and x is the VBHP on each vertebral level).

The linear, exponential and logarithmic regressions provided significant predictions of parameters related to the anterior vertebral structures from the values of VBHP. However, third-order polynomial prediction equations allowed an improvement on these predictions (P-values < 0.001), e.g., end-plates and spinal canal ($R^2$; 0.970-0.995) as well as pedicle heights and the spinous process ($R^2$; 0.811-0.882), in addition to a reasonable prediction of the parameters of the posterior vertebral structures which have shown a low or no correlation with VBHP in previous studies, e.g., pedicles inclination and transverse process ($R^2$; 0.514-0.693) (ANOVA). The inclusion of more than four coefficients increased the $R^2$ values but the obtained correlations did not significantly improve the parameter predictions. The polynomial predictions were generally within or close to the regions of the 95% confidence intervals of the experimental data of Panjabi et al. (1991; 1992) (Figure 4). Comparisons of the theoretical predictions with two sets of experimental data indicated that the predictions generally agree well with these data (Figure 5).
The present study provided a time efficient approach for the prediction of morphometry of the human thoracic and lumbar vertebrae. It allows a better understanding of statistical correlations between these vertebral dimensions and could be used to provide data for geometrical modeling of the human vertebrae. It requires the measurement of only one parameter per vertebra (VBHP) from a lateral radiograph, and the set of developed prediction equations. Vertebral models based on this type of parameterized geometry could be used in biomechanical studies which require variation of the geometry, such as in spinal deformations, including scoliosis. All correlation coefficients found in the current study were considerably better than the values obtained in previous studies. Scoles et al. (1988) reported the impossibility to establish useful predictors for pedicle dimensions based on the size of the vertebral body; Lavaste et al. (1992) developed a method to reconstruct lumbar vertebral geometry from radiographs.
using multiple-linear regression analysis, requiring six given parameters per vertebra to predict the vertebral geometry with a digitalization process that showed a relative error of approximately 15%; Laporte et al. (2000) required the measurement of 15 parameters per thoracic vertebra from radiographs in order to predict each other parameter; Breglia (2006) used only linear regressions with the same data from Panjab as used in the current study and could not predict the parameters related to posterior structures.

The differential in the current study in relation to these previous studies is based on two facts that were considered in the statistical analyses: (1) The data corresponding to the vertebral level L5 were not included in the regressions. Several studies reporting the remarkable morphological differences found in the structures of this vertebral level when compared with the neighbouring vertebrae as due to L5 to being in a transition zone, from lumbar to sacral region (Berry et al. 1987; Zindrick et al. 1987; Scoles et al. 1988; Panjabi et al. 1989; 1992). (2) Linear and nonlinear regressions were tested and compared. The relationships between the vertebral variables follow a curved line, not a straight line. Fitting a nonlinear equation such as polynomial regression provides better results because polynomial equations can be used to create a generic curve through the data points; more coefficients better fit the data.

There are three advantages to the use of the developed approach to predict 20 vertebral parameters per vertebral level (T1-L4) with radiographic measurement of the VBHP. This reduces by approximately 94% the need for individual measurement of 20 parameters per vertebral level; it provides information about the angular parameters that were not measurable in radiographs; and since this statistical approach is based on the geometrical relationships between the vertebrae, the measurement of the VBHP of a subject provides parameters taking into account geometric characteristics specific of the subject.
3. Prediction of the human thoracic and lumbar articular facet joint morphometry from radiographic images


Although it is well known that some dimensions of the articular facet joints (AFJ) (e.g. facet height / width or facet angles) play a major role in spinal deformities such as scoliosis, little is known about statistical correlations between these dimensions and the size of the vertebral bodies. Breglia (2006) investigated only two AFJ parameters and a poor correlation between them and the VBHP was found. Other studies that investigated statistical correlations between AFJ parameters and many other parameters reported that a unique parameter could not provide an accurate prediction (Lavaste et al. 1992; Skalli et al. 1993; Maurel et al. 1997; Laport et al. 2000). It would be of clinical interest to use such relationships for subject-specific predictions of AFJ parameters for mathematical modelling of the spine from a single dimensions measurable from radiographs. The aim of this study was to generate prediction equations for 20 parameters of the human thoracic and lumbar AFJ from T1 to L4 as a function of only one given parameter, the VBHP.

In order to carry out statistical analyses, the anatomical measurement of the VBHP and 20 anatomical measurements related to the size and orientation of the human thoracic (T1-12) and lumbar (L1-4) AFJ were selected from the data of Panjabi et al. (1991; 1992; 1993) (Figure 6). To perform linear and nonlinear regression with these data, the same methodology used in the Chapter 2 (Kunkel et al. (2010)) was adopted with the parameter VBHP as the predictor variable. However, due to the existence of a considerable difference between the morphometry of the AFJ in the thoracic and lumbar regions, a modification was introduced in order to achieve a better prediction of the AFJ parameters. It refers to separate regressions using thoracic (T1-12) and lumbar (L1-4) data together, thoracic data alone, and lumbar data alone. (1) The identification of the best prediction equations was based on values of $R^2 > 0.5$ associated with a probability
level of $P$-value < 0.05 and a standard error of the estimate (SE) < 30% of the standard deviations of the experimental data of Panjabi et al. (1993). For validation, the theoretical predictions were plotted against the experimental data of Panjabi et al. (1993) and Cotterill et al. (1986).

**Figure 6:** Schematic representation of the anatomical parameters that were considered for linear and nonlinear regression analyses: Vertebral body height posterior and dimensions of the articular facet joints linear and angular.

Third-order polynomial regressions in contrast to the linear, exponential, logarithmic and polynomial regressions with other orders provided the best results with significant correlations between each of the AFJ parameters and VBHP. The polynomial regressions using the thoracic and lumbar data together showed variable correlations with VBHP ($R^2$, from 0.516 to 0.950) providing significant prediction equations for all selected AFJ parameters from VBHP (an exception was FWSL). When considering the polynomial regressions for only the thoracic data (T1-12), this resulted in improvements for predictions of 70% of the thoracic AFJ parameters such as an increase of $R^2$ (from 0.650 to 0.973), an increase in
the significance and a decrease of SE. Polynomial regressions considering only lumbar data (L1-4) did not reach the minimum criteria required for the selection of the prediction equations and the polynomial coefficients obtained from the regressions using the thoracic and lumbar data together were used. Third-order polynomial regressions provided moderate to high correlations between the AFJ parameters and VBHP (e.g. facet height superior and interfacet width ($R^2$, 0.605-0.880); facet height inferior, interfacet height and sagittal / transverse angle superior ($R^2$, 0.875 - 0.973)). Different correlations were found for facet width and transverse angle inferior in the thoracic ($R^2$, 0.703 - 0.930) and lumbar ($R^2$, 0.457 - 0.892) regions.

Comparisons with experimental data of Panjabi et al. (1993) showed that the best predictions were found for FHIR with a mean percent error of approximately 14% in T12 and a maximal error of 7% in all other levels. The largest error of approximately -17% was found for FHSL predictions in the lumbar level (Figure 7). High correlations were found for TASL with VBHP for all levels ($R^2$, 0.785–0.938). TAIR displayed a poor correlation ($R^2 = 0.526$) for the lumbar levels (Figure 7). The predictions with the data of Panjabi et al. (1993) showed the largest mean percent error of approximately 10%. Comparison of the predictions of the interfacet heights and width with experimental data of Cotterill et al. (1986) indicated mean percent errors < 16%, with the exception of the thoracolumbar junction (T12 - L1).

The best predictions of facet orientations were found for the transverse angles, probably because these parameters show very little variability within the vertebrae from T1 to L4. Notably in the midthoracic region (i.e. T3-8) excellent predictions with errors < 10% could be achieved for most parameters of the AFJ. In contrast, in the thoracolumbar junction (T12-L1) were found predictions with errors of up to -15% for all sagittal angles. This was due to the large variability of this region within individuals being the AFJ either frontally oriented as in the thoracic vertebrae or sagittally oriented as in the lumbar vertebrae. This is in accordance with Goel & Weinstein (1990) and Masharavi et al. (2004) who showed that the morphology of the first lumbar vertebra is distinct from the other vertebrae with a transition from the typically thoracic to the lumbar vertebra.
Figure 7: Polynomial predictions of some linear (FHIR and FHSL) and angular (TASL and TAIR) parameters of the thoracic and lumbar articular facet joints from VBHP, superimposed on experimental data of Panjabi et al. (1993)*. Dotted curves indicate standard deviation of both the predictions and experimental data. $R^2$ is provided for thoracic and for lumbar levels. Only mean percent errors > 5% for all vertebral levels are shown.

Due to the superposition of several anatomical structures, specifically in the sagittal thoracic region of the spine, the direct measurement of the main AFJ parameters considering each vertebral level cannot be performed using lateral radiographs. Moreover, the lumbar AFJ are difficult to image with radiographs because they are both curved and oblique to the sagittal plane. The advantage of using the generated set of prediction equations is the capability to obtain size and
orientations of the AFJ considering individual variability from only a single parameter per vertebra (VBHP) measurable on a lateral X-ray. It could be used to provide data for parameterized finite element modelling considering patient-specific AFJ morphometry (Figure 8).

Figure 8: Geometrical model of the thoracic spine including the articular facet joints. The VBHP obtained from lateral radiographs allowed generation of AFJ data using the set of prediction equations.

This study showed that it was possible to establish useful predictors for human thoracic and lumbar AFJ parameters based on the size of the vertebral body. The generated set of prediction equations enables fast acquisition of 20 geometrical parameters of the AFJ as a function of a single parameter (VBHP) which is measurable in lateral radiographs. Since the vertebral body height is unique for each person and vertebral level, the predicted AFJ parameters are also specific to an individual. This approach could be used for parameterized patient-specific modelling of the spine to explore the clinically important mechanical roles of the articular facets in pathological conditions, such as scoliosis.
4. Morphometric analysis of the relationships between intervertebral disc and vertebral body heights: An anatomical and radiographic study of the human thoracic spine


Morphometric studies on the human intervertebral discs have focused on the cervical and lumbar regions, resulting in limited data on the thoracic region. Intervertebral disc height is an important dimension often used as a diagnostic tool in orthopaedics as well as in mathematical modeling of the human spine. The main aim of this study was to measure the human thoracic intervertebral discs heights by direct and radiographic measurements. Additionally, the heights of the vertebral bodies were measured, and the prediction of the disc heights based on the vertebral bodies was investigated.

Five different heights of the intervertebral discs and vertebral bodies were measured directly and on radiographs of 72 cadaveric spine segments of 15 females (mean age of 58.67 ± 10.74 years, range: 43-80 years) and 15 males (mean age of 56.20 ± 11.65 years, range: 37-79 years) (Figure 9). Six segments were available for each spinal level from C7-T1 to T11-12. A grading system indicated that only mild to moderate degenerative changes were found in the discs and end-plates. Three adimensional morphometric indices were calculated based on studies for lumbar intervertebral discs (Twomey & Taylor 1987; Amonoo-Kuofi 1991).

Lateral radiographs of each spine segment were made using a Faxitron automatic X-ray (Hewlett Packard, Mc Minnville, USA). For the radiographic measurements, individual radiographs were placed on a viewing table and eight anatomical landmarks were identified using Farfan’s method (1973) (Figure 9). The disc and vertebral heights were measured using an electronic digital caliper with an accuracy of ± 0.05 mm. Frozen spinal segments were sectioned in the horizontal plane through each of the upper and lower vertebral bodies. A saw
microtome was used to produce sagittal sections of the discs (Leica SP4000, Leica Microsystems, Wetzlar, Germany). A sliding vernier caliper was used for the measurement of the disc heights (Mitutoyo, Absolute Digimatic, Tokyo, Japan).

Each set of radiographic and anatomical measurements was carried out by two observers. Inter- and intra-observer errors were examined and expressed as a coefficient of variation (CV). Linear regression was used to examine the correlation between the radiographic and anatomical measurements, and to calculate the accuracy of the radiographic one. The heights of the discs and the vertebral bodies were individually regressed by a least-square estimation process based on Kunkel et al. (2010). Linear and nonlinear regression analyses were employed to find the best functions to fit each of these parameters in a prediction equation.

**Figure 9:** Morphometric parameters and indices of the thoracic intervertebral disc. The anatomical landmarks used are indicated by white arrowheads. In the lateral conventional radiographs of the spinal segments (a) and in the sagittal sections of the specimens (b). The images are from a thoracic segment (T9-10) of a 57 year old female donor.
The parameters ADH, VBHA and VBHP were chosen as predictor variables because they could be measured on the radiographs with an acceptable accuracy. An ANOVA was performed to define the significance of the prediction equations (\(P\)-value < 0.05) that were evaluated using experimental data of Todd & Pyle (1928). Radiographic measurements of the disc heights displayed lower repeatability and were shorter than the anatomical ones (approximately 9% for anterior and 37% for posterior heights). The disc height measurements were better repeated when obtained directly from the discs (CV = 0.79 - 0.93) than from the radiographs (CV = 0.49 - 0.82). A lower repeatability was found for radiographic measurement of the PDH (CV = 0.49). Anatomical measurements were reproduced with errors ranging from 1.7% to 6.1% for ADH, 17% to 26.1% for PDH, and 1.7% to 5.1% for VBHA and VBHP. The thickness of the discs varied from 4.5 to 7.2 mm, with the middle heights approximately 22.7% greater. There was a constant relationship between the disc thickness and the vertebral bodies’ heights at all levels (ratio disc : body of approximately 1:4.1).

In general, the disc heights showed good correlations with the vertebral body heights \(\left(R^2, 0.659-0.835, P\text{-values} <0.005\right)\) (ANOVA). An exception was the MDH, for which no significant correlations were found \(\left(R^2 < 0.6, P\text{-value} > 0.05\right)\). A set of 10 polynomial equations was generated for the prediction of thoracic disc heights from parameters that could be accurately measured on the radiographs (ADH, VBHA and VBHP). The polynomial predictions were generally within or close to the region of the 95% confidence intervals of the experimental data measured in the current study (Figure 10).
Figure 10: Radiographic values of the VBHP were used for predictions of the parameters ADH, PDH and VBHA at all levels of the thoracic spine. The predicted values were superimposed on experimentally measured anatomical data. Dotted and continuous curves indicate SD. Mean percent errors of the predictions larger than 10% are indicated. Po, posterior; an, anterior; cr, cranial; ca, caudal.

The evaluation of the predictability of the regression equations using VBHA and VBHP of the dataset of the radiographic measurements showed that good results could be obtained. Using the dataset of Todd & Pyle (1928), a comparison of predicted PDH from radiographic ADH showed a greatest error of approximately -13% in the upper and -17% in the lower regions of the thoracic spine.

In the current study, the two main sources of ambiguity found in radiographic measurements of disc heights (the disc orientation with respect to the central X-ray beam, and the estimation of differences among different observers)
were minimized using the recommendations of Pope et al. (1977) and Andersson et al. (1981). The difficulty in identifying the bony landmarks was overcome by strictly controlling the vertebral position, and preserving the relationships between the intervertebral discs and the vertebral bodies. The radiographic ADH and PDH measurements were shorter than the anatomical ones probably because the anatomical measurements included the cartilaginous end plates that cannot be readily identified on radiographs. Comparison of these direct and radiographic measurements with other studies was difficult due to the fact that there are few comparative data in the literature (e.g. no published data related to MDH was found). For ADH, a good agreement was found with anatomical values of Todd & Pyle (1928), and radiographic values of Manns et al. (1986) and Giles & Singer (2000), although the same was not found for the radiographic PDH values compared with Giles & Singer (2000).

As expected, the radiographic measurements of the thoracic VBHA and VBHP showed very good agreement with the literature (Todd & Pyle, 1928; Cotterill et al. 1986; Berry et al 1987; Scoles et al. 1988; Panjabi et al. 1991; 1992). The generated set of regression equations allowed prediction of the thoracic disc heights from radiographic measurement of the VBHP. ADH could be predicted, with a largest error of approximately 26% and MDH could only be predicted from ADH (largest error of approximately 15%). For estimation of PDH, both ADH and vertebral heights provided good predictions. From the measurement of the vertebral height were predicted values of PDH with approximately 26% error; which was less than the radiographic measurement. For the creation of parameterized models of the human thoracic discs, the use of these prediction equations could eliminate the need for direct measurement on intervertebral discs reducing the error produced by radiographic measurements for the posterior disc heights (Figure 11).
This study provided an accurate database for the thoracic intervertebral disc heights besides of a statistical approach to predict these parameters from radiographic measurements of the VBHP. This may serve as an anthropometric reference for mathematical modelling as well as for anatomical and biomechanical studies of the human spine.
5. Conclusion

In this PhD-thesis, the morphometric relationships between anatomical data of the human thoracic and lumbar vertebrae and thoracic intervertebral discs were described by linear and nonlinear regression analyses. It allowed the generation and validation of a set of regression equations for the prediction of 40 vertebral and 3 intervertebral disc dimensions per spinal level from the unique measurement of the vertebral body height posterior (VBHP) on lateral radiographs. As the VBHP is unique for each person and vertebral level, the predicted parameters are also specific to an individual. This statistical approach for the acquisition of subject-specific morphometry of the main thoracic and lumbar spinal dimensions from radiographic images may be applied to the construction of parameterized subject-specific models of the spine based on X-ray images alone. Such models allow the performance of studies based on variation of geometry without the need for expensive, invasive and time-consuming data collection, such as direct measurement or reconstruction of medical images.

The hypotheses that were formulated at the beginning of this manuscript were tested and the results showed that: (1) There are only some vertebral dimensions that are measurable on lateral radiographs with ease and accuracy (EPDS, EPDI, VBHA, VBHP and SPL) (Figure 2). No AFJ dimension can be measured on lateral radiographs with ease and accuracy (Figure 6). The intervertebral disc heights cannot be accurately measured on lateral radiographs, the lower repeatability was found for the posterior heights (Figure 9). (2) It was possible to find moderate (e.g. pedicles inclination and transverse process) to high (e.g. the dimensions related to end-plates, spinal canal, heights of pedicles and spinous process) correlation between the investigated dimensions and only one dimension measurable on radiographs, the VBHP. In relation to AFJ parameters, a good correlation was found for the linear dimensions (heights, widths and interfacet distances) and orientations (transverse and sagittal angle) with vertebral body heights. With the exception of the middle disc height, it was possible to find moderate to good correlations for the thoracic intervertebral disc heights and the VBHP. (3) The exclusion of the vertebral dimensions related to the level L5 improved all the correlations. With the exception of the AFJ dimensions, there was not found better correlations between the vertebral dimensions considering only the thoracic or only the lumbar spine. It was found better correlations between the
linear and angular AFJ dimensions considering only the thoracic levels. Correlations considering only lumbar data on AFJ did not satisfy the criteria required and for this reason correlations using the combined thoracic and lumbar data together were used. (4) The analysis of covariance indicated that nonlinear regressions (third order polynomial) were able to describe these correlations better than linear regressions. (5) Using the measurement of only the VBHP and the generated set of prediction equations, it was possible to predict vertebral morphometry of the thoracic and lumbar spine with the exception of the level L5. For AFJ dimensions, the best predictions were achieved for the thoracic levels that showed a mean error of approximately 10%, while the lumbar level displayed a mean error of approximately 16% (ANOVA). Using the measurement of only the VBHP and the generated set of prediction equations, it was possible to predict thoracic intervertebral disc heights with an error less than the error of direct measurement. (6) Many vertebral dimensions that are not visible and that cannot be measured on lateral radiographs could be predicted with this statistical approach (e.g. EPWS, EPWI, PWL, PWRPSI, PSIL, SCW, SCD and TPW). All the selected AFJ dimensions that are not visible and that cannot be measured on lateral radiographs could also be predicted. The middle intervertebral disc height of the thoracic spine that does not show a good visibility on lateral radiographs could also be predicted. (7) The radiographic measurement of the VBHP in the thoracic and lumbar levels of the spine of a subject allowed specific predictions for this subject. (8) The regression equations could be validated for some vertebral dimensions by comparisons of predictions with experimental data. For the thoracic intervertebral discs, the regression equations could only be validated for the posterior disc heights by comparisons of predictions with experimental data.
6. Summary

Adolescent idiopathic scoliosis is the most common form of scoliotic deformations of the human spine. Severe cases of scoliosis are treated surgically using rigid implants. However, there is a lack of consensus on the choice of surgical approach and instrumentation to correct the scoliotic spine. Therefore, the morphometric aspects of the scoliotic spine and the effects of different types of implants should be more investigated. Such investigation requires the development of mathematical models with patient-specific and modifiable geometry. Statistical correlations between anatomical dimensions of human vertebral structures indicate a potential for the prediction of vertebral morphometry. This approach could allow prediction of vertebral and intervertebral disc morphometry from a unique initial dimension.

The aim of this research was to perform linear and nonlinear regression analyses with published and measured anatomical data to generate prediction equations for vertebral and intervertebral disc dimensions of the human thoracic and lumbar spine as a function of only one given dimension measurable by X-ray. Each vertebral parameter was considered individually as a potential predictor variable in terms of its correlation with all of the other parameters, together with the ease of measurement in lateral radiographs. The parameter vertebral body height posterior was chosen and the statistical analyses described in this research are related to this parameter.

Third-order polynomial regressions, in contrast to the linear, exponential and logarithmic regressions provided moderate to high correlation between the thoracic and lumbar vertebral body heights and the vertebral anterior and posterior structures (endplates and spinal canal \( R^2, 0.970–0.995 \); pedicle heights and the spinous process \( R^2, 0.811–0.882 \)), in addition to a reasonable correlation of the posterior vertebral structures, which have shown a low or no correlation in previous studies (pedicle inclination and transverse process \( R^2, 0.514–0.693 \); facet height superior and interfacet width \( R^2, 0.605–0.880 \); facet height inferior, interfacet height and sagittal / transverse angle superior \( R^2, 0.875–0.973 \)). Different correlations were found for facet width and transverse angle inferior in the thoracic \( R^2, 0.703–0.930 \) and lumbar \( R^2, 0.457–0.892 \) regions. (\( P\text{-values} < 0.001, \text{ANOVA} \)). The anterior, middle and posterior heights of the thoracic intervertebral discs were measured directly and on radiographs of 72 spine
segments from 30 donors (age 57.43 ±11.27 years) for all levels of the thoracic spine. The thickness of the discs varied from 4.5 to 7.2 mm, with the middle heights approximately 22.7% greater. Radiographic measurements displayed lower repeatability and were shorter than the anatomical ones (approximately 9% for anterior and 37% for posterior disc heights). The disc heights showed good correlations with the vertebral body heights ($R^2$, 0.659-0.835, $P$-values < 0.005) (ANOVA). A set of 50 equations was generated for the prediction of the vertebral and intervertebral discs dimensions based on the radiographic measurement of the vertebral body height posterior. It was possible to establish useful predictions for all investigated dimensions based on the size of the vertebral bodies. Comparisons of the theoretical predictions with other sets of experimental data indicated that the predictions generally agree well with the experimental data.

New data on thoracic disc morphometry was provided in this study. A time-efficient approach for obtaining anatomical data for the description of human thoracic and lumbar vertebral and disc geometry was provided by this method, which requires the measurement of only one parameter per vertebra (vertebral body height posterior, which is readily performed on lateral radiographs) and the set of developed prediction equations. As the vertebral body height is unique for each person and vertebral level, the predicted dimensions are also specific to an individual. This approach eliminates the need for direct measurement or 3D reconstructions from medical images for creation of parameterized patient-specific modelling of the scoliotic spine.
7. References


Stokes IAF (1994) Three-dimensional terminology of spinal deformity: A report presented to the scoliosis research society by the scoliosis research society working group on 3-D terminology of spinal deformity. *Spine* 19, 123-256.


A. Acknowledgements

I have to say thank you to many people for their support through the different stages of this thesis. It will not be enough to express my gratitude in words to all these people who helped me.

I would like to express my deep and sincere gratitude to my advisor, Prof. Dr. Hans-Joachim Wilke, who provided me the great opportunity to conduct my research within his research group. I am grateful for his patience, constant support and advise guiding me in the right direction over the last three years.

My best complements and gratitude to the enthusiastic supervision of Dr. Hendrik Schmidt. Thanks for the relevant discussions, helpfull suggestions and critical comments during this work. I have learned a lot from him and without his help I could not have finished my dissertation successfully.

I wish to express special thanks to Dr. med. Georg von dem Bussche who died months before the completion of my Ph.D. but stayed very close to my efforts until the last moment. Where ever you are, I hope you know that your words of encouragement were not in vain. You were right when you told me: do not give up you will get it!

I would also like to thank the Deutsche Forschungsgemeinschaft (German Research Foundation), grand number (Wi-1352/12-1), for financial support of this research. Many thanks to all colleagues in the Institute for the nice working atmosphere and the unproblematic mutual support.

Finally and most importantly, I would like to thank Ralf Kunkel, Oliver Tepasse, Silke Süsse, Sandra Reitmaier, Doyle Raymer and my family members for their support, encouragement and love I received while doing my thesis.
B. Scientific Curriculum Vitae

**Personal Data**  
Maria Elizete Kunkel  
July, 1st 1971 Fortaleza (Brazil)

**Academic Background**

1996 - 2000 **BSc. in Physics**  
Federal University of Ceara, Institute of Physics, Fortaleza, Brazil  
Project: “Thermal diffusivity of conducting polypyrrole”  
Scholarship: National Council for Scientific Technological Development

2001 - 2003 **MSc. in Bioengineering**  
University of Sao Paulo, Sao Carlos, Brazil  
Institute of Orthopaedic and Traumatology of the Hospital of Sao Paulo  
Thesis: “Analysis of bone fracture risk using ultrasonometry and mechanical compressions essays”  
Research Fellowship: The State of Sao Paulo Research Foundation

2003 - 2004 **Specialization, Scientific Journalism**  
State University of Campinas, Campinas, Brazil  
Laboratory of Advanced Journalism Studies - Media-Science Program  
Research Fellowship: The State of Sao Paulo Research Foundation

2005 - 2007 **Research Assistant**  
Technical University of Braunschweig, Braunschweig, Germany  
Institute for Robotics and Process Control, Medical Robotic Group  
Project: “Robot Assisted Endoscopic Sinus Surgery”  
Director: Prof. Dr. Friedrich M. Wahl

2008 – 2010 **Research Assistant and Ph.D student**  
University of Ulm, Ulm, Germany  
Institute of Orthopaedic Research and Biomechanics, Spine Group  
Thesis: “A statistical approach to predict subject-specific morphometry of the thoracic and lumbar spine from radiographic images”  
Research Fellowship: German Research Foundation (DFG)  
Advisor: Prof. Dr. Hans J Wilke
C. Papers
Prediction equations for human thoracic and lumbar vertebral morphometry

Maria E. Kunkel, Hendrik Schmidt and Hans-Joachim Wilke

Institute of Orthopaedic Research and Biomechanics, University of Ulm, Ulm, Germany

Abstract

Statistical correlations between anatomical dimensions of human vertebral structures have indicated a potential for the prediction of vertebral morphometry, which could be applied to the creation of simplified geometrical models of the spine excluding the need for preliminary processing of medical images. The aim of this study was to perform linear and nonlinear regressions with published anatomical data to generate prediction equations for 20 vertebral parameters of the human thoracic and lumbar spine as a function of only one given parameter that was measured by X-ray. Each parameter was considered individually as a potential predictor variable in terms of its correlation with all of the other parameters, together with the readiness with which lateral X-rays could be obtained. Based on this, the parameter vertebral body height posterior was chosen and the statistical analyses described here are related to this parameter. Our linear, exponential and logarithmic regressions provided significant predictions of anterior vertebral structures. However, third-order polynornal prediction equations allowed an improvement on these predictions (P-values < 0.001), e.g. endplates and spinal canal (R², 0.970–0.995) as well as pedicle heights and the spinous process (R², 0.811–0.882), in addition to a reasonable prediction of the posterior vertebral structures, which have shown a low or no correlation in previous studies, e.g. pedicle inclination and transverse process (R², 0.514–0.693) (ANOVA). Comparisons of the theoretical predictions with two other sets of experimental data indicated that the predictions generally agree well with the experimental data. A time-efficient approach for obtaining anatomical data for the description of human thoracic and lumbar geometry was provided by this method, which requires the measurement of only one parameter per vertebra (vertebral body height posterior) from a lateral X-ray and the set of developed prediction equations. Vertebral models based on this type of parameterized geometry could be used in biomechanical studies that require geometry variation, such as in spinal deformations, including scoliosis.

Key words polynomial regression; prediction; vertebral morphometry; vertebral parameters.

Introduction

During recent decades, finite element analyses have been performed to provide a better understanding of the biomechanics of the human spine. Several finite element models have been developed and are summarized in Gilbertson et al. (1995) and Fagan et al. (2002). As geometrical factors exert a noticeable influence on the behavior of the spine (Robin et al. 1994), reliable simulations of human spine behavior require complex 3D modeling of the main anatomical structures, e.g. vertebrae, intervertebral discs and ligaments.

Correspondence
Hans-Joachim Wilke, Institute of Orthopaedic Research and Biomechanics, Helmholtzstrasse 14, D-89081 Ulm, Germany. Tel: 0049 731 500 55320; fax: 0049 731 500 55302; E: hans-joachim.wilke@uni-ulm.de

Accepted for publication 3 November 2009
Article published online 21 December 2009

Human vertebral geometry has typically been obtained, in vivo, through the 3D reconstruction of medical images, such as computed tomography or magnetic resonance imaging. This technique provides accurate vertebral assessment but requires a long processing time and considerable computational power is required for the manual or semi-automatic segmentation of the images. Moreover, the patient has to be submitted to relatively high doses of ionizing radiation. Alternative procedures have included stereo-radiographic approaches using X-rays (Aubin et al. 1997; Dumas et al. 2004). However, these require a long and tedious process of identification of numerous anatomical landmarks. Some semi-automatic methods have shown fast vertebral reconstruction (Pomero et al. 2004) but they require specific software and hardware.

In-vitro measurements with cadaveric vertebrae have been taken directly from bony specimens or have been obtained from medical images (Krag et al. 1988). These studies have focused on only one specific anatomic struc-
ture, such as the dimensions of the vertebral body (Hall et al. 1998), spinal canal, pedicles (Zindrick et al. 1987; Marchesi et al. 1988; Moran et al. 1989) and facet joints (Masharawi et al. 2004); a limited set of structures (Berry et al. 1987); or a limited set of vertebrae such as thoracic (Cotterill et al. 1986; Scates et al. 1988; Aharinejad et al. 1990) or lumbar vertebrae (Semaan et al. 2001). The most complete collection of quantitative 3D-surface anatomy of the main vertebral parameters for the thoracic and lumbar human spine has been provided in Panjabi et al. (1991, 1992). As this dataset has been used in the current study, a detailed description of the measured parameters is provided in the Materials and methods.

Investigations of correlations between anatomical dimensions of the human vertebral structures have indicated that vertebral relationships could be used to predict vertebral morphometry without the preliminary processing of medical images. Statistical analyses that were performed using simple linear regression analyses between the main vertebral parameters and the vertebral body height (e.g. Scates et al. 1988; Breglia, 2006) have found low or no correlations for some important parameters, such as pedicle dimensions. Scates et al. (1988) described the posterior structures as being highly variable and largely unpredictable.

X-rays are frequently used in clinical diagnosis for patients as well as in biomechanical experiments with human vertebral samples. Some studies have used multiple-linear regression analyses (e.g. Lavaste et al. 1992; Laporte et al. 2000) to provide methods for the reconstruction of the human vertebrae from two X-rays (anterior-posterior and lateral). However, to explain 100% of the variability for each parameter, the measurement of six to 15 initial parameters per vertebra on X-rays was needed. Moreover, none of these previous studies have performed an evaluation of the predictability of the generated equations with another set of experimental measurements.

The aim of this study was to perform linear and nonlinear regression analyses with published anatomical data to generate prediction equations for 20 vertebral parameters of the human thoracic and lumbar spine as a function of only one given parameter measured by X-ray.

Fig. 1 Schematic representation of the vertebral anatomical parameters that were considered for linear and nonlinear regression analyses.

© 2009 The Authors
Journal compilation © 2009 Anatomical Society of Great Britain and Ireland
Materials and methods

Study population

Vertebral anatomical data were collected from the studies of Panjabi et al. (1991, 1992) and included in this study. This data set was considered as being an approximate average for non-pathological human spines. It provided linear and angular dimensions of the main parameters from human cadaveric thoracic and lumbar vertebrae. The mean age of the subjects (n = 12) was 46.3 years (range: 15–59 years), weight was 67.8 kg (range: 54–85 kg), height was 167.8 cm (range: 157–178 cm) and the male: female ratio was 8:4. In order to carry out statistical analyses, 15 linear and six angular vertebral parameters were selected from this dataset to describe the size and shape of the human thoracic (T1–12) and lumbar (L1–4) vertebrae (Fig. 1). The values of the vertebral parameters related to the vertebral level L5 were not included in the analysis.

Statistical analysis

The initial assumption for this study was that 20 vertebral parameters on each level of the thoracic (T1–12) and lumbar (L1–4) spine could be considered as a variable that can be predicted (Fig. 1). All vertebral parameters that were selected for this study were tested as a possible predictor variable. Each vertebral parameter was individually regressed against the possible predictor variable by a least-squares estimation process. Based on the level of correlation with the other parameters and ease of measurement on lateral X-rays, the parameter vertebral body height posterior (VBHP) was chosen and the statistical analyses described in this study are related to this parameter. Linear and nonlinear regression analyses were employed to find the best functions to fit each parameter in a prediction equation.

During the statistical analyses, several hypotheses were tested for each parameter: (i) a function could not fit the data significantly better than a horizontal line (no relationship between the two selected variables); (ii) a second-order equation could not fit the data significantly better than a linear equation; (iii) a third-order equation could not fit the data significantly better than a second-order equation, and so on. The statistical procedure performed on each parameter corresponds to a four-step procedure that is illustrated as an example in Fig. 2.

In the first step, least-squares estimation was used to find equations to describe the relationship between two vertebral parameters, e.g. the variables (EPWS) and VBHP, each data point represents the mean value in different vertebral levels of 12 cadavers. Initially, a linear regression was performed, fitting an equation of the form \( y = C_1 + C_2x \) to the data. The fraction of the overall variance of the EPWS that was reduced by this line was determined by the \( R^2 \) value. A logarithmic and an exponential curve with equations of the form \( y = C_1 + C_2 \ln(x) \) and

![Fig. 2 Description of the statistical procedure performed for two vertebral parameters.](image)

© 2009 The Authors
Journal compilation © 2009 Anatomical Society of Great Britain and Ireland
y = C_{1}e^{C_{2}x}, respectively, were then used to test the increase in R^2. Next, polynomial equations including more coefficients (C_{1}, C_{2}, C_{3}, C_{4}, etc.) were used to find the best fit of the data points. This was continued until adding another higher-order term did not significantly increase R^2 (Fig. 2A).

The second step was to perform an ANOVA to select an equation from the generated set, which could predict the EPWS values significantly better. It was based not only on quality of fit but also on the physical meaning of the prediction equations (Motulsky & Christopoulos, 2004). High values of R^2 associated with a P-value < 0.01 indicated the third-order polynomial as the best-fitting equation that could provide the best approximation to the experimental values of EPWS.

In the third step it was evaluated how the selected best-fitting, in this case the polynomial equation fits the EPWS data significantly better than a linear equation. Linear and third-order polynomial predictions of the EPWS were superimposed on experimental values together with their respective SD (Fig. 2B). The quality of these regressions was assessed by examining the respective residual plots. The linear equation was inappropriate for the description of the EPWS data because residuals clustering indicated that the data differed systematically (not just randomly) from the prediction curves. Positive residuals tended to cluster together at the first thoracic and the last lumbar vertebrae, whereas negative residuals clustered together in the transition zone from the thoracic to the lumbar region. In contrast, polynomial residual plots had a random arrangement of residuals, which was more appropriate to predict EPWS (Fig. 2B).

The fourth step corresponds to the evaluation of the predictability of the best-fitting equation of the set of equations developed in the third step using experimental data on two further datasets. The dataset of Berry et al. (1987) includes 12 vertebral parameters of three thoracic vertebrae (T2, T7 and T12) and four lumbar vertebrae (L1–4). The dataset of Scolas et al. (1988) includes 10 vertebral parameters of five thoracic vertebrae (T1, T3, T6, T9 and T12) and two lumbar vertebrae (L1 and L3) of male and female data.

Results

In general, there were no large differences for the correlations of each of the individual 20 vertebral parameters with VBHP when comparing linear, exponential and logarithmic regressions with each other. For this reason, only the linear predictions are provided from these results (Figs 3, 4 and 5). High correlations were found for parameters related to endplates (EPWS, EPWI, EPDS and EPDI) and vertebral bodies (VBW and VBD) (R^2, from 0.923 to 0.959) (Fig. 3) (please see Fig. 1 for all abbreviations). Moderate values of R^2 (from 0.520 to 0.793) were achieved in pedicle heights (PHL and PHR) and transverse inclination left (PTIL) (Fig. 4).
as well as in the spinal canal (SCW and SCD) (Fig. 5). However, about 50% of the investigated parameters showed low or no correlation with VBHP. These were the dimensions of endplate inclinations (EPIS and EPIL) (Fig. 3), pedicles (PWL, PWR, PTIR, PSIL and PSIR) (Fig. 4) and other posterior structures (SPL and TPW) (Fig. 5).

In contrast to the above regressions, third-order polynomial regressions provided the best results with significant correlations between all selected parameters and VBHP (Table 1). As the dataset of Panjabi et al. (1991, 1992) does not include VBW and VBD, an alternative method for the prediction of these parameters was used. The inclusion of more than four coefficients increased the $R^2$ values but indicated that the obtained correlations did not significantly improve parameter predictions. For instance, fourth- and fifth-order polynomial regressions between the PWL and VBHP resulted in $R$-values > 0.05.

The parameters EPWS, EPWI, EPDS, EPDI, VBW and VBD that showed high correlations by linear, logarithmic and exponential regressions exhibited, after third-order polynomial regressions, an increase of $R^2$ (from 0.970 to 0.982, $P$-values < 0.01) (Fig. 3). Similarly, the correlations with PHL, PHR, PTIL, SCW and SCD were improved and $R^2$ values ranging from 0.693 to 0.964 were achieved (Figs 4 and 5). Furthermore, for those parameters that displayed low or no correlation with anterior procedures (EPIS, EPIL, PWL, PWR, PTIR, PSIL, PSIR, SPL and TPW), polynomial regressions achieved reasonable correlations ($R^2$, from 0.514 to 0.693, $P$-values < 0.05) (Figs 3, 4 and 5). An exception was PTIL for which the best results were obtained after exponential regression ($R^2 = 0.757$) (Fig. 4C).

The prediction of the vertebral parameters related to anterior vertebral structures using linear, exponential, logarithmic and polynomial prediction equations did not demonstrate significant differences (Fig. 6). Moreover, polynomial prediction equations were required to predict the parameters related to posterior vertebral structures. The polynomial predictions are generally within or close to
Prediction equations for human thoracic and lumbar vertebral morphometry, M. E. Kunkel et al. 325

Spinal canal, spinous and transverse process

![Graphs showing spinal canal, spinous and transverse process predictions](image)

**Fig. 5** Linear and polynomial predictions of other vertebral posterior structures (SCW, SCD, SPL and TPW) (A-D) superimposed on experimental data of Panjabi et al. (1991, 1992)*. Dotted curve indicates SD of the experimental data.

the regions of the 95% confidence intervals of the experimental data of Panjabi et al. (1991, 1992).

Using the dataset of Berry et al. (1987), a comparison of predicted EPWS and EPDI showed mean percent errors of −14.93 and 31.86%, respectively for T1; all other levels were very close to experimental data with mean percent errors of −0.32 to 9.68% (Fig. 7A). Predictions of PHL showed better results for thoracic levels with the smallest error being −0.05 mm (−0.8%) for PHL (T2) and a mean percent error of approximately 22.5% for thoracic and 24.6% for lumbar

Table 1 Polynomial coefficients (C₁, C₂, C₃ and C₄) for prediction equations of 20 parameters per vertebral level of the human thoracic and lumbar spine.

<table>
<thead>
<tr>
<th>Vertebral parameter</th>
<th>Abbreviation</th>
<th>C₁</th>
<th>C₂</th>
<th>C₃</th>
<th>C₄</th>
<th>SD</th>
<th>R²</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Endplate</td>
<td>Width</td>
<td>EPWS</td>
<td>121.65</td>
<td>0.742</td>
<td>-0.010</td>
<td>1.195</td>
<td>0.982</td>
<td>1.07e-10</td>
</tr>
<tr>
<td></td>
<td>Depth</td>
<td>EPWI</td>
<td>300.140</td>
<td>-43.509</td>
<td>2.206</td>
<td>-0.035</td>
<td>1.454</td>
<td>0.976</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EPDS</td>
<td>-60.076</td>
<td>8.983</td>
<td>-0.293</td>
<td>0.004</td>
<td>0.852</td>
<td>0.981</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EPDI</td>
<td>-63.590</td>
<td>9.473</td>
<td>-0.300</td>
<td>0.003</td>
<td>0.769</td>
<td>0.981</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EPIS</td>
<td>-66.833</td>
<td>12.035</td>
<td>-0.691</td>
<td>0.013</td>
<td>0.699</td>
<td>0.606</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EPIII</td>
<td>66.233</td>
<td>-9.095</td>
<td>0.418</td>
<td>-0.066</td>
<td>0.606</td>
<td>0.514</td>
</tr>
<tr>
<td>Vertebral body</td>
<td>Width</td>
<td>VBW**</td>
<td>4.149</td>
<td>0.748</td>
<td>-0.350</td>
<td>0.004</td>
<td>0.523</td>
<td>0.995</td>
</tr>
<tr>
<td></td>
<td>Depth</td>
<td>VBD**</td>
<td>-80.223</td>
<td>10.313</td>
<td>-0.350</td>
<td>0.004</td>
<td>0.523</td>
<td>0.995</td>
</tr>
<tr>
<td>Pedicle</td>
<td>Width</td>
<td>PWL</td>
<td>230.261</td>
<td>-34.915</td>
<td>1.777</td>
<td>-0.029</td>
<td>1.682</td>
<td>0.590</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PWR</td>
<td>157.740</td>
<td>-23.284</td>
<td>1.168</td>
<td>-0.019</td>
<td>1.446</td>
<td>0.537</td>
</tr>
<tr>
<td></td>
<td>Height</td>
<td>PHL</td>
<td>168.200</td>
<td>-27.194</td>
<td>1.522</td>
<td>-0.027</td>
<td>0.954</td>
<td>0.853</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PHR</td>
<td>105.820</td>
<td>-17.256</td>
<td>0.999</td>
<td>-0.018</td>
<td>0.872</td>
<td>0.879</td>
</tr>
<tr>
<td></td>
<td>Transverse inclination</td>
<td>PTIL</td>
<td>-10.658</td>
<td>2.9889</td>
<td>-0.099</td>
<td>-0.001</td>
<td>2.731</td>
<td>0.693</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PTRIR</td>
<td>-202.510</td>
<td>31.347</td>
<td>-1.496</td>
<td>0.023</td>
<td>2.877</td>
<td>0.524</td>
</tr>
<tr>
<td></td>
<td>Sagittal inclination</td>
<td>PSIL</td>
<td>305.290</td>
<td>-39.194</td>
<td>1.734</td>
<td>-0.025</td>
<td>0.406</td>
<td>0.524</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PSIR</td>
<td>-275.130</td>
<td>53.937</td>
<td>-3.119</td>
<td>0.057</td>
<td>3.403</td>
<td>0.669</td>
</tr>
<tr>
<td>Spinal canal</td>
<td>Width</td>
<td>SCW</td>
<td>206.750</td>
<td>-26.838</td>
<td>1.218</td>
<td>-0.017</td>
<td>0.634</td>
<td>0.964</td>
</tr>
<tr>
<td></td>
<td>Depth</td>
<td>SCD</td>
<td>-2.449</td>
<td>3.8323</td>
<td>-0.254</td>
<td>0.006</td>
<td>0.573</td>
<td>0.811</td>
</tr>
<tr>
<td>Spinal process</td>
<td>Length</td>
<td>SPL</td>
<td>-947.110</td>
<td>168.10</td>
<td>-9.310</td>
<td>0.170</td>
<td>3.472</td>
<td>0.882</td>
</tr>
<tr>
<td>Transverse process</td>
<td>Width</td>
<td>TPW</td>
<td>-343.070</td>
<td>80.885</td>
<td>-5.050</td>
<td>0.102</td>
<td>7.259</td>
<td>0.616</td>
</tr>
</tbody>
</table>

SD in mm (for linear dimensions) or in degree (for angular dimensions). The basic form of the prediction equations is $y = C_1 + C_2x + C_3x^2 + C_4x^3$ where $y$ is the value of the parameter to be predicted and $x$ is the value of the VBHP on each vertebral level.

S, superior; I, inferior; L, left; R, right.

*For VBW, $x$ is the value of EPWS/EPWI on each vertebral level.

**For VBD, $x$ is the value of EPDS/EPDI on each vertebral level.

© 2009 The Authors
Journal compilation © 2009 Anatomical Society of Great Britain and Ireland
Fig. 6 Geometric models of the human thoracic (T1–12) and lumbar (L1–4) vertebrae constructed with parameters related to endplates and vertebral bodies (EPWS, EPW, EPDS, EPDI, EPIS, EPI, VBW and VBD). The first model corresponds to the data of Panjabi et al. (1991, 1992) and was created using eight parameters per vertebral level (a total of 128 parameters). The other models were generated using only the values of the VBHP of each vertebral level and predicted parameters from linear, exponential, logarithmic and polynomial equations.

Fig. 7 Comparison of some predicted vertebral parameters (EPWS, PHP, PSIL and SCW) with corresponding experimental data from Berry et al. (1987) (left column, A–D) and Scolas et al. (1988) (right column, E–H) in selected vertebral levels. The means and 95% confidence intervals (dotted lines) of the experimental and predicted values are shown.
levels (Fig. 7B). Polynomial pedicle predictions showed a high error for PSIL (T12) (Fig. 7C). Predictions related to the SCW and SCD also displayed better results for thoracic levels with the largest error being 1.19 mm (7.93%). Lumbar levels showed an approximate mean percent error of 23% (SCW) and 31% (SCD) (Fig. 7D).

With the dataset of Scules et al. (1988), predictions of EPWS and VBD showed a range of mean percent errors of −2.68 to 23.48%, with the largest errors occurring in EPWS (L1) (Fig. 7E). The shortest error for PHL was −0.69 mm (−4.66%) for T12 and a mean percent error of approximately 18.5% for thoracic and 45.6% for lumbar levels was found (Fig. 7F). Polynomial pedicle predictions showed a high error for PSIL (T1) (Fig. 7G). Predictions of SCW and SCD showed similar results to the prediction with the dataset of Berry et al. (1987), with the largest error being 4.25 mm (22.1%) for thoracic levels (Fig. 7H).

Discussion

Linear and nonlinear regression analyses were performed with the anatomical data of Panjabi et al. (1991, 1992) to generate prediction equations for 20 vertebral parameters per vertebral level of the human thoracic (T1–12) and lumbar (L1–4) vertebrae as a function of the VBHP. The parameters corresponding to the vertebra L5 were not included in the analyses because L5 shows remarkable morphological differences for some parameters when compared with the other lumbar vertebrae (Berry et al. 1987; Zindrick et al. 1987; Scules et al. 1988). This is probably due to the position of L5 being localized in the final transition zone, from lumbar to sacral region (Panjabi et al. 1989, 1992).

In this study two assumptions were necessary. First, despite the high anatomical variability of the human vertebrae, the dataset of Panjabi et al. (1991, 1992) was assumed to be representative of the adult population without spinal pathology. Second, it was assumed that the dimensions of the vertebral structures described in this dataset were obtained precisely. As the three datasets used in this study were provided from in-vitro measurements, further investigations are necessary to evaluate the predictability of the regression equations with a dataset from patients.

Third-order polynomial equations represented the best regression approximation as indicated after analysis of covariance (Table 1). SEs indicated that, with few exceptions, such as for pedicle inclinations, the best fit values for the prediction equations were accomplished with reasonable certainty. Pedicle inclinations showed a wide variation that can be observed in the wide confidence interval of the sagittal plane angle for the mid-thoracic vertebrae (Fig. 4C,D,G,H).

Our results were compared, when possible, with existing published data. All correlation coefficients generated using polynomial regressions were considerably better than the values obtained by Breglia (2006) using simple linear regressions on the data of Panjabi et al. (1991, 1992). The parameters related to posterior structures that could not be predicted with the regressions of Breglia (2006) have shown a moderate correlation after polynomial regressions. Linear regression procedures are straightforward and the results appear to be readily evaluated statistically. However, the relationships between the vertebral variables follow a curved line, not a straight line. Although the methods used for fitting a nonlinear equation such as polynomial regression are extensions of linear regression, the results are better because polynomial equations can be used to create a generic curve through the data points; more coefficients create a more flexible curve, which could better fit the data.

Comparisons of the theoretical predictions with two other sets of experimental data (Berry et al. 1987; Scules et al. 1988) indicated that the predictions generally agree well with the experimental data. Although the differences in the predictions of pedicle inclination (Fig. 7C,G) have been relatively great, a reasonable correlation between the main posterior elements and VBHP was found. This is not in accordance with Scules et al. (1988) who declared that it was not possible to establish useful predictors for pedicle dimensions based on the size of the vertebral body. Differences in predicted values may also be attributed to technical factors related to obtaining these anatomical data, such as different protocols of preparation and measurement. Furthermore, there are individual variations and aging that can induce substantial changes in each individual's vertebrae (Berrnick & Cailliet, 1982; Dicinti et al. 1995).

Lavaste et al. (1992) developed a method to reconstruct lumbar vertebral geometry from two X-rays (anterior–posterior and lateral) using multiple-linear regression analysis. However, to predict the vertebral geometry, six given parameters per vertebra were required. A digitalization process to define these parameters showed a relative error of approximately 15%. Moreover, the orientation and width of the pedicles were not taken into consideration. Laporte et al. (2000) performed a similar study in thoracic vertebrae, which required the measurement of 15 parameters per vertebra by X-ray in order to explain 100% of the variability for each parameter.

The advantage of using the generated set of prediction equations (Table 1) is the capability to model vertebral geometry in each level of the thoracic and lumbar spine, with the exception of L5, using only one parameter per vertebra (VBHP), which can be easily measured on conventional lateral X-rays.

Conclusion

The present study shows that nonlinear regression analyses provide a time-efficient approach for modeling of the human vertebrae, allowing a better understanding of statistical correlations between vertebral dimensions. The geom-
etry that was reconstructed using the predicted vertebral parameters may be applied for the construction of finite element models of the spine without the need for expensive, invasive and time-consuming data collection, such as medical images. Another advantage is that this approach allows the values of the vertebral parameters to be changed, producing different vertebral morphologies. This could be used for the development of parameterized models of the spine to perform studies based on geometry variation, such as in spinal deformations, including scoliosis.

Acknowledgements

This study was financially supported by the German Research Foundation (Wi-1352/12-1).

Conflict of interest statement

Each author of this study did not and will not receive benefits in any form from a commercial party related directly or indirectly to the content of this study.

References


Prediction of the human thoracic and lumbar articular facet joint morphology from radiographic images

Maria E. Kunkel, Hendrik Schmidt and Hans-Joachim Wilke
Institute of Orthopaedic Research and Biomechanics, University of Ulm, Ulm, Germany

Abstract
The articular facet joints (AFJ) play an important role in the biomechanics of the spine. Although it is well known that some AFJ dimensions (e.g., facet height/width or facet angles) play a major role in spinal deformities such as scoliosis, little is known about statistical correlations between these dimensions and the size of the vertebral bodies. Such relations could allow patient-specific prediction of AFJ morphology from a few dimensions measurable by X-ray. This would be of clinical interest and could also provide parameters for mathematical modeling of the spine. Our purpose in this study was to generate prediction equations for 20 parameters of the human thoracic and lumbar AFJ from T1 to L4 as a function of only one given parameter, the vertebral body height posterior (VBHP). Linear and nonlinear regression analyses were performed with published anatomical data, including linear and angular dimensions of the AFJ and vertebral body heights, to find the best functions to describe the correlations between these parameters. Third-order polynomial regressions, in contrast to the linear, exponential and logarithmic regressions, provided moderate to high correlations between the AFJ parameters and vertebral body heights; e.g., facet height superior and intercept width \( R^2, 0.605-0.880 \); facet height inferior, intercept height and sagittal/transverse angle superior \( R^2, 0.875-0.973 \). Different correlations were found for facet width and transverse angle inferior in the thoracic \( R^2, 0.703-0.930 \) and lumbar \( R^2, 0.457-0.892 \) regions. A set of 20 prediction equations for AFJ parameters was generated (P-values < 0.005, ANOVA). Comparison of the AFJ predictions with experimental data indicated mean percent errors < 13%, with the exception of the thoracolumbar junction (T12-L1). It was possible to establish useful predictions for human thoracic and lumbar AFJ dimensions based on the size of the vertebral bodies. The generated set of equations allows the prediction of 20 AFJ parameters per vertebral level from the measurement of the parameter VBHP, which is easily performed on lateral X-rays. As the vertebral body height is unique for each person and vertebral level, the predicted AFJ parameters are also specific to an individual. This approach could be used for parameterized patient-specific modeling of the spine to explore the clinically important mechanical roles of the articular facets in pathological conditions, such as scoliosis.

Key words articular facet joints; human anatomy; spinal morphology; zygapophyseal joints.

Introduction
The articular facet joints (AFJ) play an important role in the biomechanics of the spine; they transmit a significant percentage of spinal loading, and provide translational, rotational and axial stability in the spine (Lorenz et al. 1983; Adams & Hutton, 1983; Onan et al. 1998). The shape, position and orientation of the AFJ strongly regulate the physiological motion of the spine (Taylor & Twomey, 1986; White & Panjabi, 1990). A patient-specific prediction of vertebral morphometric data (e.g., size and orientation of the AFJ) could be of clinical interest in the evaluation of operative and non-operative spinal treatments. For example, during clinical or radiographic examination of a patient with a spinal deformity such as scoliosis, the physicians are faced with the problem that it is not possible to know what the original anatomical dimensions of this spine were before deformity started. Most procedures for spinal deformity corrections are based on the average values of vertebral dimensions of a healthy spine, without taking into account that each patient has a specific morphometry. One possibility would be to use an X-ray of a patient and, from direct measurement of a dimension of an intact vertebra (e.g., vertebral body height), predict other dimensions (e.g.)
articular facet size or orientation) by using the relationships between them.

Another important issue for such predictions of vertebral morphometry is to provide parameters for mathematical modeling of the spine. Shirazi-Adl (1991, 1994), Zander et al. (2003) and Schmidt et al. (2008a, b, 2009) investigated the AFJ in normal and pathological conditions using finite element models. The geometry of these models often comes from 3D reconstruction of computed tomography, which requires a considerable processing time and computational power. Finite element models with a simple but parameterized geometry could be an alternative to these complex models because they would allow different vertebral geometries to be fitted.

The human vertebral morphometry has been measured in a number of studies (Table 1) and using patient-specific stereoradiographic reconstruction techniques (Aubai et al. 1997; Petit et al. 1998; Pomero et al. 2004). Previous investigations of statistical correlations between dimensions of vertebral structures have been used to predict vertebral dimensions. However, the relationships between the geometrical parameters describing the different parts of a given vertebra and the vertebral body height are only well known for the anterior structures and some posterior structures (e.g. pedicles) (Scoles et al. 1988; Kunkel et al. 2010).

Although it is well known that some AFJ parameters, such as facet height and width or facet angles, play a major role in spinal deformities such as scoliosis due to pathological changes in the anatomy of the posterior structures (Parent et al. 2002; Aebi, 2005), little is known about vertebral relationships between AFJ parameters and vertebral heights. Breglia (2006) investigated only two AFJ parameters and found a poor correlation between them and the vertebral body height posterior (VBHP). Other studies investigated statistical correlations of AFJ parameters not only with VBHP but with all other vertebral parameters; in these cases, 6–15 initial parameters were necessary for the prediction of some AFJ parameters (Lavaste et al. 1992; Skalli et al. 1993; Maurel et al. 1997; Laporte et al. 2000). A quantitative analysis of the relationship between the AFJ parameters and VBHP allowing patient-specific predictions has not yet been investigated.

The purpose of the current study was to generate prediction equations for 20 parameters of the human thoracic

<table>
<thead>
<tr>
<th>Reference</th>
<th>Technique</th>
<th>Vertebral level</th>
<th>Facet geometric parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>van Schaik et al. (1985)</td>
<td>CT</td>
<td>L3-5</td>
<td>Transverse plane angle</td>
</tr>
<tr>
<td>Cotterill et al. (1986)</td>
<td>CT</td>
<td>T6, T12, L3</td>
<td>Interfacet height/width</td>
</tr>
<tr>
<td>Berry et al. (1987)</td>
<td>DM</td>
<td>T2, T7, T12, L1-5</td>
<td>Transverse plane angle</td>
</tr>
<tr>
<td>Scoles et al. (1988)</td>
<td>DM</td>
<td>T1, T3, T6, T9, L1, L3, L5</td>
<td>Interfacet height</td>
</tr>
<tr>
<td>Ahmed et al. (1990)</td>
<td>CT</td>
<td>L2-5</td>
<td>Inferior facet pedicle distance</td>
</tr>
<tr>
<td>Panjabi et al. (1993)</td>
<td>CT</td>
<td>T1-12, L1-5</td>
<td>Inferior facet/mid-pedicle length</td>
</tr>
<tr>
<td>Boszczyk (1997)</td>
<td>DM</td>
<td>T12, L1-5</td>
<td>Facet height/width</td>
</tr>
<tr>
<td>Ebraheim et al. (1997)</td>
<td>DM</td>
<td>T1-12</td>
<td>Facet area</td>
</tr>
<tr>
<td>Laporte et al. (2000)</td>
<td>DM</td>
<td>T1-12</td>
<td>Transverse/sagittal plane angle</td>
</tr>
<tr>
<td>Dai (2001)</td>
<td>CT/MRI</td>
<td>L4-5</td>
<td>Face thickness</td>
</tr>
<tr>
<td>Masharawi et al. (2004)</td>
<td>DM</td>
<td>T1-12, L1-5</td>
<td>Sagittal plane angle</td>
</tr>
<tr>
<td>Masharawi et al. (2005)</td>
<td>DM</td>
<td>T1-12, L1-5</td>
<td>Face concavity/convexity</td>
</tr>
<tr>
<td>Masharawi et al. (2007a)</td>
<td>DM</td>
<td>L1-5</td>
<td>Transverse plane angle</td>
</tr>
<tr>
<td>Wang &amp; Yang (2009)</td>
<td>CT</td>
<td>L4-5</td>
<td>Sagittal plane angle</td>
</tr>
</tbody>
</table>

CT, computed tomography; DM, direct measurement; MRI, magnetic resonance imaging.
and lumbar AFJ as a function of only one given parameter measurable by X-ray, the VBHP.

Materials and methods

Study population

Vertebral anatomical data were collected from Panjabi et al. (1991, 1992, 1993) and were included in this study. To carry out statistical analyses, measurements of the VBHP and 20 anatomical measurements were selected to describe the size and orientation of the human thoracic (T1–T12) and lumbar (L1–L4) AFJ (Fig. 1).

Statistical analysis

To perform linear and nonlinear regression with these data, the same methodology used by Kunkel et al. (2010) was adopted. The parameter VBHP was used as the predictor variable, and the values of the parameters related to the vertebral level L5 were not included in the analysis. However, due to the existence of a considerable difference between the morphometry of the articular facets in the thoracic and lumbar regions, a modification was introduced to achieve a better prediction of the AFJ parameters. It refers to separate regressions using thoracic (T1–T12) and lumbar (L1–L4) data together, thoracic data alone, and lumbar data alone. A brief description of the implemented methodology in this study follows.

Fig. 1 Schematic representation of the anatomical parameters that were considered for linear and nonlinear regression analyses. Vertebral body height posterior and linear and angular dimensions of the articular facet joints. The facet surfaces were approximated by a plane. The orientation of the planes was defined by two angles made by the facet plane with the sagittal and transverse anatomic planes.

© 2010 The Authors
Journal of Anatomy © 2010 Anatomical Society of Great Britain and Ireland
Correlation and regression analyses with AFJ parameters and VBHP

Each AFJ parameter selected for this study from T1-12 and L1-4 was correlated with VBHP. A least-squares regression analysis was performed to find linear and nonlinear functions to describe the relationship between each pair of parameters. These functions represented prediction equations which take the forms

\[ y = C_1 + C_2x \text{ for linear, } \]

\[ y = C_1 + C_2n(x) \text{ for logarithmic, } \]

\[ y = C_1 + C_2X + C_3X^2 + C_4X^3 + \cdots + C_nX^{n-1} \]

for polynomial equations, where \( y \) was the value of the articular facet parameter to be predicted, \( x \) was the value of the VBHP on each vertebral level, and \( C_1, C_2, C_3, C_4, \ldots, C_n \) were the regression coefficients. The fraction of the overall variance of each facet parameter that was reduced by a specific regression, \( R^2 \) value, was used to assess the best function of the set of generated prediction equations. For the polynomial equations, the number of coefficients was continually increased until adding another higher-order term did not significantly increase \( R^2 \).

Identification of the best prediction equation

A ANOVA was performed to define the significance of each prediction equation that fits a given facet parameter. The respective residual plots were examined to assess the quality of these equations. The identification of the best prediction equations was based on the following criteria: values of \( R^2 > 0.5 \) associated with a probability level of \( P \)-value < 0.05 and a standard error of the estimate (SE) < 30% of the standard deviations of the experimental data of Panjabi et al. (1993).

Evaluation of the predictability of the prediction equation

For each AFJ parameter, the theoretical predictions were plotted against the corresponding known experimental data of Panjabi et al. (1993) and Cotterill et al. (1986) considering their respective confidence limits. The dataset of Cotterill et al. (1986) included three AFJ parameters (interface height and width, and transverse angle superior) of two thoracic (T6 and T12) and one lumbar (L3) vertebrae. As these three parameters provided in this dataset did specify where the measurements were obtained (right or left side, superior or inferior), the predictions of these parameters in our study were performed considering all possibilities.

Results

Third-order polynomial regressions, in contrast to the linear, exponential, logarithmic and polynomial regressions with other orders, provided the best results with significant

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Abbreviation</th>
<th>( C_1 )</th>
<th>( C_2 )</th>
<th>( C_3 )</th>
<th>( C_4 )</th>
<th>SE</th>
<th>( R^2 )</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height</td>
<td>FHL</td>
<td>-4.775</td>
<td>4.189</td>
<td>-0.309</td>
<td>0.007</td>
<td>1.18</td>
<td>0.647</td>
<td>0.0046</td>
</tr>
<tr>
<td></td>
<td>FHSR</td>
<td>33.916</td>
<td>-2.520</td>
<td>0.068</td>
<td>0.001</td>
<td>0.87</td>
<td>0.751</td>
<td>0.0006</td>
</tr>
<tr>
<td></td>
<td>FHL</td>
<td>62.954</td>
<td>-6.484</td>
<td>0.235</td>
<td>-0.002</td>
<td>0.68</td>
<td>0.910</td>
<td>1.94E-06</td>
</tr>
<tr>
<td></td>
<td>FHR</td>
<td>82.879</td>
<td>-10.102</td>
<td>0.444</td>
<td>-0.006</td>
<td>0.64</td>
<td>0.924</td>
<td>5.61E-07</td>
</tr>
<tr>
<td></td>
<td>FWSR</td>
<td>381.763</td>
<td>-59.777</td>
<td>3.175</td>
<td>-0.056</td>
<td>0.7</td>
<td>0.771</td>
<td>0.0051</td>
</tr>
<tr>
<td></td>
<td>FWSR</td>
<td>244.770</td>
<td>-36.675</td>
<td>1.850</td>
<td>-0.032</td>
<td>0.46</td>
<td>0.850</td>
<td>0.0011</td>
</tr>
<tr>
<td></td>
<td>FWIL</td>
<td>383.000</td>
<td>-61.279</td>
<td>3.325</td>
<td>-0.059</td>
<td>0.60</td>
<td>0.788</td>
<td>0.0045</td>
</tr>
<tr>
<td></td>
<td>FWIR</td>
<td>314.610</td>
<td>-50.508</td>
<td>2.763</td>
<td>-0.050</td>
<td>0.60</td>
<td>0.703</td>
<td>0.0164</td>
</tr>
<tr>
<td>Width</td>
<td>IFHL</td>
<td>45.467</td>
<td>-5.543</td>
<td>0.329</td>
<td>-0.005</td>
<td>0.79</td>
<td>0.970</td>
<td>2E-06</td>
</tr>
<tr>
<td></td>
<td>IFHR</td>
<td>-56.782</td>
<td>11.697</td>
<td>-0.628</td>
<td>0.013</td>
<td>0.76</td>
<td>0.973</td>
<td>1.35E-06</td>
</tr>
<tr>
<td>Interface height</td>
<td>IFWS</td>
<td>744.410</td>
<td>-111.100</td>
<td>5.625</td>
<td>-0.094</td>
<td>1.47</td>
<td>0.880</td>
<td>0.0005</td>
</tr>
<tr>
<td></td>
<td>IFWI</td>
<td>620.110</td>
<td>-95.960</td>
<td>5.0701</td>
<td>-0.088</td>
<td>0.89</td>
<td>0.868</td>
<td>0.0007</td>
</tr>
<tr>
<td>facet orientations</td>
<td>Transverse angle</td>
<td>TASL</td>
<td>-629.850</td>
<td>106.150</td>
<td>-5.322</td>
<td>0.089</td>
<td>2.09</td>
<td>0.922</td>
</tr>
<tr>
<td></td>
<td>TASR</td>
<td>-468.340</td>
<td>81.873</td>
<td>-4.122</td>
<td>0.070</td>
<td>1.70</td>
<td>0.938</td>
<td>1.65E-07</td>
</tr>
<tr>
<td></td>
<td>TAIL</td>
<td>-772.290</td>
<td>131.960</td>
<td>-6.800</td>
<td>0.116</td>
<td>1.40</td>
<td>0.930</td>
<td>5.73E-05</td>
</tr>
<tr>
<td>Sagittal angle</td>
<td>TAIR</td>
<td>-294.800</td>
<td>50.407</td>
<td>-2.529</td>
<td>0.040</td>
<td>1.98</td>
<td>0.785</td>
<td>0.0047</td>
</tr>
<tr>
<td></td>
<td>SRL</td>
<td>998.880</td>
<td>-149.700</td>
<td>8.0381</td>
<td>-0.143</td>
<td>1.04</td>
<td>0.952</td>
<td>1.31E-05</td>
</tr>
<tr>
<td></td>
<td>SAIL</td>
<td>-1084.000</td>
<td>160.740</td>
<td>-8.4545</td>
<td>0.147</td>
<td>1.41</td>
<td>0.904</td>
<td>0.0002</td>
</tr>
<tr>
<td></td>
<td>SAIIR</td>
<td>-2549.600</td>
<td>463.78</td>
<td>-27.063</td>
<td>0.521</td>
<td>8.47</td>
<td>0.849</td>
<td>0.0012</td>
</tr>
<tr>
<td></td>
<td>SAIIR</td>
<td>2375.500</td>
<td>-434.840</td>
<td>25.490</td>
<td>-0.493</td>
<td>8.20</td>
<td>0.862</td>
<td>0.0084</td>
</tr>
</tbody>
</table>

SE in mm (for facet linear parameter) or in degree (for facet angular parameters).

The basic form of the prediction equation is \( y = C_1 + C_2x + C_3x^2 + C_4x^3 \), where \( y \) is the value of the facet parameter to be predicted and \( x \) is the value of the VBHP on each vertebral level. S, superior; I, inferior; L, left; R, right. Values in bold indicate facet parameters that show the same polynomial coefficients for thoracic and lumbar vertebrae.

© 2010 The Authors
Journal of Anatomy © 2010 Anatomical Society of Great Britain and Ireland
correlations between each of the AFJ parameters and VBHP. The inclusion of more than four polynomial coefficients increased the $R^2$ values; however, ANOVA S indicated that the obtained correlations did not significantly improve parameter predictions. For this reason, only the results of third-order polynomial predictions are provided (Table 2 for thoracic and Table 3 for lumbar regions).

Considering the previously established criteria, the polynomial regressions using the thoracic and lumbar data together (T1–12 and L1–4) showed variable correlations with VBHP ($R^2$ 0.516–0.950), providing significant prediction equations for all selected AFJ parameters from VBHP (an exception was FWSL).

The polynomial regressions considering only the thoracic data (T1–12) resulted in improvements for predictions of 70% of the thoracic AFJ parameters such as an increase of $R^2$ (from 0.650 to 0.973), an increase in the significance and a decrease of SE (Table 2). In the case of the other thoracic AFJ parameters, such as facet heights (FHSI, FHSS, FHLI and FHIR) and transverse plane angles (TASL and TASS), where no improvement was achieved, the polynomial coefficients obtained from the regressions using the thoracic and lumbar data together were accepted.

Polynomial regressions considering only lumbar data (L1–4) did not satisfy the minimum criteria required for the selection of the prediction equations. This was probably due to the low number of observations in the lumbar region (just four parameter values per vertebrae). Therefore, the polynomial coefficients obtained from the regressions using the thoracic and lumbar data together were used to predict the lumbar AFJ parameters (Table 3).

**Facet linear parameters predictions**

High correlations were found for inferior facet heights (FHIL and FHIR) with VBHP ($R^2$, 0.910–0.924). Superior facet heights (FHSU and FHSS) showed moderate correlations ($R^2$, 0.647–0.751). Comparisons with experimental data of Panjabi et al. (1993) showed that the best predictions were found for FHIL with a mean percent error of approximately 14% in T12 and a maximal error of 7% in all other levels (Fig. 2A). The largest error of approximately −17% was found for FHSU in the lumbar level (Fig. 2D). For facet widths (FWSL, FWSR, FWIL, FWIR), no significant difference was found between the correlations of the widths of the superior and inferior facets with VBHP. The best correlations with VBHP were achieved on the thoracic levels ($R^2$, 0.703–0.850) where a mean percent error < 10% was found (e.g. Fig. 2B,E). Although these parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Abbreviation</th>
<th>$C_1$</th>
<th>$C_2$</th>
<th>$C_3$</th>
<th>$C_4$</th>
<th>SE</th>
<th>$R^2$</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Facet dimensions</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Height</td>
<td>FHSI</td>
<td>−4.775</td>
<td>4.188</td>
<td>−0.309</td>
<td>0.007</td>
<td>1.18</td>
<td>0.647</td>
<td>0.0046</td>
</tr>
<tr>
<td></td>
<td>FHSR</td>
<td>33.916</td>
<td>−2.519</td>
<td>0.068</td>
<td>0.001</td>
<td>0.87</td>
<td>0.751</td>
<td>0.0006</td>
</tr>
<tr>
<td></td>
<td>FHLI</td>
<td>62.954</td>
<td>−6.484</td>
<td>0.235</td>
<td>−0.002</td>
<td>0.68</td>
<td>0.910</td>
<td>1.49E-06</td>
</tr>
<tr>
<td></td>
<td>FHIR</td>
<td>82.879</td>
<td>−10.102</td>
<td>0.444</td>
<td>−0.006</td>
<td>0.64</td>
<td>0.924</td>
<td>5.62E-07</td>
</tr>
<tr>
<td>Width</td>
<td>FWSL</td>
<td>240.180</td>
<td>−35.123</td>
<td>1.759</td>
<td>−0.029</td>
<td>1.49</td>
<td>0.457</td>
<td>0.0416</td>
</tr>
<tr>
<td></td>
<td>FWSR</td>
<td>177.180</td>
<td>−25.063</td>
<td>1.233</td>
<td>−0.020</td>
<td>1.07</td>
<td>0.516</td>
<td>0.0283</td>
</tr>
<tr>
<td></td>
<td>FWIL</td>
<td>109.750</td>
<td>−14.135</td>
<td>0.647</td>
<td>0.010</td>
<td>1.10</td>
<td>0.595</td>
<td>0.0255</td>
</tr>
<tr>
<td></td>
<td>FWIR</td>
<td>70.833</td>
<td>−8.667</td>
<td>0.396</td>
<td>−0.006</td>
<td>1.09</td>
<td>0.559</td>
<td>0.0168</td>
</tr>
<tr>
<td>Interfacet height</td>
<td>IFHL</td>
<td>135.720</td>
<td>−20.994</td>
<td>1.201</td>
<td>−0.021</td>
<td>1.16</td>
<td>0.950</td>
<td>4.11E-08</td>
</tr>
<tr>
<td></td>
<td>IFHR</td>
<td>97.261</td>
<td>−14.658</td>
<td>0.856</td>
<td>−0.015</td>
<td>1.33</td>
<td>0.942</td>
<td>1.06E-07</td>
</tr>
<tr>
<td>Interfacet width</td>
<td>IFWS</td>
<td>595.510</td>
<td>−85.587</td>
<td>4.185</td>
<td>−0.067</td>
<td>1.78</td>
<td>0.818</td>
<td>9.80E-05</td>
</tr>
<tr>
<td></td>
<td>IFWIL</td>
<td>321.070</td>
<td>−43.273</td>
<td>2.100</td>
<td>−0.033</td>
<td>2.50</td>
<td>0.605</td>
<td>0.0091</td>
</tr>
<tr>
<td><strong>Facet orientations</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transverse angle</td>
<td>TASL</td>
<td>−629.850</td>
<td>106.150</td>
<td>−5.322</td>
<td>0.089</td>
<td>2.09</td>
<td>0.922</td>
<td>5.71E-07</td>
</tr>
<tr>
<td></td>
<td>TASS</td>
<td>−468.340</td>
<td>81.873</td>
<td>−4.122</td>
<td>0.070</td>
<td>1.70</td>
<td>0.938</td>
<td>1.65E-07</td>
</tr>
<tr>
<td></td>
<td>TAIL</td>
<td>−578.400</td>
<td>98.978</td>
<td>−4.951</td>
<td>0.082</td>
<td>1.65</td>
<td>0.892</td>
<td>4.45E-06</td>
</tr>
<tr>
<td></td>
<td>TAIR</td>
<td>−394.580</td>
<td>70.418</td>
<td>−3.485</td>
<td>0.057</td>
<td>3.24</td>
<td>0.526</td>
<td>0.0254</td>
</tr>
<tr>
<td>Sagittal angle</td>
<td>SASL</td>
<td>−1384.100</td>
<td>260.400</td>
<td>−15.230</td>
<td>0.292</td>
<td>10.44</td>
<td>0.875</td>
<td>1.02E-05</td>
</tr>
<tr>
<td></td>
<td>SASR</td>
<td>895.720</td>
<td>−180.630</td>
<td>10.957</td>
<td>−0.217</td>
<td>10.08</td>
<td>0.876</td>
<td>9.99E-06</td>
</tr>
<tr>
<td></td>
<td>SAIL</td>
<td>24.358</td>
<td>24.433</td>
<td>−2.355</td>
<td>0.064</td>
<td>14.45</td>
<td>0.808</td>
<td>0.0001</td>
</tr>
<tr>
<td></td>
<td>SAIR</td>
<td>−68.384</td>
<td>−14.160</td>
<td>1.824</td>
<td>−0.055</td>
<td>13.93</td>
<td>0.829</td>
<td>6.74E-05</td>
</tr>
</tbody>
</table>

SE in mm (for facet linear parameter) or in degree (for facet angular parameters).

The basic form of the prediction equations is $y = C_1 + C_2x + C_3x^2 + C_4x^3$, where $y$ is the value of the facet parameter to be predicted and $x$ is the value of the VBHP on each vertebral level. $S$, superior; $I$, inferior; $L$, left; $R$, right. Values in bold indicate facet parameters that show the same polynomial coefficients for thoracic and lumbar vertebrae.
showed poor correlation for lumbar levels ($R^2$, 0.457–0.559) good predictions could be achieved with the largest error of 28.4% in the FWSL (L1) prediction (Fig. 2E). The interfacet heights and widths (IFHL, IFHR, IFWS and IFWI) exhibited high correlations with VBHP ($R^2$, 0.818–0.973) with the exception of thoracic IFWI ($R^2$ = 0.605). Independent of thoracic or lumbar levels, the best correlations were found for interface heights. Predictions of these parameters showed a mean percent error < 11% for all vertebral levels (e.g. Fig. 2C). The mean percent errors were < 12% (for thoracic) and < 18% (for lumbar) for the IFWS and IFWI (e.g. Fig. 2F).
Facet angular parameters predictions

The transverse angles showed high correlations for TASL, TASR and TAIL with VBHP for all levels ($R^2$, 0.785-0.938). TAIR displayed a poor correlation ($R^2 = 0.526$) for the lumbar levels. For the predictions with data of Panjabi et al. (1993) the largest mean percent error found was approximately 10% (TAIR, L4). All other predictions including lumbar levels showed an error < 6% (e.g. Fig. 3A,C). The sagittal angles superior and inferior (SASL, SASR, SAIL and SAIR) also showed high correlations with VBHP, with $R^2$ ranging from 0.808 to 0.952. For SASR and SASL, very good predictions using the data of Panjabi et al. (1993) were found for thoracic levels, with a mean percent error < 4%; the lumbar predictions for these parameters showed variable errors of −0.6 to −9.3% (e.g. Fig. 3B). SAIL and SAIR predictions in the T11 level showed a considerable mean percent error of approximately 27%; all other thoracic levels displayed an error < 9%. The lumbar predictions showed errors of 5–20% (e.g. Fig. 3D).

Evaluation of the prediction equations

The third-order polynomial predictions were generally within or close to the regions of the 95% confidence intervals of the experimental data of Panjabi et al. (1993) (Fig. 4). Using the dataset of Cotterill et al. (1986), the comparisons with experimental and predicted thoracic IFHR and IFHL showed a mean percent error of approximately 13% (T6) and an error of approximately 0.22 mm (< 2%) (T12) (Fig. 5A,D). The L3 prediction showed the largest error of approximately 2.6 mm (9%) for IFHL (Fig. 5D). The predictions of the IFWS and IFVI exhibited a mean percent error < 16% for the thoracic level and better results for L3, respectively 1.7 mm (6.3%) and 1.01 mm (3.8%) (Fig. 5B,E). The predictions of the facet orientation, TASR and TASL, showed very similar results to experimental data values, with mean percent errors of approximately −11% (T6), −5% (T12) and −9% (L3) (Fig. 5C,F).

Fig. 3 Polynomial predictions of parameters related to orientations of the human thoracic and lumbar articular facet joints (TASL, SASL, TAIR and SAIL) from VBHP, superimposed on experimental data of Panjabi et al. (1993)*. Dotted curves indicate standard deviation of both the predictions and experimental data. $R^2$ is provided for thoracic and for lumbar levels. Only mean percent errors > 5% for all vertebral levels are shown. Best predictions (left); worst predictions (right).

© 2010 The Authors
Journal of Anatomy © 2010 Anatomical Society of Great Britain and Ireland
Discussion

In this study, the morphological relationships between anatomical characteristics of the human AFJ and VBHP were described by linear and nonlinear regression analyses. A set of prediction equations for AFJ parameters of the thoracic (T1–12) and lumbar (L1–4) spine was generated as a function of the VBHP (Tables 2 and 3).

SEs indicates that, with few exceptions, polynomial predictions were satisfactory for all AFJ parameters. The exceptions were in the facet dimensions in the thoracic region (T2 and 9) and facet orientation in the lumbar region (L1 and 4) (Fig. 4). The best predictions of facet orientations were found for the transverse angles. Excluding the level T1, no errors > 5% were found in the prediction of the transverse angles of the thoracic or lumbar regions, probably because these parameters show very little variability within the vertebrae from T1 to L4. Notably in the midthoracic region (i.e. T3–8), excellent predictions with errors < 10% could be achieved for most parameters of the AFJ. In contrast, predictions with errors of up to –15% were found for all sagittal angles in the thoracolumbar junction (T12–L1) (Fig. 4). This was due to the large variability of this region within individuals, with the AFJ being either frontally oriented, as in the thoracic vertebrae, or sagittally oriented, as in the lumbar vertebrae. This is in accordance with Goel & Weinstein (1990) and Masharawi et al. (2004) who showed that the morphology of the first lumbar vertebra is distinct from the other vertebrae, with a transition from the typically thoracic to the lumbar vertebra.

Our results were compared, when possible, with existing published experimental measurements of AFJ geometry (Table 1). However, it was not possible to carry out the evaluation of the predictability of all best-fitting equations using experimental data from more datasets. This was due to a lack of availability of measurements in the literature, including values of VBHP and facet parameters in the same dataset. Berry et al. (1987) provided data on the values of VBHP and interfacet height in some vertebral levels but a reference system different to Panjabi et al. (1993) was used. The dataset of Boszczyk (1997) provides accurate experimental measurements of VBHP and the main AFJ parameters, but these were obtained using different landmarks to Panjabi et al. (1993). Ebraheim et al. (1997) provided a large quantity of data on facet parameters but no information about the size of the vertebral bodies. Masharawi et al. (2004, 2005, 2008) performed direct measurement on normal spine of facet and vertebral body parameters but the values of VBHP of these studies were not provided.

All correlation coefficients generated in the current study were considerably better than those obtained by Breglia (2006). He correlated interfacet width and inclinations with VBHP by simple linear regression, finding a poor or even no correlation. Our results showed high correlations for these AFJ parameters after nonlinear regressions. The advantages of using nonlinear regressions to fit vertebral data were described in a previous study (Kunkel et al. 2010). Comparisons of the theoretical predictions with the dataset of Cotterill et al. (1986) indicated that the predictions closely agreed with the experimental data.

© 2010 The Authors
Journal of Anatomy © 2010 Anatomical Society of Great Britain and Ireland
Although the differences in the predictions of lumbar facet parameters were moderate, an excellent correlation between the thoracic facet parameters and VBHP was found (Fig. 5).

It should be emphasized that the predictions using the set of equations generated in the current study are an approximation and should not be extrapolated beyond the limits of the data of Panjabi et al. (1991, 1992). Furthermore, the AFJ show individual and segmental variation (Bernick & Cailliet, 1982; Taylor & Twomey, 1986; Wang & Yang, 2009; Ahmed et al. 1990; Diacinti et al. 1995). Moreover, the facet surfaces that were described here as planar are usually curved (Taylor & Twomey, 1986). Nevertheless, as the two datasets used in this study were provided from in vitro measurements, further investigations are necessary to evaluate the predictability of the regression equations with a dataset from patients.

The advantage of using the generated set of prediction equations (Tables 2 and 3) is the capability to obtain size and orientations of the AFJ considering individual variability from only a single parameter per vertebrae (VBHP) measurable on lateral X-ray. Direct measurement of the main AFJ parameters, considering each vertebral level, cannot be performed in X-rays due to the superposition of several anatomical structures, specifically in the sagittal thoracic region of the spine. Moreover, the lumbar AFJ are difficult to image with X-rays because they are both curved and oblique to the sagittal plane.

Another advantage of using the prediction equations is that they can provide data for parameterized finite element
modeling considering patient-specific AFJ morphology. Thus the geometric congruence between adjacent articular facets could be ensured, and the AFJ changes both between subjects and between vertebral levels maintained. This could avoid the practice adopted in the construction of some models where the AFJ are redirected to force the lower facet of a vertebra to become congruent with the upper facet of the one below (e.g. Maurel et al. 1997; Breglia 2006). Such approximations could produce errors in the modeling of facet contact at different spinal levels.

Conclusion

The present study shows that it is possible to establish useful predictors for human thoracic and lumbar AFJ parameters based on the size of the vertebral body. The generated set of prediction equations enables fast acquisition of geometrical parameters of the AFJ as a function of a single parameter (VBHP), which is measurable in X-rays. As the VBHP is unique for each person and vertebral level, the predicted size and orientations of the AFJ are also specific to an individual. It may be applied for parameterized patient-specific modeling of the spine based on X-ray images alone. Such models make it possible to explore the clinically important mechanical roles of the articular facets in spinal deformities, including scoliosis.

Acknowledgements

This study was financially supported by the German Research Foundation (Wi-1352/12-1).

Conflict of interest statement

The authors of this study did not and will not receive benefits in any form from a commercial party related directly or indirectly to the content of this study.

References

Morphometric analysis of the relationships between intervertebral disc and vertebral body heights: an anatomical and radiographic study of the human thoracic spine

Maria E. Kunkel,1 Andrea Herkommer,1 Michael Reinehr,2 Tobias M. Böckers2 and Hans-Joachim Wilke1

1Institute of Orthopaedic Research and Biomechanics, University of Ulm, Ulm, Germany
2Institute of Anatomy and Cell Biology, University of Ulm, Ulm, Germany

Abstract

The main aim of this study was to provide anatomical data on the heights of the human intervertebral discs for all levels of the thoracic spine by direct and radiographic measurements. Additionally, the heights of the neighboring vertebral bodies were measured, and the prediction of the disc heights based only on the size of the vertebral bodies was investigated. The anterior (ADH), middle (MDH) and posterior heights (PDH) of the discs were measured directly and on radiographs of 72 spine segments from 30 donors (age 57.43 ± 11.27 years). The radiographic measurement error and the reliability of the measurements were calculated. Linear and non-linear regression analyses were employed for investigation of statistical correlations between the heights of the thoracic disc and vertebral bodies. Radiographic measurements displayed lower repeatability and were shorter than the anatomical ones (approximately 9% for ADH and 37% for PDH). The thickness of the discs varied from 4.5 to 7.2 mm, with the MDH approximately 22.7% greater. The disc heights showed good correlations with the vertebral body heights ($R^2$, 0.659–0.835, $P$-values < 0.005; ANOVA), allowing the generation of 10 prediction equations. New data on thoracic disc morphometry were provided in this study. The generated set of regression equations could be used to predict thoracic disc heights from radiographic measurement of the vertebral body height posterior. For the creation of parameterized models of the human thoracic discs, the use of the prediction equations could eliminate the need for direct measurement on intervertebral discs. Moreover, the error produced by radiographic measurements could be reduced at least for the PDH.

Key words: anatomical measurement; disc morphometry; intervertebral disc height; radiographic measurement; thoracic vertebrae.

Introduction

The thoracic spine is the most common site for spinal deformities such as kyphosis and scoliosis (Lord et al. 1995). Despite this, and in contrast to cervical and lumbar discs, the morphometry of the adult thoracic intervertebral disc (TIVD) has received limited attention and until now relatively few data have been available in the current literature. For example, accurate anatomical data on the heights of the TIVD including all levels of the thoracic spine of a representative adult population are very scarce. Previous studies showed limitations either in accuracy, study population, parameters recorded or disc level. Anatomical data on TIVD are a requirement for both the development of new spinal implants and for the creation of mathematical models of the human spine.

Direct measurement on specimens is the best method for extracting morphometric data from anatomical structures. However, relatively few studies on TIVD morphometry have been carried out due to the difficulty in obtaining intact human specimens. Huxthal (1968) and Manns et al. (1986) measured anterior disc height (ADH) using radiographs of...
female patients, but only a limited number of thoracic levels (from T5–6 to T11–12) were investigated. Todd & Pyle (1928) measured only ADH and only male cadavers were used, while the age distribution for this sample was not reported; Pooni et al. (1986) used only a few elderly cadavers between 73 and 85 years old, but the data were presented only as a percentage of the total spine height; radiographic measurements by Goh et al. (1999) and Giles & Singer (2000) were used to investigate thoracic kyphosis, but the ADH and posterior heights (PHD) of the disc were not provided and only a segmental trend was reported. Some of these measurements were performed on plain radiographs considering the superior and inferior vertebral corners (Pooni et al. 1986; Goh et al. 1999; Giles & Singer, 2000). Whereas it has the advantage of eliminating the need for sample preparation, in some reports on lumbar discs the accuracy and repeatability of radiographic measurements of disc heights have been questioned (Pope et al. 1977; Andersson et al. 1981). This was due to a lack of the requisites needed to perform geometric measurements with relative accuracy such as the use of a standard vertebral position, control of the film-specimen-focus distances and optimal visualization of the bony landmarks. Furthermore, in some investigations on TIVD morphometry, errors due to radiographic magnification bias or the inter- and intraobserver reliability of the radiographic measurements were not taken into account (Hurzthal, 1968; Manns et al. 1986; Pooni et al. 1986). The error of radiographic measurement of the heights of TIVDs was never accurately investigated.

Statistical correlations between the main anatomical dimensions of the human vertebral structures have been quantified in previous studies (Scoles et al. 1988; Lavaste et al. 1992; Laporte et al. 2000; Breglia, 2006; van der Houwen et al. 2010). Recently, thoracic and lumbar vertebral morphometry was predicted with reasonable accuracy using only the dimension of the vertebral body heights measured on lateral radiographs and a set of regression equations (Kunkel et al. 2010, 2011). A similar method could be used for the prediction of TIVD dimensions as an alternative to anatomical or radiographic measurements. However, the relationships between morphometric dimensions of the TIVD and vertebrae have never been investigated. To the authors’ knowledge, to date no report has investigated the possibility of establishing useful predictors for TIVD dimensions based only on the size of the vertebral bodies. Such a method could provide data for patient-specific modeling of the spine where the shape and size of the TIVD need to be considered.

The main aim of this study was to provide anatomical data on the heights of the human intervertebral discs for all levels of the thoracic spine by direct and radiographic measurements. The radiographic measurements error was also estimated. Additionally, the heights of the neighboring vertebral bodies were measured, and the prediction of the disc heights based only on the size of the vertebral bodies was investigated.

Materials and methods

Study sample and parameters

Seventy-two isolated spine segments (each segment includes a vertebral pair and intervertebral disc between the vertebrae)
from a total of 30 human spines were examined. For morphometric measurements and statistical analyses six segments were available for each spinal level from C7-T1 to T11-12. Thirty-seven spine segments were from 15 females (mean age of 58.67 ± 10.74 years, range: 43–80 years) and 35 were from 15 males (mean age of 56.20 ± 11.65 years, range: 37–79 years). The discs were not classified into age or gender groups. Because there is not a grading system for the anatomical or radiographic identification of degenerative change in TIVDs, an overview of features of the discs (nucleus and annulus) and vertebral end-plate and vertebral body of the thoracic spine was proposed based on previous studies on lumbar discs; macroscopic classification schemas (Nachemson, 1979; Galante, 1967, Thompson et al. 1990; Adams et al. 1996; Wilke et al. 2006) and studies taking into account pathological changes to lumbar discs (Friberg & Hirsch, 1949; Hirsch & Schajowicz, 1953; Vernon-Robert & Pirie, 1977). A set of five morphometric parameters was measured both on lateral radiographs obtained in controlled conditions and directly on sagittal sections of the specimens (Fig. 1). From these measurements, three adimensional morphometric indices were calculated based on previous methods for lumbar discs (Twomey & Taylor, 1987; Amonoo-Kuofi, 1991). The junctional segment C7-T1 was also included for the observation of anatomical variations in the cervicothoracic discs in the transition from mobile cervical to rigid thoracic spine.

Specimen preparation, radiographic imaging and measurement

The spines were dissected into individual segments free of soft tissues. The ribs were sawn and segments containing the whole disc attached to its upper and lower vertebralae were stored at −28°C. Lateral and antero-posterior radiographs were taken using a Faxitron automatic X-ray machine (Hewlett Packard, McMinnville, USA). Each segment was placed in a neutral, standard position and a standard film-focus distance of 60 cm, time of 60 s and a tube voltage of 46.5 kV were used. The X-ray beam was centered on the discs. Potential error due to off-center positioning of the spinal segments from the X-ray was examined and a factor for corrections of differences in magnification was calculated. For the radiographic measurements, individual radiographs of the spinal segments were placed on a viewing table and eight anatomical landmarks representing the four corners on the extreme anterior and posterior margins of the end-plates of the vertebralae were marked using Farfan’s method (1973) (Fig. 1a). The disc and vertebral heights were measured using an electronic digital caliper (Mitutoyo, Absolute Digimatic, Tokyo, Japan) with an accuracy of ± 0.05 mm. The radiographs were calibrated by means of a scale placed on the rig close to the specimen. Radiographs with overlay from other structures or of deficient film quality were excluded.

Specimen preparation and anatomical measurement

To perform the direct measurements on the discs, frozen spinal segments were sectioned in the horizontal plane through each of the upper and lower vertebralae bodies using a high-precision saw (Exacta; PSI Medical, Grünwald, Germany). The posterior elements were removed and segments containing the whole disc attached to a thick portion of the upper and lower vertebralae bodies were maintained. Two rods, each 3.0 mm in diameter and 20 mm in length, were fixed into each vertebral body indicating the frontal and median sagittal plane of the TIVD. To produce sagittal sections of the TIVD, each specimen was frozen in an ice block that was individually mounted into a holder with adjustable height for a saw microtome (Leica SP4000; Leica Microsystems, Wetzlar, Germany). The ice blocks were subjected to sagittal sectioning based on the position of the rods. A sliding vernier caliper (Mitutoyo, Absolute Digimatic, Tokyo, Japan) was used for the measurement of TIVD heights, including the cartilaginous end-plates, by using the previously described anatomical landmarks in addition to two mid-vertebral points located on the superior and inferior end-plates for the measurement of the middle disc height (MDH) (Fig. 1b).

Inter- and intra-observer reliability

Each set of radiographic and anatomical measurements was carried out by two observers. Inter-observer errors were examined by repeating the measurement of all parameters in all radiographs and anatomical specimens. Intra-observer errors were examined by one observer making repeated measurements in 10 radiographs from 10 individual specimens at five different spinal levels with some minutes between each repeated measurement. The measurement precision for each parameter was expressed as a coefficient of variation (CV).

Statistical analysis

Linear regression was used to examine the correlation between the radiographic and anatomical measurements of the ADH and PDH, and to calculate the accuracy of the radiographic measurement in relation to the anatomical one. The heights of the discs and the anterior and posterior vertebralae bodies (VBHA and VBHP) were individually regressed against the parameters ADH, VBHA and VBHP by a least-squares estimation process using a methodology based on Kunkel et al. (2010, 2011). Linear and non-linear regression analyses were employed to find the best functions to fit each of these parameters in a prediction equation. The parameters ADH, VBHA and VBHP were chosen as predictor variables because they could be measured on radiographs with an acceptable accuracy. This was not the case for the MDH and PDH, which were excluded as predictor variables. An ANOVA was performed to define the significance of the prediction equations (P < 0.05) that were evaluated using experimental data of Todd & Pyle (1928).

Results

The grading system proposed to classify the thoracic spinal segments consisted of four grades: (i) no degeneration; (ii) mild degeneration; (iii) moderate degeneration; and (iv) strongly degenerated. The description of the grading scale is as follows. Nucleus: (i) elastic, bright, clear delineation from the annulus; (ii) slightly fibrotic, no clear delineation from the annulus; (iii) fibrous, dry, fissured, discolored, bleeding through cavities, loss of the annulus-nucleus boundary; (iv) fibrous, dry, brownish, brittle, partially replaced by scar tissue. Annulus: (i) concentrically arranged fiber ring plates, regular onion-shaped grain, shiny, sinewy;
Table 1  Anatomical and radiographic measurements of the anterior, middle and posterior human T1D heights.

<table>
<thead>
<tr>
<th>Disc level</th>
<th>Anterior disc height (ADH)</th>
<th>Posterior disc height (PDH)</th>
<th>Middle disc height (MDH)*</th>
<th>Average disc height **</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Anatomical measurement</td>
<td>Radiographic measurement</td>
<td>Anatomical-radiographic ratio</td>
<td>Anatomical measurement</td>
</tr>
<tr>
<td>C7-T1</td>
<td>4.5 (0.27)</td>
<td>3.96 (0.22)</td>
<td>-0.54 (0.14)</td>
<td>4.5 (0.51)</td>
</tr>
<tr>
<td>T1-2</td>
<td>4.5 (0.77)</td>
<td>3.69 (0.62)</td>
<td>-0.81 (0.17)</td>
<td>4.3 (0.62)</td>
</tr>
<tr>
<td>T2-3</td>
<td>3.4 (0.97)</td>
<td>3.23 (0.62)</td>
<td>-0.17 (0.17)</td>
<td>3.5 (0.99)</td>
</tr>
<tr>
<td>T3-4</td>
<td>3.3 (0.30)</td>
<td>3.07 (0.44)</td>
<td>0.23 (0.17)</td>
<td>3.2 (0.30)</td>
</tr>
<tr>
<td>T4-5</td>
<td>3.0 (0.74)</td>
<td>2.85 (0.36)</td>
<td>-0.15 (0.15)</td>
<td>3.3 (0.24)</td>
</tr>
<tr>
<td>T5-6</td>
<td>3.5 (0.37)</td>
<td>3.36 (0.29)</td>
<td>0.14 (0.14)</td>
<td>3.6 (0.47)</td>
</tr>
<tr>
<td>T6-7</td>
<td>4.1 (0.35)</td>
<td>3.70 (0.41)</td>
<td>0.40 (0.40)</td>
<td>4.1 (0.65)</td>
</tr>
<tr>
<td>T7-8</td>
<td>4.2 (0.97)</td>
<td>4.06 (0.67)</td>
<td>-0.35 (0.14)</td>
<td>3.6 (0.90)</td>
</tr>
<tr>
<td>T8-9</td>
<td>5.6 (1.17)</td>
<td>4.52 (0.43)</td>
<td>1.08 (0.52)</td>
<td>5.0 (0.91)</td>
</tr>
<tr>
<td>T9-10</td>
<td>5.4 (1.74)</td>
<td>4.88 (1.03)</td>
<td>0.52 (0.70)</td>
<td>4.2 (1.00)</td>
</tr>
<tr>
<td>T10-11</td>
<td>7.2 (1.21)</td>
<td>5.91 (0.77)</td>
<td>1.29 (0.70)</td>
<td>5.8 (1.00)</td>
</tr>
<tr>
<td>T11-12</td>
<td>6.0 (1.14)</td>
<td>5.90 (0.70)</td>
<td>0.10 (0.10)</td>
<td>4.8 (1.26)</td>
</tr>
</tbody>
</table>

Refer to Fig. 1 for abbreviations.
All measurements are in mm.

*No radiographic measurement was performed for the MDH.

**Average disc height is the average of the anatomical measurement of the ADH and PDH at each vertebral level. o e digital.
(ii) sharply contoured, concentrically arranged fiber ring plates (drier appearance); (iii) disordered fibrous structure of the lamellae, fiber faults, fiber fabric ring pronounced dry-looking, sprouting of blood vessels; (iv) ruptures in the annulus, fiber breaks, cracks, fissures, defects. End-plate: (i) well-built hyaline end-plate, even thickness; (ii) hyaline with irregular thickness; (iii) local cartilage defects; (iv) complete destruction of cartilaginous end-plate. Vertebral body: (i) rounded margins; (ii) small projections from the margins; (iii) first osteophytes on the edge < 2 mm; (iv) osteophytes on the anterior vertices > 2 mm. The anatomical and radiographic inspection of the spinal segments selected for this study showed mild to moderate degenerative changes (grades ii and iii).

**Inter- and intra-observer reliability of the measurements**

Inter-observer reliability showed that measurements of the TIVD heights were better repeated when obtained directly

<table>
<thead>
<tr>
<th>Vertebral level</th>
<th>Vertebral body height anterior (VBHA)</th>
<th>Vertebral body height posterior (VBHP)</th>
<th>Average vertebral body height*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
</tr>
<tr>
<td>C7</td>
<td>13.89</td>
<td>1.42</td>
<td>14.38</td>
</tr>
<tr>
<td>T1</td>
<td>14.49</td>
<td>1.23</td>
<td>15.28</td>
</tr>
<tr>
<td>T2</td>
<td>15.01</td>
<td>1.51</td>
<td>16.11</td>
</tr>
<tr>
<td>T3</td>
<td>15.65</td>
<td>1.85</td>
<td>17.41</td>
</tr>
<tr>
<td>T4</td>
<td>15.42</td>
<td>1.46</td>
<td>18.15</td>
</tr>
<tr>
<td>T5</td>
<td>15.84</td>
<td>1.07</td>
<td>17.33</td>
</tr>
<tr>
<td>T6</td>
<td>16.04</td>
<td>1.43</td>
<td>18.22</td>
</tr>
<tr>
<td>T7</td>
<td>15.94</td>
<td>1.61</td>
<td>18.67</td>
</tr>
<tr>
<td>T8</td>
<td>16.99</td>
<td>1.70</td>
<td>20.05</td>
</tr>
<tr>
<td>T9</td>
<td>18.26</td>
<td>2.12</td>
<td>20.25</td>
</tr>
<tr>
<td>T10</td>
<td>18.98</td>
<td>1.40</td>
<td>20.35</td>
</tr>
<tr>
<td>T11</td>
<td>19.60</td>
<td>1.92</td>
<td>22.67</td>
</tr>
<tr>
<td>T12</td>
<td>20.80</td>
<td>1.96</td>
<td>23.12</td>
</tr>
</tbody>
</table>

Refer to Fig. 1 for abbreviations.
All measurements are in mm.
*Average vertebral body height is the average of the VBHA and VBHP at each vertebral level.

**Table 3** Morphometric indices derived from measurements on the intervertebral discs and vertebral bodies heights.

<table>
<thead>
<tr>
<th>Disc level</th>
<th>Relative disc height index (l₁)</th>
<th>Disc : vertebral body height ratio</th>
<th>Disc convexity index (l₂)</th>
<th>% MDH to average disc height</th>
<th>Disc antero-posterior wedging index (l₃)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C7-T1</td>
<td>0.32</td>
<td>1:3.1</td>
<td>0.63</td>
<td>20.55</td>
<td>1.00</td>
</tr>
<tr>
<td>T1-2</td>
<td>0.30</td>
<td>1:3.4</td>
<td>0.65</td>
<td>23.11</td>
<td>1.06</td>
</tr>
<tr>
<td>T2-3</td>
<td>0.22</td>
<td>1:4.5</td>
<td>0.83</td>
<td>39.65</td>
<td>0.97</td>
</tr>
<tr>
<td>T3-4</td>
<td>0.20</td>
<td>1:5.1</td>
<td>0.67</td>
<td>25.17</td>
<td>1.03</td>
</tr>
<tr>
<td>T4-5</td>
<td>0.19</td>
<td>1:5.3</td>
<td>0.80</td>
<td>37.50</td>
<td>0.89</td>
</tr>
<tr>
<td>T5-6</td>
<td>0.21</td>
<td>1:4.7</td>
<td>0.67</td>
<td>25.58</td>
<td>0.97</td>
</tr>
<tr>
<td>T6-7</td>
<td>0.24</td>
<td>1:4.2</td>
<td>0.68</td>
<td>25.95</td>
<td>1.01</td>
</tr>
<tr>
<td>T7-8</td>
<td>0.23</td>
<td>1:4.4</td>
<td>0.68</td>
<td>26.75</td>
<td>1.16</td>
</tr>
<tr>
<td>T8-9</td>
<td>0.29</td>
<td>1:3.5</td>
<td>0.57</td>
<td>12.56</td>
<td>1.13</td>
</tr>
<tr>
<td>T9-10</td>
<td>0.25</td>
<td>1:4.0</td>
<td>0.58</td>
<td>13.74</td>
<td>1.29</td>
</tr>
<tr>
<td>T10-11</td>
<td>0.33</td>
<td>1:3.0</td>
<td>0.52</td>
<td>3.50</td>
<td>1.23</td>
</tr>
<tr>
<td>T11-12</td>
<td>0.26</td>
<td>1:3.9</td>
<td>0.60</td>
<td>16.77</td>
<td>1.25</td>
</tr>
</tbody>
</table>

Refer to Fig. 1 for abbreviations.

\[ l₁ = \frac{(ADH + PDH)}{(VBHA + VBHP)} \] based on Amoooc-Kuofi (1991).
\[ l₂ = \frac{MDH}{(ADH + PDH)} \] based on Twomey & Taylor (1987).
\[ l₃ = \frac{ADH}{PDH} \].

The ratio of disc: body was calculated by dividing 1 by the value of \( l₁ \).

© 2011 The Authors
Journal of Anatomy © 2011 Anatomical Society of Great Britain and Ireland
from the specimens (CV = 0.79–0.93) than from the radiographs (CV = 0.49–0.82). A lower repeatability was found for radiographic measurement of the PDH (CV = 0.49). For radiographic measurements of the VBHA and VBHP a high repeatability was found (CV = 0.95–0.98). Intra-observer reliability showed that anatomical measurements were reproduced with errors ranging from 1.7 to 6.1% for ADH, 17 to 26.1% for PDH and 1.7 to 5.1% for VBHA and VBHP. Reproducibility of the measurements from repeat radiographs was generally 15% lower.

### Intervertebral discs and vertebral body heights

A wide variation in TVD heights was found in the anatomical measurements (Table 1). Direct measurement of the ADH varied from approximately 4.5 mm at C7–T1, with a gradual decrease towards T4–5 (approximately 3 mm), increasing again caudally to approximately 7.2 mm at T10–11, and decreasing again to approximately 6 mm at T11–12 (Table 1). PDH measured directly on the specimens followed a trend similar to ADH, but from the disc level T7–8 there was an increase of approximately 21% in the values. The average disc height that corresponded to the average of the ADH and PDH at each vertebral level varied from 3.2 to 6.5 mm (mean value of 4.3 ± 1 mm, Table 1). The average vertebral body height varied from 14.2 to 21.96 mm (Table 2). The MDH was on average 22.7% higher than the average disc height (Tables 1 and 3). Radiographic ADH and PDH values were shorter than the anatomical ones (approximately 9% for ADH and 37% for PDH). From these comparisons, a height linear correlation was found for ADH ($R^2 = 0.921$) (Fig. 2a), but only a moderate correlation for PDH ($R^2 = 0.690$) (Fig. 2b).

### Morphometric indices

The index $I_1$ enabled a comparison of the TVD height with the heights of neighboring vertebral bodies (Table 3). There was a constant relationship between the disc thickness and the vertebral bodies’ heights at all levels (ratio disc : body of approximately 1 : 4.1) (Fig. 3). The index $I_2$ indicated that the ovality of the disc did not follow a trend as one descends the thoracic spine. It was more pronounced at the T2–3 level where MDH was almost 40% of the average disc height (Table 3; Fig. 3). The index $I_3$ showed that with the exception of the cervicothoracic discs (C7–T1) all discs were wedge-shaped. There was a trend for a posterior wedge configuration from the T7–8 level onwards, the ADH being approximately 21.25% greater than the PDH. However, in the upper and middle thoracic region (from T1–2 to T5–7) both anteriorly and posteriorly minimal wedge shapes were found with a maximum difference between these values of approximately 2.77%. From these morphometric indices,
the TIVD could be classified into three distinct regions as an approximation of the vertebral regions of the thoracic spine (Panjabi et al. 1991a; Fig. 3). The upper region of transition from cervical to thoracic from C7–T1 to T3–4 was characterized by a gradual decrease caudally of the ADH and PDH until the thinnest disc at T4–5, with a sliding posterior wending. The middle region from T4–5 to T6–7 showed sliding anterior wedge-shaped discs, and the lower region from the apex of the thoracic spine T7–8 to T11–12 contained more posterior wedge-shaped discs. Comparisons with the literature were provided for measurements of the disc heights (Fig. 4) and vertebral bodies heights (Fig. 5).

Disc and vertebral body height correlations
In general, the heights of the TIVDs presented had good correlations with the vertebral heights, that were significant \( (R^2 = 0.659-0.835, \ P < 0.005; \ ANOVA) \) (Table 4). An exception was the MDH, for which no significant correlations with the vertebral body heights were found \( (R^2 < 0.6, \ P > 0.05) \). A set of 10 polynomial equations was generated for the prediction of TIVD heights from parameters that could be accurately measured on the radiographs (ADH, VBHA and VBHP; Table 4). The polynomial predictions, using the generated set of regression equations, were generally within or close to the region of the 95% confidence intervals of the experimental data measured in the current study (Fig. 6). The evaluation of the predictability of the regression equations using VBHA and VBHP of the data set of the radiographic measurements of the current study showed that good results could be found (Figs 7 and 8). Using the data set of Todd & Pyle (1928), a comparison of predicted PDH from radiographic ADH showed a greatest error of approximately –13% in the upper and –17% in the
Morphometric analysis of the relationships between intervertebral disc and vertebral body heights, M. E. Kunkel et al.

Fig. 5 Comparison of the anterior (a) and posterior (b) heights of the human vertebral bodies obtained in the present study with published data. Means values of radiographic measurements. Dotted lines indicate SD of the experimental values of the present study. VBHA, vertebral body height anterior; VBHP, vertebral body height posterior.

Table 4 Polynomial coefficients (C1, C2, C3, C4 and C5) for prediction equations of the parameters related to the heights of the TIVD and vertebral bodies for all spinal levels from C7–T1 to T11–12. The vertebral parameters come from radiographic measurements, whereas the disc parameters are from anatomical measurements performed in the current study.

<table>
<thead>
<tr>
<th>Predictor parameter</th>
<th>Predicted parameter</th>
<th>R²</th>
<th>P-value</th>
<th>SE</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADH</td>
<td>MDH</td>
<td>0.726</td>
<td>0.0004</td>
<td>0.37</td>
<td>3.500</td>
<td>0.453</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PDH</td>
<td>ADH</td>
<td>0.906</td>
<td>0.0002</td>
<td>0.27</td>
<td>-2.149</td>
<td>3.067</td>
<td>-0.538</td>
<td>0.037</td>
</tr>
<tr>
<td>VBHA</td>
<td>MDH</td>
<td>0.835</td>
<td>0.0017</td>
<td>0.60</td>
<td>544.560</td>
<td>-97.473</td>
<td>5.795</td>
<td>-0.113</td>
</tr>
<tr>
<td>PDH</td>
<td>VBHA</td>
<td>0.576</td>
<td>0.0640</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>VBHP</td>
<td>ADH</td>
<td>0.667</td>
<td>0.0260</td>
<td>0.52</td>
<td>360.580</td>
<td>-63.935</td>
<td>3.783</td>
<td>-0.074</td>
</tr>
<tr>
<td>VBHP</td>
<td>PDH</td>
<td>0.953</td>
<td>2.7E-06</td>
<td>0.66</td>
<td>-180.00</td>
<td>31.073</td>
<td>-1.646</td>
<td>0.030</td>
</tr>
<tr>
<td>VBHP</td>
<td>VBHA</td>
<td>0.780</td>
<td>0.0053</td>
<td>0.66</td>
<td>298.43</td>
<td>-46.993</td>
<td>2.561</td>
<td>-0.045</td>
</tr>
<tr>
<td>VBHP</td>
<td>MDH</td>
<td>0.571</td>
<td>0.0676</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>VBHP</td>
<td>PDH</td>
<td>0.659</td>
<td>0.0282</td>
<td>0.53</td>
<td>201.190</td>
<td>-32.029</td>
<td>1.705</td>
<td>-0.030</td>
</tr>
<tr>
<td>VBHP</td>
<td>VBHA</td>
<td>0.943</td>
<td>6.5E-06</td>
<td>0.58</td>
<td>44.199</td>
<td>-5.305</td>
<td>0.286</td>
<td>-0.004</td>
</tr>
</tbody>
</table>

Refer to Fig. 1 for abbreviations.

The basic form of the prediction equations is \( y = C_1 + C_2 x + C_3 x^2 + C_4 x^3 \) where \( y \) is the value of the parameter to be predicted and \( x \) is the value of the predictor parameter on each spinal level.

lower regions of the thoracic spine (Fig. 9a). The predictions of the VBHA and VBHP exhibited a mean percent error < 17% (Fig. 9b,c).

Discussion

In the present study, the heights of human TIVDs from the C7–T1 to T11–12 spinal level were measured directly on the sagittal section of 72 specimens and on their radiographs. The main aim was to provide these anatomical data and estimate the error of the radiographic measurements. Additionally, heights of the neighboring vertebral bodies were measured for the investigation of predictions of TIVD dimensions based on the size of the vertebral bodies.

Disc height is an important dimension often used as a diagnostic tool in orthopedics as well as in mathematical modeling of the human spine. Although Oliver & Middleton (1991) reported that TIVDs have a nearly uniform thickness, our anatomical observations indicated that there
is no single exact disc height because the planes that bound the TIVD superiorly and inferiorly were not parallel (Fig. 1). A geometric model of the thoracic discs based on these parameters provides a better visualization of this variation, which occurs in different parts of the same disc as well as in different regions of the thoracic spine (Fig. 3). However, this may be due to the age of the subjects (Vernon-Robert & Pirie, 1977; Twomey & Taylor, 1987) or to other factors such as loss of disc height in cases of scoliosis or disc herniation. Possible sources of error in these measurements could also be due to post mortem changes or the degree of disc degeneration (Peacock, 1952; Walmsley, 1953; White & Panjabi, 1990; Goh et al. 2000).

In the current study, the two main sources of ambiguity found in radiographic measurements of disc heights (the disc orientation with respect to the central X-ray beam, and the estimation of differences among different observers) were minimized using the recommendations of Pope et al. (1977) and Andersson et al. (1981). The difficulty in identifying the bony landmarks was overcome by strictly controlling the vertebral position, preserving the relationships between the TIVD and the vertebral bodies. However, even when the specimens were radiographed under these controlled and standard conditions the same degree of accuracy that was seen for the anatomical measurement was still not achieved (Table 1; Fig. 2). This was due to the difficulty in the identification of the vertebral bony landmarks, particularly where many overlapping shadows were found, for example in the measurements of the PDH at the upper thoracic spine. It was not possible to compare radiographic and anatomical measurement of the MDH because the midline distance between the oval radiographic images of the proximal and distal vertebral end-plates could not be identified (Edmondston et al. 1999). Our radiographic ADH and PDH values were shorter than the anatomical ones, probably because the anatomical measurements included the cartilaginous end-plates that cannot be readily indentified on radiographs.

Comparison of our direct and radiographic measurements with other studies on TIVD was difficult due to the fact that there are few comparative data in the literature (e.g. no published data related to MDH were found). For ADH, a good agreement was found with anatomical values of Todd & Pyle (1928; Fig. 4a) and radiographic values of Manns et al. (1986) and Giles & Singer (2000) (Fig. 4b); although the same was not found for the radiographic PDH values compared with Giles & Singer (2000) (Fig. 4c). The small variations between the radiographic measurements could
be due to radiographic magnification bias, positioning errors and distortion due to parallax effects.

As expected, the radiographic measurements of the thoracic vertebral bodies heights showed very good agreement with other studies where these values have already been well established (Todd & Pyle, 1928; Cotterill et al. 1986; Berry et al. 1987; Scales et al. 1988; Panjabi et al. 1991a, b) (Fig. 5). However, the cartilaginous endplates were not considered for this measurement, and this could slightly interfere in this measurement. Although this was not a major goal of our study, accurate measurements of these parameters were necessary so that we could perform analysis of the correlations with the measurements of disc height. The morphometric indices for TIVD showed a ratio of disc to vertebral body height of approximately 1:4.1, with a progressive increase in the spine motion in the sagittal plane in the lower region (1:3.8) where the disc height was greater and the thoracic segments were less impeded by the constraint of the thoracic cage. This agrees with Kapandji (1985) and White & Panjabi (1990) who reported the thoracic region as the least mobile of the spine.

Due to the fact that TIVD heights provided in this study were obtained from in vitro measurements of isolated spine
Fig. 8 Radiographic values of the VBHP were used for polynomial predictions of the parameters ADH (a), PDH (b) and VBHA (c) at all levels of the thoracic spine. The predicted values were superimposed on anatomical data that were measured in the present study. Dotted and continuous curves indicate SD of the experimental and predicted values, respectively. Mean percent errors of the predictions larger than 10% are indicated. ADH, anterior disc height; an, anterior; ca, caudal; cr, cranial; PDH, posterior disc height; po, posterior; VBHA, vertebral body height anterior; VBHP, vertebral body height posterior.

segments of cadavers, the axial load applied to the thoracic spine due to bodyweight could not be considered. Therefore, the measured values in the current study should be slightly larger than the radiographic values of a living person in a sitting or standing position. This could be an important point from both arthroplasty and modeling standpoints.

Using the set of prediction equations generated in this study it was possible to estimate heights of the thoracic discs from initial radiographic measurement of the vertebral heights (Figs 6–8). ADH could be predicted, with a largest error of approximately 26%, from measurements of the VBHA or VBHP. MDH could only be measured with statistical significance from the ADH measurements (largest error of approximately 15%). For estimation of PDH, both ADH and vertebral heights provided good predictions. From the measurement of the vertebral height were predicted values of PDH with approximately 26% error, which was less than the radiographic measurement of this parameter in all thoracic levels (Table 1; Figs 7 and 8). The values of VBHA and VBHP allowed very good predictions with errors of less than 10%. The generated equations are thus valid under these limited circumstances. It is also important to point out that the errors caused by the measurement of radiographic vertebral bodies may lead to errors in predicting the height of the disc. Moreover, further investigations
are necessary to evaluate the predictability of the regression equations with a data set from patients.

This study provided an accurate and comprehensive data base to describe the geometry of the T12VD. This may serve as an anthropometric reference for mathematical modeling, as well as for anatomical and biomechanical studies of the human spine, where dimensions and relations of spinal bony segments in the mid-sagittal plane are of importance.

**Conclusion**

The current increased interest in spinal implants and biomechanical models of spinal deformation, including scoliosis, calls for a detailed knowledge of its anatomy and of relationships between the disc and the vertebrae. The present study contributes by providing new anatomical data on thoracic disc morphometry, particularly the disc heights and their relationships with thoracic vertebral body heights. These data are important for understanding the biomechanics and morphology of the spine. The generated set of prediction equations quantitatively describe these relationships and could be used to produce morphometric data on thoracic disc. For the creation of parameterized models of the human thoracic disc, the use of the prediction equations could eliminate the need for direct measurement on intervertebral discs. Moreover, the error produced by radiographic measurements could be reduced at least for the PDH.
Acknowledgement

This study was financially supported by the German Research Foundation (WI-1352/12-1).

Conflict of interest statement

Each author of this study did not and will not receive benefits in any form from a commercial party related directly or indirectly to the content of this study.

References


