In Vivo Measurement of Vertebral Endplate Surface Area in the Whole Spine

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Introduction: Measurement of the endplate surface area provides baseline information to be used for estimation of stress in intervertebral discs, estimation of disc volume and determination of size of spinal implants in addition to anthropological studies. Due to the complex 3D endplate geometry, 3D models are necessary for accurate measurement of the endplate surface area. The objective of this study was to contribute with baseline geometric information from a cohort of spine patients using subject-based 3D CT models.

Methods: This IRB-approved study was conducted on 26 patients (13 male, 13 female; range 22-76 years, average age 56.6 years old). The patients received whole-spine myelography CT imaging and were diagnosed with lumbar disc herniation (n = 7), lumbar spinal canal stenosis (n = 15), low back pain (n = 1) and cervical spondylosis (n = 2), respectively. CT images were reconstructed using a commercial 3D reconstruction software package. Both superior and inferior endplates were segmented from each vertebra, enabling thus the creation of 3D surface mesh models of the superior and inferior (relative to each vertebral body) endplates. A total of 1,248 endplate models were created from 624 vertebral bodies from C2 through S1. The area of each endplate was calculated by summation of individual surface area mesh elements that were part of the endplate model. From the point-cloud data set of each endplate model, the centroid was also calculated in order to determine the cranio-caudal distances between the centroid of S1 and all endplates above it. Individual vertebral body heights were determined by the distances between centroids of superior and inferior endplates within the vertebral body. Similarly, disc heights were determined by the distances between the centroid of inferior endplate in the cranial vertebral body and the centroid of the superior endplate of the caudal vertebral body. Cumulative distances of the vertebral body heights and disc heights from the centroid of S1 endplate were calculated. Gender effects were compared with unpaired t-tests. Level effects were sought with ANOVA. The superior vs. inferior endplate areas for each vertebral body and the superior vs. inferior endplate areas for each intervertebral disc were compared with paired t-tests. Linear correlation between the endplate area vs. the cranio-caudal height or the cumulative distance in reference to S1 endplate was analyzed. Results are presented as mean ± SD.

Results: The endplate areas were larger in males on both the superior and inferior endplates at all levels except S1 (p<0.016). In males, the maximum area was found at the inferior endplate of L4 and the minimum area was at the superior endplate of C3. In females, the maximum area was at the superior endplate of L5 and the minimum area was at superior endplate of C3. The superior area increased from C3 through C6, decreased from C6 through T1, and increased again from T1 through L5. In the inferior areas, the maximum and minimum areas were found at L4 and C3, respectively. The inferior area increased from C3 through C5, decreased from C5 through C7, increased C7 through L4 and decreased at
L5 (Fig.2). The inferior endplate areas were higher as compared with the superior endplate area within the same vertebral body at C5, T1 through L1 and L4, but lower at C6 and C7 (Fig. 2). Within the disc, the areas of the inferior endplate of the cranial vertebral body (cranial endplate for the disc) were higher as compared with the areas of the superior endplate of the caudal vertebral body (caudal endplate for the disc) at T1/T2, T2/T3, T3/T4, T4/T5 and T6/T7 discs, while lower at C4/C5, C6/C7, C7/T1, T10/T11, T12/L1 and L2/L3 (Fig. 2). Strong linear correlations were found between the endplate area vs. the cranio-caudal height from the S1 endplate both in male and female with R2 values of 0.841 and 0.827, respectively. Similarly, strong linear correlations were found between the endplate area vs. the commutative distance from the S1 endplate both in male and female with R2 values of 0.842 and 0.824, respectively.

Discussion: Although other anthropological studies report linear dimensions for the vertebrae using cadaveric specimens [1-3], this study is the first to measure in-vivo surface-areas of the bony endplates in the entire human spine. The results of the present study showed gender differences at all levels but S1. Overall, the endplate surface area increased with each successive lower spinal level. This finding may be due to larger body mass in humans and more muscle force seen in the lower spinal levels. The present study used two different parameters describing the distance from S1; the vertical distance in the standing position and the distance along the center of the spinal column. Although equivalent results were obtained by using these parameters in the present study, the latter distance may be more appropriate due to less effects of the posture during imaging and spinal deformities such as hyper lordosis, kyphosis and scoliosis, and more importantly, when the results are compared with those in quadrupeds. The increased endplate area with each successive lower spinal level is expected to be caused by a larger inferior endplate within each vertebral body or larger endplate area in the caudal side within each disc. However, the results of the comparison between the superior and inferior endplate within the vertebral body or within the disc, especially in the thoracic spines, did not support this theory. A morphological study of the lumbar endplates reported that cranial endplates relative to the disc (inferior endplate of the vertebral body in the present study) showed concave geometry while caudal endplates (superior endplate of the vertebral body in the present study) were flat [1]. Since the present study measures surface geometry of the endplate in 3D, the endplate area in the present study appears to be larger than the cross sectional area in the concave shape endplate. Future studies will compare differences between the surface area and the projected area.

Significance: Information on the endplate area is essential for design of spine devices such as artificial discs and interbody devices, as well as related preoperative planning of spinal surgery.
Fig. 1 Whole-spine 3D model and endplate surface model.
Fig. 2  Endplate area by spinal level and anatomical position (superior or inferior). *; Inferior > superior within a vertebral body (p<0.05), **; Inferior < superior within a vertebral body (p<0.05), #; Inferior of cranial vertebral body > superior of caudal vertebral body (p<0.05), ##; Inferior of cranial vertebral body < superior of caudal vertebral body (p<0.05) (mean ± SD).

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