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Texture analysis using complex wavelet decomposition for knee osteoarthritis detection: Data from the osteoarthritis initiative[☆]

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ABSTRACT

The classification of subjects with different stages of knee OsteoArthritis (OA) using bone texture analysis is a challenging task in medical imaging. This paper presents a new approach for texture analysis of radiographic OA in knee X-ray images. First, a preprocessing step based on a 2D finite impulse response filter is applied on the X-ray images. Then, a set of image content descriptors is extracted from the complex wavelet decomposition using different statistics of a new concept of the relative phases of complex coefficients. The Von Mises and wrapped Cauchy probability density functions are used to model the distribution of relative phase coefficients. Finally, the estimated parameters for each image are used in the classification task, to verify the effectiveness and robustness of the proposed texture analysis on knee X-ray images from the OsteoArthritis Initiative (OAI). Results show that the proposed approach leads to improved texture analysis with a classification rate of 80.38%.

1. Introduction

OsteoArthritis (OA) is a complex heterogeneous joint disease characterised by cartilage degradation and bone changes [1]. OA is the major cause of mobility limitation and physical disability for those with affected knees in the elderly [2]. The detection of OA is of importance since earlier treatment could prevent the destruction of cartilage and bone. Knee OA changes include narrowing of the joint space width and the formation of osteophytes [1], which can be visualized from radiographs. Kellgren and Lawrence [3] (KL) developed a manual classification system based on radiographic criteria dividing the disease into five stages of OA severity; normal, doubtful, minimal, moderate and severe. KL grade 0 indicates a definite absence of osteoarthritis, while the KL grade 2 indicates definite OA [3].

Knee OA changes can be assessed using texture analysis of trabecular bone structure on X-ray images [4,5]. Several texture analysis techniques have been proposed to study the OA changes. In [4], knee X-ray images were analyzed using different feature extraction techniques, such as Zernike features, multiscale histograms, Haralik textures, first four moments and Tamura texture features. Features were extracted using different transforms (wavelet, Fourier, and Chebyshev) of the images. The Fisher score was used to select the useful image features while rejecting the noisy ones. Then a weighted nearest neighbor rule was used to predict the KL grades. Using 193 X-ray images, the authors have obtained 80.4% of accuracy in detecting minimal OA (KL grade 2) from normal knees (KL grade 0). Woloszynski et al. [5] proposed a rotation invariant texture classification method of Signature Dissimilarity

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Measure (SDM). They obtained 78.8% of accuracy in the detection of knee OA using a dataset of 137 X-ray images (68 normal and 69 OA). Normal subjects had KL grade 0 in both knees, while OA subjects had KL grade 2 or 3 in at least one knee. Recently in [6,7], the Hurst parameter H was estimated using fractal signature analysis, a quadratic variations estimator and the Whittle estimator. This parameter was then used for OA progression and initiation [6,7]. All these methods suffer either from computational complexity [4] or from the use of a global approach based on similarity patterns [5]. Another limitation is the size of the databases used in these studies. New techniques must therefore be investigated.

One of the most promising techniques for OA diagnosis is the complex wavelet transforms. Their efficiency has been demonstrated in trabecular bone analysis in the case of osteoporosis [8], but they are not widely used in OA. Complex wavelets have the advantage of providing near shift invariance and good directional selectivity which are suitable for texture analysis. Several variants of the wavelet transforms have been proposed to achieve exact shift invariance, one good example is the Undecimated Dual Tree Complex Wavelet Transform [9]. This transformation offers also both magnitude and phase information. Magnitude components depict the strength of edges, while phase components denote the location of features [10]. Many image processing applications use only the magnitude or real part of complex wavelet coefficients, despite the fact that phase components contain important information of an image which is useful for texture characterization [10]. Recently, considerable research has been devoted to relative phase coefficients for texture analysis and image segmentation [10,11]. The relative phase was initially defined by Vo and Oraintara [10] as the difference between two neighboring complex wavelet coefficients and its statistical properties were studied in depth in [11].

In this paper, a novel texture analysis method for knee OA detection is proposed. The method is based on a new concept of relative phase which exploits more than two adjacent complex wavelet coefficients. Firstly, a preprocessing step based on a high-pass filter is applied on selected ROIs from X-ray images. Then, the Undecimated Dual Tree Complex Wavelet Transform is performed on each filtered ROI. Secondly, the proposed relative phase is computed and modeled using two circular distributions, the Von Mises and the Wrapped Cauchy distributions. The parameters of both models are estimated by maximizing the likelihood estimator. Finally, the estimated parameters are used for the classification task to distinguish between normal knee (KL grade 0) and minimal OA (KL grade 2), which is the most challenging problem in OA detection.

The manuscript is organized as follows: Section 2 presents the proposed method. Section 3 describes the dataset and selected regions of interest. Section 4 reports the experimental results and a comparison with other similar methods. The final section presents the conclusions.

2. Methods

The proposed method is divided into five main parts. First, an image preprocessing step is introduced to keep the crucial information of bone texture. Second, the Undecimated Dual Tree Complex Wavelet Transform is employed on the filtered ROIs. Third, a new relative phase of complex wavelets coefficients is adopted and modeled using the von Mises and the wrapped Cauchy distributions. Fourth, the parameters of each model are estimated using the maximum likelihood estimator algorithm. Finally, the estimated parameters are used in the classification task.

2.1. Preprocessing step

It has been observed in previous studies [12,13], that the trabecular bone structure can be better analyzed in the high frequency components. Based on these studies, a dedicated high pass Finite Impulse Response (FIR) filter was developed for knee trabecular texture. The best known methods for FIR filter design are based on window design, frequency sampling and weighted least squares design [14]. The most popular one is the window design method since it is easy to use and it gives an ideal frequency selective filter and a linear phase characteristic.

A filtering in the Fourier domain was employed to analyze the high frequency components of trabecular bone using a circular filter [13]. The circular filter is an ideal high pass filter, which consists of removing frequencies lower than the cut-off frequency f_c before performing the inverse Fourier transform. The impulse response of an ideal high pass filter has a sharp transition between the stopband and the passband as shown in Fig. 1(a). This abrupt transition in the frequency domain comes with oscillations and a ringing effect in the spatial domain due to the Gibbs Phenomenon [15]. However, this artifact can be minimized by using a smoothed window instead of a rectangular one. In this paper, a high pass FIR filter was designed using a Gaussian window. The impulse response of the high pass filter is expressed in the frequency domain by Eq. (1):

$$H(u, v) = 1 - exp\left[-\frac{(u^2 + v^2)}{2f_c^2}\right] \tag{1}$$

where f_c is the cut-off frequency of the filter. This frequency was estimated as the maximum of the Power Spectral Density (PSD) over the increments of the lines of each image [12]. Fig. 1(b) shows the magnitude of the frequency response in the case of a 1D filter.

The filtering process is merely the product of the impulse response in the frequency domain presented in Eq. (1), called also frequency response, and the ROI's Fourier transform. Then, the inverse Fourier transform of the multiplication results gives the filtered ROI.

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