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Trabecular architecture analysis in femur radiographic images using fractals

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Abstract

Trabecular bone is a highly complex anisotropic material that exhibits varying magnitudes of strength in compression and tension. Analysis of the trabecular architectural alteration that manifest as loss of trabecular plates and connection has been shown to yield better estimation of bone strength. In this work, an attempt has been made toward the development of an automated system for investigation of trabecular femur bone architecture using fractal analysis. Conventional radiographic femur bone images recorded using standard protocols are used in this study. The compressive and tensile regions in the images are delineated using preprocessing procedures. The delineated images are analyzed using Higuchi's fractal method to quantify pattern heterogeneity and anisotropy of trabecular bone structure. The results show that the extracted fractal features are distinct for compressive and tensile regions of normal and abnormal human femur bone. As the strength of the bone depends on architectural variation in addition to bone mass, this study seems to be clinically useful.

Keywords
Trabecular bone, Higuchi's fractal analysis, osteoporosis, porosity, texture analysis

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Introduction

Bone can be characterized as a dynamical tissue that adapts to continuously varying loading conditions to maintain the skeletal integrity. The bone strength and fracture resistance of the skeleton depend on the mass, architecture and geometric and material properties of the tissues.[1–3] The size, shape, orientation and spatial distribution of the bones are to be optimal for their structural strength and functions.[4] Factors such as age, trauma and disease process affect the tissue properties leading to changes in bone strength. Structural and mechanical analyses performed on bones demonstrate differences in their strength and fracture risk independently of bone mineral density.[5]

Analysis of bone strength is complex as trabecular changes are localized and the magnitudes of early changes are not highly correlated to apparent density.[6] Bone structure analysis plays an important role to determine the architectural changes and indirectly to assess parameters that provide surrogates for diagnosis.[7] The evaluation of femur bone strength depends not only on bone mineral content but also on the qualitative and geometric parameters such as hip axis length, neck-shaft angle and neck diameter.[8] No single measurement is used fully to characterize the structural integrity of bone or predict the occurrence of a fracture.[9] It has been found that radiological techniques have been widely used to provide quantitative information on the bone structure[10]

Conventional radiographs are commonly used to exploit the information of trabecular texture patterns in human femur specimens.[11] However, the texture analysis methods are less sensitive to changes in spatial variation. Hence, nonlinear mathematics is used to extract the texture patterns from femur bone images. The radiographic projection images are not only spectrally and spatially complex, but they often exhibit certain

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similarities at different spatial scales. Fractal geometry is proved to be a useful tool in quantifying the microstructure of complex images.[12] It has the property of describing such complex images by a directly computed result called fractal dimension.[13–15]

The fractal dimension is a quantitative measure of self-similarity and scaling. Studies have shown that the changes in this value are associated with changes in structural properties.[16] Assessment of trabecular microarchitecture using texture and fractal methods is shown to have potential clinical applications. In recent years, fractal analysis of plain radiographs has been employed to assess the trabecular structure and to demonstrate the increased risk of fracture in osteoporosis. It has been shown that the evaluation of structural parameters using fractals may have a complementary role in predicting bone strength.[17] Hence, there has been considerable research interest in various fractal methods of image analysis for assessing trabecular structures in radiographs of femur bones.

It has been reported by several authors that a significant correlation exists between apparent porosity or mineralization derived from X-ray radiographs and equivalent parameters of three-dimensional (3D) images.[18–22] Hence, in this work, an attempt has been made to analyze apparent compressive and tensile strength of normal and abnormal human femur bones in conventional radiographic images using fractal-based analysis.

Methods

Forty pelvis images recorded using clinical X-ray units are considered in this study. The standard anterior–posterior view is used to image all subjects, and the recorded radiographs are digitized using an AGFA digitizer. Auto threshold binarization algorithm is then employed to recognize the presence of mineralization in the digitized images. This process minimizes the information loss and is suitable for trabecular images.[23]

A delineation method proposed by Singh et al.[24] is used to identify the compressive and tensile regions. In this study, regions of interest corresponding to the compressive and tensile regions are cropped using windows of constant size of 300 × 150.[25] The quantitative analyses are also performed on the delineated images to derive apparent porosity and total area. The percentage of apparent porosity is taken as the ratio of void area to the total area. This ratiometric analysis is considered to avoid image artifacts, magnification and poor resolution.

Two-dimensional femur bone images are preprocessed to form one-dimensional landscapes of the image contour and then their complexity is analyzed. By stepping through a gray value image of length of N pixels and height of M pixels row by row, the sum of the gray values in each row, G_m ($m = 1, \ldots, M$), is calculated. The sum values are normalized by using the largest among them (G_{mmax}), and this series of numbers, called horizontal landscape, is given by

$$NGS_m = \frac{G_m}{G_{mmax}} \quad (m = 1, \ldots, M) \tag{1}$$

Higuchi's fractal dimension D_f is calculated directly from these data, without embedding them in a phase space. The total length $L(k)$ of the curve defined by every kth point is evaluated and fractal dimension D_f is determined from the scaling that $L(k)$ is proportional to k^{-D_f}. This procedure is repeated for several k values, and Higuchi's fractal dimension D_f is obtained from the log–log plot of L versus k using the least squares method.[26]

Similarly, stepping through the same image column by column ($n = 1, \ldots, N$), the sum of the gray values in each column, G_n ($n = 1, \ldots, N$), is calculated. The sum values are normalized by using the largest of those values G_{nmax}, and this series of numbers, called vertical landscape, is given by

$$NGS_n = \frac{G_n}{G_{nmax}} \quad (n = 1, \ldots, N) \tag{2}$$

Diagonal landscape is constructed using a similar counting technique, stepping through the same image in a diagonal direction. Higuchi's fractal dimension is calculated from horizontal, vertical and diagonal landscapes.[27]

Results

Representative planar radiographic images of normal and abnormal femur trabecular bones are shown in Figure 1(a) and (b), respectively. The trabecular patterns are distinct and are closely arranged in normal images. In abnormal samples, trabecular spacing is large with high discontinuities. The overlap between trabeculae is found to be less in abnormal when compared to normal images. The images are processed with Singh index delineation method to identify the (1) compressive region and (2) tensile region[24,25] as shown in Figure 1(c).

The compressive and tensile strength regions of femur bone are preprocessed to form one-dimensional landscapes of the image contour in horizontal, vertical and diagonal directions. Higuchi's fractal dimension D_f is calculated from the corresponding landscapes for quantifying the heterogeneity and anisotropy of trabecular femur bone.

The means of fractal values of various landscapes of compressive and tensile regions are presented in Table 1. In normal subjects, vertical landscape and horizontal landscape provide low fractal values for compressive and tensile regions, respectively. This could be due to homogeneity of the trabecular patterns. The diagonal landscape provides high fractal values in both the regions of abnormal subjects. These fractal values

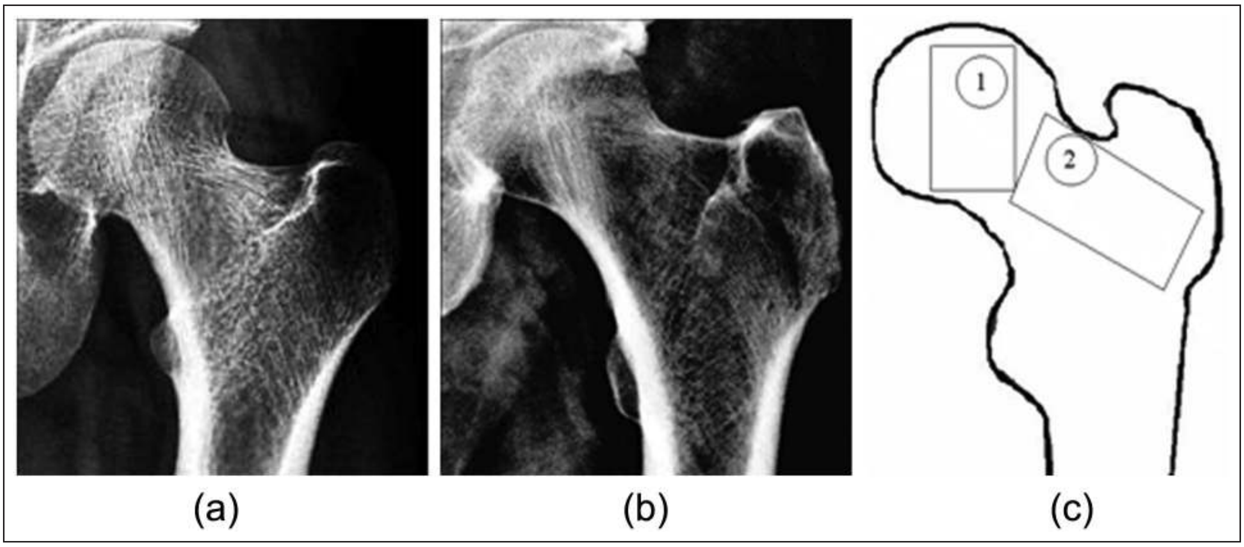

Figure 1. (a) Normal bone, (b) abnormal bone and (c) representative strength region.

Table 1. Normalized mean Higuchi's fractal dimension values for compressive and tensile regions.

Region of interest	Compressive region			Tensile region		
Higuchi's fractal dimension	Horizontal landscape	Vertical landscape	Diagonal landscape	Horizontal landscape	Vertical landscape	Diagonal landscape
Normal	0.85	0.74	0.96	0.85	0.90	0.92
Abnormal	0.84	0.75	0.94	0.85	0.86	0.90

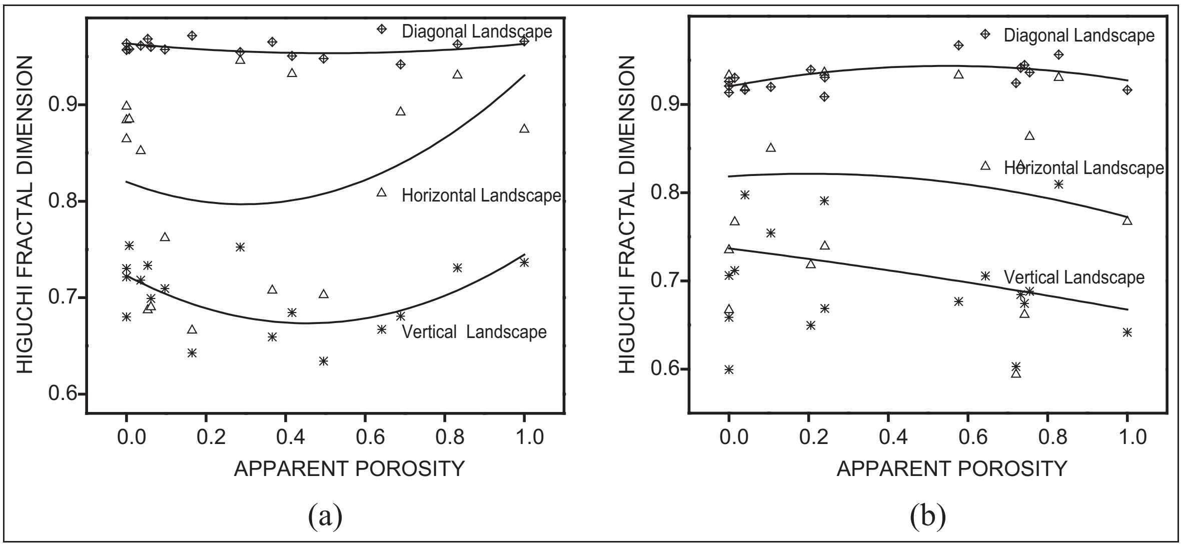

Figure 2. Variations of fractal values with porosity in compressive regions of (a) normal and (b) abnormal subjects.

appear to reflect anisotropy of the trabecular structure. The overlap in fractal values of various landscapes between normal and abnormal subjects may be due to heterogeneous and complex biomechanical behavior of bones.

The variations in the fractal values for the observed apparent porosity are shown in Figures 2 and 3. The scattergrams showing the variations of Higuchi's fractal values of horizontal, vertical and diagonal landscapes with porosity of compressive region for normal and abnormal subjects are shown in Figure 2(a) and (b), respectively.

Fractal dimension values are found to be distinct for all the three landscapes in both normal and abnormal

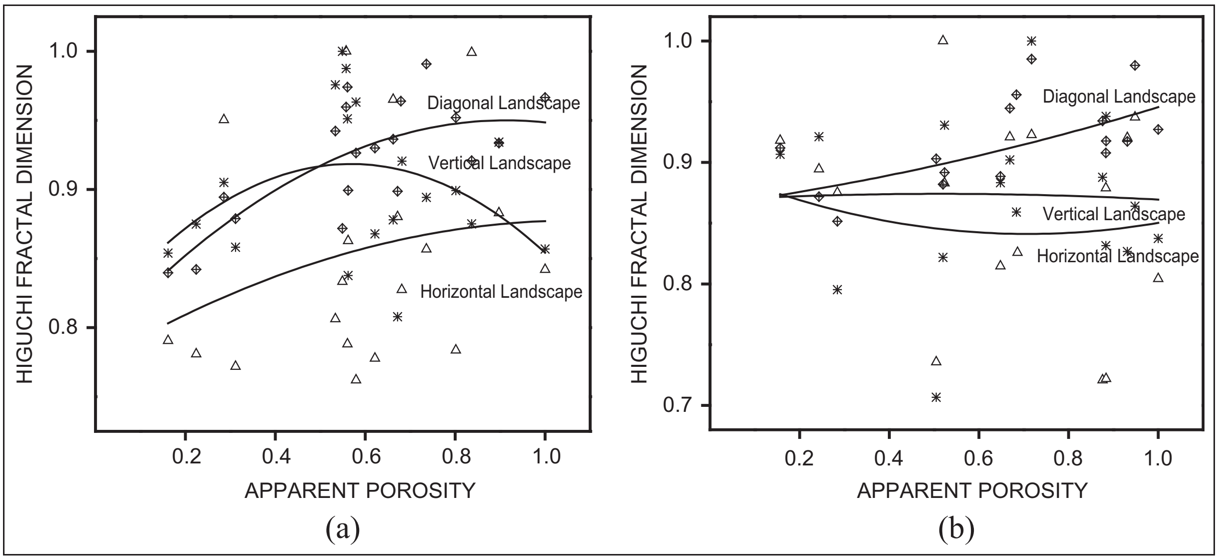

Figure 3. Variations of fractal values with porosity in tensile regions of (a) normal and (b) abnormal subjects.

Table 2. Correlation values of Higuchi's fractal dimension with porosity of compressive and tensile regions.

Region of interest	Compressive region			Tensile region		
Higuchi's fractal dimension	Horizontal landscape	Vertical landscape	Diagonal landscape	Horizontal landscape	Vertical landscape	Diagonal landscape
Normal	0.37	0.58	0.60	0.27	0.37	0.76
Abnormal	0.14	0.25	0.66	0.09	0.62	0.63

images. The fractal dimension is found to be high for diagonal landscape and is low for vertical landscape. In normal subjects, the correlation between fractal values with apparent porosity is found to be high for diagonal and vertical landscapes. The magnitude of fractal values of diagonal landscapes is high for abnormal subjects, which could be due to reduction in bone mass and altered structural integrity. Also, the correlation between fractal values with apparent porosity is found to be high for diagonal landscape.

The scattergram showing the fractal values of horizontal, vertical and diagonal landscapes derived from tensile region for normal and abnormal subjects is shown in Figure 3(a) and (b), respectively. The fractal values of horizontal landscape for normal subjects are low and vary widely with porosity. There is no distinct variation between fractal values of vertical and diagonal landscapes. The fractal values of diagonal landscape increase with increase in porosity values and are found to have better correlation.

The fractal values of various landscapes for abnormal subjects are found to be high. This demonstrates the ability of fractal analysis to characterize inhomogeneity of trabecular structure. The high values of fractals are considered to be indices of higher structural complexity. The scatter in fractal values of horizontal landscape is found to be more. The fractal values of vertical and diagonal landscapes are observed to have better correlation.

The correlation of fractal values of various landscapes of compressive and tensile regions with the porosity of normal and abnormal subjects is presented in Table 2. In compressive and tensile regions, the fractal values of diagonal landscape provide better correlation for both normal and abnormal subjects. Hence, it appears that these fractal values could be used as a discriminative measure. However, the fractal values of horizontal landscapes of compressive and tensile regions have poor correlation for both normal and abnormal subjects. The fractal values of vertical landscape have better correlation for compressive region of normal subjects and tensile region of abnormal subjects. These fractal values appear to characterize trabecular alterations along the loading lines of force.

The landscape fractal values extracted from compressive and tensile regions of femur bone images are compared using *p*-test significance. The differences in values of horizontal landscapes ($p < 0.2$) and vertical landscapes ($p < 0.05$) for normal and abnormal images are found to be statistically significant for compressive and tensile regions. However, the differences in fractal values of diagonal landscapes appear to be statistically highly significant ($p < 0.005$) for compressive and tensile regions.

Conclusion

Characterization of trabecular architecture is an essential component in the analysis of bone strength. Various morphological methods have been employed to analyze trabecular structure alterations.[28,29] Fractal-based analysis is one of those measures, which has been used to quantify the complexity of this structure.[17] In this work, Higuchi's fractal dimension method is employed to analyze the structural architecture in human femur bone radiographic images. The regions of interest of the considered images are delineated using Singh index method. Apparent porosity is derived from these regions. Higuchi's fractal values are computed for horizontal, vertical and diagonal landscapes of normal and abnormal strength regions and are correlated with apparent porosity. The results show that Higuchi's fractal method is able to represent architectural variations in compressive and tensile regions of femur bone radiographic images. Fractal values of vertical landscape show better correlation for compressive region in normal images. It is observed that fractal dimension calculated using diagonal landscape shows better correlation with porosity in both strength regions. It appears that these fractal features could be the adjunct parameter for the estimation of bone mass as they reflect the spatial architectural characteristics of the trabecular bone. As automated analysis of trabecular architecture is important for mass screening and monitoring of osteoporosis-like disorders, this study seems to be clinically highly significant.

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Conflict of interest

The authors report no conflicts of interest. The submitted article was not yet published in whole or in part in any other journal or is not under consideration for publication elsewhere. Also, the submitted text is a reliable work of all mentioned authors.

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