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Application of geometrical measurements in the assessment of vertebral strength

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Summary

Background: The study was aimed at the development of parameters that could be used as predictors of vertebral strength. Proposed parameters describing vertebral geometry and/or shape can be established on the basis of routine spine roentgenograms, making roentgenography a novel tool for vertebral fracture risk assessment in the future.

Material/Methods: 20 human cadaveric L3 vertebrae were included in the study. Dual-energy X-ray absorptiometry (DXA) was used for an assessment of bone mineral density (BMD). Quantitative computed tomography (QCT) was performed to measure the volumetric bone density as the most reliable parameter in vertebral fracture risk assessment. Geometrical measurements were performed on the basis of high quality and high resolution computer tomography 3-dimensional images. Biomechanical tests were performed to measure vertebral strength. Two parameters were defined on the basis of extensive research: the ratio between vertebral base area and its height (A/H), and the ratio of vertebral coronal width to coronal height (W/H). Correlations between vertebral mechanical strength – its BMD, QCT density, A/H and W/H were calculated.

Results: The best correlation to bone durability was achieved for QCT density ($r=0.882$), while correlation strength for BMD ($r=0.779$) and A/H ($r=-0.773$) were comparable. W/H correlated better than BMD to mechanical strength (–0.788).

Conclusions: Geometrical parameters of vertebrae potentially measured on spine radiograms could be used as predictors of vertebral durability. The calculated correlation coefficients suggest that one of the proposed parameters works better than the commonly used BMD.

Key words: **BMD • DXA • QCT • vertebral strength • vertebral biomechanics**

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Background

Bone strength assessment is a relevant parameter in diagnostics, e.g. in osteoporosis. In practice, bone fracture risk is considered and evaluated on the basis of areal bone mineral density (BMD) measurements performed using dual-energy X-ray absorptiometry (DXA) [1–5]. Biomechanical properties of the bone depend on its composition, shape, size, as well as micro- and macro-architecture [2,6,7]. The DXA method does not assess bone complexity [8], nonetheless it is commonly used due to its simplicity, low cost and wide availability. Many investigators reported weak correlation between bone fracture risk and BMD [1], suggesting other methods for bone quality assessment.

A perfect approach seems to involve a micro-architecture analysis [2,8]. A high resolution 3-dimensional imaging of selected bone of an individual patient and its subsequent 3-dimensional reconstruction, allows for a computer simulation of bone bearing under physical loads [9]. Such attempts were made, but are currently limited to peripheral sites, because only peripheral computed tomography and peripheral magnetic resonance imaging deliver sufficient image resolutions for bone studies [9]. Micro-architecture

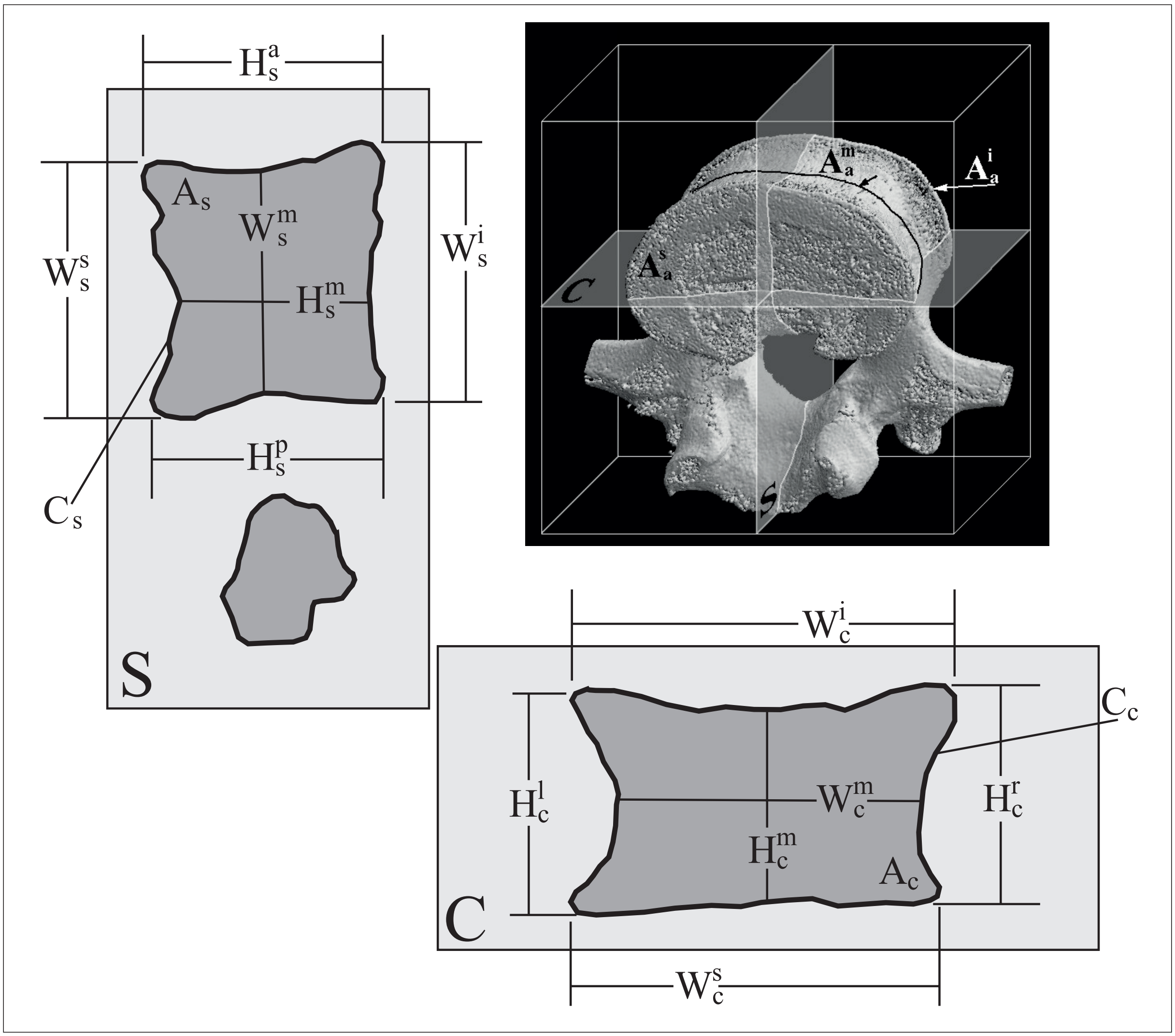

Figure 1. A schematic view of measurements of L3 presented in our study. There are two planes shown (top-right): coronal (denoted as C), and sagittal (denoted as S). Most measurements were performed in C and S planes (see text for more details) but also three axial cross-sectional areas were measured: A_a^s – axial superior base area, A_a^m – axial cross-section area of the most contracted site and A_a^i – axial inferior base area.

analysis is possible in the case of a forearm, but not in case of a hip or a spine [2,8].

Due to a limited application of micro-architecture analysis in hip and spine, morphometry could possibly be applied to support the DXA method at these locations. Promising results were achieved in femoral bone studies [5] and radiogrammetry applied to the forearm delivers results with quality comparable or higher than that of the DXA [4,10,11].

Geometrical measurements can be successfully applied in the diagnosis of vertebral fractures [1] so their application in vertebral fracture risk also seems natural. Many investigators suggested such solutions [1,6,7,12]. Diacinti et. al. [1] proposed a sum of anterior vertebral body highs (AHs) as a predictive parameter for vertebral fractures. Their *in vivo* studies proved that the AHs correlated better with the fracture risk than the BMD.

Our study aimed to propose new shape and/or size -related indexes allowing for a more reliable fracture risk prediction than the BMD in vertebra. Based on *in vitro* studies of 20 cadaveric vertebrae, two parameters were chosen as the most promising in an assessment of bone strength: (1) relation of the average vertebra base area to the average vertebra height (A/H), and (2) antero-posterior vertebral width to vertebral height ratio (W/H). In our study, CT 3-dimensional vertebral images were applied, but the adaptation of chosen parameters for reontgenography is simple. A/H and W/H can be easily measured on standard antero-posterior and lateral reontgenograms of the spine.

Material and Methods

The study was performed on 20 cadaveric L3 vertebrae taken from males aged 22 to 81 years. The wide donor age range was chosen in order to cover the entire clinically-observed BMD range. All vertebrae were embedded in 20 cm in diameter plastic containers filled with 0.9% NaCl solution to simulate soft tissue and were analyzed with computed tomography (CT), quantitative computed tomography (QCT) and DXA.

Siemens Sensation 10 (Siemens, München, Germany) CT unit was used for the CT and volumetric density measurements (QCT). Sequence studies were performed with a slice thickness of 0.6 mm and a step size of 0.1 mm. The volumetric density was calculated within the trabecular bone region by comparing the region of interest average Hounsfield unit with density phantoms. The BMD of all vertebrae was measured with Lunar DPX-IQ (Lunar, Madison, US). Standard densitometric protocol was applied.

Mechanical properties of vertebrae were tested by an Instron 5566 testing device (Instron, High Wycombe, UK). The samples were compressed by increasing the displacement of one of the bases in order to achieve the load causing the vertebrae crush. Displacement-load curves were collected and the value of the load causing vertebrae fracture (F_{max}) was registered.

After all experimental studies, the CT scans were reconstructed in 3-dimensions and morphometric measurements were done on the reconstructed images. Such approach, instead of simple geometric measurements directly on real vertebrae, had three advantages: (1) it minimized errors due to possible soft tissue residue being left on vertebral surface, (2) it was possible to choose precisely and undoubtedly the proper cross sections for measurements, and finally (3) the precise measurement of real cross-sectional area was possible and simple. There was a custom developed software used for reconstructions and measurements.

Geometrical measurements were taken in sagittal and coronal cross-sections containing the vertebral body axis. Three axial cross-sections were considered - two containing superior and inferior vertebrae base, respectively, and one containing the most contracted cross-section of the vertebral body.

Measured parameters are explained in Figure 1. Subsequent parameters were measured on the coronal cross-section: W_c^i – inferior coronal width, W_c^s – superior coronal width, W_c^m – the shortest vertebral body width in coronal view, H_c^l – left coronal height, H_c^r – right coronal height, H_c^m – smallest coronal height in coronal view, C_c – real coronal cross-section circumference, A_c – real coronal cross-section area. Similarly in the sagittal view: W_s^i – inferior sagittal width, W_s^s – superior sagittal width, W_s^m – the shortest vertebral body width in sagittal view, H_s^a – anterior sagittal height, H_s^p – posterior sagittal height, H_s^m – smallest sagittal height on coronal view, C_s – real sagittal cross-section circumference, A_s – real sagittal cross-section area.

Additionally, three axial cross-sectional areas were measured: A_a^s – axial superior base area, A_a^m – axial cross-section area of the most contracted site and A_a^i – axial inferior base area.

On the basis of biomechanical tests and geometrical measurements, the stress causing vertebral fracture (P_{max}) was calculated [8]:

$$P_{max} = \frac{F_{max}}{A_a^m} \quad (1)$$

P_{max} as the estimator of bone strength was correlated with BMD, QCT densities and with geometrical parameters by means of Pearson's correlation.

Measured geometrical parameters were combined in different ways to achieve as good correlation to P_{max} as possible. Between all, two were chosen as the best correlating: A/H and H/W defined as follows:

$$A/H = \frac{(\overline{A}_a^s + \overline{A}_a^i)}{2} \cdot \frac{6}{(H_c^l + H_c^m + H_c^r + H_s^p + H_s^m + H_s^a)} \quad (2)$$

$$W/H = \frac{W_c^m}{H_c^m} \quad (3)$$

A/H is the ratio of average vertebral base (superior and inferior) areas, to the average measured height on coronal and sagittal views. $\overline{A}_a^s$ and $\overline{A}_a^i$ are the estimated areas of superior and inferior vertebral bases instead of the real measured. Potential application of proposed parameters lies in the possibility of establishing A/H on the basis of spine roentgenograms in lateral and antero-posterior projections. Such projections allow for the estimation of sagittal and coronal heights and widths but not for the real measurements of base areas. The assumption was applied that vertebral base shapes can be approximated by an ellipse of axes measured as sagittal and coronal widths. So ASa' and AIa' are defined as:

$$\overline{A}_a^s = \frac{\pi \cdot W_c^s \cdot W_s^s}{4} \quad (4)$$

$$\overline{A}_a^i = \frac{\pi \cdot W_c^i \cdot W_s^i}{4} \quad (5)$$

Considered parameters were correlated by means of Pearson's correlation coefficient. The significance of observed differences between subsequent Pearson's correlation coefficients were tested with the use of Hotteling's test.

Results

The P_{max} parameter estimating the vertebral strength was correlated by means of Pearscon's linear correlation coefficient with QCT, BMD, A/H and W/H. Calculated correlation coefficients showed on the $p<0.001$ confidence level the statistically significant linear correlations between P_{max} and all considered parameters. QCT density presented the strongest correlation with P_{max} ($r=0.882$). BMD and A/H correlate with bone strength on similar levels ($r=0.779$ for BMD, and $r=-0.773$ for A/H) nevertheless BMD showed positive, while A/H showed negative correlations. The last parameter, W/H measured in the most narrow part of vertebrae in its antero-posterior projection correlates negatively but stronger to P_{max} than BMD ($r=-0.788$).

Table 1. Pearson's correlations coefficients calculated to judge the dependences between vertebrae strength P_{max} (the max load divided by the vertebrae axial cross-sectional area) and bone mineral density measured in the dual energy X-ray absorptiometry (BMD), real trabecular bone density measured in quantitative computer tomography (QCT) and two geometrical-shape parameters introduced in paper: A/H and W/H. For all cases p<0.001.

	QCT density	BMD	A/H	W/H
P_{max}	0.883	0.779	–0.773	–0.788

All correlation coefficients calculated for the considered parameter sets are shown in Table 1. The Hotteling's test applied for the results presented in Table 1 showed that all differences between observed Pearson's coefficient were statistically significant.

Discussion and Conclusions

It was shown in the presented study that geometric vertebral parameters can correlate well with their mechanical strength. Two parameters were delivered: A/H and W/H which describe the vertebral shape. Both correlate negatively with vertebral strength but the correlation's absolute value is as high as that achieved for BMD, which still stays as the most frequently used predictive factor in fracture risk assessment.

The higher the ratio between vertebral base size and its height is, the lower the vertebral durability is. In other words, flat vertebrae are more susceptible to fractures than non-flat. This could be explained by the changes in bone shape and size with age, which are the result of natural bone adaptation [6]. It could be also related to vertebral history. If any fractures occurred in the past influencing the vertebral shape, then future fractures are more likely. It should be pointed out that old fractures tend to increase the BMD measured in DXA, which could lead to false diagnosis.

High correlation between A/H, W/H and bone durability also suggests their potential use as good predictors of vertebral fracture, because fracture risk has to be unarguably dependent on bone strength. Such possibility is attractive, because both parameters can be established in roentgenography. A technique similar to forearm radiogrammetry could be applied in spine studies.

Our conclusions agree with the presented results [1,6,7,12] that show dependence between bones' mechanical properties and their geometrical parameters.

The presented study concerns the mechanical strength of insular *in vitro* L3 vertebrae and its correlation to the vertebral mechanical factors that could potentially be measured in roentgenometry. We have not yet considered potential errors influenced by roentgenography. Such tests as well as *in vivo* studies similar to those performed by Diacinti et. al [1] should be carried out to confirm the true relation between vertebral geometry and the risk of fracture. This should finally prove the clinical usefulness of the suggested solution.

Nevertheless, the relationship between vertebral mechanical durability and its geometry was unequivocally confirmed here.

References:

1. Diacinti D, Pisani D, Barone-Adesi F et al: A new predictive index for vertebral fractures: The sum of the anterior vertebral body heights. Bone, 2010; 46: 768–73
2. Van Der Linden JC, Weinans H: Effects of Microarchitecture on Bone Strength. Curr Osteoporos Rep, 2007; 5: 56–61
3. Lewiecki EM: Bone densitometry and vertebral fracture assessment. Curr Osteoporos Rep, 2010; 8: 123–30
4. Desai SP, Gravallese EM, Shadick NA et al: Hand bone mineral density is associated with both total hip and lumbar spine bone mineral density in post-menopausal women with RA. Rheumatology, 2010; 49: 513–19
5. Pulkkinen P, Partanen J, Jalovaara P et al: Combination of bone mineral density and upper femur geometry improves the prediction of hip fracture. Osteoporos Int, 2004; 15: 274–80
6. Briot K, Kolta S, Fechtenbaum J et al: Increase in vertebral body size in postmenopausal women with osteoporosis. Bone, 2010; 47: 229–34
7. Ruyssen-Witrand A, Gossec L, Kolta S et al: Vertebral dimensions as risk of vertebral fracture in osteoporotic patients: a systematic literature review. Osteoporos Int, 2007; 18: 1271–78
8. Crawford RP, Cann CE, Keaveny TM: Finite element models predict *in vitro* vertebral body compressive strength better than quantitative computed tomography. Bone, 2003; 33: 744–50
9. Edwards WB, Troy KL: Number crunching: how and when will numerical models be used in the Clinical setting? Curr Osteoporos Rep, 2011; 9: 1–3
10. Fonque-Aubert A, Chapural R, Miossec P et al: A comparative review of the different techniques to assess hand bone damage in rheumatoid arthritis. Joint Bone Spine, 2010; 77: 212–17
11. Özçakar L, Guven GS, Ünal S: Osteoporosis in Turkish HIV/AIDS patients: comparative analysis by dual energy X-ray absorptiometry and digital X-ray radiogrammetry. Osteoporos Int, 2005; 16: 1363–67
12. Mazzuoli GF, Diacinti D, Acca M et al: Relationship Between Spine Bone Mineral Density and Vertebral Body Heights. Calcif Tissue, 1998; 62: 486–90