A Morphometric Study of Human Lumbar and Selected Thoracic Vertebrae

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The results of a morphometric study of selected human vertebrae undertaken to provide data for implant design are presented in this report. Twenty-seven dimensions were measured from thoracic (T2, T7, T12) and lumbar (L1–L5) vertebrae using prepared spinal columns from 30 skeletons belonging to the Hamann-Todd Osteological Collection. Maximum and minimum pedicle dimensions indicated that the pedicles are less symmetric cephalad than they are caudal. Vertebral body height increases caudally except posteriorly where, after an initial increase, it decreases in the lower lumbar region. Major and minor body diameters and the major spinal canal diameter slightly increase caudally, whereas minor spinal canal diameter exhibits little or no change. [Key words: vertebral morphometry, pedicle dimensions, implant design]

ACCURATE ANATOMIC DESCRIPTIONS of vertebral shape are necessary for the development of implantable devices and spinal instrumentation. The authors' interest in spinal implants and fixation devices resulted in a need for more detailed morphologic and anthropometric data on the vertebrae than could be found in the existing literature.

Several previous studies have investigated the morphometry of the vertebrae but through differing experimental techniques such as direct measurements, roentgenography with plain films, and CT scans.[2,3,5,7,8,10,11,14] The studies also varied with regard to the anatomic structure of interest. Whereas some were strictly concerned with the morphometry of the vertebral body,[2,3,7,8,10,11] others concentrated on the dimensions of the spinal canal,[1–3,5,8,11] transverse process,[14] and pedicle.[6,9,12,14,16] Additional measurements receiving scrutiny include interpedicular distance[4,11] and the angle between the facet joints and lamina.[15] Nissan et al performed a multifaceted analysis which, in addition to body shape, described vertebral length, the spinous process, disc size, and the distance between spinal processes in the intact spine.[10] All of the above-mentioned studies examined lumbar vertebrae, and some studied selected cervical[1,4,5,7,10,14] and thoracic[6,9,12,13,16] vertebrae as well.

The current study was undertaken due to a lack of information needed for design projects involving instrumentation for the lumbar and thoracic vertebrae. Direct measurements were made of 27 vertebral dimensions from prepared skeletal components. Radiographs of cadaver specimens were also used to determine the cross-sectional dimensions of the pedicles. Even though some of the measurements duplicate previous studies, they are included for comparative purposes, inasmuch as experimental techniques vary between investigators. Additionally, a wide variability has been reported between demographic groups.[11]

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MATERIALS AND METHODS

Direct dimensional measurements were obtained from contemporary human skeletons belonging to one of the most extensive skeletal collections in the world, the Hamann-Todd Osteological Collection at the Cleveland Museum of Natural History in Cleveland, Ohio, which houses more than 3,000 skeletons with accompanying autopsy reports. In some instances medical histories are also available.

Vernier and outside dimension calipers were used to measure the bone geometry (precision: .1 mm). Angular measurements were taken with a goniometer (precision: 1°). For the sake of consistency, all measurements were taken by the same observer. The lumbar (L1–L5) and three thoracic (T2, T7, T12) vertebrae of randomly selected normal Caucasian male and female skeletons were studied. The sample population consisted of five men and five women from each of the fifth through seventh decades of life for a total of 30 skeletons, or 240 vertebrae. Skeletons having gross evidence of congenital or acquired vertebral pathology and/or written documentation (autopsy report) of bone abnormalities such as tumors, fractures, or arthritis were excluded from this study.

With present and future applications in mind, virtually the entire geometry of the vertebrae was quantified by recording a total of 27 measurements per vertebra. Complete descriptions of the measured parameters are presented in Figures 1–3. Three of these measurements (the angle between the pedicle and the body, the cross-sectional dimensions of the pedicle, and the distance through the pedicle and body) primarily pertain to pedicle screw fixation and are reported in greater detail elsewhere.[9]

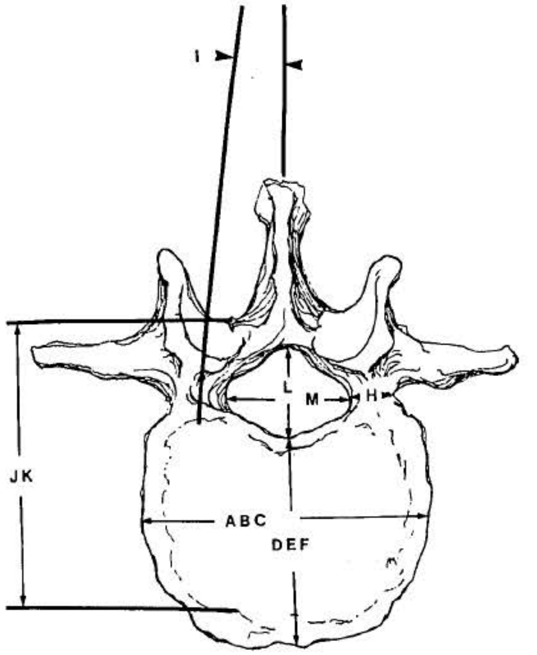

Fig 1. Description of vertebral measurements taken from the superior–inferior aspect. Major body diameter was measured along a frontal line bisecting the vertebral body and spinous process, (A) at the most superior level, (B) at the midline, and (C) at the most inferior level. Minor body diameter was measured along the midsagittal plane, (D) at the most superior level, (E) at the midline, and (F) at the most inferior level. Minor (H) dimensions of the right and left pedicles were measured regardless of orientation. Pedicle angle (I) was defined as the angle formed between the midsagittal plane and the plane bisecting the pedicle. Pedicular screw path lengths through the pedicle's center into the body to a point at the anterior border of the body's center were measured by two different approaches: (J) a straight path parallel to the midline bisector of the pedicle and (K) an oblique path representing the largest permissible deviation from this line. Minor spinal canal diameter (L) was measured along the midsagittal plane. Major spinal canal diameter (M) was measured along the frontal plane passing through the canal's midpoint.

RESULTS

The means and standard deviations of the dimensional data for all 240 vertebrae are presented in Table 1. To narrow the scope of the article, and simplify presentation of the results, the data for the males and females at all ages have been combined. Note that even with this simplification the data remain consistent, with the coefficients of variation being generally less than 10%.

The average maximum and minimum pedicle dimensions for the entire population are presented in Figure 4. Maximum and minimum dimensions were obtained for two pedicles per body, thus the data in Figure 4 represent both the right and left pedicle for each vertebra. The relative differences between the maximum and minimum dimensions demonstrate that the pedicles are less symmetric cephalad and become more so caudad. The minimum dimensions correlate well with those reported in other recent studies.[13,16]

A consistent trend is seen between vertebral body height and level (Figure 5). Three of four dimensions (anterior, posterior, right, and left height) increase progressively from T2 to L5. The posterior measurement levels off and then slightly decreases in the lumbar region. This is probably due in part to the lumbar curvature between L4 and S1. The data are in agreement with Nissan et al.[10] However, Postacchini et al[11] reported a single height measurement which did not reflect the decrease.

Major and minor body diameters were also plotted as a function of level (Figure 6). With the exception of the major diameter at T7, both dimensions exhibit slight increases caudally. Several other authors have reported similar findings[2,3,8,11,14] although only lumbar vertebrae were measured.

The dimensions of the spinal canal were also correlated to vertebral level (Figure 7). As with body height, the major spinal canal diameter increased caudally, with the exception of T7. Minor diameter showed little or no change between T2 and L5. Postacchini et al[11] and Eisenstein et al[2] reported similar data.

The anterior, posterior, right, and left body heights of all the vertebrae were averaged, and the total for each spinal column was plotted against the body height measured at autopsy. No correlation was found ($r^2 = .006$). No attempt was made to relate weight to

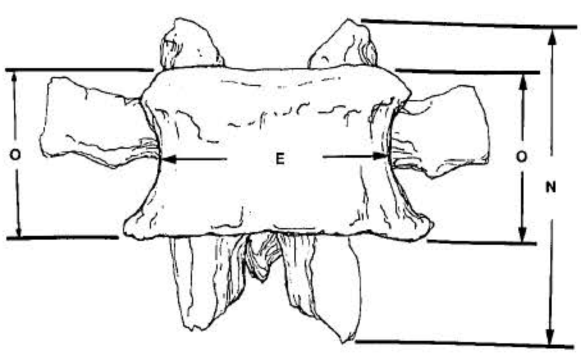

Fig 2. Description of vertebral measurements taken from the posterior–anterior view of the vertebrae. Height of the vertebrae was measured from the most superior aspect of the superior articular process to the most inferior aspect of the inferior articular process (N). Body height was measured along the frontal plane through the widest part of the body at the left and right lateral borders (O). The midline (E) major body diameter was measured along the frontal plane.

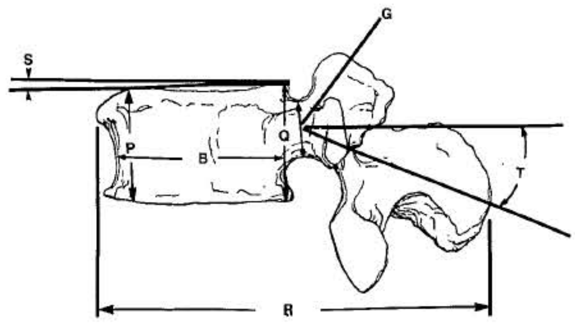

Fig 3. Description of vertebral measurements taken from the sagittal view of the vertebrae. Body height was measured along the midsagittal plane, (P) anteriorly and (Q) posteriorly. Length of the vertebrae was measured from the most anterior aspect of the body to the most posterior aspect of the spinous process (R). Body descent angle was defined as the angle between the superior surface of the body and a plane parallel to the inferior surface (S). Angle of declination of the spinous process was defined as the angle between the plane bisecting the spinous process and the plane parallel to the body's inferior surface (T). Major dimensions (G) of the right and left pedicles were measured regardless of orientation. The midline (B) minor body diameter was measured a sagittal line bisecting the vertebral body and spinous process.

Table 1. Mean and Standard Deviations for a Total of 240 Vertebrae, 30 at Each Level

Measurement	*T2*	*T7*	*T12*	*L1*	*L2*	*L3*	*L4*	*L5*
A	29.8 ± 2.4	31. ± 2.8	43.8 ± 3.3	45.2 ± 4.6	47.7 ± 4.7	49.6 ± 3.2	51.2 ± 5.6	53.4 ± 4.4
B	28.1 ± 2.5	28.0 ± 2.9	37.6 ± 3.2	39.5 ± 3.8	44.8 ± 3.1	42.3 ± 3.5	40.8 ± 3.2	46.1 ± 4.5
C	33.5 ± 2.9	33.2 ± 3.2	46.8 ± 3.8	49.1 ± 3.7	54.8 ± 4.8	53.8 ± 3.7	50.9 ± 4.6	52.7 ± 4.3
D	18.1 ± 1.5	27.0 ± 3.3	31.7 ± 4.4	31.9 ± 3.7	33.3 ± 3.7	33.9 ± 3.3	34.9 ± 3.4	35.1 ± 2.8
E	17.5 ± 1.7	26.1 ± 3.2	29.2 ± 3.4	28.9 ± 3.5	29.9 ± 3.3	31.6 ± 3.3	32.5 ± 2.9	32.4 ± 2.8
F	19.0 ± 1.6	28.0 ± 3.6	31.2 ± 3.9	32.3 ± 3.5	33.4 ± 3.4	34.2 ± 3.3	35.6 ± 3.1	34.5 ± 3.0
G								
Right	11.7 ± 1.2	12.1 ± 1.0	17.2 ± 1.6	15.6 ± 1.4	15.4 ± 1.0	14.6 ± 1.2	13.0 ± 1.3	13.8 ± 2.5
Left	11.9 ± 1.3	11.9 ± 1.0	17.0 ± 1.3	15.6 ± 1.5	15.2 ± 1.0	14.3 ± 1.0	13.2 ± 1.4	13.6 ± 2.8
H								
Right	6.1 ± 1.2	5.1 ± 1.4	7.7 ± 2.1	7.0 ± 1.9	7.4 ± 1.6	9.2 ± 1.3	10.3 ± 1.6	10.9 ± 3.4
Left	6.3 ± 1.0	4.8 ± 1.4	7.6 ± 1.5	6.9 ± 1.7	7.5 ± 1.5	9.1 ± 1.6	10.4 ± 1.6	10.5 ± 2.9
I								
Right	23 ± 6	8 ± 4	−5 ± 8	6 ± 8	11 ± 3	14 ± 4	20 ± 5	32 ± 5
Left	23 ± 6	7 ± 5	−1 ± 10	9 ± 7	12 ± 3	14 ± 4	20 ± 4	31 ± 5
J								
Right	26.4 ± 2.4	36.2 ± 3.2	38.8 ± 3.8	42.1 ± 3.8	45.2 ± 3.8	45.0 ± 3.3	44.0 ± 2.9	40.8 ± 3.2
Left	27.1 ± 2.0	36.3 ± 4.2	38.8 ± 3.8	40.2 ± 3.4	46.5 ± 3.5	45.7 ± 3.7	45.6 ± 3.9	40.3 ± 4.0
K								
Right	30.3 ± 2.3	40.7 ± 3.2	44.0 ± 5.0	47.5 ± 4.4	50.5 ± 4.0	49.0 ± 3.5	49.5 ± 3.2	47.8 ± 3.5
Left	32.1 ± 2.0	42.0 ± 4.0	46.9 ± 4.9	49.8 ± 3.7	53.1 ± 3.8	52.0 ± 3.5	53.2 ± 3.8	50.9 ± 4.3
L	15.0 ± 1.3	16.6 ± 5.0	17.2 ± 1.9	17.2 ± 1.3	16.0 ± 2.6	16.2 ± 2.6	16.1 ± 1.5	17.3 ± 2.9
M	18.3 ± 1.5	17.1 ± 5.1	20.2 ± 2.3	22.1 ± 2.3	23.0 ± 2.3	22.7 ± 1.7	22.0 ± 1.8	26.0 ± 2.5
N								
Right	31.6 ± 2.0	34.0 ± 5.1	45.5 ± 2.8	47.6 ± 3.7	45.2 ± 3.6	48.0 ± 3.2	48.5 ± 2.7	41.5 ± 4.4
Left	31.7 ± 2.0	33.0 ± 5.6	45.2 ± 2.9	47.3 ± 3.7	44.8 ± 4.6	48.6 ± 3.3	49.1 ± 3.5	42.2 ± 3.7
O								
Right	17.9 ± 1.4	19.9 ± 1.8	24.2 ± 1.7	25.6 ± 1.6	27.3 ± 1.5	26.5 ± 1.7	25.7 ± 1.3	27.0 ± 1.8
Left	17.7 ± 1.2	20.2 ± 3.5	23.9 ± 1.5	24.9 ± 1.6	27.7 ± 1.8	26.5 ± 1.7	25.7 ± 1.3	27.0 ± 1.7
P	17.6 ± 1.2	18.7 ± 2.8	23.4 ± 2.0	25.0 ± 2.9	27.9 ± 1.9	27.4 ± 1.7	26.7 ± 1.5	28.7 ± 1.9
Q	16.5 ± 1.2	19.1 ± 1.8	24.8 ± 1.8	25.8 ± 2.1	25.2 ± 2.2	26.0 ± 1.6	26.4 ± 1.7	23.1 ± 1.5
R	64.1 ± 4.6	63.9 ± 8.6	73.4 ± 11.0	79.9 ± 6.3	85.0 ± 5.8	85.6 ± 6.0	83.4 ± 5.5	74.1 ± 15.3
S	136 ± 21	110 ± 30	20 ± 7	21 ± 19	14 ± 3	17 ± 5	14 ± 4	20 ± 6
T	137 ± 21	110 ± 31	20 ± 7	18 ± 6	14 ± 4	17 ± 5	14 ± 3	20 ± 6

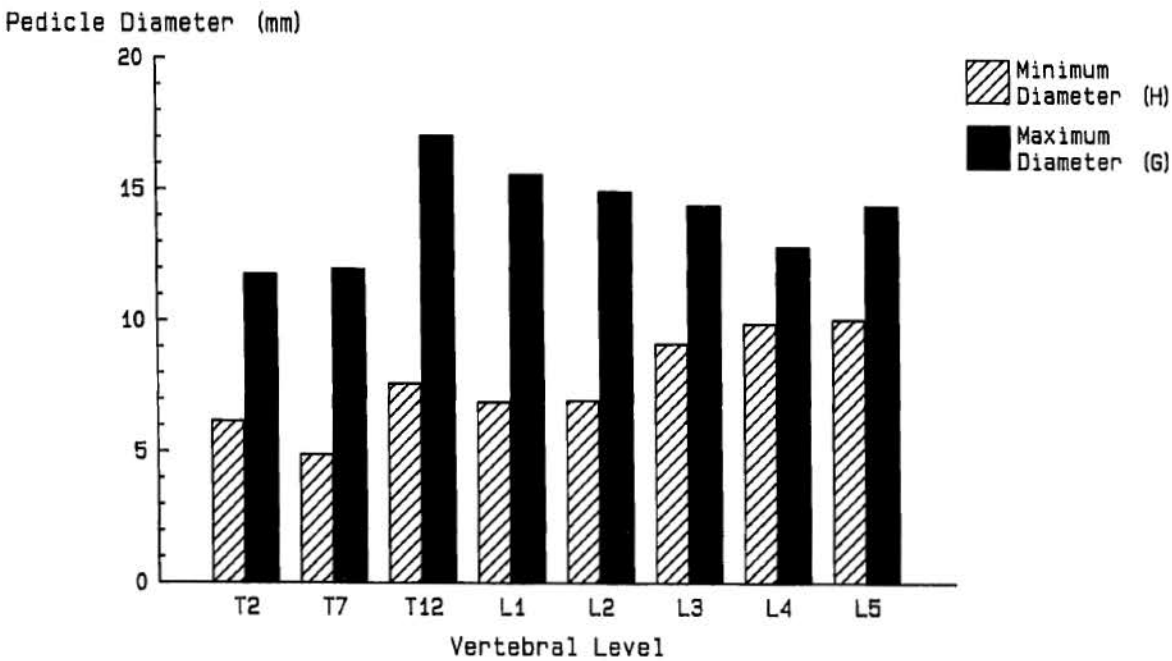

Fig 4. Minor (H) and major (G) pedicle diameters, means of 15 each males and females, fifth through seventh decades.

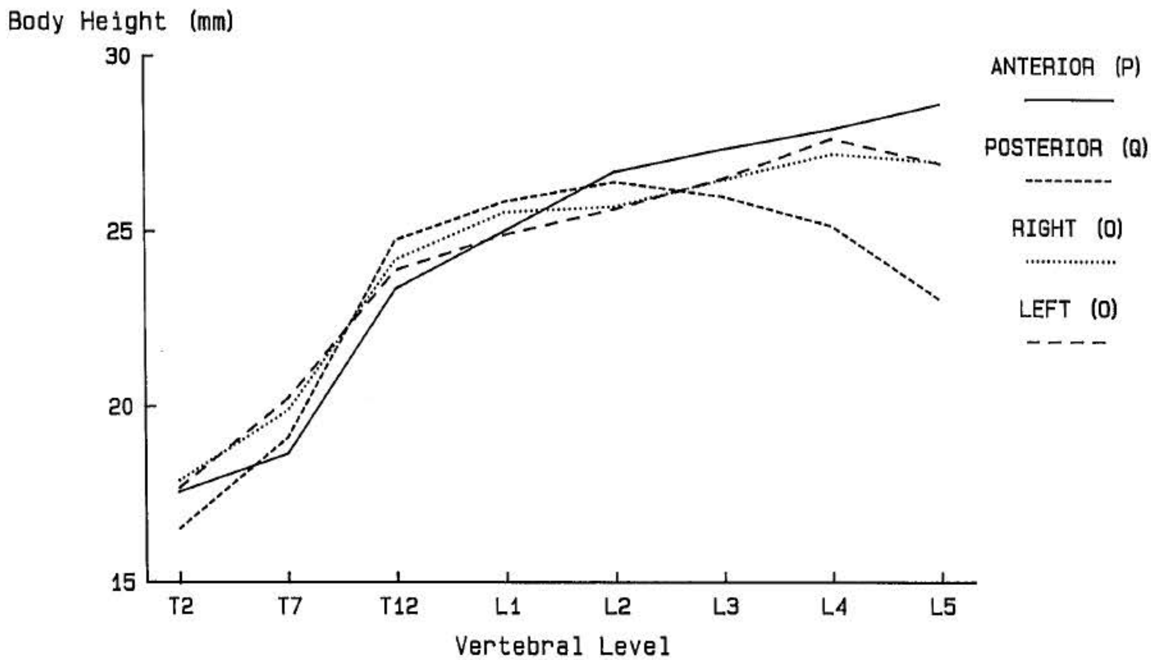

Fig 5. Body height (O,P,Q) versus vertebral level, combined data for all specimens studies.

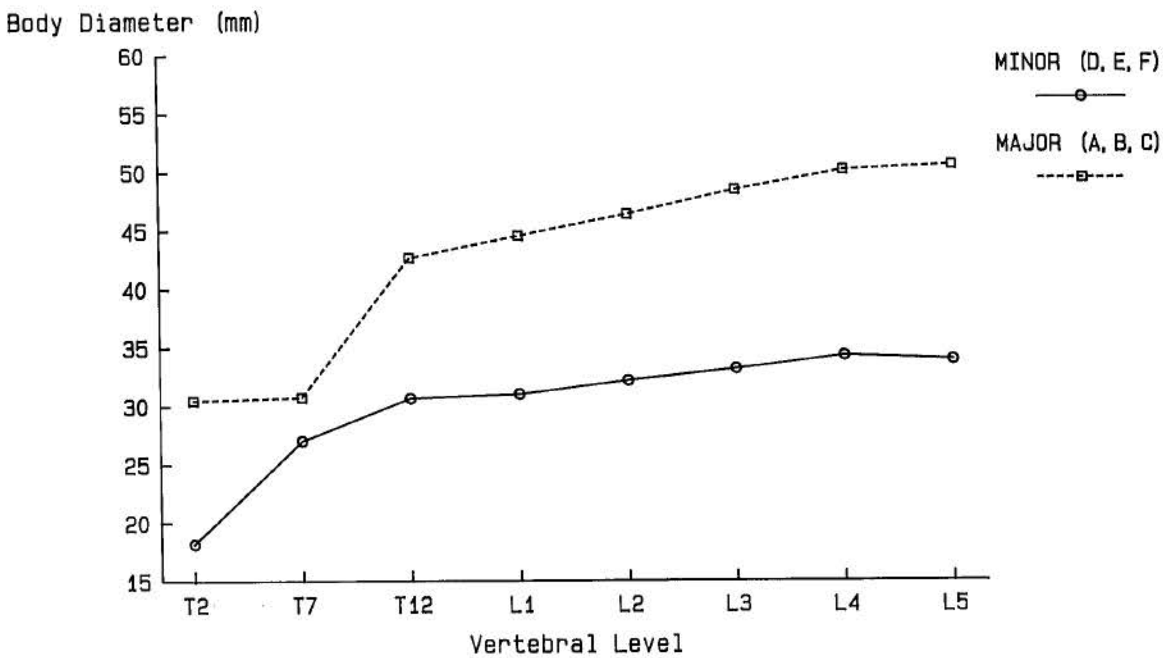

Fig 6. Body diameter versus vertebral level. Points represent means of superior (A,D), midline (B,E) and inferior (C,F) measurements for all specimens studied.

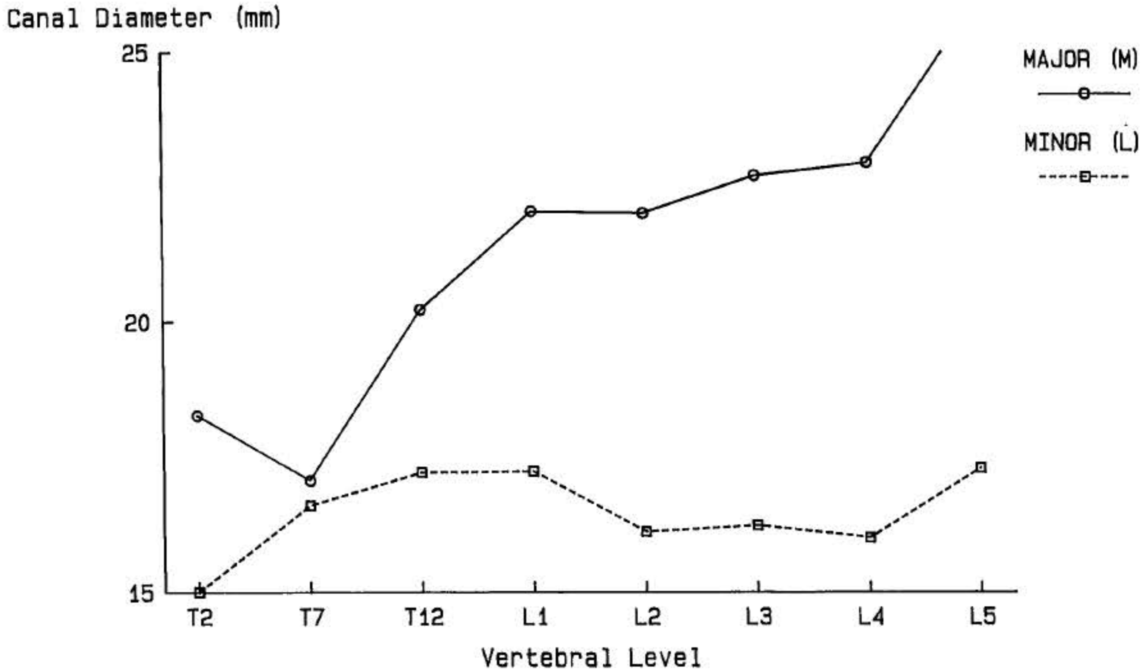

Fig 7. Major (M) and minor (L) spinal canal diameters versus vertebral level, combined data for all specimens studied.

cross-sectional dimensions, since many of the weights at autopsy appeared low relative to the height. This was possibly indicative of dehydration or decomposition of the cadaver or perhaps malnutrition during life.

DISCUSSION

The overall goal of this study was to generate information that would be useful for geometric modeling of the vertebrae. Such information has numerous potential applications. Biomechanical and ergonomic analyses of the spine frequently have need of spinal dimensions as input. Although specific requirements vary, it is hoped that these data on spinal morphometry are general enough to be useful to a variety of studies.

The authors' immediate need was in the design of spinal instrumentation. The application to pedicle screw fixation is outlined elsewhere,[9] and a total vertebra replacement has also been designed. For the one total vertebra that has been implanted, the data were used only to double check dimensions scaled from computed tomography (CT) scans. Agreement between the patient's CT data, average skeletal data, and one skeleton whose living dimensions closely matched the patient's own size, was extremely good. The artificial vertebra could thus be made to duplicate the geometry of the replaced vertebra. In instances where destruction of the vertebra is more extensive, due to trauma or gross invasion by a tumor, the data will be necessary for sizing the replacement and reconstructing normal alignment.

Through comparison of the results with other studies of spine geometry that have used CT scanning, and our own CT work for vertebral replacement, it is apparent that CT scanning can be a useful tool for evaluating spinal geometry *in vivo*. However, proper care must be exercised in regard to factors such as slice thickness, scan diameter, calibration standards, and orientation of the scanning plane relative to the anatomic structure of interest. The current data might also be applied to the detection of anatomic abnormalities by comparison of CT scans with the population averages.

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