

Morphometry of the lower lumbar intervertebral discs and endplates: comparative analyses of new MRI data with previous findings

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Abstract

Purpose Variability of the human lower lumbar geometry is related to complications of disc arthroplasty surgery. Accurate morphometric descriptions are essential for the design of artificial intervertebral discs to ensure good prosthesis-vertebra contact and better load distribution, and can improve spinal biomechanics. Unfortunately, current knowledge of the lower lumbar geometry is limited either in the representativeness of sample populations or the accuracy and comprehensiveness of measurements. The objective of this study was to establish an accurate and reliable measurement protocol, provide a comprehensive database of lower lumbar geometry, and compare and summarize geometric data as reported in the literature.

Methods T₂-weighted magnetic resonance imaging (MRI) scans of lower lumbar spine (L3–S1), taken from 109 adult subjects, were anonymized from the digital archive of a local hospital. A total of 318 intervertebral discs and 590 endplates met the inclusion criteria and were studied. Linear and planar measurements were performed using OsiriX software, and analyzed using split plot factorial (SPF) analysis of variance (ANOVA), independent

student *t* tests, paired sample *t* tests, and Tukey's honest significant difference (HSD) post hoc tests.

Results Excellent intra- and inter-observer reliabilities were achieved using the proposed measurement protocol. The results of this study indicated that male subjects had significantly larger geometric dimensions. L5/S1 discs had the smallest geometric dimensions compared to the discs at other two levels. Significant craniocaudal differences were found in endplate morphometry. The error associated with using ellipsoid methods was quantified at each lower lumbar level. A large comprehensive database compiling lower lumbar geometry from many studies was established. This study provides geometric data for the female subjects at the L5/S1 level, previously lacking in the literature.

Conclusion This study demonstrates the potential of using MRI data to establish a standard measurement protocol for morphometric quantification of the lower lumbar intervertebral discs and vertebral endplates. These results are invaluable in characterizing comprehensive lower lumbar morphometry, which may provide crucial information for planning spinal surgeries, designing artificial intervertebral discs, and for biomechanical modeling of the low back.

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Keywords Lower lumbar intervertebral disc · Endplate · Geometry · Magnetic resonance imaging (MRI) · Disc arthroplasty

Introduction

Cross-sectional area (CSA) of the load-bearing surface and the bone mineral density (BMD) of a spinal motion segment, together determine its bone mineral content (BMC) [1], which has been shown to influence the mechanical

properties of human spine [1–3], and account for much of the variance in the ultimate compressive strength [1]. Linear and planar aspects of the intervertebral discs (IVDs) and vertebral endplates (EPs) have already been employed to develop mathematical models and playing a substantial role to characterize the biomechanics of spinal behavior and investigate the potential risk of work-related low back pain (LBP) [4, 5]. Modern comprehensive approach to human lumbar spine modeling, such as finite element models (FEMs), requires more specific spinal geometry, particularly the CSAs of IVDs and EPs, to study physiological responses of the spine to various loading conditions [6–9]. It has been suggested that FEMs should account for the natural variability of the spinal geometry among the general population [10]. Recently, total disc arthroplasty has become a common surgical procedure to treat discogenic spinal pathology [11, 12]. Accurate and comprehensive descriptions of the lower lumbar morphometry may also benefit the development of spinal implants and artificial IVDs [13–15].

Geometric dimensions have been reported primarily in studies of spinal morphometry [13, 15–35], and studies of the ultimate compressive strength and fatigue failure of spinal motion segments [1, 36–42]. Unfortunately, a majority of these studies only focused on either IVDs or EPs at single spinal level. Comprehensive morphometric descriptions of the IVDs and EPs across multi lower lumbar spinal levels has been lacking in the literature, particularly regarding both the linear and planar aspects of the load-bearing surface. In addition, the accuracy and reliability of existing geometric data may be problematic due to small sample sizes and measurement techniques, resulting in large differences among study results [31, 35]. Measurement differences may be due to the lack of a standardized measurement protocol employing uniform denotations and reference landmarks [31]. Previous studies have differed in the modality of measurement, varying from direct cadaveric measurements [13, 16, 27, 28, 38–41] to image-derived measurements, including radiographs [17, 18, 21, 26], computed tomography (CT) scans [1, 15, 20, 23, 25, 29, 32–37], and magnetic resonance imaging (MRI) scans [24, 31]. Some studies simplified the measurement by approaching the irregularly-shaped IVDs and EPs with ellipsoid approximation method [20, 39], using sagittal and frontal diameters ($SD \times FD \times \pi/4$) as described by Farfan [21], which introduced systematic errors [29]. Unfortunately, errors associated with such approximation method have not yet been thoroughly quantified.

The authors' research interest was on spinal biomechanics and ergonomic assessment of work-related LBP. Therefore, this study focused on lower lumbar to facilitate further development of spinal biomechanics models. The purpose of the present study was (1) to establish a standard

measurement protocol to describe the morphometry of the lower lumbar IVDs and EPs with respect to the CSA and linear diameters in the transverse section on MRI scans, (2) to quantify the errors associated with ellipsoid estimations, and (3) to summarize previous methods used to measure spinal morphometry and compare the geometric data as reported in literature.

Materials and methods

MRI scans

Digitally archived T₂-weighted MRI scans of the adult lower lumbar spine (L3–S1) were retrieved and anonymized from the University Hospital of the University of Utah (Salt Lake City, Utah, USA). Sagittal and transverse lumbar scans were performed on a Siemens MAGNETOM Avanto 1.5 T scanner (Siemens Medical Solutions, Erlangen, Germany), with subjects oriented in a headfirst supine position. All MRI data were collected with parameters that supported morphometric analyses (MR repetition time ranged from 3000 to 4770 ms, echo time between 80 and 110 ms, and slice thickness between 3 and 4.5 mm). Subject demographic data (e.g. height, weight, age, and gender) were embedded and released along with these scans. Subject body mass index (BMI) was calculated using subject weight (in kg) and height (in m). MRI scans of subjects between the ages of 20 and 40 years were reviewed and excluded if the subjects presented with (1) evidence of morphological alterations in lumbar or thoracic spine (e.g., crushed vertebral body, trauma); and (2) any known pathology likely to alter the geometric characteristics (e.g., scoliosis, tumor). Note that all subjects did not undergo MRI for this study. The reason why these subject underwent MRI was beyond the authors' knowledge. The initial MRI scans were retrieved from the database based on radiology diagnoses that there were no specific low back disorders. In addition, all IVDs were assessed with the Pfirrmann grading system for health status by a radiologist [45]. Geometric data associated with Pfirrmann's Grade V score were intentionally excluded due to the collapsed disc space. In total, MRI scans from 109 subjects (55 females and 54 males) were retrieved, including 327 IVDs and 654 EPs. Since 9 male IVDs were Grade V (2 at L3/L4 level, 4 at L4/L5 level, and 3 at L5/S1 level), they were excluded from the analysis. In addition, twenty-three subjects (13 females and 10 males) were missing oblique slices of the L5/S1 EPs (23 CrEPs and 23 CaEPs), and were therefore excluded as well. To make it clear, exclusions were only applied to specific IVDs, not to the associated subjects. In other word, if one subject had Grade V L3/L4 IVD, but Grade I L4/L5 and L5/S1 IVDs,

only L3/L4 IVD was excluded for this subject. Institutional Review Board (IRB) approval was obtained from both Auburn University and the University of Utah.

Measurement methods

Transverse MRI scans were analyzed using an open-source, DICOM software, OsiriX (version 4.1.1, 32-bit) [43, 44]. Anatomical landmarks for geometric measurements were manually identified and traced using a computer workstation. At each level, four measurements (Fig. 1) were taken for each IVD and its adjacent cranial endplate (CrEP) and caudal endplate (CaEP). Measurements included the CSA, anteroposterior diameter (APD), mid-sagittal diameter (MSD), and frontal diameter (FD). Denotations of these dimensions are provided in Table 1. Ellipsoid-approximated CSAs were calculated using formula (1) $APD \times FD \times \pi/4$ [27] and formula (2) $MSD \times FD \times \pi/4$ [39], to quantify the associated errors. Measurements were taken only in oblique slices to minimize distortion.

Repeatability tests

Two observers measured the geometric dimensions independently from a subset of 40 randomly selected MRI

scans (20 females and 20 males). Each observer performed two rounds of measurements at a 1-month interval and with randomized observation order. Interpretations of ICC and PCC results are based on previous studies [47, 48]. Note that measurements reported in this paper was from the first measurement of the first observer. Other measurements were only used for reliability tests. Intra- and inter-observer reliabilities were assessed to using the intra-class correlation coefficient (ICC) [ICC (3,1)] [46], and Pearson's correlation coefficient (PCC).

Statistical analyses

Split plot factorial (SPF) analysis of variance (ANOVA) was used to determine the effect of gender (2 levels), spinal level (3 levels), and their interactions on the geometric dimensions. Independent Students *t* test was used to compare female and male data. Paired sample *t* tests were used to compare geometric dimensions of the EPs regarding the same IVD and vertebra. Tukey's honest significant difference (HSD) post hoc tests were performed to determine the trend of changes in the dimensions across the three spinal levels. An alpha level of 0.05 was established for all statistical tests (SPSS 19.0, IBM SPSS Statistics, Armonk, NY, USA).

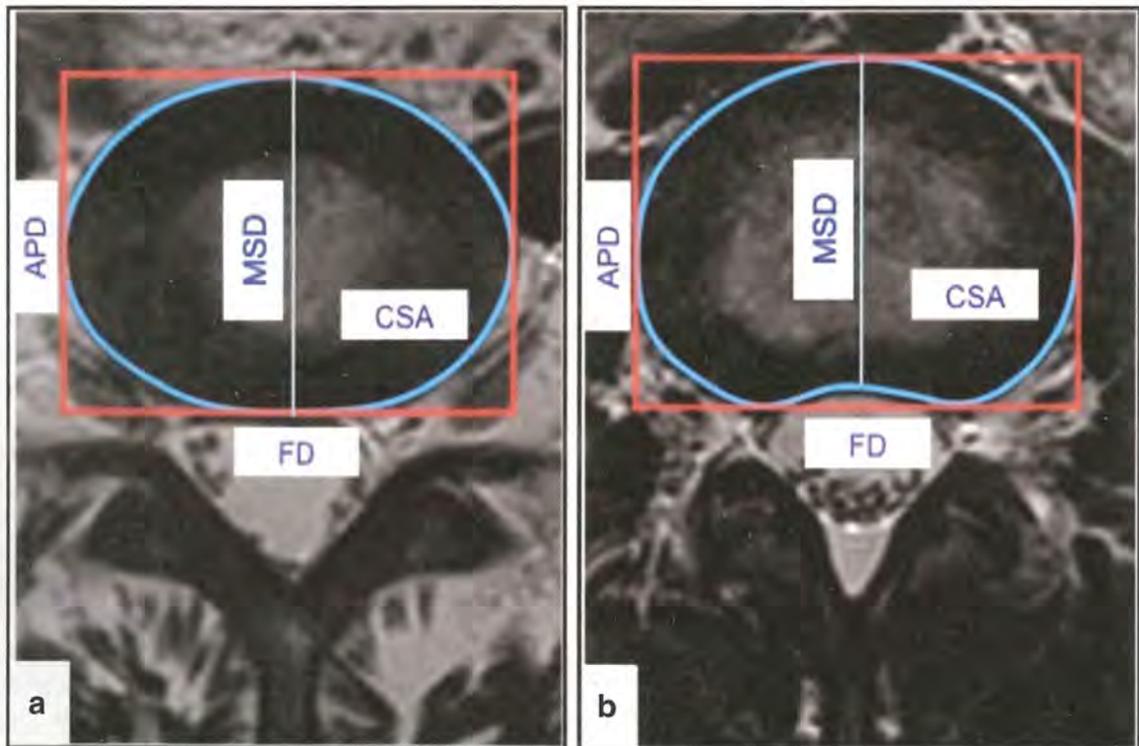


Fig. 1 Illustrations of geometric dimensions in the transverse section (Note the different APD measurements for *aoval-shaped* and *kidney-shaped* IVDs and EPs)

Table 1 Definitions of geometric dimensions measured

Dimensions	Definitions
Cross-sectional area (CSA)	Determined by tracing the actual periphery of the IVD and EP
Anteroposterior diameter (APD)	Linear distance between the anterior-most and posterior-most transverse contour extends of the IVD and EP
Frontal diameter (FD)	Linear distance between the right and left lateral-most transverse contour extends of the IVD and EP
Mid-sagittal diameter (MSD)	Linear distance between the mid-sagittal extends of the IVD and EP

Table 2 Demographic data for both genders included in the final analyses

			N	Mean	SD	Sig.
L3/L4	Age (years)	Female	55	30.1	5.8	0.704
		Male	52	30.5	5.3	
	Ht (cm) ^b	Female	41	165.72	9.46	0.000 ^a
		Male	38	178.33	9.32	
	Wt (kg)	Female	55	74.65	19.71	0.002 ^a
		Male	52	87.12	20.89	
BMI (kg/m ²) ^b	Female	41	26.68	7.20	0.648	
	Male	36	27.36	5.53		
L4/L5	Age (years)	Female	55	30.1	5.8	0.949
		Male	50	30.0	5.1	
	Ht (cm) ^b	Female	41	165.72	9.46	0.000 ^a
		Male	37	178.00	9.23	
	Wt (kg)	Female	55	74.65	19.71	0.003 ^a
		Male	50	86.71	20.21	
BMI (kg/m ²) ^b	Female	41	26.68	7.20	0.776	
	Male	35	27.11	5.39		
L5/S1	Age (years)	Female	55	30.1	5.8	0.672
		Male	51	30.6	5.3	
	Ht (cm) ^b	Female	41	165.72	9.46	0.000 ^a
		Male	35	177.58	8.54	
	Wt (kg)	Female	55	74.65	19.71	0.002 ^a
		Male	51	86.70	20.09	
BMI (kg/m ²) ^b	Female	41	26.68	7.20	0.699	
	Male	33	27.27	5.51		

^a Indicates males significantly different from females ($P < 0.05$)

^b HT data were incomplete, missing from the MRI scans

Results

Table 2 summarizes demographic data for the subjects who met the inclusion criteria. In the present study, male subjects were significantly taller and heavier than females ($P < 0.001$). Both intra- and inter-observer reliabilities were found to be excellent (ICCs >0.90 ; Pearson's >0.90)

Table 3 Reliability of measurements

	Intra-observer				Inter-observer	
	Observer I		Observer II		Observer I and II	
	ICC ^a	PCC ^b	ICC ^a	PCC ^b	ICC ^a	PCC ^b
CSAs	0.996	0.997	0.990	0.996	0.971	0.978
FDs	0.984	0.986	0.984	0.988	0.953	0.955
APDs	0.993	0.994	0.984	0.988	0.970	0.971
MSDs	0.914	0.904	0.906	0.909	0.938	0.940

^a Intra-class coefficient

^b Pearson's correlation coefficient

for every geometric dimension measured (Table 3). Table 4 presents the descriptive statistics for the geometric dimensions measured in the present study. The trends of the CSA and linear dimensions of the lower lumbar IVDs and EPs measured on MRI scans are shown in Figs. 2, 3, 4, and 5.

CSAs

Compared to females, male CSA_{IVD} was 20 % larger at the L3/L4 level ($P < 0.001$), 24 % larger at the L4/L5 level ($P < 0.001$), and 26 % larger at the L5/S1 level ($P < 0.001$). Similar trends for gender differences were also found in CSA_{CrEP} ($P < 0.001$) and CSA_{CaEP} ($P < 0.001$), but with a less pronounced effect (18 % on average). Post hoc tests revealed that CSA_{IVD}, CSA_{CrEP}, and CSA_{CaEP} remained constant from the L3/L4 to L4/L5 level but decreased at the L5/S1 level by 7, 6, and 5 % ($P < 0.05$), respectively. A gender \times level interaction in area dimensions approached the level of significance ($P = 0.088$). With respect to craniocaudal differences, CSA_{IVD} was significantly larger than the adjacent CSA_{CrEP} and CSA_{CaEP} in males with an 18 and 9 % increase ($P < 0.001$) and in females with a 17 and 4 % increase ($P < 0.01$), respectively. CaEPs generally had larger CSAs compared to CrEPs, where the difference was more pronounced in females (12 %, $P < 0.001$) than in males (9 %, $P < 0.001$). In terms of lumbar vertebrae, in both female and male L5 vertebrae, CSA_{CrEP} was larger than the corresponding CSA_{CaEP} ($P < 0.001$), while only female L4 vertebrae exhibited the same difference ($P < 0.001$). However, the difference between CSA_{CrEP} and CSA_{CaEP} in male L4 vertebrae was approaching the level of significance ($P = 0.090$).

Errors associated with ellipsoid methods

Ellipsoid methods using the APD underestimated CSA_{IVD}, CSA_{CrEP}, and CSA_{CaEP} by 2 % ($P < 0.01$) at the L3/L4

Table 4 Descriptive statistics of geometric dimensions measured on MRI scans

Geometry	Gender	L3/L4					L4/L5					L5/S1				
		N	Mean	SD	Min	Max	N	Mean	SD	Min	Max	N	Mean	SD	Min	Max
CSA _{CrEP} (cm ²)	Female	55	12.59	1.68	9.77	17.74	55	12.49	1.53	9.90	15.95	42	11.71	1.50	9.25	15.11
	Male	52	15.19	1.73	11.52	19.14	50	15.13	1.74	11.74	19.88	41	14.47	2.00	11.32	20.45
	All	107	13.85	2.14	9.77	19.14	105	13.75	2.10	9.90	19.88	83	13.08	2.23	9.25	20.45
APD _{CrEP} (cm)	Female	55	3.43	0.22	2.98	3.91	55	3.41	0.21	3.07	3.97	42	3.32	0.19	2.90	3.77
	Male	52	3.77	0.22	3.28	4.33	50	3.76	0.25	3.37	4.57	41	3.72	0.27	3.28	4.61
	All	107	3.59	0.28	2.98	4.33	105	3.58	0.29	3.07	4.57	83	3.52	0.31	2.90	4.61
FD _{CrEP} (cm)	Female	55	4.54	0.33	3.95	5.11	55	4.58	0.35	3.91	5.35	42	4.61	0.33	3.82	5.18
	Male	52	5.03	0.35	4.27	5.80	50	5.03	0.32	4.17	5.63	41	5.05	0.39	4.13	5.82
	All	107	4.78	0.41	3.95	5.80	105	4.79	0.41	3.91	5.63	83	4.83	0.42	3.82	5.82
CSA _{IVD} (cm ²)	Female	55	14.76	1.90	11.48	20.82	55	14.63	1.80	10.63	18.36	55	13.52	1.91	10.21	17.95
	Male	52	17.71	1.96	13.59	22.51	50	18.08	2.02	13.78	22.80	51	17.06	2.34	13.15	22.98
	All	107	16.19	2.43	11.48	22.51	105	16.27	2.57	10.63	22.80	106	15.23	2.76	10.21	22.98
APD _{IVD} (cm)	Female	55	3.70	0.26	3.12	4.42	55	3.68	0.23	3.21	4.16	55	3.53	0.23	3.01	4.00
	Male	52	4.03	0.24	3.47	4.61	50	4.06	0.26	3.56	4.68	51	4.01	0.32	3.47	4.76
	All	107	3.86	0.30	3.12	4.61	105	3.86	0.31	3.21	4.68	106	3.76	0.36	3.01	4.76
FD _{IVD} (cm)	Female	55	4.97	0.32	4.39	5.92	55	5.03	0.32	4.22	5.67	55	4.93	0.39	4.13	5.96
	Male	52	5.48	0.36	4.65	6.22	50	5.59	0.32	4.89	6.24	51	5.50	0.40	4.84	6.22
	All	107	5.22	0.42	4.39	6.22	105	5.29	0.43	4.22	6.24	106	5.21	0.49	4.13	6.22
CSA _{CaEP} (cm ²)	Female	55	14.04	1.75	10.36	20.00	55	13.95	1.56	10.46	17.77	42	13.35	1.78	10.21	17.60
	Male	52	16.29	1.86	11.61	19.94	50	16.47	1.95	12.37	21.04	41	15.93	2.25	12.26	22.46
	All	107	15.13	2.12	10.36	20.00	105	15.15	2.16	10.46	21.04	83	14.63	2.39	10.21	22.46
APD _{CaEP} (cm)	Female	55	3.61	0.23	3.12	4.22	55	3.50	0.21	3.12	4.03	42	3.41	0.24	2.95	4.01
	Male	52	3.84	0.23	3.22	4.41	50	3.76	0.23	3.23	4.47	41	3.74	0.31	3.15	4.64
	All	107	3.72	0.26	3.12	4.41	105	3.63	0.25	3.12	4.47	83	3.57	0.32	2.95	4.64
FD _{CaEP} (cm)	Female	55	4.85	0.32	4.10	5.48	55	5.01	0.31	4.28	5.67	42	4.96	0.39	4.19	5.92
	Male	52	5.26	0.33	4.52	5.90	50	5.44	0.36	4.71	6.21	41	5.42	0.41	4.86	6.31
	All	107	5.05	0.38	4.10	5.90	105	5.21	0.40	4.28	6.21	83	5.19	0.46	4.19	6.31
MSD _{CrEP} (cm)	Female	55	3.01	0.21	2.64	3.59	55	3.09	0.19	2.72	3.58	42	3.26	0.20	2.85	3.81
	Male	52	3.49	0.21	2.99	4.09	50	3.55	0.23	3.11	4.27	41	3.71	0.22	3.28	4.25
	All	107	3.24	0.32	2.64	4.09	105	3.31	0.31	2.72	4.27	83	3.48	0.31	2.85	4.25
MSD _{IVD} (cm)	Female	55	3.22	0.24	2.77	3.77	55	3.30	0.22	2.84	3.88	55	3.46	0.26	2.83	4.03
	Male	52	3.73	0.21	3.32	4.23	50	3.80	0.26	3.23	4.43	51	4.00	0.32	3.46	4.70
	All	107	3.47	0.34	2.77	4.23	105	3.54	0.34	2.84	4.43	106	3.72	0.40	2.83	4.70
MSD _{CaEP} (cm)	Female	55	3.08	0.23	2.60	3.62	55	3.11	0.18	2.77	3.65	42	3.32	0.20	2.82	3.78
	Male	52	3.47	0.22	2.96	4.00	50	3.52	0.24	3.11	4.22	41	3.73	0.24	3.15	4.43
	All	107	3.27	0.30	2.60	4.00	105	3.31	0.29	2.77	4.22	83	3.52	0.32	2.82	4.43

Fig. 2 CSA_{IVD} and CSA_{EP} from the L3/L4 to L5/S1 level

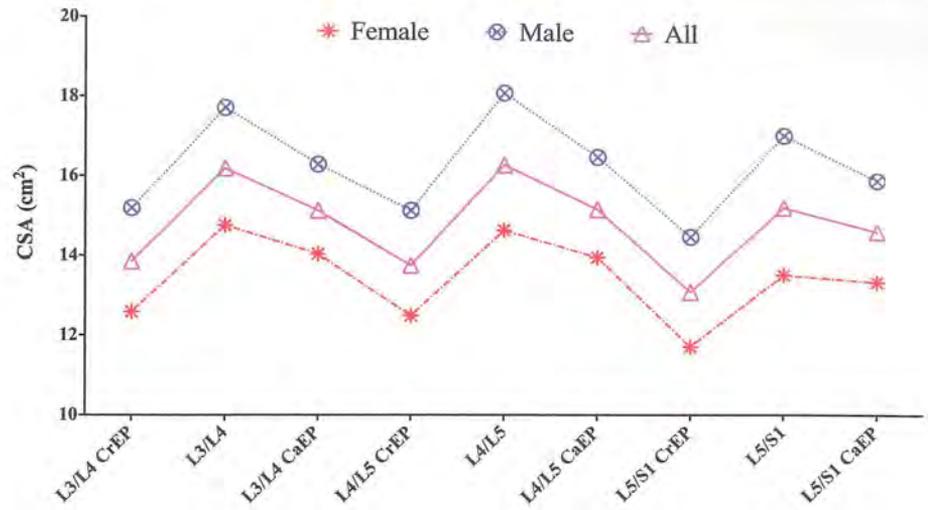


Fig. 3 APD_{IVD} and APD_{EP} from the L3/L4 to L5/S1 level

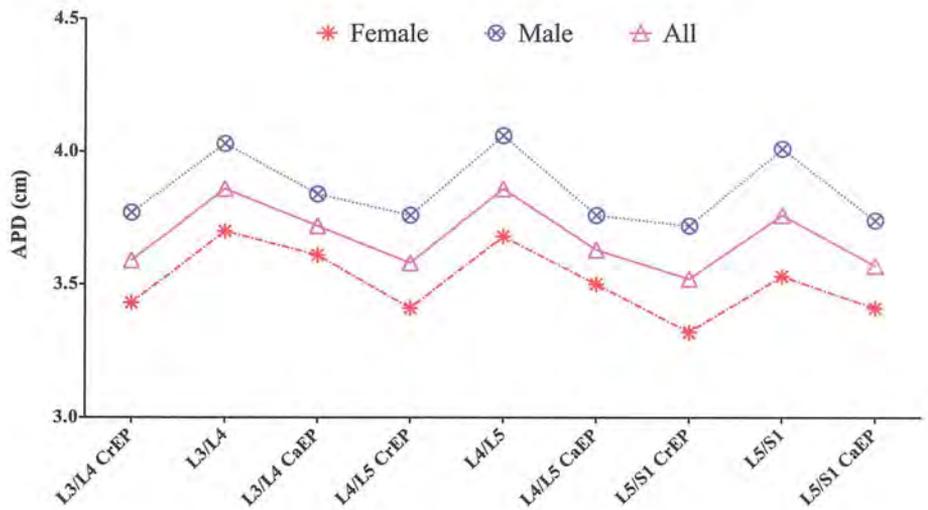


Fig. 4 FD_{IVD} and FD_{EP} from the L3/L4 to L5/S1 level

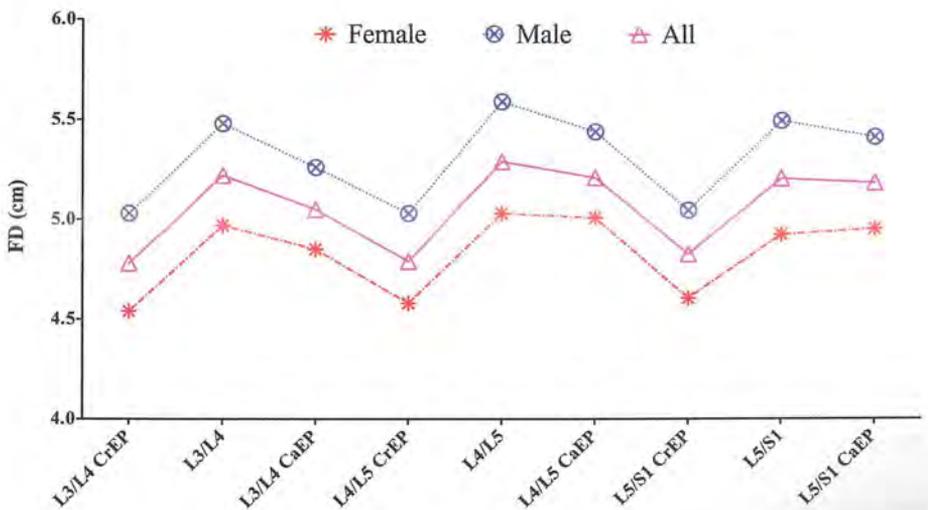
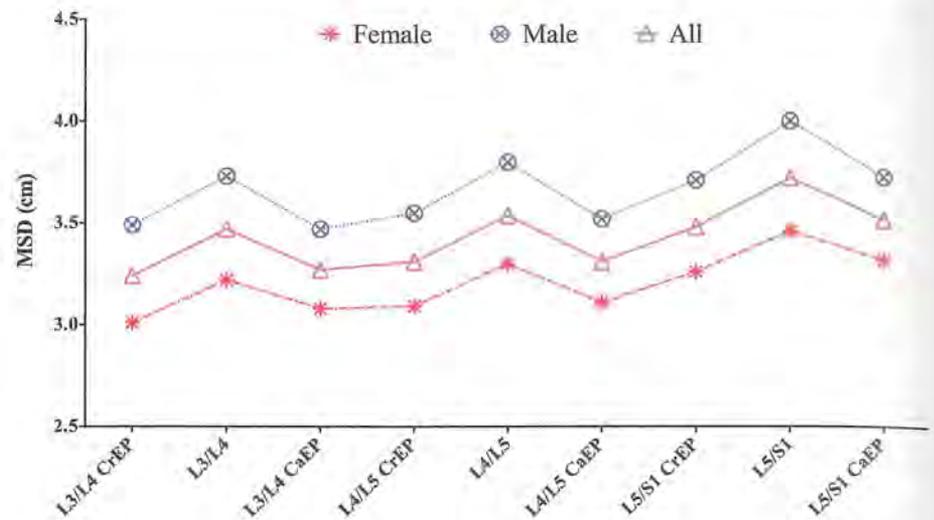


Fig. 5 MSD_{IVD} and MSD_{EP} from the L3/L4 to L5/S1 level



and L4/L5 levels, but overestimated CSA_{IVD} and CSA_{CrEP} by 3 % ($P < 0.001$) at the L5/S1 level. Ellipsoid methods using the MSD also overestimated CSA_{CrEP} ($P = 0.005$) and CSA_{IVD} ($P = 0.004$) at the L5/S1 level by 2 %. However, it yielded much greater underestimation for CSA_{IVD}, CSA_{CrEP} and CSA_{CaEP} by 10 % ($P < 0.001$) at the L3/L4 and L4/L5 levels. Absolute errors between measured data and estimations also indicated that the estimates using APD exhibited much less difference (2 %) than estimates using MSD (9 %).

Linear diameters

Statistics from the SPF ANOVA indicated that APD_{IVD} was significantly influenced by gender ($P < 0.001$) and spinal level ($P < 0.001$), as well as their interaction ($P = 0.017$) (Fig. 6). The mean FD_{IVD} in males was significantly larger than in females across all three levels ($P < 0.001$), averaging an 11 % increase, respectively. Post hoc tests indicated that the FD_{IVD} increased by 2 % from the L3/L4 to the L4/L5 level, and decreased by 2 % from the L4/L5 to the L5/S1 level ($P < 0.05$). The mean APD_{CrEP} in males was, on average, 11 % larger than in females at each level ($P < 0.001$). Post hoc tests revealed that the APD_{CrEP} remained constant from the L3/L4 to the L4/L5 level, and decreased by 2 % at the L5/S1 level ($P < 0.05$). The mean FD_{CrEP} in males was, on average, 10 % larger than in females at each level ($P < 0.001$). Post hoc tests revealed no difference in FD_{CrEP} across the three levels. APD_{CaEP} was significantly influenced by the interaction of gender and spinal level ($P = 0.044$) (Fig. 7). The mean FD_{CaEP} in males was significantly larger than in females across all three levels ($P < 0.001$), averaging a 9 % increase, respectively. Post hoc tests indicated that

the FD_{CaEP} increased by 3 % from the L3/L4 to the L4/L5 level ($P < 0.05$), and remained constant from the L4/L5 to the L5/S1 level.

Discussion

The present study investigated applications of MRI data to measure human spinal geometry and established a standard measurement protocol with each geometric dimension explicitly defined and illustrated with clear figures demonstrating each landmark referenced. This helped yield excellent intra- and inter-observer measurement reliability. Since OsiriX software has great image processing capability to evaluate MRI scans (DICOM format) [43, 44], it has become a reliable means to characterize the morphology of the human spine [49] and paraspinal musculature [50, 51] and to improve clinical diagnosis of spinal pathologies [52, 53]. Using MRI scans and advanced software, comprehensive transverse morphometry of both male and female lower lumbar IVDs and EPs was reliably measured from the L3/L4 to the L5/S1 level with a large sample size. The present study is the first, to our knowledge, to consider both linear and planar aspects of lower lumbar geometry, including both cranial/caudal EPs and IVDs. This is crucial information for the development of artificial IVD implants, particularly for female patients. Providing these data can help accommodate the variability of spinal morphology and biomechanical demand, and facilitate better prosthesis-vertebra contact, improving spinal load distribution [15, 56].

Our results showed that for a given IVD across the three lower lumbar levels, the CaEPs were significantly larger than the CrEPs. Additionally, females had more

Fig. 6 APD_{IVD} for female and male from the L3/L4 to L5/S1 level

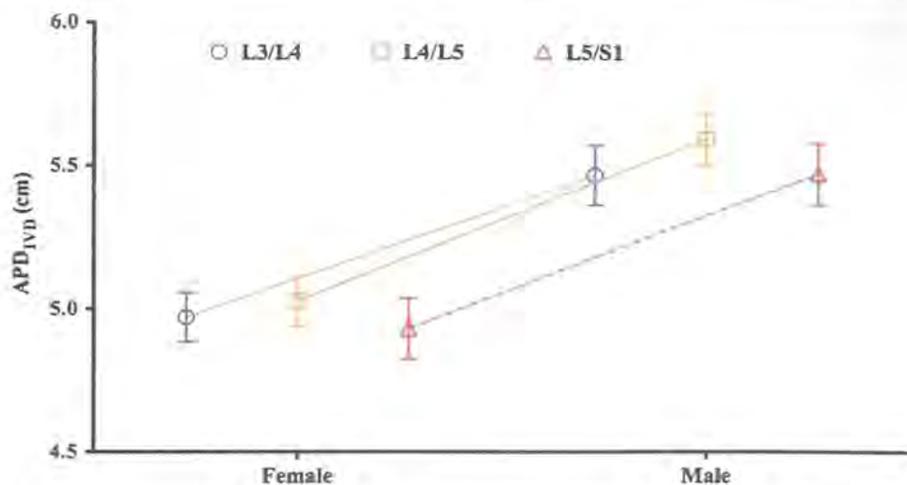
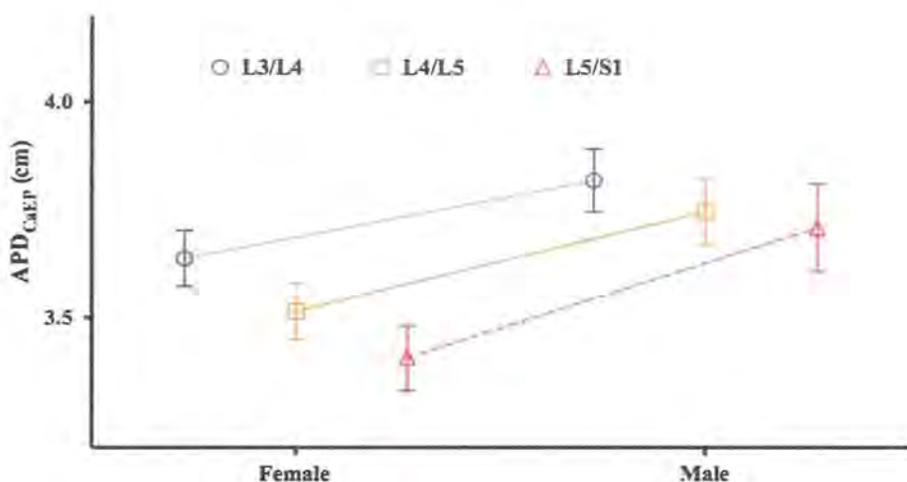


Fig. 7 APD_{CaEP} for female and male from the L3/L4 to L5/S1 level



pronounced difference (12 %) compared to males (9 %). Significant differences were also found for the CSAs of the EPs associated with the L4 and L5 lumbar vertebra. The CrEP of the L5 vertebra was significantly larger than the CaEP (12 % on average), while only the female L4 vertebrae exhibited the same difference (11 %). Seidel et al. [29] using gender-unknown cadavers, had similar findings for the L3 and L5 vertebra, but not for L4. Geometric data reported by Wang et al. [34] exhibited evidence of a similar trend, while the ones reported by Brinckmann et al. [1] and Panjabi et al. [27] showed a slight increase for the L4 vertebra. Unfortunately, these studies included no statistical analysis regarding such craniocaudal changes and there is currently very little in the literature to draw further comparisons. Meanwhile, craniocaudal asymmetry associated with the morphology of the lumbar endplates has been noted in the literature. The endplate cranial to the disc is more likely to be concave [19, 34, 56, 57], compared to the caudal one which may be more flat in the lower lumbar region [34, 56]. Some studies indicated that the asymmetry

pattern might be correlated more with disc degeneration [57] than with gender [56, 57] or age [19, 56]. In addition, the CrEP usually has higher bone mineral density (BMD) than the corresponding CaEP [58]. Therefore, the CrEPs have been assumed to be structurally stronger [34], given the fact that more vertebral fractures have been found in the CaEPs [1, 59, 60]. However, since the present study found that the CrEP had smaller CSA, one could speculate that the concavity of the CrEP may be influenced by the size of the load-bearing surface. Unfortunately, these endplate characteristics and their impact on the mechanical behaviors of spinal motion segments have not been well investigated in the literature [61]. This remains a promising area for further research.

This study found that gender had a significant influence on lower lumbar geometry. Previous studies have also reported similar gender influence on the cross-sectional area of the intervertebral discs [38, 39, 41] and endplates [14], and linear diameters [19, 33, 35]. However, in the present sample, the genders were also significantly

Table 5 Geometric data regarding the lower lumbar intervertebral disc in the literature

Authors	Subjects	Age (yrs)	Ht (cm)	Wt (kg)	Cross-sectional Area (cm ²)		
					L3/L4	L4/L5	L5/S1
Nachemson [41] (1960, caliper, Cadaver)	14 Female	59.71	–	–	15.39 (1.54)	16.10 (1.80)	
	19 Male	47.84	–	–	19.61 (2.53)	18.52 (1.27)	
Farfan [21] (1973, ellipsoid, cadaver)	6F + 6M	55.92	–	–	16.33 (2.25)	18.55 (1.85)	
Hansson et al. [38] (1980, cadaver, graph paper)	21 Female	57.67	–	–	18.05 (3.06)		
	15 Male	59.73	–	–	20.86 (3.72)		
Hutton and Adams [39] (1982, ellipsoid, cadaver)	5 Female	52.00	–	67.00	12.80 (1.00)	15.20 (1.00)	
	13 Male	38.31	–	68.46	17.00 (1.92)	18.92 (3.76)	
Colombini et al. [20] (1989, ellipsoid, CT, in vivo)	16	45.00	172.40	77.40	19.88 (3.51)	21.43 (3.89)	18.88 (3.18)
Porter et al. [42] (1989, cadaver)	9 Male	21.89	–	72.40		18.50 (1.74)	
Turk and Celan [32] (2004, CT, LBP patient/healthy)	21F + 19M	44	–	–		17.96 (2.40)	16.88 (2.06)
	30 Male	–	–	–		20.79 (1.95)	19.26 (1.65)
Tang [31] (2013, MRI, in vivo)	55 Female	30.11	165.72	74.65	14.76 (1.90)	14.63 (1.80)	13.52 (1.91)
	52 Male	30.59	178.33	87.43	17.71 (1.96)	18.08 (2.02)	17.06 (2.34)
	107 F + M	30.35	171.79	80.98	16.19 (2.43)	16.27 (2.57)	15.23 (2.76)
Authors	Subjects	Age (yrs)	Ht (cm)	Wt (kg)	Anteroposterior Diameter (cm)		
					L3/L4	L4/L5	L5/S1
Farfan [21]	6F + 6M	55.92	–	–	3.60 (0.30)	3.87 (0.13)	
Tang [31]	55 Female	30.11	165.72	74.65	3.70 (0.26)	3.68 (0.23)	3.53 (0.23)
	52 Male	30.59	178.33	87.43	4.03 (0.24)	4.06 (0.26)	4.00 (0.32)
	107 F + M	30.35	171.79	80.98	3.86 (0.30)	3.86 (0.31)	3.76 (0.36)
Authors	Subjects	Age (yrs)	Ht (cm)	Wt (kg)	Frontal Diameter (cm)		
					L3/L4	L4/L5	L5/S1
Farfan [21]	6F + 6M	55.92	–	–	5.59 (0.43)	5.90 (0.43)	
Tang [31]	55 Female	30.11	165.72	74.65	4.97 (0.32)	5.03 (0.32)	4.93 (0.39)
	52 Male	30.59	178.33	87.43	5.48 (0.36)	5.59 (0.32)	5.50 (0.40)
	107 F + M	30.35	171.79	80.98	5.22 (0.42)	5.29 (0.43)	5.21 (0.49)

Table 6 Geometric data regarding the lower lumbar cranial endplate in the literature

Authors	Subjects	Age (yrs)	Ht (cm)	Wt (kg)	CSA (cm ²)		
					L3/L4	L4/L5	L5/S1
Brinckmann et al. [1] (1989, CT, cadaver)	22 F	49.15	–	–	13.72 (1.96)	15.21 (2.20)	
	31 M	49.93	–	–	18.43 (5.77)	18.16 (2.22)	
Panjabi et al. [27] (1992, cadaver, ellipsoid)	4F + 8M	46.3	167.8	67.8	12.90 (0.64)	12.73 (0.52)	12.18 (0.59)
Drerup et al. [37] (1999, CT, in vivo)	14 Male	42.21	177.57	87.86	16.00 (1.36)		
Zhou et al. [35] (2000, CT, in vivo, patient)	71 Female	50	–	–	13.86 (1.88)		
	55 Male	49	–	–	15.98 (0.66)		
	126 F + M	50	–	–	14.92 (1.74)		
Tan et al. [30] (2004, digitized image, cadaver)	10	65.7	166	61.6	11.72 (2.06)	11.99 (3.55)	10.54 (2.10)
Seidel et al. [29] (2008, CT, cadaver)	53	33.26	179.92	82.66	16.00 (1.81)	15.84 (1.82)	15.06 (1.90)
Wang et al. [34] (2012, cadaver, laser scan)	149 Male	under 64	–	–	15.80 (2.4)	16.10 (2.50)	15.10 (2.80)
Tang [31] (2013, MRI, in vivo)	55 Female	30.11	165.72	74.65	12.59 (1.68)	12.49 (1.53)	11.71 (1.50)
	52 Male	30.59	178.33	87.43	15.19 (1.73)	15.13 (1.74)	14.47 (2.00)
	107 F + M	30.35	171.79	80.98	13.85 (2.14)	13.75 (2.10)	13.08 (2.23)
Authors	Subjects	Age (yrs)	Ht (cm)	Wt (kg)	APD/MSD (cm)		
					L3/L4	L4/L5	L5/S1
Nissan and Gilad [26] (1984, caliper, X-ray, healthy)	157 Male	26.80	174.70	72.40	3.46 (0.28)	3.49 (0.28)	3.39 (0.27)
	van Schaik et al. [33] (1985, CT, patient, mid-sagittal)	59 Female	–	–	3.26	3.33	3.42
	64 Male				3.51	3.72	3.73
	123 F + M	41.40	–	–	3.40 (0.25)	3.52 (0.30)	3.59 (0.29)
	Berry et al. [13] (1987, caliper, cadaver)	30 F + M	50 to 79	–	–	3.42 (0.33)	3.56 (0.31)
Amonoo-Kuofi [17] (1991, X-ray, healthy)	310 Female 305 Male	10 to 64	–	–	3.92 4.20	4.01 4.31	3.84 4.15
Panjabi et al. [27]	4F + 8M	46.3	167.8	67.8	3.48 (0.12)	3.39 (0.09)	3.32 (0.92)
Aydinlioglu et al. [18] (1999, X-ray, healthy, average)	97 Female	10 to 59	–	–	4.31	4.37	4.30
	103 Male				4.77	4.88	4.75
Zhou et al. [35]	71 Female	50	–	–	3.37 (0.31)	3.44 (0.28)	3.43 (0.33)
	55 Male	49	–	–	3.74 (0.31)	3.86 (0.34)	3.83 (0.38)
	126 F + M				3.53 (0.36)	3.62 (0.37)	3.60 (0.40)
Tan et al. [30]	10	65.7	166	61.6	3.02 (0.04)	3.03 (0.06)	2.87 (0.04)
van der Houwen et al. [15]	31 Female	49.8	–	–	2.54	2.81	2.51
	46 Male	49.8	–	–	3.04	3.06	2.74
Wang et al. [34]	149 Male	under 64	–	–	3.58 (0.28)	3.55 (0.29)	3.38 (0.35)
Tang [31]	55 Female	30.11	165.72	74.65	3.43 (0.22)	3.41 (0.21)	3.32 (0.19)
	52 Male	30.59	178.33	87.43	3.77 (0.22)	3.76 (0.25)	3.72 (0.27)
	107 F + M	30.35	171.79	80.98	3.59 (0.28)	3.58 (0.29)	3.52 (0.31)

Table 6 continued

Authors	Subjects	Age (yrs)	Ht (cm)	Wt (kg)	FD (cm)		
					L3/L4	L4/L5	L5/S1
van Schaik et al. [33]	59 Female	-	-	-	4.12	4.26	4.51
	64 Male	-	-	-	4.58	4.75	5.01
Berry et al. [13]	123 F + M	41.40	-	-	4.37 (0.41)	4.50 (0.38)	4.79 (0.45)
	30 F + M	50 to 79	-	-	5.38 (0.37)	5.09 (0.46)	5.27 (0.43)
Panjabi et al. [27]	4F + 8M	46.3	167.8	67.8	4.80 (0.12)	4.95 (0.14)	4.94 (0.14)
Zhou et al. [35]	71 Female	50	-	-	4.93 (0.41)	5.04 (0.42)	5.04 (0.49)
	55 Male	49	-	-	5.48 (0.36)	5.51 (0.41)	5.67 (0.53)
Tan et al. [30]	126 F + M	50	-	-	5.17 (0.48)	5.25 (0.47)	5.31 (0.60)
	10	65.7	166	61.6	4.35 (0.03)	4.53 (0.05)	4.37 (0.04)
van der Houwen et al. [15]	31 Female	49.8	-	-	3.79	4.11	4.18
	46 Male	49.8	-	-	4.06	4.89	4.66
Wang et al. [34]	149 Male	under 64	-	-	5.13 (0.37)	5.30 (0.41)	5.12 (0.45)
	55 Female	30.11	165.72	74.65	4.54 (0.33)	4.58 (0.35)	4.61 (0.33)
Tang [31]	52 Male	30.59	178.33	87.43	5.03 (0.35)	5.03 (0.32)	5.05 (0.39)
	107 F + M	30.35	171.79	80.98	4.78 (0.41)	4.79 (0.41)	4.83 (0.42)

different in height and weight, therefore, the influence of gender might be confounded with these factors. There has been evidence that gross anthropometry may be correlated with the lower lumbar geometry [20, 31, 32]. Our results showed that L5/S1 discs had the smallest load-bearing surface when compared to the L3/L4 and L4/L5 IVDs, corroborating previous studies [20, 29, 32, 34]. With the theoretically highest spinal loading experienced [62], the L5/S1 IVDs have been the most common site of pathological alterations that result in low back pain [63]. The size of a lower lumbar IVD may be related to its vulnerability to future degenerative changes and the proneness to discogenic low back pain. Healthcare interventions may be established to encourage individuals with small spinal geometry to keep a healthy diet and regular exercise to help maintain higher bone mineral density, which could help to reduce the risk of future degenerative diseases and low back pain.

The present study summarized spinal morphometry data as reported in the literature. First, errors associated with the ellipsoid approximation were quantified with respect to each lower lumbar level, indicating significant underestimations at the L3/L4 and L4/L5 level and slight overestimations at the L5/S1 level, superior to previous knowledge of an overall 9 % underestimation [29]. Our results also showed that the errors were dependent on the selection of minor axis (APD vs. MSD), which is valuable information when comparing existing geometric data [20, 21, 27, 39]. In addition, the values of reported data depend on subject demographics and the accuracy of measurement [31]. With a relatively large sample in vivo, this study found that the range of some geometric dimensions measured was substantial. Investigations with small sample sizes may not adequately describe and characterize human spinal morphometry [31, 35]. Some earlier studies performed measurement on cadavers [38, 39, 41, 42], which may be highly susceptible to post-mortem changes (e.g. loss of water content) [35, 54] and the possible influence of the preservation process that usually involves storage in freezing conditions [41] or injection of preservation fluids [55]. Therefore, cadaveric specimens may not reflect the same geometric characteristics as healthy IVDs in vivo. Measurement technique may also have an impact on the geometric data. Radiographs are highly susceptible to magnification error [54, 64], which may lead to larger dimensions measured on lateral scans [18]. These factors unfortunately reduce the ability to directly compare geometric data among existing studies. However, the review of previous studies may still provide a good understanding of the spinal geometry such as the mean and range of data. For lower lumbar IVDs (Table 5), previous studies have mainly focused on the planar aspects [20, 32, 38, 39, 41, 42], except for one study which also reported linear dimensions [21].

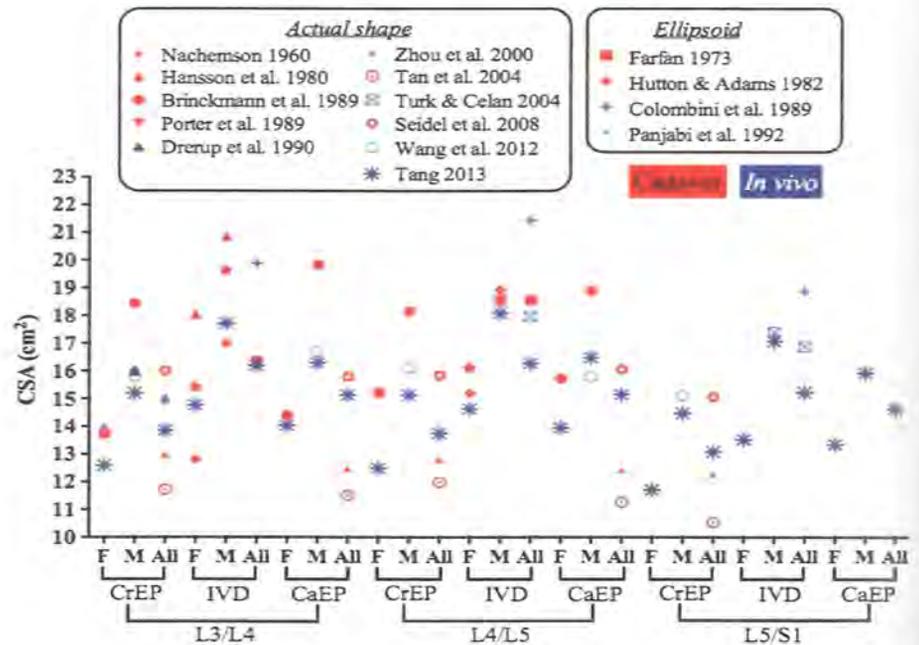
Table 7 Geometric data regarding the lower lumbar caudal endplate in the literature

Authors	Subjects	Age (yrs)	Ht (cm)	Wt (kg)	CSA (cm ²)		
					L3/L4	L4/L5	L5/S1
Brinckmann et al. [1] (1989, CT, cadaver, ellipsoid)	22 F	49.15	–	–	14.40 (1.45)	15.73 (2.48)	
	31 M	49.93	–	–	19.83 (6.85)	18.89 (2.30)	
Panjabi et al. [27] (1992, cadaver, ellipsoid)	4F + 8M	46.3	167.8	67.8	12.39 (0.58)	12.37 (0.58)	
Tan et al. [30] (2004, digitized image, cadaver)	10	65.7	166	61.6	11.52 (2.03)	11.27 (2.45)	
Seidel et al. [29] (2008, CT, cadaver)	53	33.26	179.92	82.66	15.79 (1.98)	16.06 (2.00)	
Wang et al. [34] (2012, cadaver, laser scan)	149 Male	under 64	–	–	16.70 (2.4)	15.80 (3.00)	
Tang [31] (2013, MRI, in vivo)	55 Female	30.11	165.72	74.65	14.04 (1.75)	13.95 (1.56)	13.35 (1.78)
	52 Male	30.59	178.33	87.43	16.29 (1.86)	16.47 (1.95)	15.93 (2.25)
	107 F + M	30.35	171.79	80.98	15.13 (2.12)	15.15 (2.16)	14.63 (2.39)
Authors	Subjects	Age (yrs)	Ht (cm)	Wt (kg)	APD/MSD (cm)		
					L3/L4	L4/L5	L5/S1
Postacchini et al. [28] (1983, caliper, cadaver, mid-sagittal)	63 Italian				3.2 (0.3)	3.3 (0.3)	
	58 Indian				2.9 (0.2)	2.9 (0.2)	
Nissan and Gilad [26] (1984, caliper, X-ray, healthy)	157 Male	26.80	174.70	72.40	3.43 (0.27)	3.42 (0.27)	
Berry et al. [13] (1987, caliper, cadaver, caucasian)	30 F + M	50 to 79	–	–	3.49 (0.34)	3.51 (0.28)	
Aharinejad et al. [16] (1990, cadaver/CT/MRI, mid-sagittal)	574 segments	–	–	–	3.80 (0.66)	3.76 (0.46)	
Panjabi et al. [27]	4F + 8M	46.3	167.8	67.8	3.55 (0.09)	3.47 (0.12)	
Zhou et al. [35]	71 Female	50	–	–	3.32 (0.33)	3.43 (0.35)	
	55 Male	49	–	–	3.64 (0.32)	3.76 (0.31)	
	126 F + M	50	–	–	3.46 (0.36)	3.57 (0.37)	
Tan et al. [30]	10	65.7	166	61.6	3.08 (0.02)	3.04 (0.05)	
van der Houwen et al. [15] (2010, caliper, CT, patient, mid-sagittal)	31 Female	49.8	–	–	2.61	2.77	
	46 Male	49.8	–	–	2.89	2.76	
Wang et al. [34]	149 Male	under 64	–	–	3.61 (0.28)	3.47 (0.32)	
Tang [31]	55 Female	30.11	165.72	74.65	3.61 (0.23)	3.50 (0.21)	3.41 (0.24)
	52 Male	30.59	178.33	87.43	3.84 (0.23)	3.76 (0.23)	3.74 (0.31)
	107 F + M	30.35	171.79	80.98	3.72 (0.26)	3.63 (0.25)	3.57 (0.32)
Authors	Subjects	Age (yrs)	Ht (cm)	Wt (kg)	FD (cm)		
					L3/L4	L4/L5	L5/S1
Postacchini et al [28]	63 Italian	Adult	–	–	4.7 (0.4)	4.9 (0.4)	
	58 Indian				4.1 (0.4)	4.3 (0.4)	
Berry et al. [13]	30F + M	50 to 79	–	–	5.12 (0.56)	5.34 (0.44)	
Aharinejad et al. [16]	574 segments				5.25 (1.05)	5.45 (0.60)	
Panjabi et al. [27]	4F + 8M	46.3	167.8	67.8	4.66 (0.12)	4.73 (0.12)	
Zhou et al. [35]	71 Female	50	–	–	4.67 (0.47)	5.04 (0.44)	
	55 Male	49	–	–	5.08 (0.37)	5.45 (0.49)	
	126 F + M				4.85 (0.47)	5.22 (0.51)	
Tan et al. [30]	10	65.7	166	61.6	4.20 (0.02)	4.16 (0.03)	
van der Houwen et al. [15]	31 Female	49.8	–	–	3.77	3.81	
	46 Male	49.8	–	–	4.24	4.39	
Kang et al. [23] (2011, caliper/X-ray/CT, healthy)	15 Female	41	161.2	53.4	4.38 (0.33)	4.97 (0.46)	
	35 Male	39.8	170.6	70.5	4.81 (0.34)	5.48 (0.43)	

Table 7 continued

Authors	Subjects	Age (yrs)	Ht (cm)	Wt (kg)	FD (cm)		
					L3/L4	L4/L5	L5/S1
Wang et al. [34]	149 Male	under 64	—	—	5.36 (0.37)	5.23 (0.47)	
Tang [31]	55 Female	30.11	165.72	74.65	4.85 (0.32)	5.01 (0.31)	4.96 (0.39)
	52 Male	30.59	178.33	87.43	5.26 (0.33)	5.44 (0.36)	5.42 (0.41)
	107 F + M	30.35	171.79	80.98	5.05 (0.38)	5.21 (0.40)	5.19 (0.46)

Fig. 8 Comparison to CSA data reported in the literature



For lower lumbar EPs (Tables 6, 7), previous studies have described the planar aspects of both adjacent EPs [1, 27, 29, 34] or the CrEPs only [35, 37], and for the linear aspects of both EPs [13, 15, 26, 27, 34, 35], the CrEPs [17, 18, 33], or the CaEPs [16, 28]. Previous attempts to describe both linear and planar aspects, unfortunately, failed to include both genders and describe the CaEP of the L5/S1 disc [27, 34].

The present sample had generally smaller CSAs of the lower lumbar IVDs and EPs (Fig. 8). Larger dimensions were more frequently associated with older IVDs [1, 38, 41], compared to the younger ones [29, 42], suggesting that the aging process may be associated with the increase in disc size such as osteoporosis [65]. It should be noted that Brinckmann [1] measured the endplate area after the completion of an ultimate compressive strength test, which may also alter its geometric characteristics. With respect to the linear aspects, our results appear consistent with other studies (Figs. 9, 10), located close to the overall average of all existing data. Extreme data reported in the literature may be attributed to small sample size

[21] and magnification error [17, 18]. It was noted that subject demographic data have not always been well documented, particularly missing height and weight data, which prevents further comparison with respect to the influencing factors of spinal geometry. Overall, while our results tend to be slightly smaller in planar dimensions and similar in linear dimensions compared to previous studies, differences in subjects and measurement protocols explain much of these differences. In fact, the current protocol was designed to overcome limitations associated with these previous studies by including larger samples of younger subjects in vivo and employing reliable and repeatable measurement methods.

One study limitation is that all MRI scans were collected from a medical database. Although they were scrutinized to exclude patients with obvious spinal abnormalities, pathological diseases and severe disc degeneration that might alter the spinal geometry, the present sample may not be good representation of a healthy population. Some studies has provided evidence indicating the positive

Fig. 9 Comparison to APD/MSD data reported in the literature

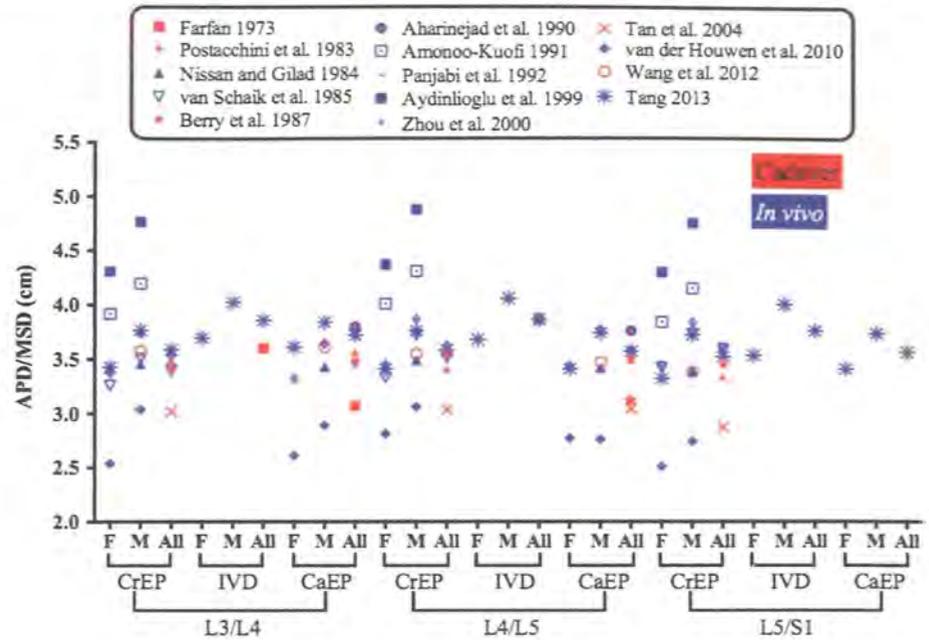
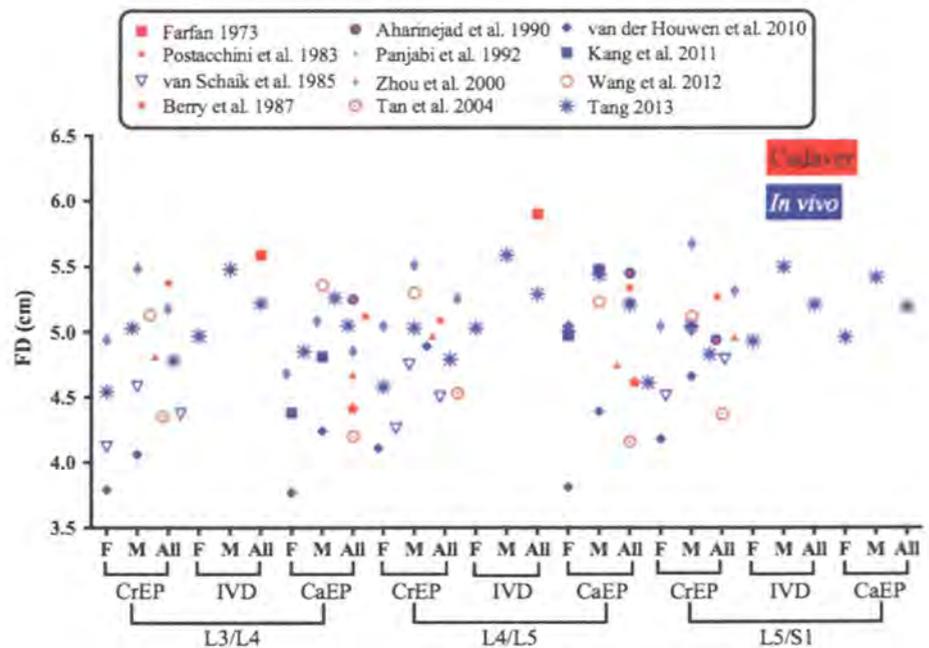


Fig. 10 Comparison to FD data reported in the literature



correlation between the disc degeneration and the vertebral endplate changes or defects [66–68]. Secondly, all MRI scans were taken in a supine position with minimal loading on the lower lumbar spine. Spinal morphometric characteristics in the transverse section may change while the subject is in a standing posture. Although some evidence was reported [69, 70], there has been very little research regarding the changes to spinal geometry caused by spinal loading.

In conclusion, this study establishes a standardized measurement protocol for lower lumbar morphometry to

address limitations of previous studies and provides valuable geometric data regarding the planar and linear aspects, which has been lacking in the literature. This study also compiles and summarizes previous morphometric data regarding the lower lumbar IVDs and EPs. The relatively large sample provides good starting point for characterizing the spinal morphometry of the general US population. The influence of gender was significant. Significant craniocaudal changes, which sometimes appeared to be interacting with gender, were also noted. As described above, this study suggests that the

development of artificial IVD implants should consider the variability of human spinal morphology. Future research should incorporate larger sample sizes with greater variation in age, weight, height, and disc degeneration status and investigate their associations with the lower lumbar morphometry.

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Compliance with ethical standards

Conflict of interest None of the authors has any potential conflict of interest.

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