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Trabecular bone characterization using circular parametric models

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ABSTRACT

Texture analysis of radiographic bone X-ray images presents a major challenge for pattern recognition and medical applications. Classifying such textures from osteoporotic and healthy subjects is a difficult task. In this paper, we propose a new approach combining wavelet decomposition and parametric circular models to capture the statistical behavior of phase coefficients. We demonstrate that, unlike the magnitude components, the wavelet phase coefficients convey local and structural information across scales and orientations which are of great interest for the study of trabecular bone texture. To assess how well the proposed circular models fit phase coefficients, the statistical test of Kuiper and graphical analysis Quantile–Quantile plots were used. The Support Vector Machine (SVM) and the Neural Network (NN) classifiers were used to evaluate the efficiency of the proposed models to classify two populations composed of osteoporotic patients and control subjects. Using Gabor filters and the Wrapped Cauchy model, an Area Under Curve (AUC) rate of 96.45% was achieved with the SVM classifier. To compare the performance of the proposed parametric approach to other non-parametric texture analysis techniques, the Receiver Operating Characteristic (ROC) analysis was performed. Results have proven that the proposed approach provides the best performance in terms of ROC curves.

1. Introduction

Osteoporosis is a degenerative disease that causes bone fragility and susceptibility to fractures. It is characterized by a severe loss of bone mass but also a deterioration of bone microarchitecture [34]. Therefore, bone mass is not the only factor to take into account; other skeletal and microarchitectural factors must also be considered [7]. Bone Mineral Density (BMD), which measures the mineral content of the bone and provides an excellent indicator for osteoporosis, is routinely determined by Dual Energy X-Ray Absorptiometry (DXA) [2]. However, BMD remains insufficient for predicting fractures [6]. Indeed, it has been demonstrated that assessing osteoporosis using bone mass is confusing [35,40]. Considerable attention has therefore been paid to the investigation of bone microarchitecture [43]. In fact, it has been proven that associating bone microarchitectural features to the conventional BMD coefficients offers a promising tool for preventing fracture risk [22]. Some three-dimensional techniques for bone microarchitecture assessment have been proposed [17]. They are not frequently used however, as they are costly, of limited availability or traumatic for patients. Although other technologies such as the Trabecular Bone Score (TBS) [42] have attempted to evaluate the alteration of trabecular bone microarchitecture, none of them are used in clinical practice. Several investigations have therefore been based on the study of two-dimensional bone radiographs using various texture analysis techniques [27]. Fractal analysis in non-Euclidean mathematics has been extensively studied in the medical field [25]. Fractal geometry relies on the fractal dimension to describe textures exhibiting complex, irregular and self-similarity behaviors. The fractal nature of bone has been demonstrated, and fractal analysis has been recognized as a suitable model-based tool to quantify bone changes [19]. This analysis can be achieved using fractional

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Brownian motion (fBm) and its increments, fractional Gaussian noise (fGn) [26]. Other extended models of the fBm process, mainly the piecewise-fBm and the nth-order-fBm models, have proven to be more suitable for the study of bone microarchitecture [13]. Related to fractal geometry, lacunarity analysis has also been proposed for osteoporosis detection [47]. Other studies have used higher-order statistics to characterize bone structural changes [23]. Transform approaches, such as wavelets and Gabor, have also been applied to the quantification of bone changes [37]. Other studies have pointed out the usefulness of morphological parameters for bone microarchitecture analysis [41]. Recently, some hybrid analyses that combine statistical and structural methods, such as the Local Binary Pattern (LBP) operator, have been studied for their ability to recognize changes within trabecular bone [14].

So far, approaches devoted to extracting useful features to diagnose osteoporosis have focused on non-parametric methods. These methods have concerned, for instance, the high-order features [23] developed from statistical approaches, shape properties [41] based on structural primitives and global self-similar patterns [19] describing the irregularity within bone texture. However, there is another range of techniques for texture analysis that has not yet been explored for bone analysis, namely parametric approaches [36]. Unlike non-parametric methods, parametric techniques make assumptions about the probability distribution and attempt to describe samples using compact parametrized models. When models used are appropriate and their parameters are estimated accurately, parametric methods work better on highly stochastic textures. These methods can therefore extract important information needed for analyzing and understanding bone texture.

In the present study, we analyze calcaneus radiographs using the circular parametric models. First, a directional multiscale analysis was performed on each image using four complex transforms: the Pyramidal Dual Tree Directional Filter Bank (PDTDFB) [30], the Complex Dual Tree Wavelet Transform (CDTWT) [20], the Fully Anisotropic Morlet Wavelet Transform (FAMWT) [29] and a set of Gabor filters [10]. The phase responses were then captured and isolated. To study the behavior of the phase coefficients in the complex wavelet domain, two circular parametric models were investigated: the Wrapped Cauchy (WC) and the Von Mises (VM) models [28,16]. Next, to determine whether these models are consistent with our data, quantitative analysis was conducted using the statistical test of Kuiper [21] and the Quantile–Quantile (Q–Q) plots [46]. The experiments were conducted on two different populations, Osteoporotic Patients (OP) and Control Cases (CC). Parametric models' ability to distinguish between images in the database was assessed using the classification task. Lastly, to compare the performance of the proposed parametric approach to other non-parametric methods, the ROC analysis was performed to discriminate subjects with and without osteoporosis.

2. Materials and methods

This section describes the clinical protocol used for the database acquisition. It also provides a full description of the proposed approach.

2.1. Materials

Thanks to its availability and efficiency, the X-ray modality was used for imaging the heel bone known also as the calcaneus. The calcaneus is an appropriate site for investigating bone changes for many reasons. Firstly, it is subjected to compression and tension forces due to body weight which makes its structure anisotropic. Consequently, the structural changes of bone associated with osteoporosis become accessible. In addition, the calcaneus is largely made up of spongy layers and surrounded by thin tissues which facilitate the examination of the damage caused by osteoporosis. Using calcaneus bone also preserves the other body organs from radiation.

The X-ray device used the tungsten tube and an 1-mm aluminum filter. The focal-calcaneus distance was set at 1 m. Calcaneus was placed in contact with the sensor. The tube voltage was fixed at 36 kV and the exposure condition was set at 18 mA, with an exposure time of 80 ms. Regions of interest (ROIs) were defined by physicians using anatomical markers points that can easily be identified on the calcaneus images. These ROIs were located on bone areas that contain only the trabecular network. The size of the acquisition field was fixed at 105 μm. An example of the ROI ($2.7 \times 2.7\,cm^2$) taken from the calcaneus is displayed in Fig. 1. The database includes 174 subjects, half of whom are osteoporotic and half are control cases. A control healthy subject has uniform tensile and compressive trabeculae while in an osteoporotic subject the structure is anisotropic due to the gradual loss of tensile trabeculae. Images of size 400×400 whose pixels are 16-bit gray level were acquired from the X-rays films. Fig. 2 shows two samples from both the CC and OP groups. As can be seen, the visual inspection of these radiographs does not provide any clues as to the category of the subject, making discrimination of these samples a challenging task.

2.2. Methods

As indicated in Fig. 3, this method comprises four stages. The first stage is complex decomposition in which the four complex transforms were performed. Only the phase coefficients of each transform were kept. In the second step, model parameter estimation, the MLE was used to estimate the parameters of the VM and the WC models. Third, parametric model adequacy was assessed using the statistical test of Kuiper and Q–Q plots. In the last step, classification, the SVM and the NN classifiers trained with different

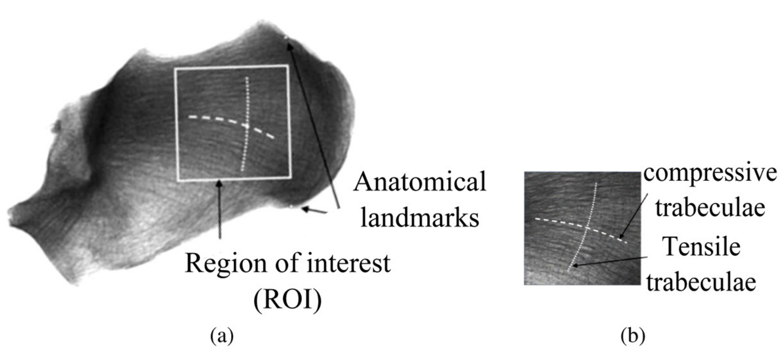

Fig. 1. Radiography of the calcaneus (a) and the extracted ROI (b) (white square in (a)).

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