Assessment of Fourier Tools for Cancellous Bone Structure Analysis

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Abstract

The usefulness of Fourier analyses as a tool for determining key parameters of cancellous bone structure is investigated. The autocorrelation function is used to determine measures of preferred orientation of trabeculae and anisotropy. Peaks in the power spectrum are used to determine average trabecular strut spacing. Good agreement and high correlations were observed when these frequency domain measurements were compared to currently used histomorphometric parameters. The most attractive feature of frequency analyses is the elimination of segmentation and the resulting bias inherent in current methodologies. The potential for obtaining structural information from frequency analyses is demonstrated and merits further exploration.

1. Introduction

Bone mineral density (BMD) is a major component in determining the mechanical properties of cancellous bone [1]. However, there is a substantial amount of overlap in BMD measurements for individuals with and without fractures at cancellous bone sites [2]. Given this overlap, other factors in addition to BMD must contribute to the overall mechanical properties of cancellous bone. It is generally accepted that these "other factors" have to do with bone architecture, or how the bone mass is distributed.

In order to quantify bone architecture, a number of parameters have grown out of traditional two-dimensional (2D) histomorphometric methods, and more recently been applied to three-dimensional (3D) micro-computed tomography (μCT) images. These parameters typically include measures of bone surface area, trabecular thickness (Tb.Th), trabecular separation (Tb.Sp), trabecular number and degree of anisotropy (DA) [3].

A study by Ulrich et al. using 3D structural analysis of μCT scans and micro-finite element analyses, found that the prediction of elastic constants (Young's modulus and shear modulus) of various cancellous bone specimens was improved when one or more of these structural parameters was included with bone density [4]. In the best case, regression r^2 values were increased from 53% (bone density alone) to 92% with the inclusion of Tb.Sp and DA.

Although structural parameters have shown some promise towards improving the prediction of bone properties, these methods involve segmentation of images, turning each voxel into "bone" or "marrow" values, effectively reducing the amount of information in the images and biasing subsequent quantitative analyses. Alternatively, simple frequency analyses may be a potentially useful tool for looking at image features, eliminating the need for segmentation.

The purpose of this pilot study is to assess whether parameters obtained in the frequency domain are related to the key structural parameters of spacing and anisotropy. Two different frequency analyses using fast Fourier transforms (FFT) of μCT datasets are investigated. First, the autocorrelation function is computed from the FFT and used to determine preferred orientation and a measure of anisotropy. Second, key frequency components from the FFT are used to obtain a measure of trabecular strut spacing. Both analyses are compared, where possible, to parameters obtained from conventional histomorphometric analyses.

2. Methods

All image data was obtained using a high resolution desktop micro-computed tomography machine (SkyScan, Aartselaar, Belgium) with a resolution of 15.63 microns. Datasets were analysed using the bundled CTAnalysis (CTAn) software (version 1.03) as recommended by the manufacturer.

Software routines for all frequency analyses were implemented in Matlab software (MathWorks Inc., Natick, MA), utilizing built in FFT functions on unaltered image data. All image processing was done using a standard desktop PC (P4, 3 GHz processor).

2.1 Anisotropy & orientation

Measures of anisotropy and preferred orientation of trabeculae were obtained through applying the autocorrelation function (ACF). The ACF describes the correlation of an image with itself when displaced in all directions; values remain high along directions parallel to preferred orientation, but decay rapidly where features are short. The ACF is well defined in object space, however, computation in much simplified in the frequency domain. ACF is usually applied in the context of image enhancement, but has more recently been used as a quantitative tool in the field of geophysics for the fabric analysis of rock grains on 2D images [5].

Although applicable to 2D and 3D image sets, as a first step the ACF was applied to 2D images of spine specimens (pixel area: 512x512). Two spine sections were chosen which exhibited either no clear preferred trabecular orientation (Figure 2a) or an obvious preferred trabecular orientation (Figure 3a). The second specimen image was also rotated anti-clockwise by 45 degrees to test the ACF calculated parameters with a known rotation (Figure 4a).

Once the ACF was computed, a binary image was created with data points valued greater than 35% of the total range to yield a representative “elliptical” shape for the ACF. From these data points, a measure of anisotropy was determined by computing the ratio of minimum eigenvalue to maximum eigenvalue (Vmin/Vmax), where a value of 1 represents complete isotropy and 0 complete anisotropy. Preferred orientation was also computed from the eigenvector corresponding to the maximum eigenvalue and was compared with calculations of “total orientation” obtained from the CTAn software. For a 2D image, CTAn computes the “total orientation” parameter using a weighting scheme on orientations from each “individual” trabecula in the image after segmentation.

2.2 Trabecular strut spacing

For the initial tests using FFTs to determine trabecular strut spacing, a set of ten open-celled aluminium foam specimens (ERG Aerospace, Oakland, CA) was scanned and analysed. These foams are a reasonable model of cancellous bone and are generally isotropic in structure (see Figure 1). As shown in Table 1, the foams were specified to have a one of three average pore sizes (10, 20, or 40 pores per inch) and within each pore size category, a range of apparent densities, given as a percentage of the total volume, was also specified.

Table 1. Aluminium foam sample descriptions

Specimen	Pores per inch	Apparent densities (%)
1-3	10	2.46, 7.30, 11.08
4-7	20	3.97, 6.93, 10.73, 11.19
8-10	40	4.06, 6.92, 11.90

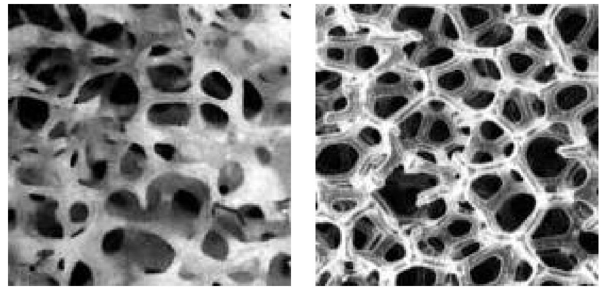

Figure 1. a) Cancellous bone specimen, b) Open-celled metal foam sample

MicroCT scans of each foam specimen were taken. Volumes equivalent to 400x400x400 voxels were extracted from the centre of each data set and 3D FFTs and corresponding power spectra were computed. The major frequency components were identified from the peak power values. As a first estimate of major trabecular strut spacings, the first 30 peak frequencies were selected, converted to equivalent period in terms of pixels and then averaged and compared with the sum of Tb.Sp and Tb.Th parameters determined from CTAn. The sum of Tb.Sp and Tb.Th was used as an estimate of the mean peak-to-peak distances in the data similar to what one would expect to be measured by Fourier analyses. As the foams are also expected to be fairly isotropic, directionality of the frequencies was not included in the analyses.

3. Results

3.1 Anisotropy & orientation

The 2D spine images and their associated ACF shapes are displayed in figures 2-4. In order to more easily evaluate the shape of the ACF visually, the values are plotted as contours and an enlargement focused on the central quarter of the ACF is shown. The values greater than 35% of the total range that are used in the eigenvalue calculations fall within the regions enclosed by the fourth contour.

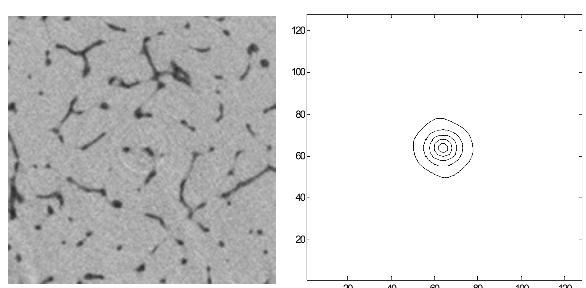

Figure 2. a) Spine specimen with no clear preferred orientation of trabeculae, b) ACF contour plot of central region

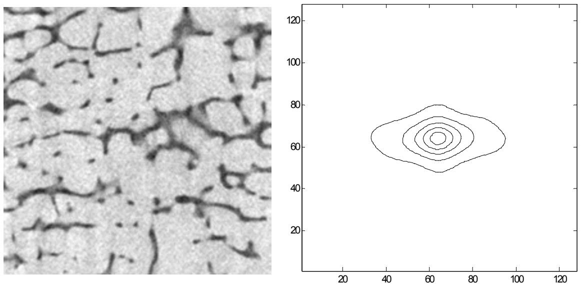

Figure 3. a) Spine specimen with primarily horizontal orientation of trabeculae, b) ACF contour plot of central region

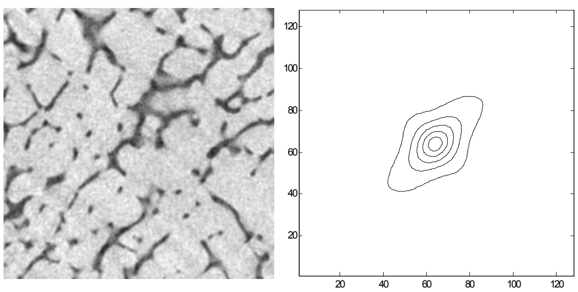

Figure 4. a) Spine specimen from 3a, manually rotated by 45°, b) ACF contour plot of central region

The calculated eigenvalue ratio (Vmin/Vmax), the preferred orientation (direction of Vmax), and the "total orientation" values from CTAn are given in Table 2. In the first spine specimen, the Vmin/Vmax value near 1 indicates high isotropy as predicted from visual inspection. Although a preferred direction is computed for this specimen, orientation varies significantly with small changes in contour levels since the shape is near circular; unsurprisingly, the value is quite different from the CTAn orientation. In contrast to this, the second spine specimen Vmin/Vmax value indicates more anisotropy. The preferred trabecular orientation computed from the maximum eigenvalue lies close to the horizontal axis (0°) as one might expect from visual inspection. The CTAn calculated "total orientation" angle is further from the horizontal, but still in that general direction; however this parameter combines the orientations from the individual trabeculae segments which can vary greatly with threshold selection, particularly in the smaller segments.

The manually rotated image yields a similar Vmin/Vmax value to the original, and a preferred orientation only 0.57° from the predicted value of 47.49°. Slight differences are expected as the specimen areas are not exactly identical; the larger 1024x1024 original image was rotated and the central 512x512 area was extracted to avoid artefacts due to the shape of the region. The CTAn orientation was 2.52° from the predicted value of 35.37°.

Table 2. Anisotropy & preferred orientations

Specimen	Vmin/Vmax	Preferred orientation	CTAn "total orientation"
Spine 1	0.94	-28.10°	34.24°
Spine 2	0.38	2.49°	-9.63°
Spine 2 rotated 45°	0.43	47.86°	37.89°

3.2 Trabecular strut spacing

The plot of the average period from the 30 Fourier components with the highest magnitude versus the sum of Tb.Sp and Tb.Th from CTAn for the 10 aluminium foam specimens is shown in Figure 5. Simple linear regression analysis indicates a significant relationship with r^2 =0.92, p<0.001.

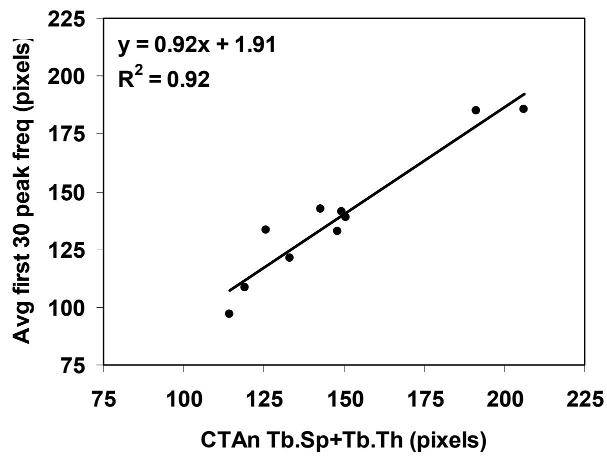

Figure 5. Average peak-to-peak distances from FFT calculations vs. CTAn parameters

4. Discussion

The objective of this study was to assess the ability of parameters obtained in the frequency domain to quantify key aspects of cancellous bone structure. The potential usefulness of the ACF as a tool for quantifying anisotropy and preferred orientation of trabeculae has been demonstrated. Although the ACF was only applied to 2D images in this study, it should be fully applicable to 3D datasets and will be applied in future studies.

It has been observed that there is a preferential resorption of horizontal trabecular struts in vertebral bodies with increasing age [6]. A previous study applying spatial autocorrelation specifically in horizontal and vertical directions to 2D magnetic resonance images of the calcaneus indicated measurable differences between a normal and an osteoporotic individual [7]. A preferential loss in struts should be detectable with ACF analyses and application of this method with representative 3D bone specimen datasets should be explored. Analyses could be focused on the structural parameters in the preferred direction or alternately, in the least preferred direction, as this indicates the "weakest" direction in terms of structure. It should also be noted that the ACF is a global method and any local anisotropy is averaged out. It may be useful to explore applying ACFs to smaller subsets throughout the volume for identifying these local differences.

A contour level of 35% of the total range was selected as there was general stability in the orientation and anisotropy values around this level for the anisotropic spine specimen. In future applications, anisotropy and orientation may be computed over a range of contour levels to select the most appropriate cut-off level. A physical or virtual 3D model with variable degrees of anisotropy would also be useful in the further development of the ACF as a quantitative tool.

The potential of using major Fourier components to determine a measure of strut spacing in 3D has also been demonstrated. Using the isotropic aluminium foam specimens, a significant relationship was found with the mean of the first 30 peak frequency periods and the equivalent measure from standard histomorphometric quantitation (Tb.Sp+Tb.Th). Further testing is required to see if this relationship will hold for highly anisotropic materials, or whether only peak frequencies along preferred/principal directions are key. Some limited application of power-spectral analysis has previously been done with 2D FFTs on plain radiographs to summarize orientations and sizes in the trabecular pattern [8]. However, to our knowledge, FFT analysis has not been used on 3D datasets to extract structural information as described in the present study.

In currently used techniques for structural analysis, segmentation is required for the 3D reconstruction of cancellous bone specimens upon which the subsequent structural parameter calculations are based. Proper image segmentation is not a trivial step in the quantification process and remains the topic of much research and development. Analyses in the frequency domain are particularly attractive because no segmentation is needed, eliminating any bias associated with identification of the bone and marrow boundaries.

In contrast to the many complex algorithms used in analyses based on 3D reconstructions [3], the Fourier tools evaluated are simple and straightforward to implement. Matlab was utilized in this study for its availability and convenience, with built in image file handling, FFT and inverse FFT routines. However, Matlab's memory handling limited the size of 3D matrices and consequently, the portion of the dataset that could be easily analysed. As standard desktop computing power continues to increase, many FFT algorithms are readily available for use in building custom routines to take advantage of the full datasets.

In conclusion, the usefulness of Fourier analyses as a tool for quantifying key structural parameters in cancellous bone has been demonstrated. The ACF was used to determine measures of preferred orientation of trabeculae and anisotropy. Major frequency components from the FFT were used as a measure of strut spacing in open-celled aluminium foams yielding a high correlation with conventional histomorphometric parameters. Continued work in this area is merited to further investigate whether additional structural information may be teased out of the frequency domain. Validation is needed to see if any of these parameters will ultimately improve upon the prediction of cancellous bone stiffness and strength.

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