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Pedicle Screws Challenged: Lumbar Cortical Density and Thickness Are Greater in the Posterior Elements Than in the Pedicles

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Abstract

Study Design: Controlled laboratory study.

Objective: To measure the total bone mineral density (BMD), cortical volume, and cortical thickness in seven different anatomical regions of the lumbar spine.

Methods: Using computed tomography (CT) images, 3 cadaveric spines were digitally isolated by applying filters for cortical and cancellous bone. Each spine model was separated into 5 lumbar vertebrae, followed by segmentation of each vertebra into 7 anatomical regions of interest using 3-dimensional software modeling. The average Hounsfield units (HU) was determined for each region and converted to BMD with calibration phantoms of known BMD. These BMD measurements were further analyzed by the total volume, cortical volume, and cancellous volume. The cortical thickness was also measured. A similar analysis was performed by vertebral segment. St Mary's Medical Center's Institutional Review Board approved this study. No external funding was received for this work.

Results: The lamina and inferior articular process contained the highest total BMD, thickest cortical shell, and largest percent volumes of cortical bone. The vertebral body demonstrated the lowest BMD. The BMDs of the L4 and L5 segments were lower; however, there were no statistically significant differences in BMD between the L1-L5 vertebral segments.

Conclusion: Extrapedicular regions of the lumbar vertebrae, including the lamina and inferior articular process, contain denser bone than the pedicles. Since screw pullout strength relies greatly on bone density, the lamina and inferior articular processes may offer stronger fixation of the lumbar spine.

Keywords

selective densitometry, spinolaminar plate, cortical thickness, lumbar spine, bone mineral density, extrapedicular fixation.

Introduction

Pedicle screw fixation is currently the preferred method of posterior thoracolumbar fixation for a variety of pathologies, ranging from spine degeneration, deformity, instability, neoplasms, infections and trauma.[1] Pedicle screw loosening is a known complication of posterior spinal fusion and can lead to suboptimal outcomes, including the need for reoperation.[2] Related fixation failures may include screw bending and breakage.[3] While many factors contribute to screw loosening such as stress shielding[4] and toggling,[3,5] low bone mineral density (BMD) is a major risk factor for spine construct failure.[5-8] Although most studies report low rates of pedicle screw loosening in nonosteoporotic patients,[2,9-11] this complication may occur in up to 10% to 25% of osteoporotic patients undergoing traditional pedicle screw fixation.[12,13]

Although pedicle screw fixation is most commonly used, other regions of the lumbar vertebrae possess greater bone

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density and may be better zones for posterior spinal instrumentation.[14] However, few studies have been published on the bone quality of anatomical regions within the lumbar spine. In a study comparing traditional pedicle and cortical screws, Mai et al[16] found that the BMD along the cortical screw trajectory was significantly higher in both nonosteoporotic and osteoporotic patients. The difference in bone density between the 2 trajectories was even greater for patients with osteoporosis than for those without osteoporosis. In a similar study comparing 7 predefined regions of the lumbar spine in nonosteoporotic cadaveric specimen, Hohn et al[14] reported that the lamina and inferior articular processes have significantly higher BMD than the pedicles and other vertebral regions.

While Hohn et al[14] found the posterior elements to exhibit high total BMD, they do not report other indicators of bone quality such as cortical volume, cortical thickness, and cortical-cancellous bone ratios. BMD may only explain 60% to 70% of the variability in bone strength, while the remaining bone strength is determined by other factors such as the bone geometry, cortical thickness and porosity, and trabecular bone morphology.[15] In addition, Hohn et al[14] were unable to detect any differences between the extrapedicular regions requiring a more granular comparison. Since cancellous bone is more affected by osteoporosis,[17] anatomical regions of the lumbar spine with a high cortical-cancellous bone ratio may represent ideal sites for extrapedicular fixation in osteoporotic patients. It remains unclear whether this ratio differs among the posterior elements. In addition, previous studies suggest that regional alterations to trabecular architecture influence the biomechanics of the vertebral body with little effect on overall bone density.[18,19] Therefore, it is possible that variations in cortical BMD, cancellous BMD, and cortical-cancellous bone ratio also exist among the posterior elements despite their similarity in average total BMD. Furthermore, previous research suggests that loads applied to the lumbar spine differ according to vertebral segment.[20] Yet few studies have investigated vertebral segment-specific differences in BMD within the lumbar spine.[21,22]

The goal of this study was to measure and compare the bone quality of 7 different anatomical regions (and potential fixation sites) in each of the 5 vertebrae of the lumbar spine. We investigated the bone quality of these regions by assessing the average total bone BMD, cortical BMD, cancellous BMD, cortical-to-cancellous bone ratio, cortical volume, and cortical thickness using computed tomography (CT) imaging and 3-dimensional software modeling. Our second aim was to compare the total BMD, cortical BMD, and cancellous BMD by vertebral segment (L1-L5). A greater understanding of bone quality may be useful when developing new fixation strategies to reduce the risk of screw loosening, pullout, and construct failure.

Methods

Study Specimens and CT Imaging

Three cadaveric spinal columns were imaged and analyzed for the present study (2 males, 1 female, age 35, 70, and 90 years).

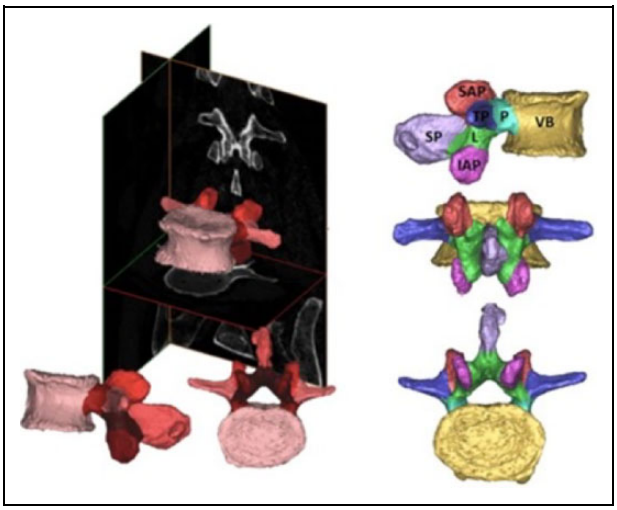

Figure 1. Images depicting the data collection process, including the conversion of computed tomography (CT) scans to engineering solid models. The 2-dimensional images (left) are segmented from a series of CT images to define volumes. Each vertebra was divided into 7 regions (right) followed by further segmentation of cancellous and cortical bone within each anatomic volume. SAP, superior articular process; IAP, inferior articular process; L, lamina; P, pedicle; SP, spinous process; TP, transverse process; VB, vertebral body.

All 5 lumbar vertebrae were analyzed from each for a total of 15 vertebrae. High-resolution helical CT scans were conducted on all specimens. All scans were performed on the same scanner (GE Lightspeed VCT) with the same imaging parameters (64-slice, 512 × 512 pixel resolution) to reduce interspecimen variability.

CT Image Segmentation

CT scans were postprocessed using commercial medical image processing software (Mimics; Materialise, Leuven, Belgium). The lumbar spine (L1-L5) was digitally isolated from surrounding tissue by applying a preset thresholding filter for adult bone to the CT scans. Using this thresholding as well as manual segmentation, the lumbar spine model was separated into 5 separate vertebrae, followed by segmentation of each vertebra into 7 predefined anatomic regions (Figure 1). When visible, suture lines were utilized as anatomic boundaries between vertebral regions. The right and left superior articular processes, inferior articular processes, laminae, pedicles, and transverse processes were also isolated using the Mimics software (Figure 2A). This resulted in 30 individual bone measurements for each of these anatomical regions (3 specimens × 5 vertebrae per specimen × 2 regions per vertebra) and 15 individual bone measurements for the spinous process and vertebral body (3 specimens × 5 vertebrae per specimen × 1 region per vertebra).

The same team member segmented each vertebral region to reduce interobserver variability. This team member segmented the L1-L5 transverse processes, pedicles, inferior articular processes, and superior articular processes twice from 2 of the

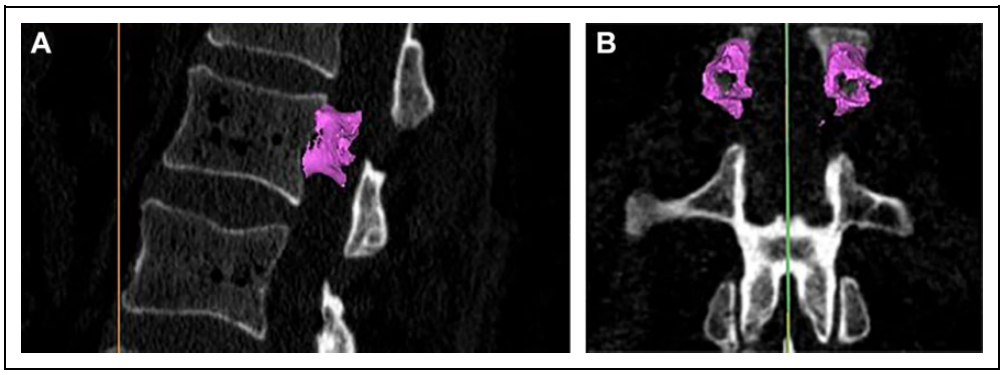

Figure 2. (A) Three-dimensional rendering of cortical bone within the pedicles of the L1 vertebra using (A) sagittal magnetic resonance images (MRI). Cortical and cancellous bone was separated by a filter algorithm provided by the segmentation software. (B) Three-dimensional rendering of cortical bone within the pedicles of the L1 vertebra using (B) coronal MRI. The methods used to determine cortical and cancellous bone mineral density (BMD) have been previously described in detail.[26,28]

study specimens to assess the inherent variability in the manual segmentation protocol. A previous study using this method of segmentation produced an average difference in BMD of 1.5% between the first and second measurements of the same anatomical region (SD $\pm$0.7%).[14] The largest percent discrepancy between the repeated measures was 3.0%.

Bone Density, Volume, and Thickness Measurements

Cortical and cancellous bone was separated by a filter algorithm provided by the segmentation software. The filter for cancellous bone included pixels with Hounsfield units (HU) between 200 and 450 HU. For cortical bone, the filter included pixels between 450 and 1400 HU. Average total, cortical, and cancellous BMD measurements of each anatomical region and from each vertebral segment (L1-L5) were recorded. A cortical-cancellous ratio was calculated as the mean cortical BMD divided by the mean cancellous BMD. The cortical bone, cancellous bone, and non-bone volumes were also assessed (Figure 2B). The nonbone volume reflects the porosity of the anatomical regions. The cortical wall thickness was measured using an algorithm provided by the segmentation software.[23]

Conversion From HU to BMD

Conversion from HU to BMD units (mg/cm^3) was performed in accordance with previously described guidelines.[24-27,29] In brief, HUs were converted to BMD through a calibration equation derived from CT scans of tissue surrogate materials (Electron Density Phantom, Model 62; CIRS) using the same scanning protocol that was used for all specimens. Specifically, "phantoms" of 200 and 800 mg/cm^3 were utilized to account for the known range of BMD in various anatomic locations.[24] These "phantom" blocks have been previously reported to produce reliable calibration formulas between HU and BMD and are not influenced by CT mode, slice thickness, reconstruction algorithm, or pitch factor.[24,29] The results of a previous HU to BMD analysis produced a linear calibration relationship of 1 mg/mL for every 0.78 HU.[14] Validation studies using this protocol report that the bone mineral content of vertebrae can be measured with an accuracy of 6% compared with ash weight gold standard.[26] Similar work by Cann and Genent[27] found no significant differences between direct measurement of calcium ash and CT measurements of BMD in the thoracic vertebrae.

Outcome Measures and Statistical Analysis

The primary outcome measures from densitometry were mean total, cortical, and cancellous BMD for each vertebral segment (L1-L5) and anatomical region. One-way analysis of variance was conducted to determine any significant differences in the cortical volume and cortical thickness of the vertebral regions, with $\alpha = .05$.

St Mary's Medical Center's Institutional Review Board approved this study. No external funding was received for this work.

Results

Densitometry by Anatomical Region

The BMDs for each anatomical region are displayed in Table 1. The mean total BMD of the lamina and inferior articular process were higher than the pedicles ($P = .042$ and $P = .059$, respectively). However, the difference in total BMD between the lamina and pedicle was greater in the 35-year-old specimen and less pronounced in the 70- and 90-year-old specimens, as demonstrated in Figure 3. The vertebral body demonstrated the lowest total BMD ($P < .05$ for all comparisons).

Mean BMD of the cortical bone alone was highest in the lamina, superior articular process, and inferior articular process. The vertebral body demonstrated a significantly lower cortical bone density compared to these anatomical regions ($P = .0054$, $P = .0002$, and $P = .0001$, respectively). The cortical densities of the lamina and articular processes were higher than the pedicles. Specifically, the cortical density of the inferior articular process was 11% higher; however, the difference was not statistically significant ($P = .057$). The

Table 1. Bone Density, Volume, and Thickness Results by Anatomical Region.[a]

Anatomical Region	Mean BMD Total (mg Ca^{2+}HA/mL)	Mean BMD Cortical (mg Ca^{2+}HA/mL)	Mean BMD Cancellous (mg Ca^{2+}HA/mL)	Cortical-Cancellous Ratio	Cortical Bone Volume (mL)	Cancellous Bone Volume (mL)	Nonbone Volume (mL)	Percent Cortical Bone (% by Volume)	Cortical Thickness (mm)
Inferior articular process	392.4 ± 98.4	533.4 ± 64.9	216.3 ± 9.4	2.5	1.4 ± 0.9	0.7 ± 0.9	0.3 ± 0.2	51 ± 18.3	1.18 ± 0.27
Lamina	396.2 ± 116.9	502.1 ± 79.1	206.9 ± 11.4	2.4	2.7 ± 1.7	1.3 ± 1.7	0.8 ± 0.3	52 ± 15.9	1.22 ± 0.19
Pedicle	305.5 ± 77.0	481.2 ± 70.7	204.6 ± 11.7	2.4	1.0 ± 0.6	0.9 ± 0.6	0.8 ± 0.4	36 ± 11.6	0.94 ± 0.16
Superior articular process	306.8 ± 79.2	519.9 ± 51.3	206.4 ± 7.3	2.5	1.5 ± 0.7	1.1 ± 0.7	0.6 ± 0.2	34 ± 13.9	0.94 ± 0.18
Spinous process	283.6 ± 74.5	477.9 ± 40.0	207.0 ± 8.5	2.3	2.0 ± 1.4	1.9 ± 1.4	1.1 ± 0.4	36 ± 13.6	1.04 ± 0.17
Transverse process	173.7 ± 61.8	478 ± 84.3	202.9 ± 12.7	2.3	0.5 ± 0.5	1.2 ± 0.5	1.5 ± 1.0	14 ± 11.1	0.68 ± 0.16
Vertebral body	147.2 ± 26.9	421.6 ± 69.8	189.9 ± 3.9	2.2	3.5 ± 2.3	11.2 ± 2.3	15.8 ± 4.2	10.9 ± 5.2	0.78 ± 0.15

Abbreviations: BMD, bone mineral density; Ca^{2+}HA, calcium hydroxyapatite.
[a]All data presented as mean ± standard deviation.

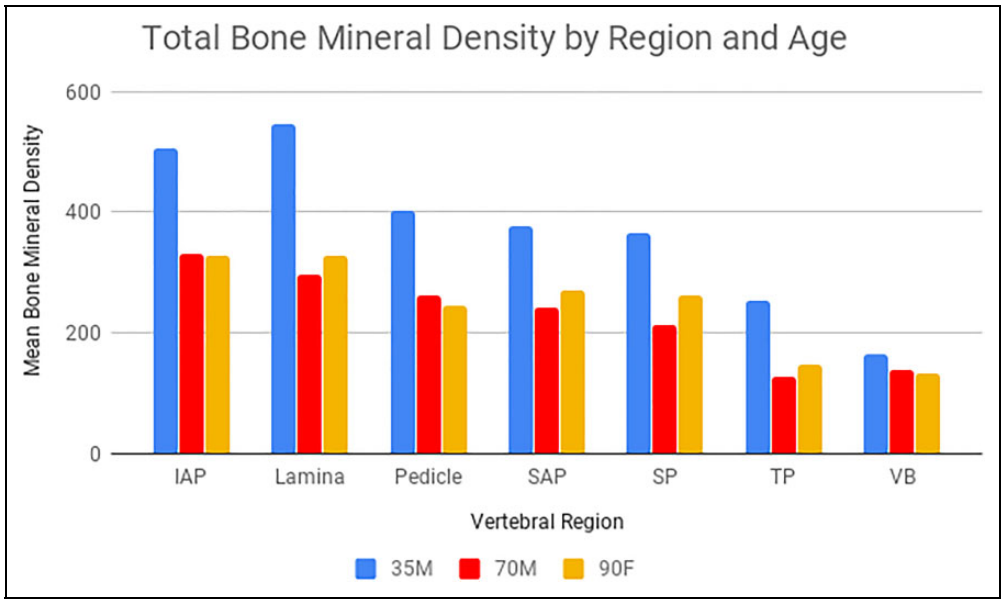

Figure 3. Mean bone mineral density (mg Ca^{2+}HA [calcium hydroxyapatite]/mL) of the vertebral regions for each specimen. The specimens are labeled with "M" for male or "F" for female, followed by 2-digit age. All data presented as mean ± standard deviation.

density of the cancellous bone in the inferior articular process was significantly higher than all other regions ($P < .05$ for all comparisons). However, the differences in cancellous BMD between the anatomical regions were relatively small. The highest cortical-cancellous ratios were found in the lamina and both articular processes. The only statistically significant difference between ratios was the superior articular process and the vertebral body ($P = .013$).

The bone densities, volumes, and thicknesses for each anatomical region are displayed in Table 1 and Figures 3–6. The lamina and the inferior articular process exhibited the highest percentage of cortical bone by volume and both were significantly higher than the pedicles (Figure 4A, $P = .033$ and $P = .049$, respectively). The transverse process and the vertebral body exhibited the lowest volume percentage of cortical bone. This trend in percentage of cortical bone was also observed within each specimen despite their differences in age, as demonstrated in Figure 4B.

The lamina exhibited the largest amount of cortical bone volume, apart from the vertebral body (Table 1). The difference in cortical bone volume between the lamina and the vertebral body were not statistically significant ($P = .68$). The vertebral body contained the highest cancellous bone volume and nonbone volume (Figure 5, $P < .0001$ for all comparisons). However, there were no statistically significant differences among the other regions.

The lamina and inferior articular process exhibited the highest cortical wall thickness, and both were significantly higher than the pedicles (Figure 6A, $P = .002$ and $P = .011$, respectively). However, the difference in cortical wall thickness

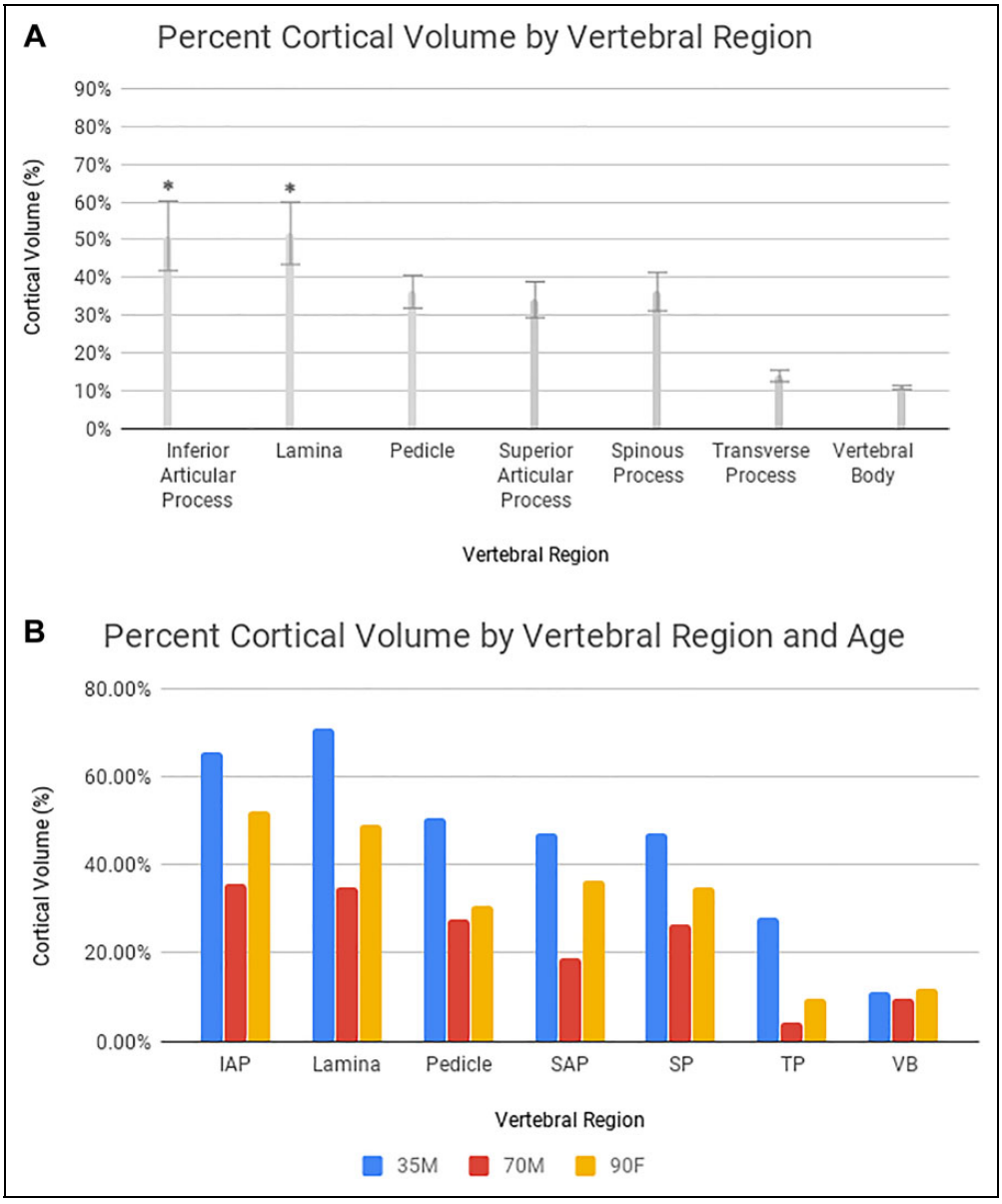

Figure 4. (A) Percent cortical volume for each anatomical region. Statistically different means ($P < .05$) as compared with the pedicle are annotated and indicated with an asterisk. (B) Percent cortical volume by anatomical region and specimen age.

between the lamina and pedicle was greater in the 35-year-old specimen and less pronounced in the 70- and 90-year-old specimens, as demonstrated in Figure 6B.

Densitometry by Vertebral Segment

The BMDs of each vertebral segment are displayed in Table 2. The mean BMDs of both the cortical and cancellous bone were lower at L4 and L5 compared with L1-L3. The L4 and L5 vertebrae also had lower cortical-cancellous ratios. However, there were no statistically significant differences in total BMD, cortical BMD, cancellous BMD, or cortical-cancellous ratio between the L1-L5 vertebral segments ($P > .05$ for all comparisons).

Discussion

Pedicle screw loosening is an important complication of posterior spinal fusion, particularly among osteoporotic patients.[2,12,13] Expandable and cement-augmented pedicle screws are often used to decrease the risk of screw pullout and fixation failure.[1] Extrapedicular regions of the lumbar vertebrae possess greater total BMD and may offer stronger fixation compared with the pedicles.[14] The purpose of this study was to assess the total BMD, cortical BMD, cancellous BMD, cortical volume, and cortical thickness of 7 different anatomical regions of the lumbar spine. Our results indicate that the lamina and inferior articular process have a higher cortical thickness and percentage of cortical volume than the pedicles and other

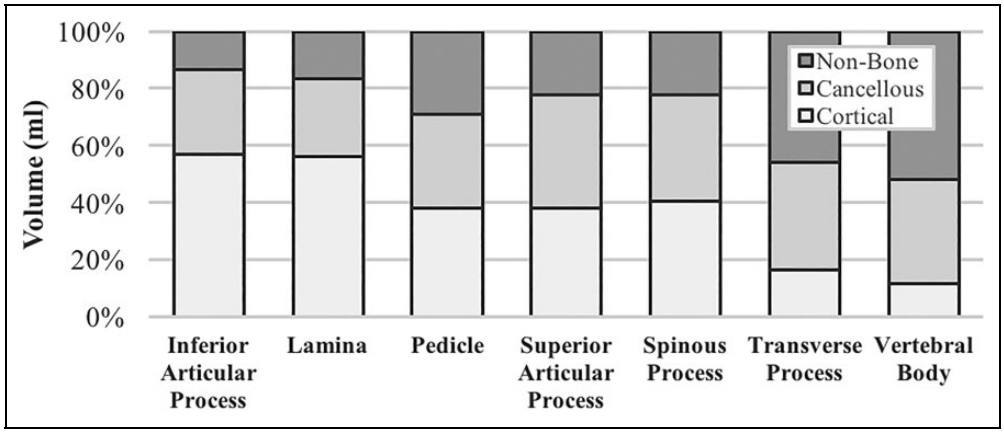

Figure 5. The cortical, cancellous, and nonbone (porous) volume percentages of each region.

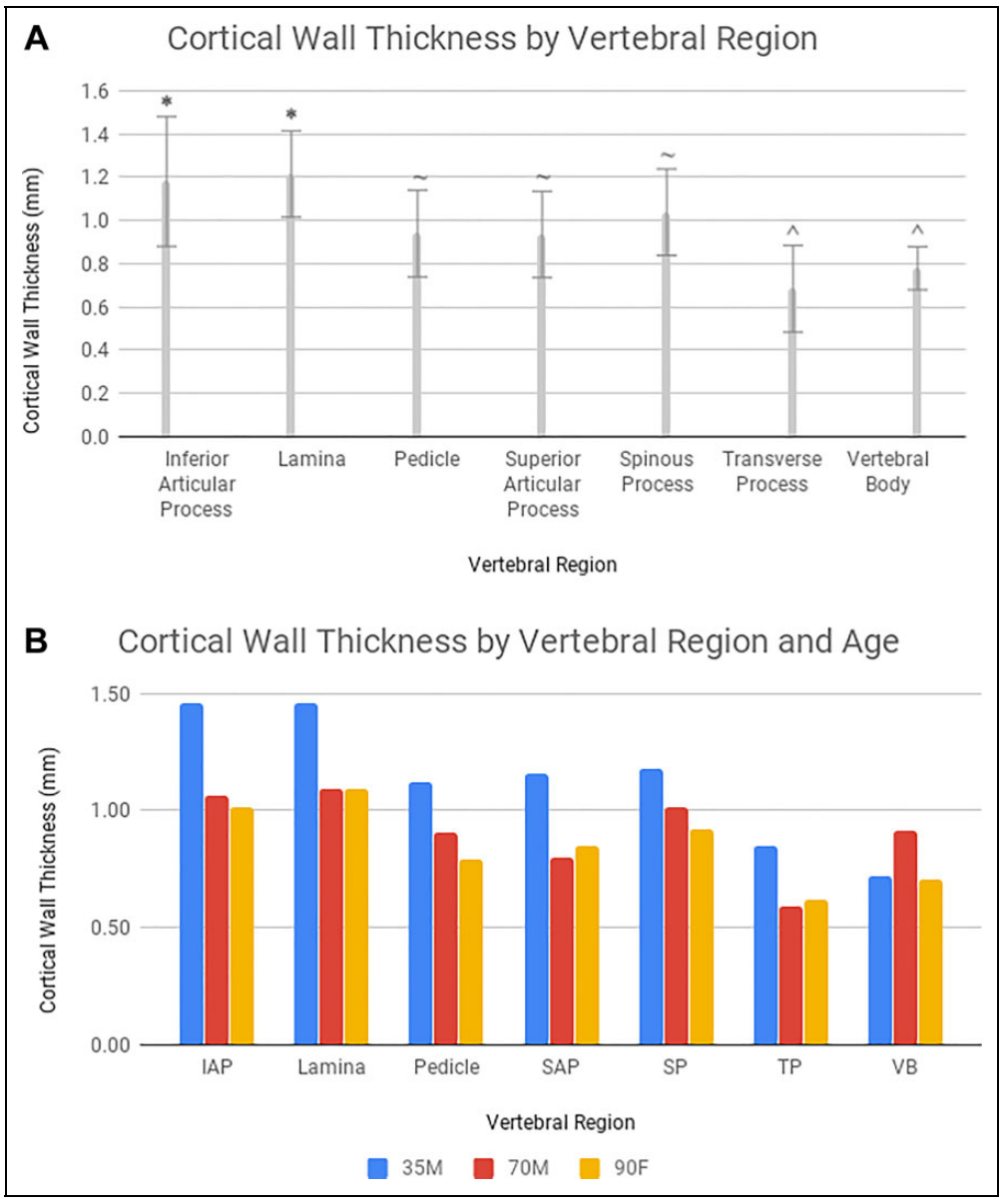

Figure 6. (A) Cortical volume ratio of each anatomic region calculated as a percentage of the total volume. Means not connected by the same annotation symbol (*, ^, or ∼) are significantly different from one another ($P < .05$). (B) Cortical wall thickness by anatomical region and specimen age.

Table 2. Bone Density, Volume, and Thickness Results by Vertebral Segment.[a]

Vertebral Segment	Mean Total BMD (mg Ca^{2+}HA/mL)	Mean Cortical BMD (mg Ca^{2+}HA/mL)	Mean Cancellous BMD (mg Ca^{2+}HA/mL)	Cortical - Cancellous Ratio	Cortical Bone Volume (mL)	Cancellous Bone Volume (mL)	Nonbone Volume (mL)	Percent Cortical Bone (% by Volume)	Cortical Thickness(mm)
L1	262.9 ± 118.3	502.1 ± 92.8	207.3 ± 11.7	2.4 ± 0.4	1.1 ± 0.9	2.3 ± 3.9	2.8 ± 5.6	27.9 ± 18.3	0.92 ± 0.3
L2	280.5 ± 123.0	516.2 ± 67.6	207.1 ± 10.5	2.5 ± 0.2	1.4 ± 1.1	2.4 ± 4.0	3.1 ± 5.8	32.3 ± 19.5	0.95 ± 0.26
L3	290.1 ± 118.8	505.0 ± 59.8	208.6 ± 9.0	2.4 ± 0.2	1.7 ± 1.4	2.6 ± 4.2	3.1 ± 6.0	33.7 ± 19.4	0.97 ± 0.26
L4	304.7 ± 121.3	471.3 ± 69.1	204.8 ± 13.0	2.3 ± 0.3	2.1 ± 1.8	2.8 ± 4.5	3.0 ± 5.8	37.5 ± 21.0	1.00 ± 0.24
L5	294.3 ± 122.6	475.7 ± 71.2	201.8 ± 13.8	2.3 ± 0.2	2.3 ± 2.2	2.9 ± 4.8	2.8 ± 4.7	35.9 ± 21.2	1.00 ± 0.24

Abbreviations: BMD, bone mineral density; Ca^{2+}HA, calcium hydroxyapatite.
[a]All data presented as mean ± standard deviation.

vertebral regions, although the differences in cortical thickness were less pronounced in older specimens. To the authors' knowledge, this is the first study to compare the cortical thickness of different anatomical regions within the lumbar spine.[30,31] The total BMD and cortical BMD of the lamina and inferior articular process were also higher than those values in the pedicles, but only the difference in total BMD was statistically significant. Since screw pullout strength relies greatly on bone density,[6-8] fixation at the lamina and inferior articular processes may reduce the risk of screw loosening and construct failure. We did not observe any statistically significant differences in total, cortical, or cancellous BMD between the L1-L5 vertebrae.

Substantial differences in BMD between vertebral levels have been previously reported in the cervical spine.[23] However, few studies have investigated BMD variations within the lumbar vertebrae. In a study using CT scans and 3-dimensional modeling, Yoganandan et al[32] found that the BMD of the vertebral bodies did not vary significantly among the L1-L5 vertebrae. In contrast, other studies have reported that the L4-L5 vertebral bodies have a higher BMD.[21,33] Each of these studies measured the BMD of an area of cancellous bone within the vertebral bodies, and cortical bone and nonbone areas were excluded from density measurements. Our study analyzed the total, cortical, and cancellous BMD of each anatomical region and vertebral segment including the posterior elements. Knowledge of the potential differences in BMD among the L1-L5 levels may be useful in guiding surgical treatment and fixation strategies. In the cervical spine, Anderst et al[23] suggested that anterior cervical fusion of C6-C7 may require a larger interbody spacer due to significantly lower BMD of the vertebral endplates at these levels and a higher likelihood of graft subsidence.

Few studies have been published previously on the bone quality of the posterior column in the lumbar spine. However, several cadaveric biomechanical studies have compared stiffness, range of motion, and load to failure of pedicle screw and extrapedicular fixation methods.[35,36] For example, Ferrara et al[35] found no differences in stability between translaminar screw and traditional pedicle screw fixation after long-term cyclic loading of the lumbar spine. However, this biomechanical study did not use osteoporotic specimen. Coe et al[36] showed increased load to failure of laminar hooks compared to pedicle screws in osteoporotic bone.

According to the results of our study, facet and translaminar screws traverse anatomical regions of the spine that have high total BMDs, cortical volumes, and cortical thicknesses. On the other hand, pedicle screw trajectories involve the pedicles and vertebral bodies, which demonstrated moderate and low BMDs and cortical volumes respectively. While "traditional pedicle screw" trajectories follow the anatomical axis of the pedicle and engage both cortical and cancellous bone, newer cortical trajectories are directed laterally and do not involve the cancellous bone of the vertebral body.[37]

Our study used CT scans and image processing software to determine the bone density of 7 predefined anatomic regions of the lumbar spine. The use of CT, rather than DEXA (dual-energy X-ray absorptiometry), represents a strength of this study. While useful clinically, DEXA scans may be less able to detect variations in BMD within specific regions of the vertebrae.[34] In contrast to DEXA, CT scans are also less susceptible to confounding factors such as variation in bone size and overlying osteophytes.[38-40] In addition to BMD, our study used multiple measures of bone quality, including cortical volume, cortical thickness, and the cortical-cancellous bone ratio. As shown previously by Pollintine et al,[18] specific anatomical regions within the spine may demonstrate differences in trabecular bone architecture without altering the overall BMD.

Our algorithm for measuring cortical thickness has its limitations. Some studies suggest that CT does not produce accurate measurements of cortical thickness.[41-53] Although Prevrhal et al[43] demonstrated that cortical thickness can be measured using CT with an error of less than 10%, the error in detecting cortical width may increase significantly for shell thicknesses less than 1.2 mm. However, studies using direct anatomical measurement, which may represent the gold standard, have reported wide variations in cortical thickness of the lumbar vertebral bodies.[30,31,41,44] Because of the limited resolution of CT scanners used in clinical practice and the small thickness of the vertebral shell (thicknesses less than 0.5 mm have been reported in the lumbar spine,[31,45,46] CT scans likely overestimate cortical thickness of the vertebral bodies.[41,43,47] As a result, the cortical thickness of the pedicles, spinous processes, transverse processes, and vertebral body may actually be lower than reported in our study. In addition, some authors have questioned the validity of HU to BMD conversions when cone beam computed tomography (CBCT) is used.[48,49]

Conversion methods are based on the underlying assumption that CT numbers are mostly consistent throughout the volume of interest, which requires that the tissue is represented by the same CT numbers for any voxel in a given volume and CT examination.[49] In our study, all scans were sequentially performed on the same scanner with the same imaging parameters to reduce interspecimen variability.

Additional limitations of this study include its limited sample size, wide range of specimen ages, and lack of osteoporotic specimens. Our 90-year-old female specimen likely had osteoporosis or osteopenia; however, we did not use DEXA to confirm the overall BMD of our specimens. Despite the relatively small sample size, we were still able to demonstrate statistically significant differences in total BMD, percentage of cortical bone volume, and cortical thickness between the laminae/inferior articular processes and the pedicles. It is possible that a larger sample size may be sufficiently powered to detect differences in BMD between the L1-L5 vertebral segments. Furthermore, a larger sample size may also allow for the comparison of bone density by factors such as gender, age, and osteoporosis. Of note, the differences in total BMD and cortical wall thickness between regions were less pronounced in older specimens than in the younger specimen. Last, degenerative changes, including vertebral osteophytes, facet joint degeneration, and sclerosis of intervertebral discs have been shown previously to artificially elevate BMD measured by DEXA scan.[39,54-57] Future studies should adjust for the relative contributions of degenerative changes to bone mineral density measurements of the anatomical regions.

Significant differences in BMD of the posterior elements may exist between younger and older specimens. Although our study lacked osteoporotic specimen confirmed by DEXA, our conclusions are unlikely to change given our finding that the laminae and inferior articular processes demonstrate similar cancellous volumes and cancellous BMDs compared with the pedicles. In addition, the highest cortical-cancellous ratios were found in the lamina and both articular processes. Since previous studies suggest that cancellous bone is more affected by osteoporosis than cortical bone,[15,17] the differences in BMD between anatomical regions are unlikely to change significantly in osteoporotic specimen.

Conclusion

Although pedicle screw fixation is the most widely used method of posterior thoracolumbar fusion, extrapedicular regions of the vertebrae may contain denser bone. In the present study, we found that the inferior articular processes and laminae have significantly higher total BMD, cortical bone percentage, and cortical thickness than the pedicles and other anatomical regions of the lumbar spine. Our results suggest that extrapedicular fixation may reduce the risk of screw loosening and construct failure compared with pedicle screw fixation. Patients with osteoporosis may especially benefit from the development of extrapedicular fusion strategies due to the relatively higher BMD of these fixation sites. Additional studies are necessary to determine whether these differences in bone quality translate into reduced rates of screw loosening and need for reoperation in clinical settings.

Declaration of Conflicting Interests

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References

1. Verma K, Boniello A, Rihn J. Emerging techniques for posterior fixation of the lumbar spine. *J Am Acad Orthop Surg*. 2016;24: 357-364.
2. Galbusera F, Volkheimer D, Reitmaier S, Berger-Roscher N, Kienle A, Wilke H. Pedicle screw loosening: a clinically relevant complication? *Eur Spine J*. 2015;24:1005-1016.
3. Law M, Tencer AF, Anderson PA. Caudo-cephalad loading of pedicle screws: mechanisms of loosening and methods of augmentation. *Spine (Phila Pa 1976)*. 1993;18:2438-2443.
4. Huiskes R, Weinans H, van Rietbergen B. The relationship between stress shielding and bone resorption around total hip stems and the effects of flexible materials. *Clin Orthop Relat Res*. 1992;(274):124-134.
5. Okuyama K, Abe E, Suzuki T, Tamura Y, Chiba M, Sato K. Can insertional torque predict screw loosening and related failures? An in vivo study of pedicle screw fixation augmenting posterior lumbar interbody fusion. *Spine* (*Phila Pa 1976*). 2000;25: 858-864.
6. Halvorson TL, Kelley LA, Thomas KA, Whitecloud TS 3rd, Cook SD. Effects of bone mineral density on pedicle screw fixation. *Spine (Phila Pa 1976)*. 1994;19: 2415-2420.
7. Hu SS. Internal fixation in the osteoporotic spine. *Spine (Phila Pa 1976)*. 1997;22(24 suppl):43S-48S.
8. Okuyama K, Abe E, Suzuki T, Tamura Y, Chiba M, Sato K. Influence of bone mineral density on pedicle screw fixation: a study of pedicle screw fixation augmenting posterior lumbar interbody fusion in elderly patients. *Spine J*. 2001;1:402-407.
9. McAfee PC, Weiland DJ, Carlow JJ. Survivorship analysis of pedicle spinal instrumentation. *Spine (Phila Pa 1976)*. 1991; 16(8 suppl):S422-S427.
10. Esses SI, Sachs BL, Dreyzin V. Complications associated with the technique of pedicle screw fixation. A selected survey of ABS members. *Spine (Phila Pa 1976)*. 1993;18:2231-2238.

11. Faraj AA, Webb JK. Early complications of spinal pedicle screw. *Eur Spine J*. 1997;6:324-326.
12. Ohtori S, Inoue G, Orita S, et al. Comparison of teriparatide and bisphosphonate treatment to reduce pedicle screw loosening after lumbar spinal fusion surgery in postmenopausal women with osteoporosis from a bone quality perspective. *Spine (Phila Pa 1976)*. 2013;38:E487-E492.
13. Wu ZX, Gong FT, Liu L, et al. A comparative study on screw loosening in osteoporotic lumbar spine fusion between expandable and conventional pedicle screws. *Arch Orthop Trauma Surg*. 2012;132:471-476.
14. Hohn EA, Chu B, Martin A, et al. The pedicles are not the densest regions of the lumbar vertebrae: implications for bone quality assessment and surgical treatment strategy. *Global Spine J*. 2017;7:567-571.
15. Seeman E, Delmas PD. Bone quality—the material and structural basis of bone strength and fragility. *N Engl J Med*. 2006;354: 2250-2261.
16. Mai HT, Mithell SM, Hashmi SZ, Jenkins TJ, Patel AA, Hsu WK. Differences in bone mineral density of fixation points between lumbar cortical and traditional pedicle screws. *Spine J*. 2016;16: 835-841.
17. Armas LA, Recker RR. Pathophysiology of osteoporosis: new mechanistic insights. *Endocrinol Metab Clin North Am*. 2012; 41:475-486.
18. Pollintine P, Dolan P, Tobias JH, Adams MA. Intervertebral disc degeneration can lead to "stress-shielding" of the anterior vertebral body: a cause of osteoporotic vertebral fracture? *Spine (Phila Pa 1976)*. 2004;29:774-782.
19. Simpson EK, Parkinson IH, Manthey B, Fazzalari NL. Intervertebral disc disorganization is related to trabecular bone architecture in the lumbar spine. *J Bone Miner Res*. 2001;16:681-687.
20. Singer K, Edmondston S, Day R, Breidahl P, Price R. Prediction of thoracic and lumbar vertebral body compressive strength: correlations with bone mineral density and vertebral region. *Bone*. 1995;17:167-174.
21. Salzmann SN, Shirahata T, Yang J, et al. Regional bone mineral density differences measured by quantitative computed tomography: does the standard clinically used L1-L2 average correlate with the entire lumbosacral spine? *Spine J*. 2019;19:695-702.
22. Cody D, Goldstein SA, Flynn MJ, Brown EB. Correlations between vertebral regional bone mineral density (rBMD) and whole bone fracture load. *Spine (Phila Pa 1976)*. 1991;16: 146-154.
23. Anderst WJ, Thorhauer BS, Lee JY, Donaldson WF, Kang JD. Cervical spine bone mineral density as a function of vertebral level and anatomic location. *Spine J*. 2011;11:659-667.
24. Anderst WJ, Baillargeon E, Donaldson WF 3rd, Lee JY, Kang JD. Validation of a noninvasive technique to precisely measure in vivo three-dimensional cervical spine movement. *Spine (Phila Pa 1976)*. 2011;36:E393-E400.
25. Genant HK, Cann CE, Ettinger B, Gordan GS. Quantitative computed tomography of vertebral spongiosa: a sensitive method for detecting early bone loss after oophorectomy. *Ann Intern Med*. 1982;97:699-705.
26. Laval-Jeantet AM, Cann CE, Roger B, Dallant P. A postprocessing dual energy technique for vertebral CT densitometry. *J Comput Assist Tomogr*. 1984;8:1164-1167.
27. Cann CE, Genant HK. Precise measurement of vertebral mineral content using computed tomography. *J Comput Assist Tomogr*. 1980;4:493-500.
28. Wong M, Papa A, Lang T, Hodis HN, Labree L, Detrano R. Validation of thoracic quantitative computed tomography as a method to measure bone mineral density. *Calcif Tissue Int*. 2005;76:7-10.
29. Pemler P, Schneider U, Besserer J. Evaluation of the electron density phantom CIRS Model 62 [in German]. *Z Med Phys*. 2001;11:25-32.
30. Ritzel H, Amling M, Posl M, Hahn M, Delling G. The thickness of human vertebral cortical bone and its changes in aging and osteoporosis: a histomorphometric analysis of the complete spinal column from thirty-seven autopsy specimens. *J Bone Miner Res*. 1997;12:89-95.
31. Edwards WT, Zheng Y, Ferrara LA, Yuan HA. Structural features and thickness of the vertebral cortex in the thoracolumbar spine. *Spine (Phila Pa 1976)*. 2001;26:218-225.
32. Yoganandan N, Pintar FA, Stemper BD, et al. Trabecular bone density of male human cervical and lumbar vertebrae. *Bone*. 2006;39:336-344.
33. Budoff J, Khairallah W, Li D, et al. Trabecular bone mineral density measurement using thoracic and lumbar quantitiative computed tomography. *Acad Radiol*. 2012;19:179-183.
34. Wang Y, Videman T, Boyd SK, Battie MC. The distribution of bone mass in the lumbar vertebrae: are we measuring the right target? *Spine J*. 2015;15:2412-2416.
35. Ferrara LA, Secor JL, Jin BH, Wakefield A, Inceoglu S, Benzel EC. A biomechanical comparison of facet screw fixation and pedicle screw fixation: effects of short-term and long-term repetitive cycling. *Spine (Phila Pa 1976)*. 2003;28:1226-1234.
36. Coe JD, Warden KE, Herzig MA, McAfee PC. Influence of bone mineral density on the fixation of thoracolumbar implants: a comparative study of transpedicular screws, laminar hooks, and spinous process wires. *Spine (Phila Pa 1976)*. 1990;15:902-907.
37. Santoni BG, Hynes RA, McGilvray KC, et al. Cortical bone trajectory for lumbar pedicle screws. *Spine J*. 2009;9:366-373.
38. Link TM, Lang TF. Axial QCT: clinical applications and new developments. *J Clin Densitom*. 2014;17:438-448.
39. Rand T, Seidl G, Kainberger F, et al. Impact of spinal degenerative changes on the evaluation of bone mineral density with dual energy X-ray absorptiometry (DXA). *Calcif Tissue Int*. 1997;60: 430-433.
40. Guglielmi G, Floriani I, Torri V, et al. Effect of spinal degenerative changes on volumetric bone mineral density of the central skeleton as measured by quantitative computed tomography. *Acta Radiol*. 2005;46:269-275.
41. Silva MJ, Wang C, Keaveny TM, Hayes WC. Direct and computed tomography thickness measurements of the human, lumbar vertebral shell and endplate. *Bone*. 1994;15:409-414.
42. Prevrhal S, Fox JC, Shepherd JA, Genant HK. Accuracy of CT-based thickness measurement of thin structures: modeling of limited spatial resolution in all three dimensions. *Med Phys*. 2003;30:1-8.

43. Prevrhal S, Engelke K, Kalender WA. Accuracy limits for the determination of cortical width and density: the influence of object size and CT imaging parameters. *Phys Med Biol*. 1999; 44:751-764.
44. Ma YZ, Tang HF, Chai BF, et al. The treatment of primary vertebral tumors by radical resection and prosthetic vertebral replacement. *Clin Orthop Relat Res*. 1987;(215):78-90.
45. Sandor T, Feisenberg D, Kalender WA, Clain A, Brown E. Compact and trabecular components of the spine using quantitative computed tomography. *Calcif Tissue Int*. 1992;50: 502-506.
46. Vesterby A, Mosekilde L, Gundersen HJ, et al. Biologically meaningful determinants of the in vitro strength of lumbar vertebrae. *Bone*. 1991;12:219-224.
47. Liebschner MA, Kopperdahl DL, Rosenberg WS, Keaveny TM. Finite element modeling of the human thoracolumbar spine. *Spine (Phila Pa 1976)*. 2003;28:559-565.
48. Liu Y, Bauerle T, Pan L, et al. Calibration of cone beam CT using relative attenuation ratio for quantitative assessment of bone density: a small animal study. *Int J Comput Assist Radiol Surg*. 2013; 8:733-739.
49. Molteni R. Prospects and challenges of rendering tissue density in Hounsfield units for cone beam computed tomography. *Oral Surg Oral Med Oral Pathol Oral Radiol*. 2013;116:105-119.
50. Anderst WJ, West T, Donaldson WF 3rd, Lee JY. Cervical spine bone density in young healthy adults as a function of sex, vertebral level and anatomic location. *Eur Spine J*. 2017;26:2281-2289.
51. Schreiber JJ, Anderson PA, Rosas HG, Buchholz AL, Au AG. Hounsfield units for assessing bone mineral density and strength: a tool for osteoporosis management. *J Bone Joint Surg Am*. 2011; 93:1057-1063.
52. Pickhardt PJ, Pooler BD, Lauder T, del Rio AM, Bruce RJ, Binkley N. Opportunistic screening for osteoporosis using abdominal computed tomography scans obtained for other indications. *Ann Intern Med*. 2013;158:588-595.
53. Martin CT, Skolasky RL, Mohamed AS, Kebaish KM. Preliminary results of the effect of prophylactic vertebroplasty on the incidence of proximal junctional complications after posterior spinal fusion to the low thoracic spine. *Spine Deform*. 2013;1:132-138.
54. Annis P, Lawrence BD, Spiker WR, et al. Predictive factors for acute proximal junctional failure after adult deformity surgery with upper instrumented vertebrae in the thoracolumbar spine. *Evid Based Spine Care J*. 2014;5:160-162.
55. Giambini H, Roghani RS, Thoreson AR, Melton LJ 3rd, An KN, Gay RE. Lumbar trabecular bone mineral density distribution in patients with and without vertebral fractures: a case-control study. *Eur Spine J*. 2014;23:1346-1353.
56. Smith MW, Annis P, Lawrence BD, Daubs MD, Brodke DS. Early proximal junctional failure in patients with preoperative sagittal imbalance. *Evid Based Spine Care J*. 2013;4:163-164.
57. Atalay A, Kozakcioglu M, Cubuk R, Tasali N, Guney S. Degeneration of the lumbar spine and dual-energy X-ray absorptiometry measurements in patients without osteoporosis. *Clin Imaging*. 2009;33:374-378.