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Cervical Spine Bone Mineral Density as a Function of Vertebral Level and Anatomic Location

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Introduction

The complex geometry of the cervical spine provides multiple locations where load may be applied to each vertebra, either through articulating joint surfaces (e.g. vertebral body and facets) or through muscle and ligament attachments (e.g. lamina and spinous processes). The asymptomatic neck is capable of a wide variety of movements, ranging from simple single-plane motion (e.g. flexion-extension) to complex, multi-plane motions. Thus, it is clear that the anatomical structures that comprise the cervical vertebrae are routinely subjected to diverse combinations of load. Furthermore, the multiple joint articulations and ligament and tendon attachment sites on each bone lead to variation in the type and magnitude of loading applied to different anatomic locations within each vertebra (e.g. pedicles are loaded differently than vertebral bodies). Finally, due to the natural curvature of the cervical spine, it is probable that vertebral loading is different among cervical levels. The bone tissue, following Wolff's Law, adapts to these various loading patterns, both within an individual vertebra and among vertebra. Therefore, it follows that bone mechanical properties are likely to differ among anatomical locations within an individual vertebra and among vertebrae depending on level.

Bone mechanical properties may be estimated by bone mineral density (BMD) measurements acquired from dual-energy x-ray absorptiometry (DXA or DEXA) or quantitative computed tomography (QCT) scans. For example, DEXA scans of the cervical spine have shown a correlation between BMD and pullout strength [1, 2]. Similarly, BMD measured using QCT has been shown to be related to mechanical properties such as elastic modulus, strength, stiffness and yield load [3–7]. From the clinical perspective, a clear relationship has been established between BMD and surgical instrumentation performance, such as screw pull-out strength [8–10] and disc replacement subsidence [3]. Previously, bone mineral density measurements at specific anatomic locations within the cervical spine have been performed almost exclusively on the central vertebral body, either by measuring trabecular BMD in a single CT slice [5, 11, 12] or by measuring a large volume of trabecular bone in multiple CT scan slices [13, 14]. In addition to the central vertebral body, the only other BMD measurements of specific anatomical regions within the cervical spine were performed on the endplates [3, 11]. The relationship between site-specific bone

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characteristics and bone mechanical properties has been investigated to a limited extent in the thoracic and lumbar spine. In the thoracic spine, bone mass and thickness at specific anatomic locations within the posterior elements have been related to the strength at these sites[15], while in the lumbar spine, regional measures of bone density have been correlated to whole-bone fracture load[16].

In the case of the cervical spine, it would be beneficial to know the extent to which BMD, and therefore bone mechanical properties, vary in relation to vertebral level and anatomic location. However, this information does not currently exist. Knowledge of BMD variation according to vertebral level and anatomic location would be beneficial to surgeons who must secure instrumentation to the vertebrae during surgery, to those in the medical device industry who must design instrumentation such as screws and disc replacements, and to basic scientists who assign mechanical properties to bones in computational models of the spine.

The overall objective of this study was to characterize BMD in the cervical spine as a function of level and anatomic location. The first specific aim was to determine the overall BMD of cervical vertebrae C3–C7. The second specific aim was to determine the BMD in distinct anatomic regions within C3–C7, and the third specific aim was to correlate BMD in the central vertebral body to BMD in anatomic regions commonly used for screw fixation. The three null hypotheses tested were the following: 1) BMD does not change with vertebral level, 2) BMD is not significantly different across anatomic regions, and 3) BMD in the central vertebral body is not correlated with pedicle and lateral mass BMD.

Methods

High-resolution CT scans ($0.29 \times 0.29 \times 1.25$ mm voxels) of the subaxial cervical spine (C3–C7) were collected from 22 subjects following IRB approval (overall average age 48 ± 7 yrs; range 35–61 yrs; 13 F, 9 M). Ten subjects were diagnosed with cervical radiculopathy within 30 days of data collection (age 49 ± 8 yrs; 6F, 4M; 2 smokers, 8 non-smokers) and 12 subjects were asymptomatic controls (age 46 ± 6 yrs; 7F, 5M, 3 smokers, 3 quit smoking, 6 non-smokers). All CT scans were performed on the same scanner (GE LightSpeed 16) using identical CT protocol parameters to ensure consistent BMD measurements throughout the study [17]. CT pixel values were converted from Hounsfield units into BMD values using a calibration phantom (CIRS, Model 62, Electron Density Phantom, Norfolk, VA). The tissue-equivalent plugs in this phantom are not influenced by CT mode, slice thickness, reconstruction algorithm, or pitch factor, and have been evaluated to be reliable and acceptable for quantitative analysis[18]. Bone tissue was segmented from the CT volume using a combination of commercial software (Mimics software, Materialise, Leuven, Belgium) and manual segmentation [19]. A three-dimensional (3D) model of each vertebra was generated from the segmented bone tissue. Eleven anatomically defined regions of interest were identified within each 3D bone model (Figure 1A). Additional regions of interest, approximately 2 mm in thickness, were defined on the superior and inferior endplates of the central vertebral body (Figure 1B). Custom software (Matlab, MathWorks, Inc., Natick, MA, USA) calculated the average BMD (in mg/cm^3) within each anatomic region of interest. Voxels within the cortical shell that contained negative values (e.g. bone marrow fat) were not included in any calculations. Overall BMD of each vertebra was calculated as the volume-weighted average BMD from all anatomical regions of interest. BMD values for each voxel of bone tissue were binned into $50 \text{ mg}/\text{cm}^3$ ranges (e.g. $0\text{--}50 \text{ mg}/\text{cm}^3$, $51\text{--}100 \text{ mg}/\text{cm}^3$, etc.) to determine the density distribution (by volume) of bone within each anatomical region and within each vertebra.

One-way analysis of variance was used to test for differences between radiculopathy and control subjects and between males and females at each vertebral level. Repeated measures analysis of variance, using the Bonferroni adjustment for multiple comparisons, was used to test for differences within subjects by level (C3–C7) and anatomic location, with $\alpha = .05$ for all tests. The correlation between BMD in the central vertebral body (the combination of regions 9, 10 and 11 in Figure 1A) and the pedicle and lateral mass regions was tested using Pearson correlation (SPSS, v18.0, IBM Corp., Somers, NY).

Results

Average BMD varied significantly by level. C3 and C6 BMD was significantly less than C4 and C5 (all $p \leq .007$). C7 BMD was significantly less than all other levels (all $p \leq .001$) (Table 1, Figure 2). Control subject average BMD was higher than radiculopathy subject BMD at each vertebral level, however, this difference did not reach significance at any level (p-value range: 0.06 to 0.17). Female average BMD was higher than male BMD at each vertebral level, however, this difference also did not reach significance at any level (p-value range: 0.06 to 0.09) (Table 1, Figure 2). Overall bone volume was similar in radiculopathy and control subjects at each level, while male bone volume was higher than female at each level (Table 2).

The pedicles had significantly higher BMD than all other anatomic locations (all $p \leq .001$). The lamina and lateral masses had significantly greater BMD than all anatomical regions except the pedicles (all $p \leq .001$). The anterior portion of the central vertebral body had significantly lower BMD than all other anatomical regions (all $p \leq .001$). Statistically significant differences were also observed among other anatomical locations (Figure 3).

Endplate BMD was significantly lower in C7 than at all other levels (all $p \leq .001$). C6 endplate BMD was lower than C5 endplate BMD ($p = .033$). No other significant differences in BMD were observed at the endplates (mean superior endplate BMD: 380, 393, 387, 358, 293 mg/cm³, and mean inferior endplate: 398, 382, 388, 372, 326 mg/cm³ for C3–C7, respectively). BMD values within the central vertebral body (green in Fig 1B) followed the same pattern as overall BMD density, peaking at C5 and decreasing in the directions of C3 and C7 (mean central vertebral body BMD for C3–C7, respectively: 336, 354, 360, 311, 248 mg/cm³). For these central vertebral body BMD measures, C3 was significantly less than C4 ($p = .021$), C6 was less than C4 and C5 ($p \leq .001$ and $p = .003$), and C7 was less and all other levels (all $p \leq .001$).

There was a significant, positive correlation between central vertebral body BMD and lateral mass BMD at each level. The correlation between central vertebral body BMD and pedicle BMD was statistically significant at all levels except C3 (Table 3).

Density distribution by volume plots were used to identify the source of the trend toward a difference in BMD between males and females and between radiculopathy patients and control subjects. These plots revealed very consistent patterns among all vertebrae, and similarly consistent differences between groups (male vs. female and radiculopathy vs. control). Three factors contributed to the lower BMD recorded in the male subjects. First, the males exhibited a higher volume of very low-density bone than females (Section 1 in Figure 4A). Second, in males, the peak of the volume versus bone mineral density curve occurred at a lower BMD range than in females (arrow in Figure 4A). Third, the volume of extremely high-density bone was higher in females than in males (Section 2 in Figure 4A) in spite of smaller overall bone volume in females. Further examination of bone density distribution by volume plots for each anatomical region showed that the posterior anatomical regions (the spinous process, lamina, lateral masses and pedicles) accounted for

88% of the difference in bone volume above 800 mg/cm³ in density (dense compact bone) between males and females. An example of this difference in volume of high-density bone in the posterior elements is provided in Figure 4B, while Figure 4C shows the bone density distribution typically found in each anatomical region of the vertebral body. These figures are representative of consistent findings at every level that indicated an increase in the volume of high-density bone in the posterior regions of the vertebrae in females (Figure 4B) and similar volumes of high-density bone in each region of the vertebral body in males and females (Figure 4C).

In two respects, the density distribution by volume plots for the control and radiculopathy subjects were very similar to the male and female plots. First, the radiculopathy subjects exhibited a higher volume of very low-density bone than controls (Section 1 in Figure 5A). Second, in radiculopathy subjects, the peak of the volume versus bone mineral density curve occurred at a lower BMD range than in controls (blue and red ellipses in Figure 5A). The control subjects had a larger volume of high-density bone over a wide range of BMD values (Section 2 in Figure 5A), unlike the differences in male vs. female density distribution plots, where the differences in volume of high-density bone was limited to a small range of very high density values. Further examination of bone density distribution by volume plots for each anatomical region showed that all anatomical regions of the vertebrae demonstrated this difference in the volume of high-density bone over a wide range of density values (Figure 5B and Figure 5C). Again, Figures 5A–C are representative of consistent findings at every level, showing the increased volume of high-density bone throughout all regions of the vertebrae in controls in comparison to radiculopathy patients.

Discussion

Differences in BMD by level for the entire C3–C7 vertebrae were consistent with previous reports based on single CT slices [5, 11, 20] and volumetric measurements [13, 14] of trabecular vertebral body bone density. These previous reports indicated that cervical vertebral body BMD was highest at C5 and decreased in the direction of C3 and C7 [5, 11, 13, 14, 20, 21]. Significantly lower BMD of C7 in comparison to C4–C6 has also been reported in cadaver specimens (mean age 71, 9M, 6F) [20]. A study of 30 young females (average age 24.9) [14] and another study comprising 30 young males (average age 25) [13] have also shown C7 BMD is significantly lower than C2–C6 BMD. The studies on younger subjects also indicated C6 BMD was less than C3–C5 BMD in young females [14] and C4 and C5 BMD was greater than C3 and C6, with C3 BMD significantly greater than C6 in young males [13]. The present results generally agree with these previous reports. Small discrepancies in where statistical significance was found may be due to different age subjects and different regions of the vertebrae measured for density analysis (single slice [5, 11, 20] versus trabecular region of vertebral body [13, 14] versus the entire vertebra (the current study)).

Previous studies have not proposed potential explanations for variation in BMD according to vertebral level, nor has the consistent finding of lower BMD in C7 in comparison to other levels been discussed. One possibility for differences in BMD by level is that the C3–C7 bones are subjected to different *in vivo* loads, and loading of C5 may be greatest. In response, C5 BMD is highest, as would be expected following Wolff's Law. Several possible explanations exist for the consistent finding of lower BMD in C7. First, the substantially larger C7 vertebral body, in comparison to C3–C6 vertebrae, serves to disproportionately increase volume relative to mass at C7, thus lowering C7 BMD. Second, the increased vertical orientation of the C7 lateral masses lead to decreased compressive loads on the lateral masses and pedicles. Third, the smaller range of movements experienced

by C7 may indicate a reduction in the overall variety of loading patterns applied to C7 thus decreasing the necessity for high BMD at C7.

This study revealed for the first time the significant variation in cervical vertebrae BMD with respect to anatomical location. The wide variation in BMD across different anatomical locations suggests substantial differences exist in regional bone mechanical properties. For example, it has been shown that a 25% decrease in bone tissue results in a more than 50% decrease in strength of the vertebral body [22], and BMD accounts for 60%–70% of bone strength [23]. Knowledge of the magnitude of the differences in BMD among anatomical locations can be valuable to spine surgeons who must attach instrumentation to bones. As Figure 3 shows, for posterior attachment sites, the average BMD of the pedicles is 15% higher than the lamina and lateral masses. The significant difference between pedicle and lateral mass BMD corresponds well to a previous study that found cervical pedicle screws have a significantly higher resistance to pull-out forces than lateral mass screws [24]. Differences in BMD are even larger when these posterior attachment sites are compared to the anterior attachment site of the vertebral body. In this case, the posterior sites have 60% to 120% higher BMD than the anterior attachment site. This difference in BMD between vertebral body and posterior elements implies significant differences in the mechanical properties of these anatomic regions. This implication is supported by clinical experience that shows posterior fusion results in a more solid construct following surgery than anterior fusion.

C6 and C7 endplate BMD was lower than other levels, in agreement with previous a report using cadaver specimens [11]. Furthermore, it has been shown that C6 and C7 endplates fail at significantly lower compressive loads than more cranial levels [25]. These results all indicate disc replacement design and or surgical technique may need to be modified to reduce likelihood of subsidence when the C7 level is involved.

Bone density measurements from one region of the body are not necessarily representative of BMD at other parts of the body [26]. For instance, previous studies have demonstrated a lack of correlation in BMD among the cervical and lumbar spine [13, 14]. Furthermore, BMD measurements at the hip and lumbar spine are not reflective of axial skeleton BMD [27]. Therefore, it is not clear if BMD measurements that are typically acquired from the central vertebral body are correlated with BMD measurements from sites where instrumentation is commonly attached. The significant correlation between central vertebral body BMD and lateral mass or pedicle BMD at each level (with one exception) found in this study indicates BMD at the central vertebral body may adequately reflect BMD at the anatomical locations where posterior fusion instrumentation is most commonly attached.

Lower BMD in the cervical spine of males than in females is supported by previous research. Comparison of results from two previous studies published by one group, using identical data collection techniques in each study, showed female cervical vertebral body BMD was slightly higher than male BMD in C3–C7 levels (although no test for statistical significance was made between the two studies) [13, 14]. Additionally, volumetric measures of BMD (as in the current study) have been reported to be higher in women compared with men during the reproductive years [28]. An additional explanation for the observed trend of higher BMD in females than males may be that loads applied to the cervical vertebrae are relatively similar in males and females (unlike loads to the femur or lower back, for example). Therefore, it would be expected that the amount of bone tissue required to support the loads applied to the vertebrae would be similar (i.e. the mass of cervical bone necessary would be similar between males and females). Thus, lower BMD in males could be expected given the higher volume of bone tissue at each level. It should be noted that the high bone density values that differentiated between males and females (800 mg/cm^3 and greater) in

Figure 4 are total bone mineral volume values within each density range (i.e. not corrected for smaller female bones). Thus, females, in spite of having smaller overall bone volumes, have a greater volume of high-density bone located almost exclusively in the posterior elements. This finding is in agreement with previous research that showed females within the age group of the current study have higher cortical bone mineral density than men of the same age [29].

At first glance, it may be surprising that cervical spine BMD tended to be higher in females than in males. However, it should be noted that the majority of previous reports of bone mineral density (regardless of anatomic location) have been performed using dual-energy x-ray absorptiometry (DXA or DEXA), a two-dimensional, areal measurement of bone density. DXA measurements are known to be dependent on the size of the bone being imaged [30, 31], resulting in lower BMD values for smaller bones. Volumetric BMD measurements, such as QCT, do not have this limitation. QCT is also less related to patient height or weight than DXA [32]. In fact, gender differences in BMD calculated using DXA are essentially eliminated after adjusting for body size [33].

This is the first report of a trend toward BMD differences between control subjects and radiculopathy patients. The time from radiculopathy symptom onset to data collection was four weeks or less, therefore it is unlikely that BMD values in the radiculopathy patients were decreased due to the effects of load reduction associated with limited mobility. Additionally, the ratio of males to females was nearly the same in the control and radiculopathy groups, so it is unlikely that this difference is related to gender. Although there are currently no established risk factors for the development of cervical radiculopathy [34], the results of this study suggest future research should explore the relationship between low BMD and radiculopathy.

The age of the subjects in this study was representative of patients who typically receive treatment for cervical spine disorders. While this adds to the clinical relevance of the findings, it is also a limitation of the study. The small variability in subject age precluded testing for relationships between BMD and age for this cohort. Results may be different for younger or older subjects due to the well-known changes that occur in the spine with age.

In summary, this study has characterized BMD in the cervical spine according to vertebral level and anatomic location within each vertebral level using live subjects from a clinically relevant age group. The results indicate significant differences in BMD according to vertebral level and among anatomical regions within each vertebra. These results have implications for clinicians, basic scientists and device manufacturers. The results suggest to the surgeon and device manufacturers that surgical procedures involving instrumentation attached to C7 may require a modification in instrumentation or in surgical technique in order to attain results equivalent to more superior levels. The results suggest to the basic scientist that computational models may be improved by taking into account the wide variation in BMD over different anatomical regions.

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References

1. Hostin RA, Wu C, Perra JH, et al. A biomechanical evaluation of three revision screw strategies for failed lateral mass fixation. *Spine (Phila Pa 1976)*. 2008; 33(22):2415–2421. [PubMed: 18923316]

2. Hitchon PW, Brenton MD, Coppes JK, et al. Factors affecting the pullout strength of self-drilling and self-tapping anterior cervical screws. *Spine (Phila Pa 1976)*. 2003; 28(1):9–13. [PubMed: 12544947]
3. Zhang X, Ordway NR, Tan R, et al. Correlation of ProDisc-C failure strength with cervical bone mineral content and endplate strength. *J Spinal Disord Tech*. 2008; 21(6):400–405. [PubMed: 18679093]
4. Jiang Y, Zhao J, Augat P, et al. Trabecular bone mineral and calculated structure of human bone specimens scanned by peripheral quantitative computed tomography: relation to biomechanical properties. *J Bone Miner Res*. 1998; 13(11):1783–1790. [PubMed: 9797489]
5. Ordway NR, Lu YM, Zhang X, et al. Correlation of cervical endplate strength with CT measured subchondral bone density. *Eur Spine J*. 2007; 16(12):2104–2109. [PubMed: 17712574]
6. Goldstein SA. The mechanical properties of trabecular bone: dependence on anatomic location and function. *J Biomech*. 1987; 20(11–12):1055–1061. [PubMed: 3323197]
7. Oxland TR, Lund T, Jost B, et al. The relative importance of vertebral bone density and disc degeneration in spinal flexibility and interbody implant performance. An in vitro study. *Spine (Phila Pa 1976)*. 1996; 21(22):2558–2569.
8. Zhuang XM, Yu BS, Zheng ZM, et al. Effect of the degree of osteoporosis on the biomechanical anchoring strength of the sacral pedicle screws: an in vitro comparison between unaugmented bicortical screws and polymethylmethacrylate augmented unicortical screws. *Spine (Phila Pa 1976)*. 2010; 35(19):E925–E931. [PubMed: 20098349]
9. Thiele OC, Eckhardt C, Linke B, et al. Factors affecting the stability of screws in human cortical osteoporotic bone: a cadaver study. *J Bone Joint Surg Br*. 2007; 89(5):701–705. [PubMed: 17540760]
10. Ryken TC, Clausen JD, Traynelis VC, et al. Biomechanical analysis of bone mineral density, insertion technique, screw torque, and holding strength of anterior cervical plate screws. *J Neurosurg*. 1995; 83(2):325–329. [PubMed: 7616279]
11. Kandziora F, Pflugmacher R, Scholz M, et al. Comparison between sheep and human cervical spines: an anatomic, radiographic, bone mineral density, and biomechanical study. *Spine (Phila Pa 1976)*. 2001; 26(9):1028–1037. [PubMed: 11337621]
12. Weishaupt D, Schweitzer ME, DiCuccio MN, et al. Relationships of cervical, thoracic, and lumbar bone mineral density by quantitative CT. *J Comput Assist Tomogr*. 2001; 25(1):146–150. [PubMed: 11176311]
13. Yoganandan N, Pintar FA, Stemper BD, et al. Trabecular bone density of male human cervical and lumbar vertebrae. *Bone*. 2006; 39(2):336–344. [PubMed: 16580272]
14. Yoganandan N, Pintar FA, Stemper BD, et al. Bone mineral density of human female cervical and lumbar spines from quantitative computed tomography. *Spine (Phila Pa 1976)*. 2006; 31(1):73–76. [PubMed: 16395180]
15. Sran MM, Boyd SK, Cooper DM, et al. Regional trabecular morphology assessed by micro-CT is correlated with failure of aged thoracic vertebrae under a posteroanterior load and may determine the site of fracture. *Bone*. 2007; 40(3):751–757. [PubMed: 17134950]
16. Cody DD, Goldstein SA, Flynn MJ, et al. Correlations between vertebral regional bone mineral density (rBMD) and whole bone fracture load. *Spine (Phila Pa 1976)*. 1991; 16(2):146–154. [PubMed: 2011769]
17. Bligh M, Bidaut L, White RA, et al. Helical multidetector row quantitative computed tomography (QCT) precision. *Acad Radiol*. 2009; 16(2):150–159. [PubMed: 19124100]
18. Pémier P, Schneider U, Besserer J. Evaluation of the electron density phantom CIRS Model 62. *Z Med Phys*. 2001; 11(1):25–32. [PubMed: 11487856]
19. Thorhauer, E.; Miyawaki, M.; Illingworth, K., et al. Accuracy of bone and cartilage models obtained from ct and mri. Providence, RI: American Society of Biomechanics; 2010.
20. Curylo LJ, Lindsey RW, Doherty BJ, et al. Segmental variations of bone mineral density in the cervical spine. *Spine (Phila Pa 1976)*. 1996; 21(3):319–322. [PubMed: 8742207]
21. Yoganandan N, Pintar F, Wilson CR, et al. In vitro biomechanical study of female geriatric cervical vertebral bodies. *J Biomed Eng*. 1990; 12(2):97–101. [PubMed: 2319771]

22. Bell G, Dunbar O, Beck J, et al. Variations in strength of vertebrae with age and their relation to osteoporosis. *Calcified Tissue Research*. 1967; 1(1):75–86. [PubMed: 6060146]
23. Ammann P, Rizzoli R. Bone strength and its determinants. *Osteoporos Int*. 2003; 14 Suppl 3:S13–S18. [PubMed: 12730800]
24. Jones EL, Heller JG, Silcox DH, et al. Cervical pedicle screws versus lateral mass screws. Anatomic feasibility and biomechanical comparison. *Spine (Phila Pa 1976)*. 1997; 22(9):977–982. [PubMed: 9152447]
25. Truumees E, Demetropoulos CK, Yang KH, et al. Failure of human cervical endplates: a cadaveric experimental model. *Spine (Phila Pa 1976)*. 2003; 28(19):2204–2208. [PubMed: 14520032]
26. Grampp S, Genant HK, Mathur A, et al. Comparisons of noninvasive bone mineral measurements in assessing age-related loss, fracture discrimination, and diagnostic classification. *J Bone Miner Res*. 1997; 12(5):697–711. [PubMed: 9144335]
27. Wilson J, Bonner T, Head M, et al. Variation in bone mineral density by anatomical site in patients with proximal humeral fractures. *Journal Bone and Joint Surgery (Br)*. 2009; 91(6):772–775.
28. Jarvinen TL, Kannus P, Sievanen H. Estrogen and bone--a reproductive and locomotive perspective. *J Bone Miner Res*. 2003; 18(11):1921–1931. [PubMed: 14606503]
29. Havill LM, Mahaney MC, T LB, et al. Effects of genes, sex, age, and activity on BMC, bone size, and areal and volumetric BMD. *J Bone Miner Res*. 2007; 22(5):737–746. [PubMed: 17444815]
30. Carter DR, Bouxsein ML, Marcus R. New approaches for interpreting projected bone densitometry data. *J Bone Miner Res*. 1992; 7(2):137–145. [PubMed: 1570758]
31. Bonnick, S. *Bone Densitometry in Clinical Practice: Application and Interpretation*. Totowa, NH: Humana; 1998.
32. Guglielmi G, van Kuijk C, Li J, et al. Influence of anthropometric parameters and bone size on bone mineral density using volumetric quantitative computed tomography and dual X-ray absorptiometry at the hip. *Acta Radiol*. 2006; 47(6):574–580. [PubMed: 16875335]
33. Looker AC, Beck TJ, Orwoll ES. Does body size account for gender differences in femur bone density and geometry? *J Bone Miner Res*. 2001; 16(7):1291–1299. [PubMed: 11450705]
34. Wainner RS, Gill H. Diagnosis and nonoperative management of cervical radiculopathy. *J Orthop Sports Phys Ther*. 2000; 30(12):728–744. [PubMed: 11153552]

Figure 1.

A: Anatomic regions of interest numbered from highest (1) to lowest (11) BMD.

B: Superior (red) and inferior (blue) endplates and central vertebral body (green) regions of interest.

Figure 2.

Overall BMD by vertebral level. C3 and C6 BMD were significantly less than C4 and C5 ($p < .007$) C7 BMD was significantly less than all other levels (all $p \leq .001$). Error bars on group averages are ± 1 SE.

Figure 3.

Bone mineral density by anatomic location, averaged across C3–C7 levels. Symbols to the right indicate anatomic regions with BMD that are NOT significantly different from each other (e.g. pedicles have significantly higher BMD than all other locations; lateral masses and lamina are not significantly different, but are less than pedicles and greater than all other locations, etc).

Figure 4. Average volume of bone within each 50 mg/cm³ range for the entire C3 vertebra (A) the lateral masses (B) and the exterior-lateral portion of the vertebral body (C) for males (blue) and females (red). Note differences in the low-density ranges (Section 1) and high-density ranges (Section 2) and an overall shift in average density of highest volume ranges (blue and red ellipses) for the entire vertebra (A). For females, a larger volume of bone was present in the high-density ranges for the posterior elements (e.g. (B)) but not within any anatomical portions of the vertebral body (e.g. (C)). C3 data is representative of all other levels.

Figure 5.

Average volume of bone within each 50 mg/cm³ range for the entire C3 vertebra (A) the lateral masses (B) and the exterior-lateral portion of the vertebral body (C) for radiculopathy patients (blue) and controls (red). Note differences in the low-density ranges (Section 1) and high-density ranges (Section 2) and an overall shift in average density of highest volume ranges (blue and red ellipses) for the entire vertebra (A). For controls, a larger volume of mid to high density bone was present throughout the entire vertebra, including the posterior elements (B) and all anatomic regions of the vertebral body (e.g. (C)). C3 data is representative of all other levels.

Table 1

Average ($\pm$ SD) cervical spine bone mineral density (BMD) for radiculopathy and asymptomatic control subjects and for male and female subjects.

	C3	C4	C5	C6	C7	C3-C7 average
Radiculopathy	445 $\pm$ 75	469 $\pm$ 76	471 $\pm$ 72	442 $\pm$ 64	394 $\pm$ 63	444 $\pm$ 68
Control	501 $\pm$ 83	532 $\pm$ 94	537 $\pm$ 82	499 $\pm$ 68	431 $\pm$ 62	500 $\pm$ 75
Male	440 $\pm$ 76	464 $\pm$ 90	469 $\pm$ 72	443 $\pm$ 61	385 $\pm$ 58	440 $\pm$ 69
Female	501 $\pm$ 80	530 $\pm$ 84	533 $\pm$ 82	495 $\pm$ 72	435 $\pm$ 61	499 $\pm$ 74
All Subjects	476 $\pm$ 83 [*]	503 $\pm$ 90	507 $\pm$ 83	473 $\pm$ 71 [*]	414 $\pm$ 64 ^{**}	474 $\pm$ 76

(^{*}) indicates significantly different from C4 and C5 levels;

(^{**}) indicates significantly different from C3-C6 levels. Units on all measurements are milligrams per cubic centimeter (mg/cm³).

Table 2

Average ($\pm$ SD) cervical spine bone volume for radiculopathy and asymptomatic control subjects and for male and female subjects. Radiculopathy and control bone volumes were not different ($p=.392$) while male bone volume was greater than female ($p=.021$). Overall, C5 was larger than C3 ($p=.021$), C6 was larger than C3–C5 (all $p \leq .001$), and C7 was larger than all other levels (all $p<.001$). Units on all measurements are cubic centimeters (cm^3).

	C3	C4	C5	C6	C7
Radiculopathy	10.5 $\pm$ 2.1	10.7 $\pm$ 2.2	11.3 $\pm$ 2.2	12.6 $\pm$ 2.7	15.8 $\pm$ 3.0
Control	10.4 $\pm$ 1.9	10.4 $\pm$ 2.0	10.9 $\pm$ 2.2	12.2 $\pm$ 2.5	15.2 $\pm$ 2.7
Male	12.0 $\pm$ 1.9	12.4 $\pm$ 1.5	12.8 $\pm$ 2.0	13.9 $\pm$ 2.7	17.3 $\pm$ 2.9
Female	9.3 $\pm$ 1.0	9.2 $\pm$ 1.0	9.9 $\pm$ 1.4	11.3 $\pm$ 1.8	14.1 $\pm$ 1.8
All Subjects	10.4 $\pm$ 1.9	10.5 $\pm$ 2.0	11.1 $\pm$ 2.1	12.4 $\pm$ 2.5	15.4 $\pm$ 2.8

Table 3

Correlation between BMD in the central vertebral body and BMD in the lateral masses and the pedicles.

	Lateral Mass BMD		Pedicle BMD	
	correlation to central vertebral body BMD	p-value	correlation to central vertebral body BMD	p-value
C3	.684	≤.001*	.375	.086
C4	.701	≤.001*	.567	.006*
C5	.602	.003*	.429	.046*
C6	.724	≤.001*	.668	.001*
C7	.723	≤.001*	.570	.006*