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

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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 vertebrae. 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 rela-

tively 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. Hurxthal (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 (Hurxthal, 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)
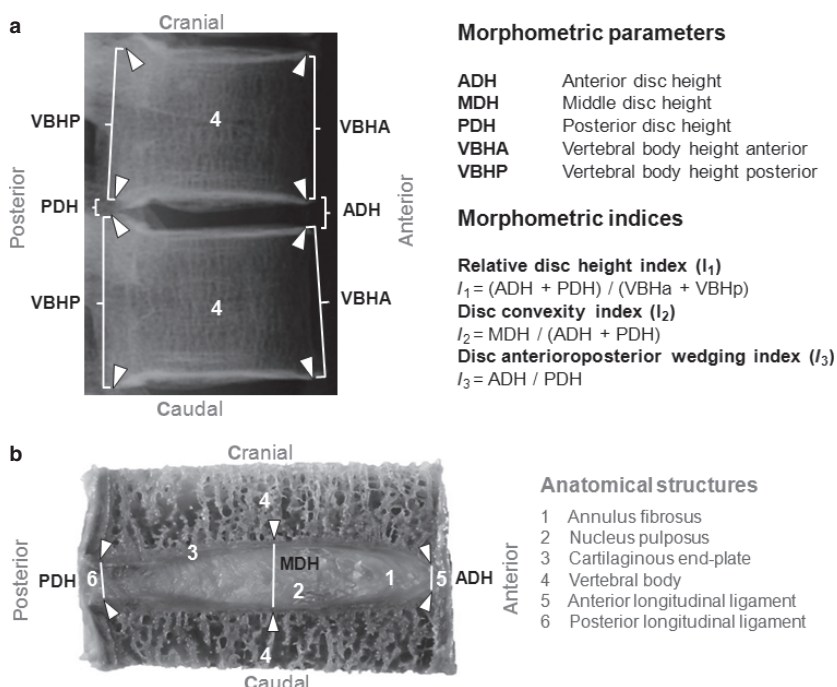

Morphometric parameters

ADH	Anterior disc height
MDH	Middle disc height
PDH	Posterior disc height
VBHA	Vertebral body height anterior
VBHP	Vertebral body height posterior

Morphometric indices

Relative disc height index (I_1)
$I_1 = (ADH + PDH) / (VBHa + VBHp)$
Disc convexity index (I_2)
$I_2 = MDH / (ADH + PDH)$
Disc anterioroposterior wedging index (I_3)
$I_3 = ADH / PDH$

Anatomical structures
1 Annulus fibrosus
2 Nucleus pulposus
3 Cartilaginous end-plate
4 Vertebral body
5 Anterior longitudinal ligament
6 Posterior longitudinal ligament

Fig. 1 Schematic representation of the parameters and indices that were considered for the morphometric analyses. The anatomical landmarks used are indicated by white arrowheads. (a) In the lateral conventional radiographs of the spinal segments all listed parameters, with the exception of the MDH, were measured. (b) In the sagittal sections of the specimens just the three heights of the intervertebral discs were measured. Images are from a thoracic segment (T9–10) of a 57-year-old female donor. ADH, anterior disc height; MDH, middle disc height; PDH, posterior disc height; VBHA, vertebral body height anterior; VBHP, vertebral body height posterior.

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 vertebrae (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 vertebrae 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 vertebrae 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 vertebral 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 vertebral 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 vertebral bodies (VBHA and VBHP) were individually regressed against the parameters ADH, VBHA and VBHP by a least-square 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 TIVD heights.

| Disc level | Anterior disc height (ADH) | | | | | | Posterior disc height (PDH) | | | | | | Middle disc height (MDH)* | | Average disc height ** |
| | Anatomical measurement | | Radiographic measurement | | Anatomical–radiographic ratio | | Anatomical measurement | | Radiographic measurement | | Anatomical-Radiographic ratio | | Anatomical measurement | | |
	Mean	SD	Mean	SD	Difference	%	Mean	SD	Mean	SD	Difference	%	Mean	SD	
C7–T1	4.5	0.79	3.96	0.22	0.54	−11.90	4.5	0.51	3.20	0.55	1.30	−28.91	5.6	0.63	4.5
T1–2	4.5	0.77	3.69	0.62	0.81	−18.01	4.3	0.62	3.04	0.56	1.26	−29.40	5.7	0.66	4.4
T2–3	3.4	0.97	3.23	0.40	0.17	−4.89	3.5	0.99	1.95	0.28	1.55	−44.22	5.8	0.79	3.5
T3–4	3.3	0.30	3.07	0.44	0.23	−6.96	3.2	0.49	2.09	0.46	1.11	−34.69	4.4	0.8	3.3
T4–5	3.0	0.74	2.85	0.36	0.15	−5.11	3.3	0.45	2.00	0.21	1.30	−39.54	5.0	0.61	3.2
T5–6	3.5	0.37	3.36	0.29	0.14	−3.93	3.6	0.47	2.10	0.30	1.50	−41.71	4.7	0.91	3.5
T6–7	4.1	0.35	3.70	0.41	0.40	−9.80	4.1	0.65	2.18	0.50	1.92	−46.72	5.5	0.45	4.1
T7–8	4.2	0.97	4.06	0.67	0.14	−3.35	3.6	0.90	2.47	0.50	1.13	−31.44	5.3	0.58	3.9
T8–9	5.6	1.17	4.52	0.43	1.08	−19.22	5.0	0.91	2.49	0.60	2.51	−50.12	6.1	0.89	5.3
T9–10	5.4	1.74	4.88	1.03	0.52	−9.70	4.2	1.10	2.97	0.60	1.23	−29.36	5.5	0.90	4.8
T10–11	7.2	1.21	5.91	0.77	1.29	−17.94	5.8	1.00	3.66	0.70	2.14	−36.83	6.7	1.18	6.5
T11–12	6.0	1.14	5.90	0.70	0.10	−1.67	4.8	1.26	3.23	0.48	1.57	−32.63	6.5	1.15	5.4

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 2 Anterior and posterior human thoracic vertebral body heights.

Vertebral level	Vertebral body height anterior (VBHA)		Vertebral body height posterior (VBHP)		Average vertebral body height*
	Mean	SD	Mean	SD	
C7	13.89	1.42	14.38	2.22	14.14
T1	14.49	1.23	15.28	1.14	14.88
T2	15.01	1.51	16.11	1.67	15.56
T3	15.65	1.85	17.41	1.12	16.53
T4	15.42	1.46	18.15	1.54	16.79
T5	15.84	1.07	17.33	2.16	16.59
T6	16.04	1.43	18.22	1.38	17.13
T7	15.94	1.61	18.67	1.64	17.31
T8	16.99	1.70	20.05	1.77	18.52
T9	18.26	2.12	20.25	2.44	19.26
T10	18.98	1.40	20.35	1.89	19.67
T11	19.60	1.92	22.67	1.38	21.14
T12	20.80	1.96	23.12	1.94	21.96

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.

Disc level	Relative disc height index (I_1)	Disc : vertebral body height ratio	Disc convexity index (I_2)	% MDH to average disc height	Disc antero-posterior wedging index (I_3)
C7–T1	0.32	1:3.1	0.63	20.55	1.00
T1–2	0.30	1:3.4	0.65	23.11	1.06
T2–3	0.22	1:4.5	0.83	39.65	0.97
T3–4	0.20	1:5.1	0.67	25.17	1.03
T4–5	0.19	1:5.3	0.80	37.50	0.89
T5–6	0.21	1:4.7	0.67	25.58	0.97
T6–7	0.24	1:4.2	0.68	25.95	1.01
T7–8	0.23	1:4.4	0.68	26.75	1.16
T8–9	0.29	1:3.5	0.57	12.56	1.13
T9–10	0.25	1:4.0	0.58	13.74	1.29
T10–11	0.33	1:3.0	0.52	3.50	1.23
T11–12	0.26	1:3.9	0.60	16.77	1.25

Refer to Fig. 1 for abbreviations.
I_1 = (ADH + PDH)∕(VBHA + VBHP) based on Amonoo-Kuofi (1991).
I_2 = MDH∕(ADH + PDH) based on Twomey & Taylor (1987).
I_3 = ADH∕PDH.
The ratio of disc: body was calculated by dividing 1 by the value of I_1.
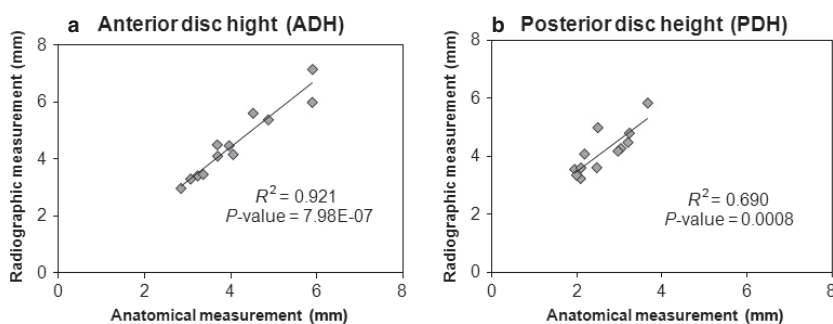
Fig. 2 Correlations between anatomical and radiographic measurements of the anterior (a) and posterior (b) disc heights considering mean values from each disc level from C7–T1 to T11–12. See Table 1 for data summaries. ADH, anterior disc height; PDH, posterior disc height.

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 TIVD 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 TIVD 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 T6–7) both anteriorly and posteriorly minimal wedge shapes were found with a maximum difference between these values of approximately 2.77%. From these morphometric indices,
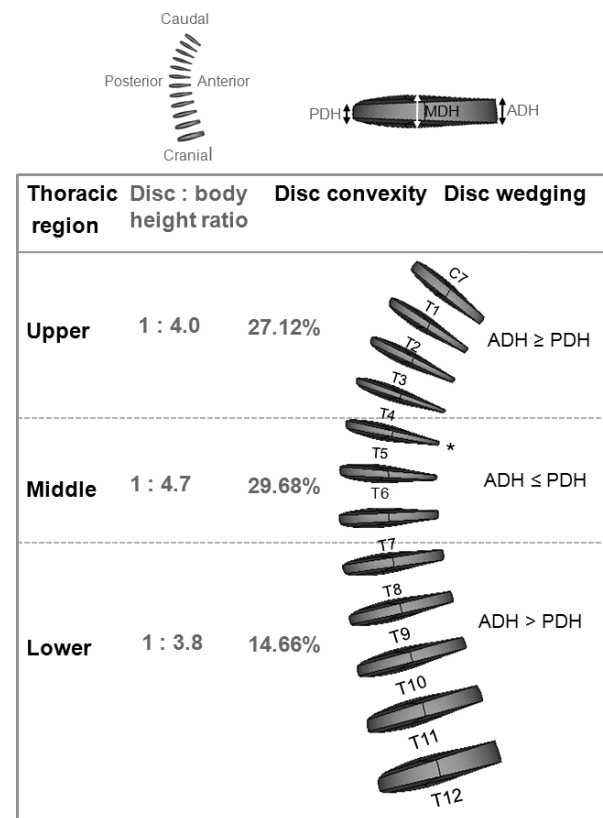

Thoracic region	Disc : body height ratio	Disc convexity	Disc wedging
Upper	1 : 4.0	27.12%	ADH ≥ PDH
Middle	1 : 4.7	29.68%	ADH ≤ PDH
Lower	1 : 3.8	14.66%	ADH > PDH

Fig. 3 Geometric model of the human thoracic discs from C7–T1 to T11–12 disc level, constructed with parameters derived from the morphometric analyses performed in this study. The thinnest disc was found in the disc level T4–5*. The shape of the human TIVDs was determined by the relationships between the anterior, middle and posterior disc heights (ADH, MDH, PDH).
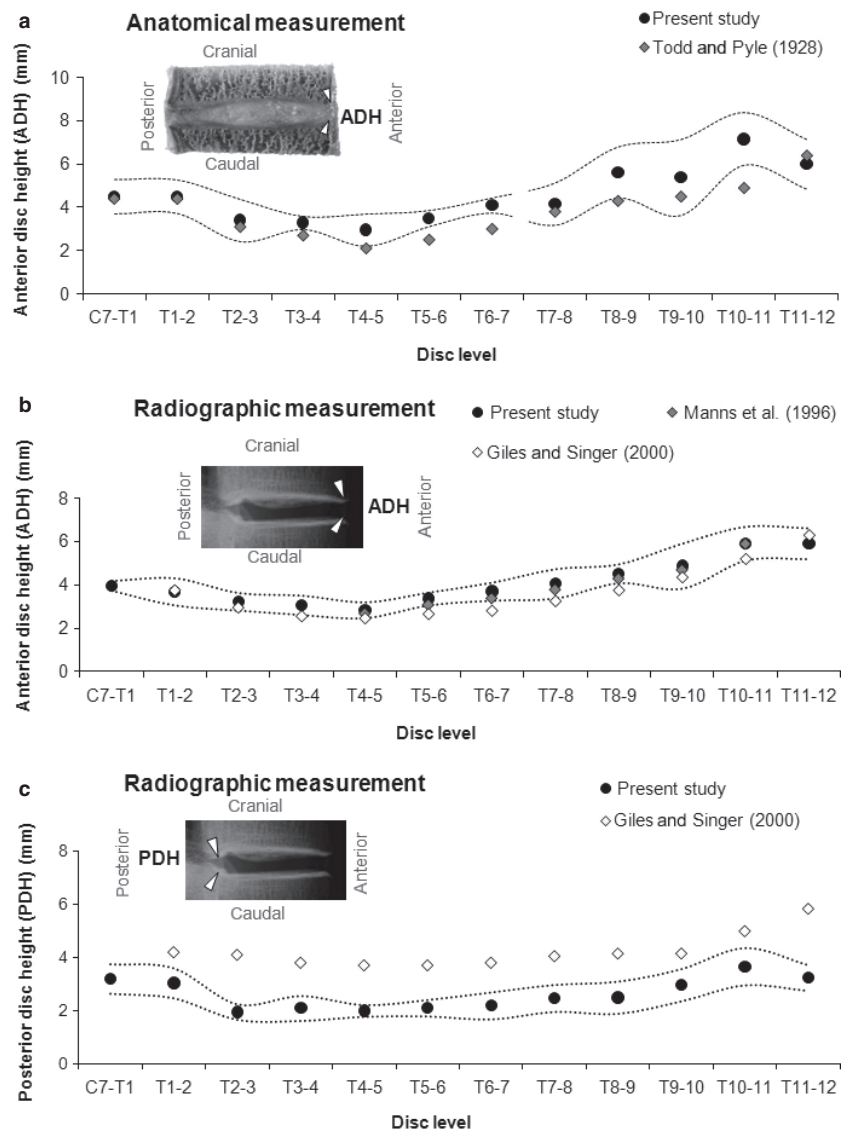
Fig. 4 Comparison of the anterior and posterior heights of the human intervertebral discs obtained in the present study with published data. Mean values of anatomical (ADH; a) and radiographic (ADH and PDH; b,c) measurements. Dotted curves indicate SD of the experimental values of the present study. ADH, anterior disc height; PDH, posterior disc height.

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 signifi-

cant ($R^2 = 0.659$–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
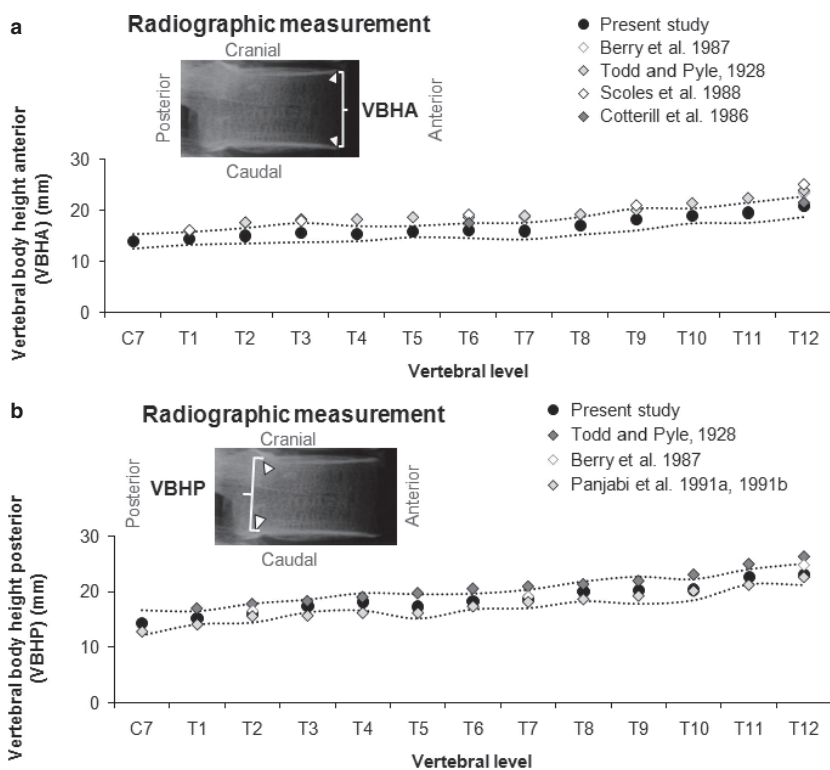
Fig. 5 Comparison of the anterior (a) and posterior (b) heights of the human vertebral bodies obtained in the present study with published data. Means values of radiographic measurements. Dotted curves indicate SD of the experimental values of the present study. VBHA, vertebral body height anterior; VBHP, vertebral body height posterior.

Table 4 Polynomial coefficients (C_1, C_2, C_3 and C_4) 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.

Predictor parameter	Predicted parameter	R^2	P-value	SE	C_1	C_2	C_3	C_4
ADH	MDH	0.726	0.0004	0.37	3.500	0.453	–	–
	PDH	0.906	0.0002	0.27	−2.149	3.067	−0.538	0.037
VBHA	ADH	0.835	0.0017	0.60	544.560	−97.473	5.795	−0.113
	MDH	0.576	0.0640	–	–	–	–	–
	PDH	0.667	0.0260	0.52	360.580	−63.935	3.783	−0.074
	VBHP	0.953	2.7E-06	0.66	−180.00	31.073	−1.646	0.030
VBHP	ADH	0.780	0.0053	0.66	298.43	−46.993	2.561	−0.045
	MDH	0.571	0.0676	–	–	–	–	–
	PDH	0.659	0.0282	0.53	201.190	−32.029	1.705	−0.030
	VBHA	0.943	6.5E-06	0.58	44.199	−5.305	0.286	−0.004

Refer to Fig. 1 for abbreviations.

SE in mm.

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 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 ana-tomical 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 & Middle-ditch (1991) reported that TIVDs have a nearly uniform thickness, our anatomical observations indicated that there
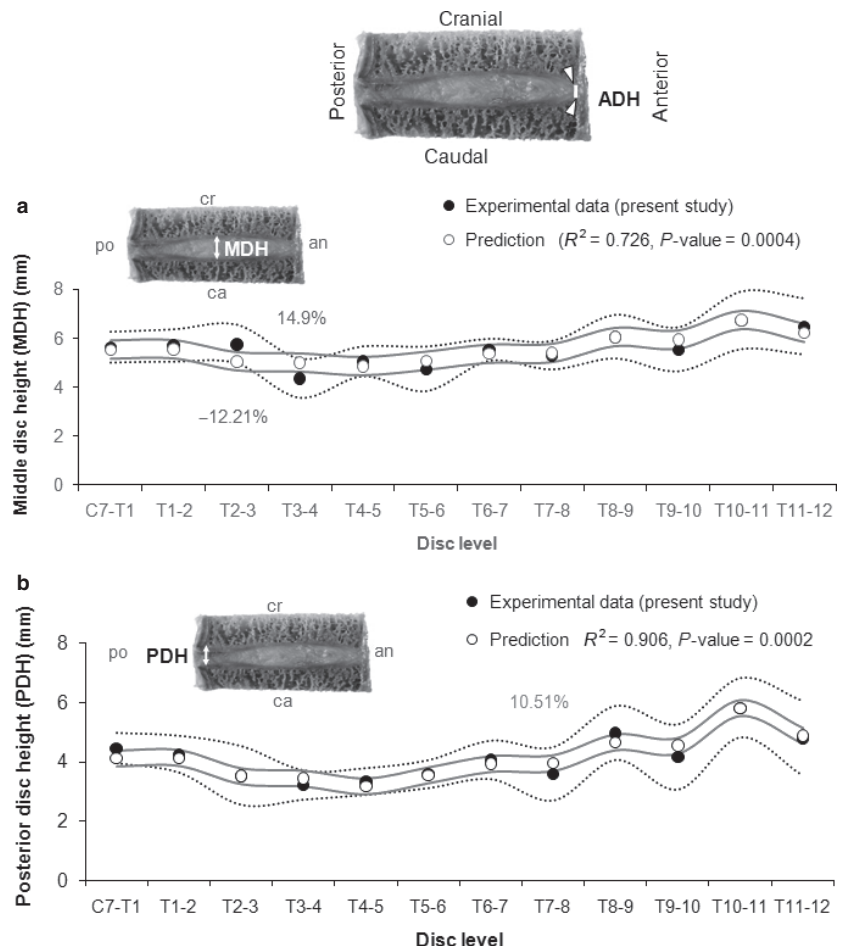
Fig. 6 Anatomical values of the ADH were used for predictions of the parameters MDH (a) and PDH (b) at all levels of the thoracic spine. The predicted values were superimposed on experimental data that were measured in the present study. Dotted and continuous curves indicate SD of the experimental and predicted values, respectively. Mean percent errors of the predictions larger than 10% are indicated. ADH, anterior disc height; an, anterior; ca, caudal; cr, cranial; MDH, middle disc height; PDH, posterior disc height; po, posterior.

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
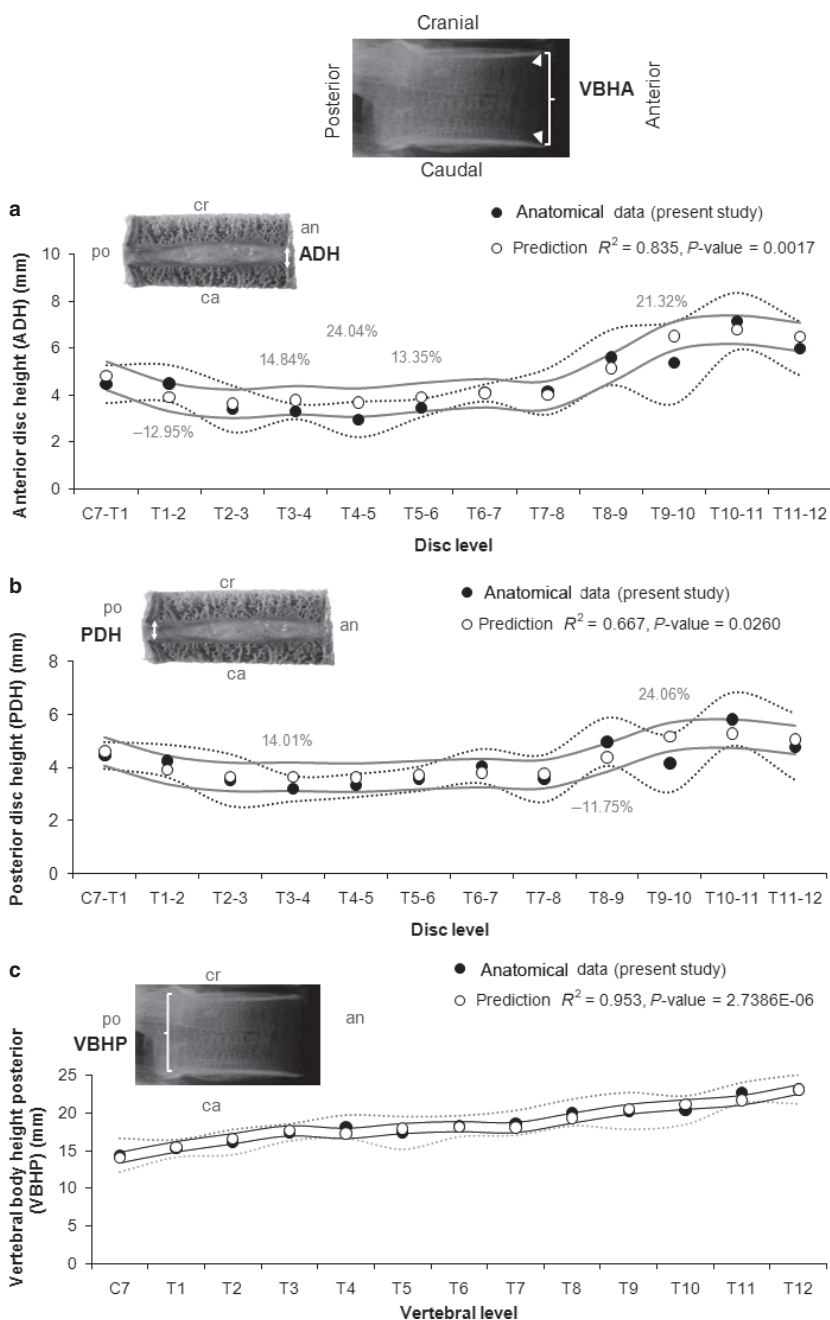
Fig. 7 Radiographic values of the VBHA were used for predictions of the parameters ADH (a), PDH (b) and VBHP (c) at all levels of the thoracic spine. The predicted values were superimposed on anatomical data that were measured in the present study. Dotted and continuous curves indicate SD of the experimental 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.

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; Scoles 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
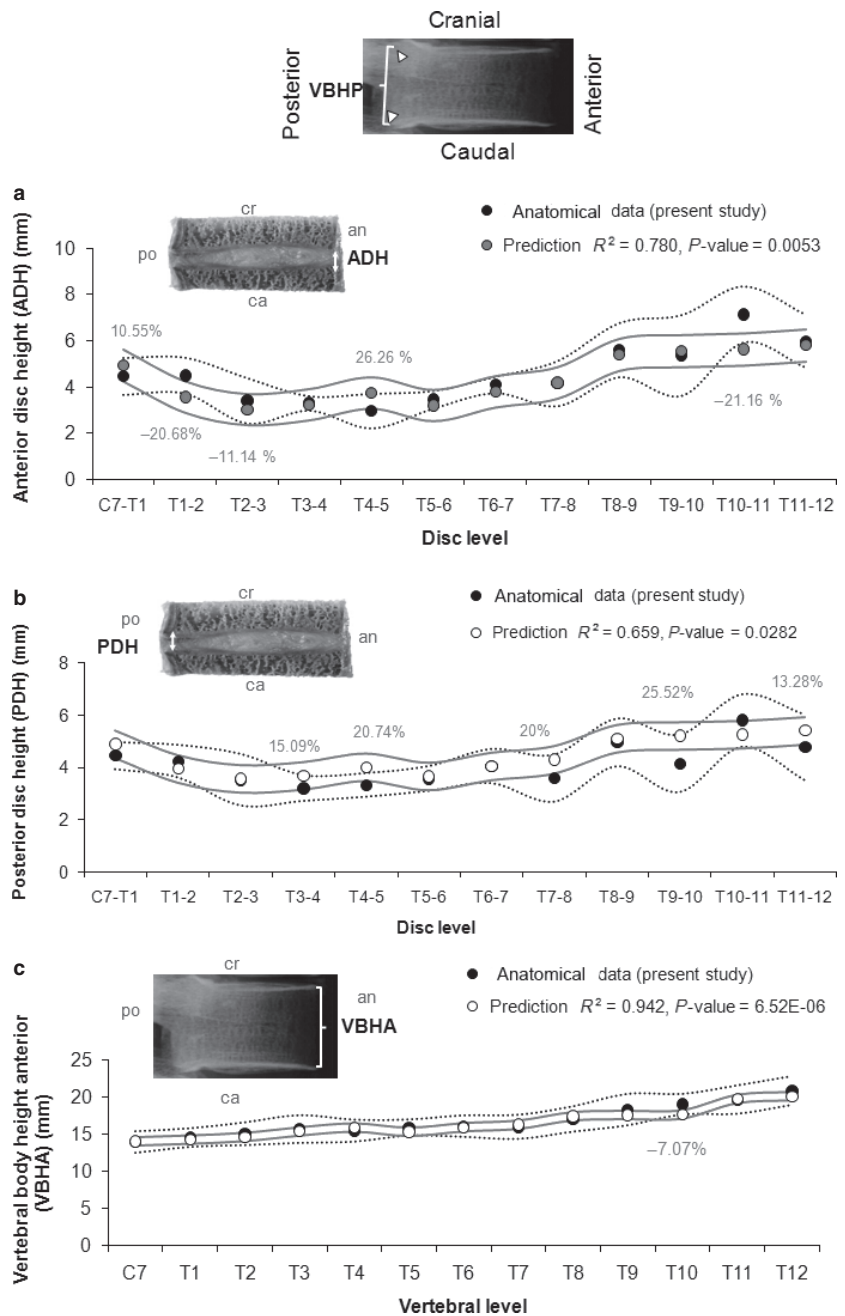
Fig. 8 Radiographic values of the VBHP were used for polynomial predictions of the parameters ADH (a), PDH (b) and VBHA (c) at all levels of the thoracic spine. The predicted values were superimposed on anatomical data that were measured in the present study. Dotted and continuous curves indicate SD 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
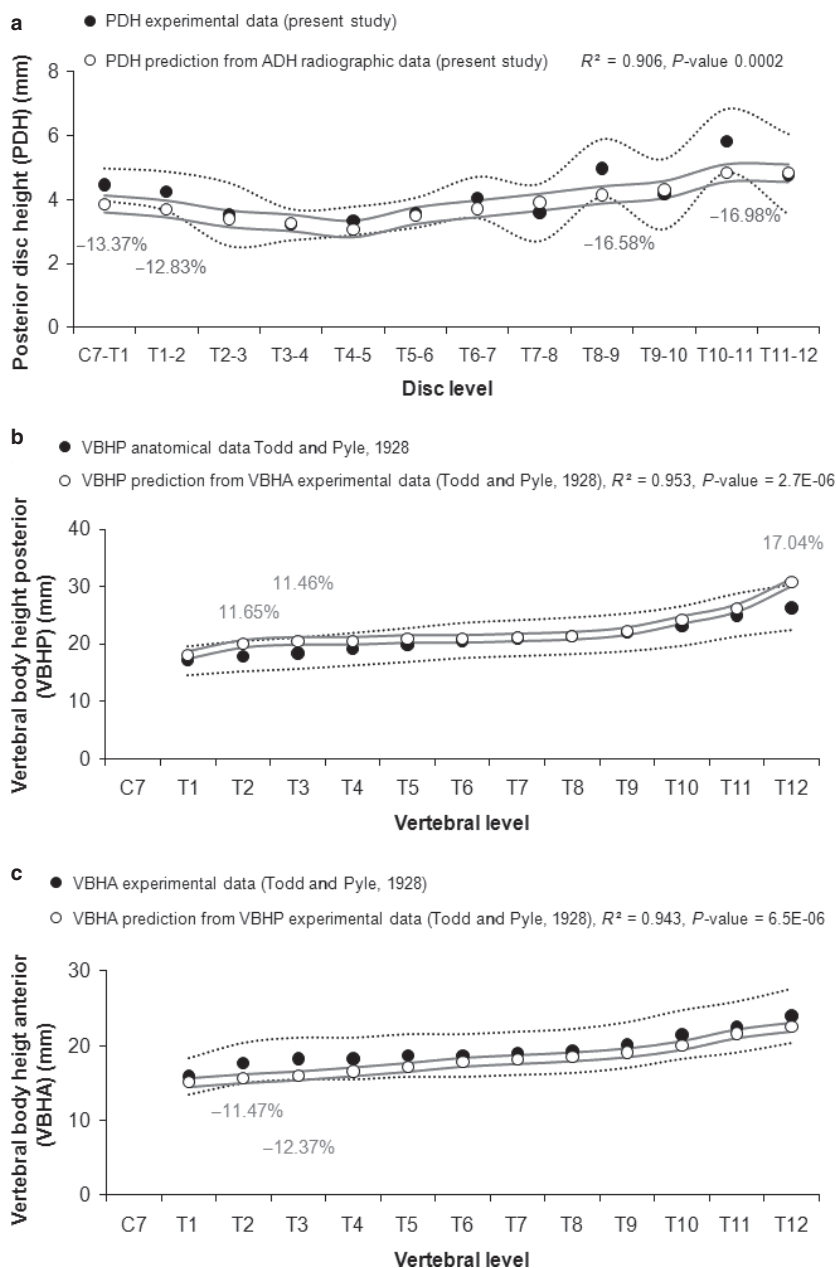
Fig. 9 Comparison of some predicted parameters (PDH, VBHP and VBHA) from anatomical measurements of Todd & Pyle (1928) with corresponding radiographic measurements of the current study. The predicted values were superimposed on experimental data. Dotted and continuous curves indicate SD of the experimental and predicted values, respectively. Mean percent errors of the predictions larger than 10% are indicated. ADH, anterior disc height; PDH, posterior disc height; VBHA, vertebral body height anterior; VBHP, vertebral body height posterior.

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 TIVD. 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 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.

Acknowledgement

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.

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