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Quantitative three-dimensional anatomy of lumbar vertebrae in Singaporean Asians

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Abstract This paper details the quantitative three-dimensional anatomy of lumbar vertebrae L1–L5 from Asian (Singaporean) subjects based on 60 lumbar vertebrae from 12 cadavers. The purpose of the study was to measure the dimensions of the various parameters of the lumbar vertebrae and thereafter to compare the data with a study performed on Caucasian specimens. Measurements were taken with the aid of a three-dimensional digitiser. The means and standard errors for linear, angular and area dimensions of the vertebral body, spinal canal, pedicle, and spinous and transverse processes were obtained for each lumbar vertebra. From this comparison, it was found that the dimensions of the vertebral body of the Asian subjects are slightly larger, with a maximum average difference of 8% for the posterior vertebral body height. The dimensions of the spinal canal, pedicle, and spinous and transverse processes of Asian subjects are smaller. The greatest difference can be found in the spinal canal area and pedicle width, which are smaller by an average of 30% and 20%, respectively. With the exception of the spinal canal depth, spinal canal area and pedicle width, all other parameters compared show a similar trend. The findings can provide more accurate modelling for analysis and spinal implant design and also allow more precise clinical diagnosis in sub-Asian groups.

Keywords Anatomy · Asian · Caucasian · Lumbar spine · Lumbar Vertebrae · Vertebral dimensions

Introduction

The study of mathematical models of the spine based on quantitative measurements of the vertebrae can lead to a better understanding of spinal kinematics and of the mechanisms of spinal injury [2, 5, 7]. They provide important information for designers of spinal instrumentation and are essential guidelines for surgeons who use these devices [3, 6].

Most of the quantitative studies on the human vertebrae have been conducted on Caucasian subjects [1, 4, 8, 10]. This paper is the first of a series of three papers which deal with lumbar, thoracic and cervical spine, respectively. It serves to report the quantitative three-dimensional anatomical parameters of the lumbar spine from the L1 to L5 vertebrae of Asians who lived in Singapore. The purpose of the study was to measure the dimensions of the various parameters of the lumbar vertebrae and to compare the data with a study performed on Caucasian subjects [8].

Materials and methods

L1–L5 vertebrae were removed from ten Chinese and two Indian cadavers of Singaporean origin (Table 1). The selected cadavers had no history of spinal abnormalities which might distort the data to be collected. The average age of the subjects was 67 years (range, 56–77 years), the average weight 62 kg (range, 50–70 kg) and average height 1.66 m (range, 1.59–1.72 m). The vertebrae were prepared by trimming off the soft tissue, leaving only the skeletal remains. The specimens were then immersed in sodium hydrochloride solution for 30 min to digest away soft tissue rem-

Table 1 Specimen data

Specimen	Age (years)	Sex	Race	Weight (kg)	Height (m)	Cause of death
1	58	M	Chinese	61	1.64	Liver carcinoma
2	68	M	Chinese	63	1.68	Fractured skull
3	74	M	Indian	59	1.61	Myocardial infarction
4	56	M	Chinese	70	1.72	Renal failure
5	77	M	Chinese	50	1.59	Pancreatic carcinoma
6	56	M	Chinese	66	1.70	Liver carcinoma
7	67	M	Chinese	62	1.66	Coronary artery disease
8	59	M	Chinese	65	1.65	Lung carcinoma
9	75	M	Indian	69	1.70	Myocardial infarction
10	63	M	Chinese	66	1.68	Broncopneumonia
11	78	M	Chinese	60	1.65	Ischemic heart disease
12	75	M	Chinese	53	1.63	Lung carcinoma
Average	67	–	–	62	1.66	–

nants. Excess sodium hydrochloride was removed by rinsing the specimens under running lukewarm water for 20 min. The specimens were then air dried and stored at a constant temperature and humidity to prevent any change in shape and dimensions.

Figure 1 shows the orthogonal views of a lumbar vertebra. Linear dimensions, angulations and areas of various vertebral parts were studied. Each part is represented by three uppercase letters and a suffix. The definitions of all the parameters are similar to those published by Panjabi et al. [8].

Each vertebra had a hole 5 mm in diameter drilled about three quarters of the way into the vertebra body from the anterior position. A screw was used to secure the vertebra to prevent it from moving. This screw was in turn clamped in a vice-clamp. Clay was used to restrict movement of the vertebra in all degrees of freedom (Fig. 2). The set-up allowed the measuring instrument to access the vertebra conveniently. The three-dimensional co-ordinates were able to be obtained without repositioning either the vertebra or the instrument. This ensured consistency in the data collection. Before commencing data collection, the measuring instrument was calibrated following established procedures recommended by the manufacturer.

The measuring instrument was a three-dimensional digitiser. It uses a direct contact probe to establish the co-ordinate system and profile of the vertebra. Accuracy of the instrument is ±0.1 mm. The instrument was connected to a computer for direct data collection and processing. To ensure the reliability of the measurements taken using the digitiser, accuracy tests were conducted. For the linear parameter, a micrometer screw gauge was used for comparison. With the micrometer set at 20 mm, the error was 1.28%, whereas this error was lower (0.44%) when the instrument was set

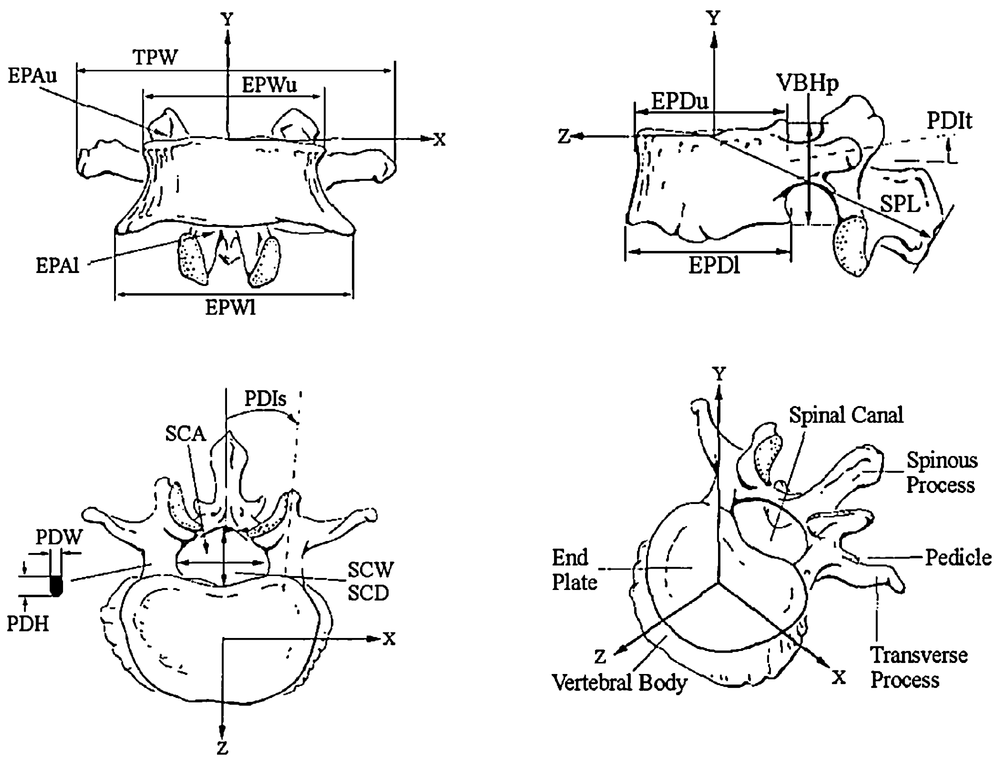

Fig. 1 Four views (front, side, top and isometric) of a lumbar vertebra. *EPAl*, lower end-plate area; *EPAu*, upper end-plate area; *EPDl*, lower end-plate depth; *EPDu*, upper end-plate depth; *EPWl*, lower end-plate width; *EPWu*, upper end-plate width; *PDH*, pedicle height; *PDIs*, left pedicle, sagittal inclination; *PDlt*, left pedicle, transverse inclination; *PDW*, pedicle width; *SCA*, spinal canal area; *SCD*, spinal canal depth; *SCW*, spinal canal width; *SPL*, spinous process length; *TPW*, transverse process width; *VBHp*, posterior vertebral body height. (Reproduced with permission from Panjabi [8])

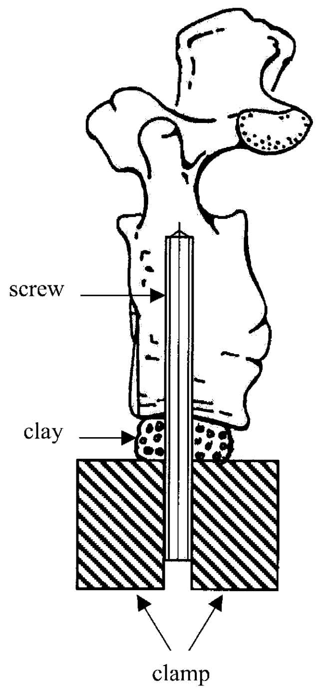

Fig. 2 Setup of specimen prior to measurement

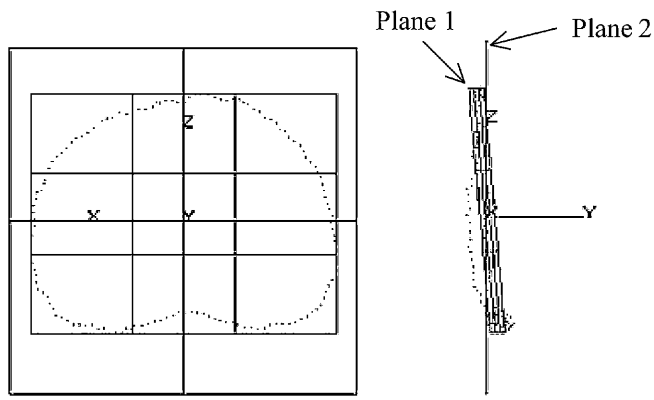

Fig. 4 Plan and side views of the best-fit upper (selected) end-plate section. The linear and area dimensions can be obtained from the plane section, while the side view is used to yield the angles

at 10 mm. For angular parameters, two angle blocks of 15° and 30° were used for the test. Two different area bars with an area of 2250 mm^2 were used to verify areas. Measurement error was found to be minimal, ranging from 0.68% to 1.71%. It can be seen from the results that the accuracy of the digitiser is high.

Before measurements were made and data collected, the vertebra co-ordinate system had to be defined. As shown in Fig. 3, the origin of the vertebra coordinate system (XYZ-axes) coincides with the centroid or centre of gravity of the upper end-plate. The posterior wall was used as a reference plane because it is fairly consistent and showed minimum variation in the presence of osteophytes. The plane is formed by three points. The first two points correspond to the first and second digitised positions “a” and “b”, respectively. The third point is the average of the third and fourth digitised positions “c” and “d”, respectively. The sequence of digitising, which follows the right-hand thumb rule, determines the Z-axis. Each digitised position was the average of ten hits to minimise error. Next, the X-axis was established by the first digitising position “b” followed by position “a”. The point was then digitised approximately at the centroid of the upper end-plate, which was later specified more exactly by polygonising the end-plate. The polygonised area was then made into a volume by giving it an infinitesimal thickness (0.1 mm), and the axis origin was obtained from the volume.

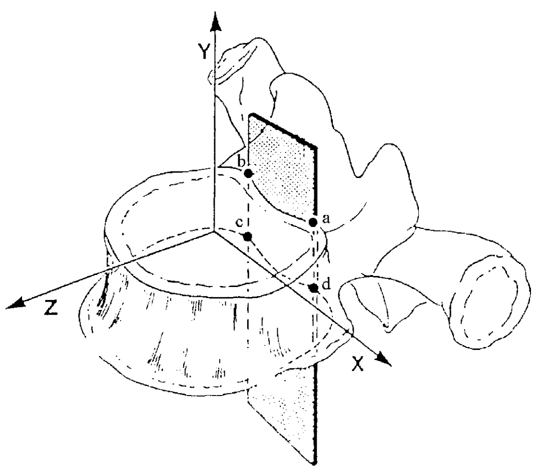

Fig. 3 Definition of the vertebra coordinate system, with the origin at the centre of the upper end-plate

Once the co-ordinate system has been established, the profile of the vertebra can be traced and digitised using the direct contact probe of the digitiser. The digitised profile was converted into a three-dimensional surface image. From the image, the three-dimensional best-fit plane can be generated automatically in any orientation. Figure 4 shows the selected best-fit plane of a vertebra end-plate. Linear and area parameters of interest can be obtained. For the former, only two points need to be marked on the figure. For the latter, the best-fit plane is polygonised into triangular mesh, from which the area is computed. The angle between any two planes, e.g. plane 1 and plane 2 of Fig. 4, can be calculated automatically.

An average of three readings was taken for each parameter. The results are divided into five areas, i.e. vertebral body, spinal canal, pedicle, spinous process and transverse process. Table 2 presents the findings for the parameters. The values of the parameters are shown as mean±standard error of mean where the standard error of mean is the sample standard deviation divided by the sample size.

Results

The trends of the linear, area and angular parameters studied are shown in Figs. 5, 6, 7, 8 and 9, respectively. Their numerical values are presented in Table 2.

Linear parameters

There is a slight increase from L1 to L4 for the upper and lower end-plate widths (EPW). The end-plate depths (EPD) are relatively constant throughout the lumbar spine. The lower parameters are generally larger than the

Table 2 Dimensions of parameters at vertebral levels L1–L5

	L1	L2	L3	L4	L5
Linear dimension (mm)					
EPWu	42.68±0.44	44.90±0.48	46.96±0.39	49.35±0.22	48.89±0.40
EPWl	46.16±0.59	48.66±0.41	51.19±0.39	53.34±0.57	51.42±0.49
EPDu	32.32±0.52	33.27±0.60	35.15±0.30	36.26±0.23	35.82±0.57
EPDl	33.59±0.56	34.35±0.58	35.55±0.47	35.62±0.73	33.75±0.51
VBHa	23.82±0.79	24.42±0.59	25.17±0.55	25.36±0.68	25.83±0.66
VBHp	26.37±0.49	27.15±0.38	25.97±0.46	25.42±0.40	23.51±0.71
SCW	22.77±0.28	22.93±0.39	22.82±0.51	23.82±0.61	27.49±0.72
SCD	14.70±0.26	13.76±0.20	13.23±0.30	13.22±0.44	13.38±0.43
PDHl	15.39±0.41	15.29±0.22	14.29±0.95	15.29±0.42	20.78±0.51
PDHr	15.43±0.33	14.98±0.27	15.15±0.42	15.72±0.41	20.08±0.39
PDWl	6.64±0.22	7.58±0.29	8.99±0.21	10.71±0.52	13.34±0.51
PDWr	6.47±0.31	7.29±0.34	8.90±0.22	10.07±0.46	13.90±0.61
SPL	60.63±1.00	64.02±0.99	67.74±0.90	64.88±1.00	59.52±1.11
TPW	63.05±1.71	75.64±1.81	83.99±2.20	79.68±1.66	83.92±2.89
Surface area (mm2)					
EPAu	1046.77±29.46	1157.62±37.73	1314.90±33.58	1355.10±23.87	1326.22±28.90
EPAl	1188.05±35.26	1283.42±31.69	1378.85±24.24	1410.99±41.74	1240.08±24.74
SCA	235.25±2.63	217.14±5.13	195.76±6.72	192.69±12.87	219.55±10.81
PDAl	79.75±3.74	87.64±4.21	113.20±2.93	124.44±5.72	186.93±6.87
PDAr	80.72±4.59	81.76±3.97	105.57±2.70	113.80±3.76	183.73±7.09
Angular dimension (°)					
EPItu	2.15±0.46	3.99±0.46	2.18±0.36	4.35±0.66	8.06±1.04
EPItl	–3.03±0.47	–1.27±0.25	2.17±0.18	3.81±0.69	12.30±0.96
PDIsl	–2.38±0.56	–6.61±0.93	–14.05±1.01	–13.53±0.90	–26.30±0.67
PDIsr	8.93±1.17	10.88±1.66	19.81±2.11	12.61±1.43	20.44±1.58
PDItl	–1.96±0.33	–2.87±0.29	–5.90±1.02	–8.61±0.78	–9.22±0.69
PDItr	–1.88±0.34	–2.26±0.49	–3.06±0.56	–7.39±1.07	–7.37±0.89

The values given are the mean±standard error of mean. EPWl, lower end-plate width; EPWu, upper end-plate width; EPDu, upper end-plate depth; EPDl, lower end-plate depth; VBHa, anterior vertebral body height; VBHp, posterior vertebral body height; SCW, spinal canal width; SCD, spinal canal depth; PDHl, left pedicle height; PDHr, right pedicle height; PDWl, left pedicle width; PDWr, right pedicle width; SPL, spinous process length; TPW, transverse process width; EPAu, upper end-plate area; EPAl, lower end-plate area; SCA, spinal canal area; PDAl, left pedicle area; PDAr, right pedicle area; EPItu, upper end-plate, transverse inclination; EPItl, lower end-plate, transverse inclination; PDIsl, left pedicle, sagittal inclination; PDIsr, right pedicle, sagittal inclination; PDItl, left pedicle, transverse inclination; PDItr, right pedicle, transverse inclination.

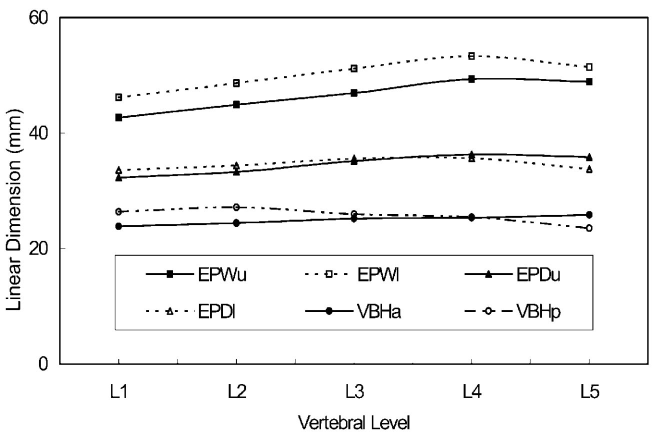

Fig. 5 Linear dimensions of vertebral body as functions of vertebral levels L1–L5. The linear dimensions are the upper (*u*) and lower (*l*) end-plates width (*EPW*) and depth (*EPD*), anterior (*a*) and posterior (*p*) vertebral body height (*VBH*)

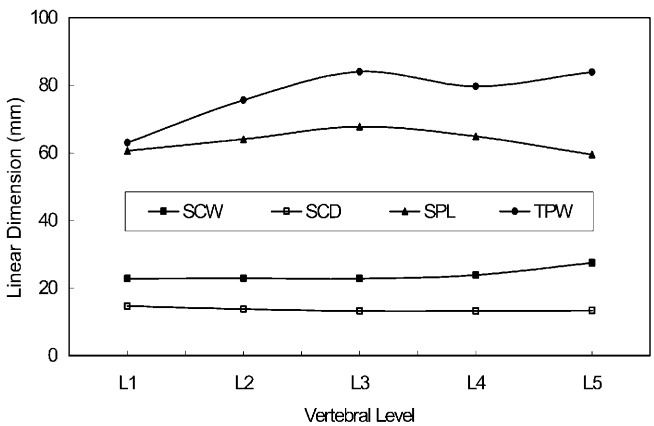

Fig. 6 Linear dimensions of spinal canal, spinous process and transverse process as functions of vertebral levels L1–L5. The linear dimensions are the spinal canal width (*SCW*) and depth (*SCD*), spinous process length (*SPL*) and transverse process width (*TPW*)

upper parameters. The posterior vertebral body height (VBHp) is higher than the anterior vertebral height (VBHa), except for at L5. This is due to the wedge shape of the vertebra, which defines the spinal curvature in the lumbar region (Fig. 5).

The linear parameters of the spinal canal are lateral width (SCW) and anteroposterior depth (SCD). The lateral width is almost constant from L1 to L4 and increases towards L5, whereas the anteroposterior depth exhibits a slightly decreasing trend from L1 to L5. The narrowest

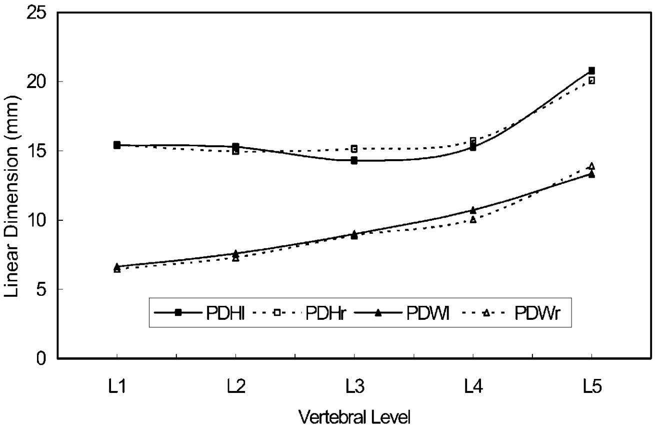

Fig. 7 Linear dimensions of pedicles as functions of vertebral levels L1–L5. The linear dimensions are the left (*l*) and right (*r*) pedicle height (*PDH*) and width (*PDW*)

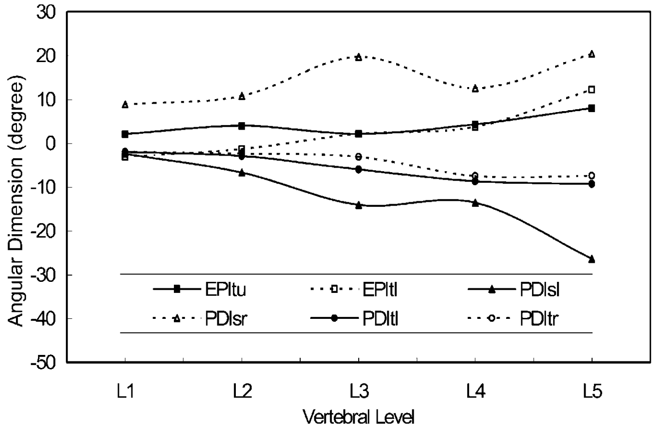

Fig. 9 Angular dimensions of end-plates and pedicles as functions of vertebral levels L1–L5. The angles are the upper (*u*) and lower (l) end-plates, transverse inclinations (*EPI*), and left (*l*) and right (*r*) pedicles, sagittal and transverse inclinations (*PDI*)

portion in the SCD parameter occurs at the L3–L4 transition, with an average value of about 13 mm (Fig. 6). The values for the spinous process length (SPL) are parabolic. The transverse process width (TPW) is somewhat similar to the spinous process length, increasing from L1 to L3 and remaining relatively constant thereafter.

The linear parameters of the pedicle are the cross-sectional height (PDH) and width (PDW). Both the height and width increase from L1 to L5. The height is consistently larger than the width. Both left and right parameters of height or width have values proximal to each other (Fig. 7).

Area parameters

The upper and lower end-plate areas (EPA) increase rather sharply from L1 to L4 before tapering off at L5. The cross-sectional area of the spinal canal (SCA) decreases gradually from L1 to L4 and then increases slightly to L5. The SCA is smallest at the L3–L4 transition, with an average value of about 194 mm^2. The cross-sectional area of the pedicle (PDA) gradually increases from L1 to L5. This is not surprising, because both height and width also increase (Fig. 8).

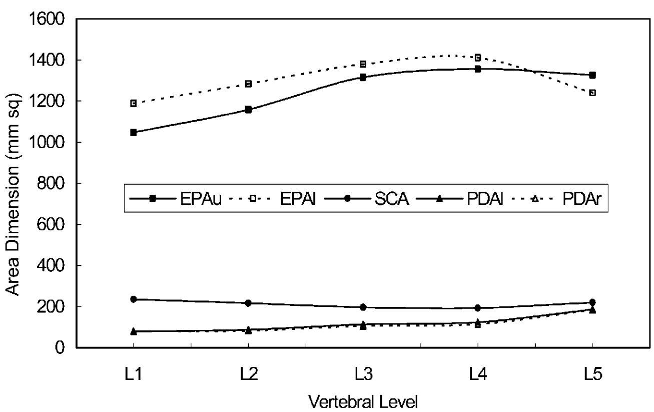

Fig. 8 Areas of end-plates, spinal canal and pedicles as functions of vertebral levels L1–L5. The areas are the upper (*u*) and lower (*l*) end-plates (*EPA*), spinal canal (*SCA*), left (*l*) and right (*r*) pedicle (*PDA*)

Angular parameters

The end-plate inclinations (EPI) are in opposite direction for L1 and L2, but gradually move into the same sense for L3, L4 and L5. The inclinations of the pedicle (PDI) exhibit a left/right symmetry for the sagittal angles. From L1 to L3, the right sagittal angle is larger than the left, and the reverse is true from L4 to L5. For the transverse angles, both the left and right pedicles have the same direction and proximal values (Fig. 9).

Discussion

Although a number of quantitative anatomical studies [1, 4, 8, 10] have been conducted on lumbar vertebrae of Caucasian subjects, the study carried out by Panjabi et al. [8] is the most comprehensive. The various parameters measured in the present study and those of Panjabi et al. [8] are compared in Table 3, using the Caucasian parameter as the reference.

For values of the parameters of the vertebral body (EPWu, EPWl, EPDu, EPDl, VBHp, EPAu, EPAl), the difference is not very large. The average difference is 4.9%, 6.4%, –1.4%, 0.5%, 8.0%, 5.9% and 6.6% for the EPWu, EPWl, EPDu, EPDl, VBHp, EPAu and EPAl, respectively. The maximum difference of 11.7% occurs at

Table 3 Comparison of measurements at vertebral levels L1–L5 from present study with those of Panjabi et al. [8]

	Difference compared with Caucasian (%)				
Parameter	L1	L2	L3	L4	L5
EPWu	3.6	5.4	6.5	5.9	3.3
EPWl	6.6	6.9	6.6	7.8	4.1
EPDu	–2.8	–3.8	–0.1	2.1	3.2
EPDl	–4.8	–1.6	2.1	5.1	1.7
EPAu	1.0	1.8	10.0	9.4	7.2
EPAl	6.4	7.2	6.8	10.8	1.8
VBHp	10.8	11.7	9.1	5.5	2.7
SCW	–3.9	–3.7	–6.1	–6.2	1.4
SCD	–22.6	–24.4	–24.4	–28.9	–32.1
SCA	–26.6	–22.7	–30.1	–33.6	–33.5
PDHl	–2.6	2.6	2.1	0.6	6.6
PDHr	–3.0	–0.1	6.7	0.1	2.4
PDWl	–27.8	–13.8	–11.0	–27.1	–30.5
PDWr	–19.1	–6.5	–12.7	–24.9	–22.8
SPL	–10.4	–10.7	–5.5	–7.4	–12.9
TPW	–11.4	–0.6	–2.0	0.4	–9.3

The average values of selected parameters are compared with those of Panjabi et al.
EPWl, lower end-plate width; EPWu, upper end-plate width; EPDu, upper end-plate depth; EPDl, lower end-plate depth; EPAu, upper end-plate area; EPAl, lower end-plate area; VBHa, posterior vertebral body height; SCW, spinal canal width; SCD, spinal canal depth; SCA, spinal canal area; PDHl, left pedicle height; PDHr, right pedicle height; PDWl, left pedicle width; PDWr, right pedicle width; SPL, spinous process length; TPW, transverse process width.

L2 in the VBHp. With the exception of the EPDu at L1–L3 and EPDl at L1–L2, all the other parameters are larger. The trends of the vertebral body parameters are similar in both studies.

For the spinal canal parameters, the average difference is about –5.0% from L1 to L4 for the SCW and –26.5% from L1 to L5 for the SCD. Although both the spinal width and depth are smaller, the latter is significantly smaller compared to the Caucasian values. This is reflected in the large average difference of about –30% in the SCA. The trend of the SCD, and hence the SCA, was found to be different in the present study, as shown in Fig. 10. The smallest SCA is located at L4 instead of L3 as reported by Panjabi et al. [8]. The considerable decrease in SCD and SCA may affect spinal management, as the size of spinal canal has been reported to be related to the incidence of low back pain [9].

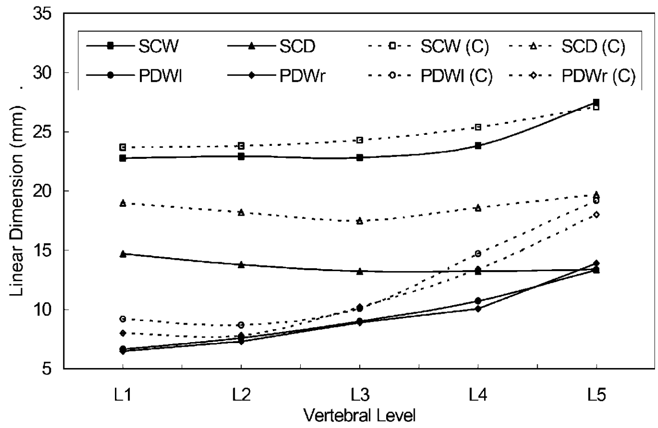

Fig. 10 Comparison of selected linear dimensions of present study with that of Panjabi [8]. The results from the latter are represented by *C*. The linear dimensions are the spinal canal width (*SCW*) and depth (*SCD*) and left (*l*) and right (*r*) pedicle width (*PDW*)

As shown in Fig. 10, the general trend of the PDW and PDH is similar to the values obtained by Panjabi and coworkers, except that for the latter, the rate of increase is higher from L3 to L5. Using the average of the right and left measurements, the average difference for the PDH and PDW is about 1.5% and –19.6%, respectively. The difference for the latter is rather significant because most existing spinal implants have been developed based on measurements obtained from Caucasians and may not produce the desired and best effect in Asians.

The trend of the SPL and TPW is similar to that in Caucasians. However, they are smaller by an average of 9.4% and 4.7%, respectively.

Conclusion

This paper a comprehensive study of the three-dimensional quantitative anatomy of Singaporean Asians, comparing the data obtained with a similar study performed on Caucasian specimens. In contrast to the larger physique of Caucasians compared with Asians, the comparison revealed larger quantitative dimensions of EPW, EPDI, VBHp, EPA and PDH values for the latter. The data may offer some explanation of the differences in the biomechanical responses of spinal segments under load, if any, and may assist in the design of spinal implant and surgical instruments for the surgical management of injured spine.

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