GA15 / P27

Assessment of Vertebral Strength using CT-image Based Finite Element Method

Shun Wu[1], Mitsugu Todo[2]
[1]Interdisciplinary Graduate School of Engineering Sciences, Kyushu University,
[2]Research Institute for Applied Mechanics.
Email: Todo@riam.kyushu-u.ac.jp

Abstract: *Traditional diagnosis criterion of osteoporosis is mainly based on single criterion, Young Adult Mean. However, single Young Adult Mean method ignores the strength of vertebra itself, another dimension of osteoporosis. This research developed a two-dimensional osteoporosis diagnosis criterion combining Young Adult Mean and bone strength predicted by finite element analysis. It has been proven that it can reduce the misdiagnosis rate the simply using Young Adult Mean value failed to detect fracture risk. In the other hand, assessment of vertebral strength via finite element is a very complex processing, not clinically applicable. The study revealed that trabecular volumetric bone mineral density is more mechanically correlated with bone strength than Young Adult Mean. Then, the indicator to estimate bone strength without finite element analysis also been studied. For healthy vertebrae without abnormality in shape, it may be achieved by measuring Logarithmic volume ratio of Extreme low density elements.*

Keyword: Osteoporosis Diagnosis, Finite Element Analysis, Vertebral Strength.

1. Introduction

Traditional diagnosis criterion of osteoporosis is mainly based on Bone Mineral Density (BMD). Generally, there are two approaches to indicate one's BMD: areal BMD (aBMD) measured by Dual-Energy X-ray Absorptiometry (DEXA) and volumetric BMD (vBMD) calculated from Quantitative Computer Tomography (QCT). The aBMD is a readily available indicator of global bone mass (total bone mineral content) of a specific site. Further, a percentage of one's aBMD of five lumbers divided by average of young lumbers aBMD derives a value called Young Adult Mean (YAM). YAM quantify the osteoporosis as YAM < 70% [1]. However, single YAM method ignores the strength of vertebra itself, another dimension of osteoporosis. The vertebral strength correlates with lumber aBMD (YAM) well ($r^2 = 0.64$) [2]. While this correlation is not based on mechanical principles. Although global bone mass is identical, vertebral strength could change significantly due to various densitometric inhomogeneities and vertebral geometry [3]. So far, assessment of vertebral strength can be achieved by CT-image based Finite Element Analysis (FEA) well [4]. The vertebral model for FEA is usually built from CT images. The voxels of CT images can reflect the volumetric BMD (vBMD). The material properties of elements in FEA can be transferred from vBMD of voxels. Hence, vBMD has a strong mechanical correlation. According to this, this research developed a two-dimensional osteoporosis diagnosis criterion based on both YAM and FEA-predicted Bone Strength (BS), in order to reduce the possibility of misdiagnosis.

On the other hand, assessment of vertebral strength via FEA is a very time-consuming processing, and requires good understanding on mechanics. As a result, the clinical application of FEA was restricted seriously over two decades. This research is also trying to find out those factors that correlate with FEA-predicted BS well. More importantly, these factors can be obtained from analyzing CT images directly, such as spatial and number distribution of vBMD and geometric features. If it can be achieved, then, the BS can be estimated quickly but as accurate as FEA.

Above all, this research aims to (1) develop a two-dimensional criterion to diagnose osteoporosis combining YAM and BS, and (2) discover factors of vBMD inhomogeneities that correlate with BS strongly.

2. Method

2.1 Vertebral strength prediction by FEA

Department of neurosurgery, Inazawa Community Hospital supplied CT images of 88 patients (23 males, 65 females), aged from 42 to 96. YAM ranged from 32 to 142. After eliminating vertebrae with surgical treatment or fractures, total 247 vertebrae was analyzed, including 19 vertebrae of T11, 47 of T12, 51 of L1, 71 of L2 and 59 of L3. Then, a generic CT-based FEA software, Mechanical Finder Clinic (MFC, RCCM), was used to extract Region of Interest (ROI) of vertebral bodies without pedicle and generate mesh. The vBMD of elements was transferred from grey degree of voxels. Material properties was determined automatically by vBMD [5]. The load of axial compression was applied by MFC automatically, see Fig. 1. The vertebral BS was defined as the load when any element of vertebral body started to generate damage.

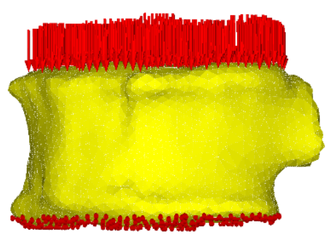

Fig. 1 load and constraint conditions. Red arrows represent load and dots mean constraints.

2.2 Measurement of vBMD inhomogeneities

Mechanical Finder (RCCM) was used to study the further vBMD distribution. MFC is a simplified version of MF. It cannot obtain vBMD distribution and specification of vertebral body. There were 26 vertebrae selected to create a more complex three-dimensional finite element model of vertebral body in MF. Mesh size and shape was determined as 1 mm and tetrahedron. The methodology of material property arrangement was same as MFC. Then, the capture tools in MF helped to calculate the average vBMD of cross-sections in transverse plane of vertebrae 1 mm by 1mm from upper to bottom surface along axial direction. Then, an axial vBMD distribution curve obtained. The trabecular area was considered by an area between local maximum values nearest to central position for upper limit and the lowest value in the curve for lower limit, as showed in Fig. 2. Trabecular vBMD (Tr.vBMD) was calculated by the average vBMD value in this trabecular area.

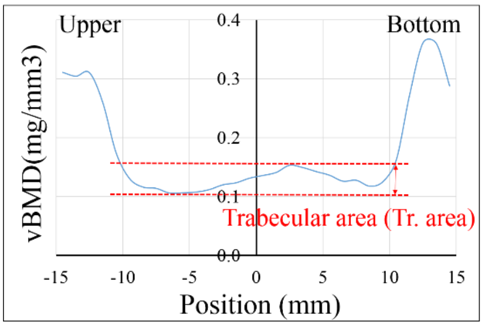

Fig. 2 The definition of Trabecular area for vertebrae.

2.3 Osteoporosis indicators

The critical YAM is 70% for diagnosing osteoporosis [1], and the critical BS was assumed as 2500 N. Therefore, two osteoporosis indicators such as the strength based OPI_{BS} and the YAM based OPI_{YAM} are defined by Equations 1 and 2, respectively.

$$OPI_{BS} = \frac{BS}{2500} \quad (1)$$

$$OPI_{YAM} = \frac{YAM}{70} \quad (2)$$

Furthermore, the Tr.vBMD based indicator $OPI_{Tr.vBMD}$ is also defined by:

$$OPI_{Tr.vBMD} = \frac{Tr.vBMD}{0.12} \quad (3)$$

where 0.12 is an osteoporotic Tr.vBMD value suggested by American College of Radiology [6].

3. Result and Discussion

3.1 2D diagnosis method for osteoporosis

Fig. 3 illustrated the proposed two-dimensional diagnosis method. Yellow area in Fig. 3 The YAM-based traditional osteoporotic area was illustrated in yellow. However, FEA displayed the existence of some vertebrae with high YAM but low BS (orange area in Fig. 3). There were 17 vertebrae and 14 patients in this area. The incidence rate was 6.9% in total 247 vertebrae, and 15.9% in total 88 patients, respectively. Only diagnosing by YAM cannot identify these vertebrae. But these has more potential that vulnerable fracture happens. It will be very dangerous if surgeries misdiagnose by the single indicator. Combination of YAM and FEA-predicted BS can reduce misdiagnosis effectively.

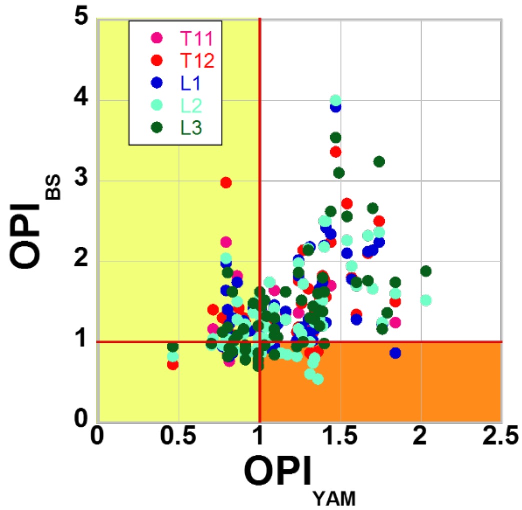

Fig. 3 Two-dimensional osteoporosis diagnosis based on OPI_{YAM} and OPI_{BS}. Vertebrae in different positions distinguish by marker colors.

3.2 vBMD inhomogeneities

To study the effect of vBMD inhomogeneities on BS, all vertebrae in Fig. 3 can be divided into 4 groups: Group A (Both YAM_{OPI} and BS_{OPI} >1), B (YAM_{OPI} >1, BS_{OPI} <1), C (YAM_{OPI} <1, BS_{OPI} >1) and D (both YAM_{OPI} and BS_{OPI} <1). The 26 vertebrae selected for the vBMD measurement in MF were evenly distributed in 4 groups, see Fig. 4(a). Then, OPI_{BS}-OPI_{YAM} relations corresponding to the 4 groups were retrieved from Figure 3 and redrawn in Figure 4 (a). The OPI_{BS}-$OPI_{Tr.vBMD}$ relations for the 4 groups are also shown in Figure 4(b).

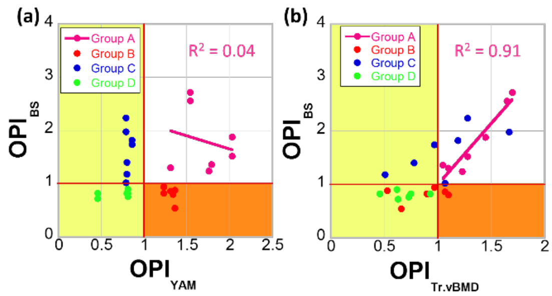

Fig. 4 (a) OPI_{BS}-OPI_{YAM} two-dimensional method. Vertebrae were divided into 4 groups. The red line displayed the correlation between BS_{OPI} and YAM_{OPI} for group A. (b) OPI_{BS}-$OPI_{Tr.vBMD}$ method. The red line displayed the correlation between OPI_{BS} and OPI_{YAM} for group A.

Based on $OPI_{Tr.vBMD}$ and OPI_{BS}, the new two-dimensional diagnosis method revealed a considerable reduction on the ratio of vertebra in orange zone from 23% to 7.7%, see in Fig. 4(b). The yellow area in Fig. 4 (b) cover more vertebrae with low strength than Fig. 4 (a). Tr.vBMD is more appropriate as a single indicator to diagnose osteoporosis.

For group A, YAM had no correlation with BS completely. Tr.vBMD linearly correlate with BS well, although such good correlation did not appear in other groups. Tr. vBMD has been proven that has a better mechanical correlation with BS. Generally, vBMD can be separated into several 4 intervals, see in Table 1. The ratio of EL can represent the degree of osteoporosis.

Table 1. Category of vBMD range

Category of	vBMD range (mg/mm^3)
Extreme Low Density, ELD	0 – 0.05
Low Density, LD	0.05 – 0.1
Middle Density, MD	0.1 – 0.2
High Density, HD	0.2 – 0.3
Extreme High, EH	> 0.3

On the other hand, the strength may change considerably due to the irregular geometry. The most common abnormality arises from Ligament Ossification (LO) and Spondylosis Deformans (SD), see in Fig. 5 (a) and (b). The existence of these abnormalities may introduce too variables for strength estimation from vBMD indicators. The orange points in Fig. 5 (c) displayed such deviation.

Therefore, excluding abnormal vertebral bodies help to understand the correlation between BS and vBMD inhomogeneities. The results revealed that a significantly linear correlation between BS and log scale of volume ratio of EL elements in vertebrae without LO and SD. Compared with FEA, the vBMD measurement in CT images could be more operative and accessible clinically. Hence, the logarithmic volume ratio of vertebral EL element show a great potential to estimate BS.

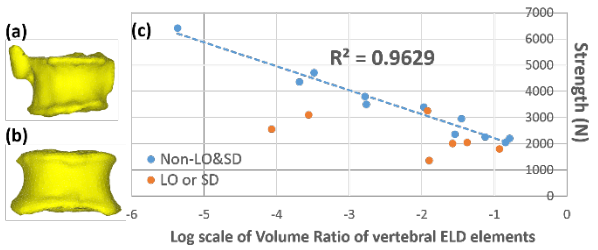

Fig. 5 (a) vertebral body with LO and (b) SD. (c) The correlation between BS and log scale of volume ratio of vertebral ELD elements. Blue and orange markers mean vertebral body without and with LO or SD respectively.

4. Conclusion

This research first developed a two-dimensional osteoporosis based on YAM and FEA-predicted BS. It helped to reduce the misdiagnosis rate that simply using YAM value failed to detect fracture risk. Then, the study revealed that Tr.vBMD is more mechanically correlated with BS than YAM. Tr.vBMD can diagnose osteoporosis better than YAM, if as a single indicator. The indicator to estimate BS directly also been studied. Logarithmic volume ratio of vertebral EL element shows a great potential. The further vBMD-related factors, such as spatial distribution, will be considered next. Following, the investigation will focus on quantifying the effect of geometric features on BS. If so, the strength of abnormal vertebrae with LO or SD can also be estimated accurately. The vertebral cases should also increase to verify the effectiveness further.

5. REFERENCES

[1] Orimo H, Nakamura T, Hosoi T, Iki M, Uenishi K, Endo N, Ohta H, Shiraki M, Sugimoto T, Suzuki T. Japanese 2011 guidelines for prevention and treatment of osteoporosis—executive summary. Arch. Osteoporos. 7(2012)3-20.

[2] Cheng XG, Lowet G, Boonen S, Nicholson PH, Van Der Perre G, Dequeker J. Prediction of vertebral and femoral strength in vitro by bone mineral density measured at different skeletal sites. J. Bone. Miner. Res. 13(1998)1439-1443.

[3] Ferretti JL, Cointry GR, Capozza RF, Frost HM. Bone mass, bone strength, muscle – bone interactions, osteopenias and osteoporosis. Mech. Ageing. Dev. 124(2003)269-279.

[4] Crawford RP, Cann CE, Keaveny TM. Finite element models predict in vitro vertebral body compressive strength better than quantitative computed tomography. Bone. 33(2003)744-750.

[5] Keyak JH, Rossi SA, Jones KA, Skinner HB. Prediction of femoral fracture load using automated finite element modeling. J Biomech. 31(1998)125-33.

[6] Radiology ACO. ACR – SPR – SSR practice parameter for the performance of musculoskeletal quantitative computed tomography (QCT). American College of Radiology, Reston.