BONE MECHANICAL STRENGTH ESTIMATION FROM MICRO X-RAY CT IMAGE

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Abstract-**QOL (Quality Of Life) in old ages has received much attention. Fracture of bones is seriously related to the QOL and is mainly caused by osteoporosis in old ages. BMD (Bone Mineral Density), an index to evaluate the mechanical strength of the bone, does not always reflect the strength. On the other hand, micro X-ray CT has revealed the inner structure of bone. Under such circumstances, an image compression technique was employed to find a better index for the evaluation. MRA (Multi Resolution Analysis) and a measure for the subband images are popular in the technique. In this study, the MRA with Harr functions and the power spectra of the subband images were employed. A linear estimation with the power spectra was performed to estimate the strength. To evaluate this method, the micro X-ray CT imaging and a destructive test of rat lumber vertebras were performed. The newly determined index is higher correlated to the bone mechanical strength than the BMD. Situation of human bone may not be so different from the rat bones. This method may be, therefore, beneficial to estimating the bone mechanical strength.**
Keywords - **Osteoporosis, micro X-ray CT, BMD (Bone Mineral Density), MRA (Multi Resolution Analysis), image compression, linear estimation**

I. INTRODUCTION

QOL (Quality Of Life) in old ages has received much attention. Fracture of bones is seriously related to the QOL because it ranks higher to be bedridden, and is mainly caused by osteoporosis in old ages. Therefore, detecting osteoporosis in early stages is important. However, to evaluate possibility of the fracture of bones itself, bone mechanical strength should be estimated. In this meaning, nondestructing test of bones is actually important.

Under the circumstances, the conventional diagnostic parameter for osteoporosis is BMD (Bone Mineral Density). However, the BMD does not always reflect the bone mechanical strength. Therefore, another closely correlated index to the bone mechanical strength should be required.

We propose an estimation method for the bone mechanical strength from a micro X-ray CT image. This method is based on an image compression technique using MRA (Multi Resolution Analysis) [1] and a linear estimation technique. We applied this method to 10 extracted lumbar vertebras of rats as a preliminary study. The parameters regarding the mechanical strength of each lumbar vertebra was separately measured by a destructive test. Correlation between the estimated and the measured bone mechanical strength parameters was evaluated.

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II. METHOD

A. Multi Resolution Analysis

MRA is quite popular technique in image processing. We have applied MRA to a section image of a bone captured by a micro X-ray CT [2]. In the MRA, 2 one-dimensional filters having exclusive passbands with respect to each other are first prepared. To simplify the explanation, those two filters are assumed to be lowpass- and highpss-filters. Second, an image, treated as a matrix $\mathbf{A}_{n,m}$ (nth individium, mth section, $n=1,2,\cdots,N$, $m=1,2,\cdots,M$), is convolved with one of filters along horizontal (row) or vertical (column) direction and then is down-sampled every two pixels. The procedure is expressed by

$$2\downarrow[\mathrm{L},\mathrm{H}]_{[\mathrm{R},\mathrm{C}]}\left(\mathbf{A}_{n,m}\right), \tag{1}$$

where $[\cdot,\cdot]$ means alternate choice. For example, if $\mathbf{A}_{n,m}$ is convolved with the lowpass filter along row and is down-sampled, then the procedure is denoted by $2\downarrow\mathrm{L}_\mathrm{R}(\mathbf{A}_{n,m})$. Usually, the MRA for images, a pair of the sequential procedures, first along row and then column, is performed. Therefore, it is described as $2\downarrow[\mathrm{L},\mathrm{H}]_\mathrm{C}(2\downarrow[\mathrm{L},\mathrm{H}]_\mathrm{R}(\mathbf{A}_{n,m}))$. Twice the down-sampling and the combinations of lowpass- and highpass-filters produce 4 images having the quarter size of the original image. Third, the same procedure can be performed recursively to produce the multi resolution subband images. Through the recursive procedures, exactly the same filters are used. However, the passband is further divided two in each procedure due to the down-sampling. The square sums of the pixels of the subband images may play role of the power spectra of the image $\mathbf{A}_{n,m}$. The power spectra have shift-invariant property. If rotation-invariant property is also required, then for example $2\downarrow\mathrm{H}_\mathrm{C}(2\downarrow\mathrm{L}_\mathrm{R}(\mathbf{A}_{n,m}))$ and $2\downarrow\mathrm{L}_\mathrm{C}(2\downarrow\mathrm{H}_\mathrm{R}(\mathbf{A}_{n,m}))$ should be treated as the same and 2 power spectra corresponding to them will be merged. Therefore, the number of the power spectra is reduced by the same treatment. Finally, the information of the original image is represented by the shift-, rotation-invariant, and merged power spectra. The power spectra, whose number is L, are denoted by vector $\mathbf{a}_{n,m}=[a_{n,m,1},a_{n,m,2},\cdots,a_{n,m,L}]^\mathrm{T}$. Note that the shift-invariant property is correct if the bone region still remains all in the image after the shift but the rotation-invariant one is not always so.

Assume that parameters regarding the mechanical strength of the same bone as captured by the micro X-ray CT are obtained by a destructive test. The parameters, whose number is K, are also denoted by vector $\mathbf{b}_n=[b_1,b_2,\cdots,b_K]^\mathrm{T}$. If a linear estimate is sought, we obtain

$$\mathbf{b}_n=\mathbf{W}^\mathrm{T}\mathbf{a}_n, \tag{2}$$

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where $\mathbf{W}$ is a $M \times K$ matrix whose columns are the weight vectors for the corresponding parameters regarding the bone mechanical strength. Now, assuming

$$\mathbf{A} = \left[\mathbf{A}_1, \mathbf{A}_2, \cdots, \mathbf{A}_{N-1}\right], \left(\mathbf{A}_n = \left[\mathbf{A}_{n,1}, \mathbf{A}_{n,2}, \cdots, \mathbf{A}_{n,M}\right]\right),$$
$$\mathbf{B} = \left[\underbrace{\mathbf{b}_1, \mathbf{b}_1, \cdots, \mathbf{b}_1}_{M}, \underbrace{\mathbf{b}_2, \mathbf{b}_2, \cdots, \mathbf{b}_2}_{M}, \cdots, \underbrace{\mathbf{b}_{N-1}, \mathbf{b}_{N-1}, \cdots, \mathbf{b}_{N-1}}_{M}\right], \quad (3)$$

(2) changes to

$$\mathbf{B} = \mathbf{W}^{\mathrm{T}}\mathbf{A}. \quad (4)$$

Using a pseudo inverse $\mathbf{A}^{-}$ of $\mathbf{A}$, we obtain

$$\mathbf{W}^{\mathrm{T}} = \mathbf{B}\mathbf{A}^{-}. \quad (5)$$

Pseudo inverse is determined under a certain criterion, to be considered later, such that $\mathbf{W}$ is optimal in the meaning by the criterion among the individiums except Nth one. If the bone mechanical strength of Nth individium $\mathbf{b}_N$ is estimated with $\mathbf{W}$ determined without any influence from Nth one, then it will be an evaluation of the effectiveness of this method. The procedure can be used any nth (not restricted in only Nth) such that the correlation coefficients between the measured and the estimated of the bone mechanical strength can be calculated for the evaluation. It makes sense because what an unknown case is estimated from known cases is a conventional diagnosis technique.

Let us now return to the criterion regarding the pseudo inverse. For this kind of overdetermined problem, least square solution is often used [3]

$$\mathbf{W}^{\mathrm{T}} = \mathbf{B}\left[\mathbf{A}^{\mathrm{T}}\mathbf{A}\right]^{-1}\mathbf{A}^{\mathrm{T}}. \quad (6)$$

We should also take importance of each spectrum $a_{n,m,l}$ (with difference of l) into account for the effective evaluation. Namely, $a_{n,m,l}$ which varies widely among individiums (with difference of n) and does not so within a individium (with difference of m) is preferable. This means that the bone mechanical strength of an individium is estimated the same from any section images of the same individium and also is estimated differently by the different individium. (Of course, if different individiums have the same mechanical strength, then $a_{n,m,l}$ is not necessary to vary.) To evaluate the importance of $a_{n,m,l}$, the matrix

$$\mathbf{C} = \mathrm{diag}\left[\frac{\mathrm{var}\left(a_{n,m,1}, n\right)}{\mathrm{var}\left(a_{n,m,1}, m\right)}, \frac{\mathrm{var}\left(a_{n,m,2}, n\right)}{\mathrm{var}\left(a_{n,m,2}, m\right)}, \cdots, \frac{\mathrm{var}\left(a_{n,m,L}, n\right)}{\mathrm{var}\left(a_{n,m,L}, m\right)}\right] \quad (7)$$

is employed. var($a_{n,m,l}$,n) (var($a_{n,m,l}$,m)) of (7) indicates variance of $a_{n,m,l}$ with difference of n (m). With (7) and a regularization for stability of the inverse matrix, (6) is modified to

$$\mathbf{W}^{\mathrm{T}} = \mathbf{B}\left[\mathbf{A}^{\mathrm{T}}\mathbf{C}\mathbf{A} + \alpha\mathbf{I}\right]^{-1}\mathbf{A}^{\mathrm{T}}\mathbf{C}, \quad (8)$$

where α and $\mathbf{I}$ are the regularization parameter and the $L \times L$ identity matrix, respectively.

III. Evaluations

A. Experiments

10 rat Lumbar vertebras (just bone hereafter) were extracted. In the 10 rats, 5 were normal and the other 5 were ovariectomy-operated. Then the bones were captured by a micro X-ray CT. The number of section image of each bone was 30 whose slice pitch was 20.7 (μm). The size and the resolution of each image were 512×512 and 25.8 (μm/pixel), respectively. For the MRA analysis, each image was decomposed up to level 3 (to be 4^3=64 subband images) by Haar functions as used for the lowpass- and highpass-filters. The square sums of the 64 subband images were merged to be the 27 power spectra in the treatment mentioned in Section II. Therefore, 27×30 power spectra were obtained per bone, and the size of $\mathbf{A}$ in (4) was 27×(30·(10–1)).

BMD, as an absorptiometry of X-ray, was approximated by the micro X-ray CT image. Here, we used the square sum of each micro X-ray CT image as the BMD. Replacing $\mathbf{A}$ by $\mathbf{A}'$ using the BMD, the size of $\mathbf{A}'$ was 1×(30·(10–1)). The estimation with $\mathbf{A}'$ apparently changed to underdetermined such that

$$\mathbf{W}^{\mathrm{T}} = \mathbf{B}\mathbf{A}'^{\mathrm{T}}\left[\mathbf{A}'\mathbf{A}'^{\mathrm{T}}\right]^{-1} \quad (9)$$

was used instead of (8). The proposed method can be compared with the BMD by the difference of the estimation results from (8) and (9).

On the other hand, a destructive test (compression versus deformation) of the extracted bones was separately performed to obtain the bone mechanical strength parameters, cut power, elasticity, perseverance, and maximum load. Then all parameters were normalized by a parameter of a bone. Consequently, the size of $\mathbf{B}$ in (4) was 4×(30·(10−1)).

B. Results and Discussions

Figs. 1(a) and (b) show a typical micro X-ray CT image of a normal rat bone (a) and its MRA images (b). Complicated structure of trabecular bone can be seen in Fig. 1(a). The original bone structure can be recognized in some subband images located around top left corner in Fig. 1(b). It is because the low frequency bands gather around the corner and maintain the approximate shape of the bone.

Figs. 1(c) and (d) show typical power spectra of a normal and an ovariectomy-operated rat bones, respectively. Those are stack plots of the power spectra from all the 30 sections. The numbers of the frequency bands are lined in frequency ascending order. The frequency bands whose power spectra are vertically spread indicate the within-bone variance of power spectra is wide.

On the other hand, Fig. 1(e) shows the stack plots of the power spectra for all the 10 rat bones. A typical power spectra is picked up from 30 ones within the same rat bones. The blue and red lines indicate the power spectra from the normal and the ovariectomy-operated rats, respectively. The secondly drawn blue lines almost overlapped with the firstly drawn red lines such that the evaluation for the bone mechanical strength qualitatively is difficult. The frequency bands whose power spectra are vertically spread indicate the inter-bone variance of power spectra is wide.

The variance ratio calculated from Figs. 1(c), (d), and (e) reflect the matrix $\mathbf{C}$ in (7). Note that Figs. 1(c), (d), and (e)

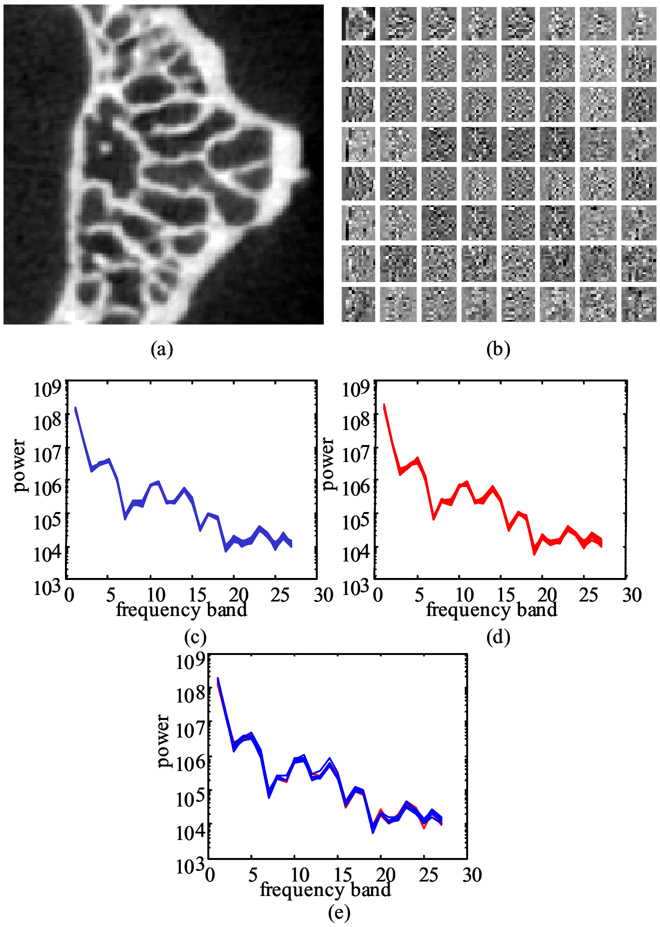

Fig. 1. A micro X-ray CT image, the MRA images, and the power spectra. (a) Typical micro X-ray CT image of image of a rat lumber vertebra. (b) The subband images of (a) by the MRA. (c) The power spectra stack plots of the MRA image of a normal rat bone. (d) The same as (c) except of an ovariectomy-operated rat. (e) The power spectra stack plots of the MRA images of all the 10 rat bones. In (c)-(e), blue and red indicate normal and ovariectomy-operated, respectively. Those power spectra are similar with respect to each other such that the qualitative evaluation for the bone mechanical strength is difficult.

are displayed by vertical semilog plots such that the apparent vertical width does not directly mean the variance.

Fig. 2 shows the estimation results of the bone mechanical strength from the micro X-ray CT images and the approximated BMD. Top left, top right, bottom left, and bottom right parts correspond to the estimation results regarding the bone mechanical strength parameters, cut power, elasticity, perseverance, and maximum load, respectively, as shown in the corresponding graphs. The parameters of the bone mechanical strength are normalized such that the units of the axes are absolute numbers. The red and blue marks indicate, as the same in Fig. 1, the normal and the ovariectomy-operated rats, respectively. The circles and crosses indicate the estimation results from the micro X-ray images (the proposed method) and from the BMD, respectively. The error bars indicate the standard deviation of the difference of the 30 section images. The blue and red marks are almost horizontally exclusively except in case of elasticity such that the ovariectomy operation closely relates

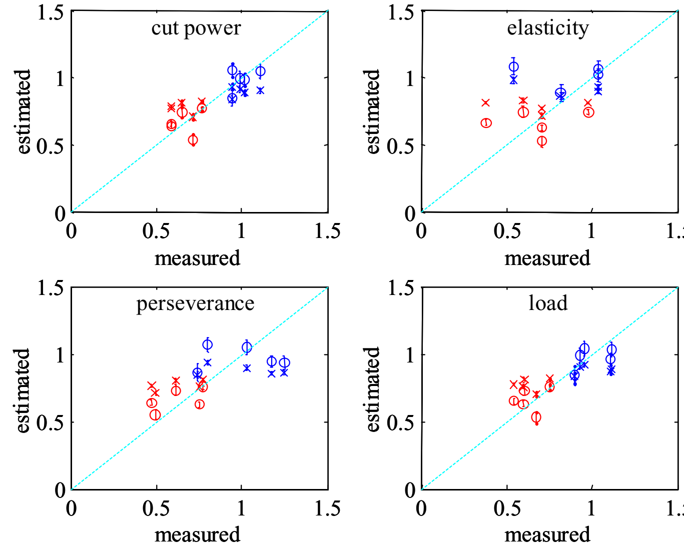

Fig. 2. Estimation results of the bone mechanical strength from the micro X-ray CT (circles) images and the BMD (crosses) approximated by the square sum of the pixels of the micro X-ray CT images (blue : normal, red: ovariectomy-operated). Left top, right top, left bottom, and right bottom correspond to the bone mechanical strength parameters, cut power, elasticity, perseverance, and load, respectively (as shown in the corresponding graphs).

TABLE I
CORRELATION COEFFICIENTS BETWEEN THE MEASURED AND THE EVALUATED

	cut power	elasticity	perseverance	max. load
micro X-ray	0.89	0.43	0.73	0.88
BMD	0.82	0.13	0.64	0.79

to the bone mechanical strength. The estimation results are also demonstrated by the correlation coefficients between the estimated and the measured bone mechanical strength parameters shown in Table I. From Fig. 2 and Table I, the results from the micro X-ray CT are more closely correlated to the bone mechanical strength than those from the BMD. However, elasticity is difficult to estimate from both of them. The reasons are expected as follows. The bone mechanical strength may consist of 3 factors, quality, quantity, and structure. Although the BMD is sensitive only to the quantity factor, the micro X-ray CT is so to not only the quantity but also the structure factors. Therefore, the estimation results from the micro X-ray CT are better than those from the BMD. However, both measurement techniques are based on absorptiometry using X-ray. X-ray may not be sensitive to the quality factor. If elasticity may depend on the quality factor on the contrary, then the estimation results from both of them become poor. For the highly correlated estimation to elasticity, one would try to extract the quality information by a nonlinear estimation. If, actually, monotonic nonlinear functions such as log-energies, entropies, and etc. were used for the measure of the subband images instead of the power spectra, then the estimation results were significantly changed. However, such nonlinear methods were not unstable with choice of the bone section image. The other measurement technique instead of using X-ray is worth being considered. First of all, we plan to use an ultrasound measurement and its fusion methods with using X-ray in the near future.

IV. Conclusion

We propose a method for estimating a bone mechanical strength from a bone section image captured by a micro X-ray CT. The method is outlined as follows. Not only the micro X-ray imaging but also the destructive test (compression versus deformation) is performed to obtain the bone mechanical strength parameters, cut power, elasticity, perseverance, and maximum load. Those above are the preparations. First, MRA with Haar functions up to level 3 is applied to the micro X-ray CT image. The MRA generates the 64 subband images. Second, a measure for each subband image is designed. In this step, taking the order of the convolution with the lowapass- and highpass-filters into account, some subband images should be treated as the same in the meaning of frequency. It indicates, from another viewpoint, that a rotation-invariant measure should be used. Therefore, the 64 subband images are merged to the 27 subband ones and the square sum of each subband image is calculated as the power spectrum. Third, weight matrix is calculated by a linear equation between the power spectra and the bone mechanical strength. Finally, the linear estimation based on the linear equation is performed to a micro X-ray CT image that has not been used for the weight matrix calculation. It makes sense because what an unknown case is estimated from known cases is a conventional diagnosis technique.

As a preliminary study, this method was applied to 10 extracted lumbar vertebras of rats (5 normal and 5 ovariectomy-operated). The correlation between the estimated bone mechanical strength and the measured ones were evaluated. As the results, the proposed method could successfully estimate the bone mechanical strength except elasticity. The correlation coefficients were high comparing with the estimation results from the BMD. Note that the BMD was approximated by the micro X-ray CT images. The estimation for the elasticity is future work.

Situation of human bones may not be so different from rat bones. This method may be, therefore, beneficial to estimating the bone mechanical strength.

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