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Joint Angle Correction in Rheumatoid Arthritis and Its Reliability Analysis Based on Phase Dispersion Quantification

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Abstract

Background: Rheumatoid arthritis is a form of autoimmune disease characterized by synovitis that can ultimately cause joint deformities and impaired functioning. The cartilage destruction is one of the most important indicators for diagnosis and treatment of rheumatoid arthritis, and it is radiographically manifested as joint space narrowing. **Issue:** In the literature, the joint space narrowing progression between a baseline and its follow-up finger joint images can be quantified by using image registration algorithm. We found that the inconsistencies of joint angles may lead to characteristic mismatches and thus severely affect the accuracy of joint space narrowing quantifications. **Methods:** In this work, we introduce a rotation invariant phase only correlation in joint space narrowing quantification for the joint angle correction. Further, we propose a confidence index to quantify the quantification reliability of phase only correlation based on phase dispersion in phase difference spectrum. **Conclusion:** In our clinical experiments, the proposed quantification method can effectively overcome and manage the mismatch due to the inconsistency of joint angles. Additionally, the confidence index shows a high consistency with the joint space narrowing progression examinations manually done by a trained radiologist and one radiological technologist.

Keywords

Rheumatoid Arthritis, Joint Space Narrowing, Frequency Domain Analysis, Radiology, Computer-Aided Diagnosis, Phase Dispersion

1. Introduction

Rheumatoid arthritis (RA) is a chronic autoimmune disease, which means that the immune system attacks healthy cells in the body by mistake. It causes inflammation resulting in painful swelling in the affected body parts. RA usually affects joints in the hands, wrists, and knees. In a joint affected by RA results in the damage of the tissues due to the inflammation on the joint lining. The progressive disease and the tissue damage can cause long-lasting or chronic pain, joint destruction and deformity. This can cause functional limitation to the patient due to the unsteadiness and thereby affecting the patient's quality of life. Previous studies show that the RA affects 0.24% to 1.0% globally [1] and 0.6% to 1.0% of people in Japan [2].

Early detection of RA in patients is important to reduce the risk for negative long-term outcomes. Early diagnosis and management of RA like slowing down or preventing the joint erosions can affect the disease outcomes [3]. X-ray radiography is a widely accepted diagnostic imaging technique for RA detection. They are common in clinics and low-cost for patient care. The Sharp/van der Heijde scoring method (SvdH) is a recognized gold standard for RA progression assessment, in which scoring of radiographic images of hand and feet are performed by subjectively assessing 38 joints [4]. Joint space narrowing (JSN) and erosion in hands and feet are the most important indicators of RA progression assessment. However, determining the JSN progression is extremely difficult, because the JSN can be less than 0.1 millimeter for one year. Considering the limitation of spatial resolution in radiographic imaging and the JSN progression being less than one pixel in patient's X-ray images, the subjective evaluation based on visual inspection results in some critical limitations in diagnosis. It may lead to time inefficiency, and prolonged diagnostic evaluations. For these reasons, image processing techniques and recently, image processing technologies are being considered for the automatic diagnosis and prognosis of RA.

In this work, we propose an algorithm to quantify the joint space narrowing progression with angle correlation in rheumatoid arthritis. Further, we present a confidence index to quantify the reliability of joint space narrowing progression quantification. The rest of the paper is organized as follows: Section 2 describes our methodology, which include a joint angle correction method based on RIPOC for JSN progression quantification and its reliability analysis based on phase dispersion quantification. In Section 3, we present the clinical datasets used in this work. In Section 4, we examine and discuss in detail our experiments and its result, and Section 5 concludes the paper with closing remarks.

2. Methodology

In this section, we propose a joint angle correction method based on RIPOC for JSN progression quantification (**Figure 1**) and analyze its reliability based on phase dispersion quantification.

2.1. Joint Space Narrowing Progression Quantification with Joint Angle Correction

As reported in [5], the image registration based JSN progression quantification

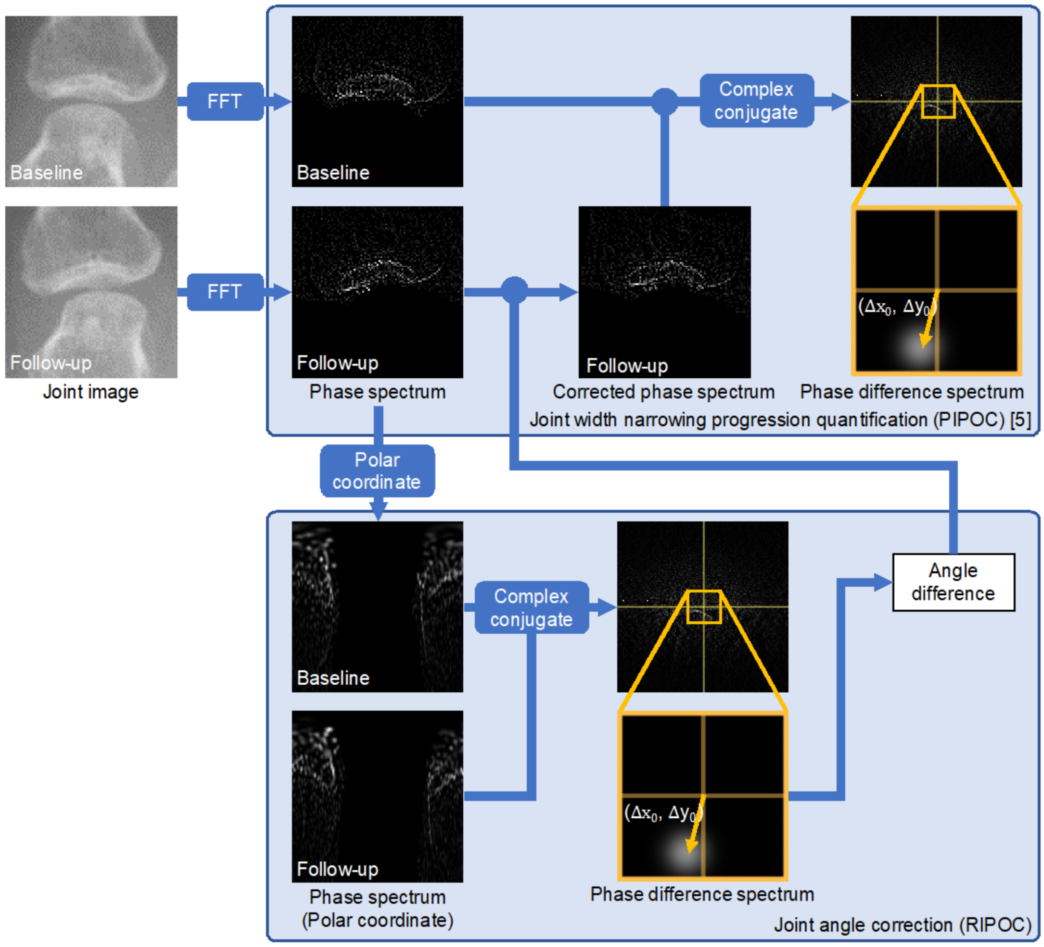

Figure 1. Overview of the proposed JSN progression quantification with joint angle correction based on rotation invariant phase only correlation (RIPOC).

framework delivers high accuracy and sensitivity in the monitoring of RA. Further, [5] reports an improved phase only correlation algorithm called "partial image phase only correlation (PIPOC)". PIPOC can simultaneously monitor the movement of multiple objects with sub-pixel accuracy. When compare to the related works, PIPOC shows promising potential in RA monitoring and diagnosis. However, from the experiments we learnt that an inconsistent angle between the upper and lower bones of the joints can affect the accuracy of JSN progression quantification, and it may also lead to mismatches. Even though using guide lines one may standardize hand posture when taking radiographic images, thus effectively reducing the number of inconsistent joint angles. However, RA can cause ankylosis in peripheral synovial joints and impair the movement and flexibility of digits, and consistent joint angle may be difficult for RA patients with limited finger function. Therefore, we introduce rotation invariant phase only correlation (RIPOC) [7] based joint angle correction in the JSN progression quantification to control such mismatch cases.

The basic pipeline of the JSN progression quantification with joint angle correction can be described as shown in **Figure 1**. Consider two joint radiographic images, a baseline joint radiography $f(x,y)$ and a follow-up joint radiography $g(x,y)$. The joint angle of $f(x,y)$ and $g(x,y)$ is different. These two joint radiographic images can be divided into upper and lower bones. The segmentation information is included in a set of binary matrixes $s_i(x,y)$ ($i=0$ indicates upper bone and $i=1$ indicates lower bone). The θ_0 and θ_1 represent the angle difference of upper and lower bone respectively. The (α_0,β_0) and (α_1,β_1) represent sub-pixel displacement of upper and lower bones respectively. Then, the follow-up joint radiography $g(x,y)$ can be represented by the baseline joint radiography $f(x,y)$ as Equation (1).

$$g(x,y)=\sum_{i=0}^{1} f\left(x\cos\theta_i+y\sin\theta_i+\alpha_i,-x\sin\theta_i+y\cos\theta_i+\beta_i\right)*s_i(x,y) \quad (1)$$

As reported in [5], segmentation in frequency domain can affect control the phase dispersion in phase difference spectrum when compared to segmentation in spatial domain. Take an example of quantifying the movement of bones, the phase spectrum of upper bone $\hat{f}_0(x,y)$, $\hat{g}_0(x,y)$ and lower bone $\hat{f}_1(x,y)$, $\hat{g}_1(x,y)$ can be denoted as Equation (2) and (3).

$$\hat{f}_i(x,y)=\mathcal{F}^{-1}\left(\mathcal{F}\left(f(x,y)w(x,y)\right)\Big/\left|\mathcal{F}\left(f(x,y)w(x,y)\right)\right|\right)*s_i(x,y) \quad (2)$$

$$\hat{g}_i(x,y)=\mathcal{F}^{-1}\left(\mathcal{F}\left(g(x,y)w(x,y)\right)\Big/\left|\mathcal{F}\left(g(x,y)w(x,y)\right)\right|\right)*s_i(x,y) \quad (3)$$

Here, $\mathcal{F}$ denotes the 2D Fast Fourier transform (FFT), and $\mathcal{F}^{-1}$ denotes the 2D Inverse Fast Fourier transform (IFFT). $w(x,y)$ denotes the window function, we used a Hanning window in this work.

Next, the bone angle of follow-up radiography is corrected to baseline radiography by using RIPOC [7], as shown in **Figure 1**. Let $M_{\hat{f}_i}(\xi,\eta)$ and $M_{\hat{g}_i}(\xi,\eta)$ denote the magnitudes of $\hat{f}_i(\xi,\eta)$ and $\hat{g}_i(\xi,\eta)$ respectively. Combining the Fourier transform property and the Fourier transform rotation property, we can represent the magnitude as in Equation (4).

$$M_{\hat{g}_i}(\xi,\eta)=M_{\hat{f}_i}\left(\xi\cos\theta_i+\eta\sin\theta_i,-\xi\sin\theta_i+\eta\cos\theta_i\right) \quad (4)$$

Rotation can be represented as a translation displacement in polar coordinates, as given in Equation (5).

$$M_{\hat{g}_i}(\rho,\theta)=M_{\hat{f}_i}(\rho,\theta-\theta_i) \quad (5)$$

As shown in **Figure 1**, combining the Equation (5) and the full image phase only correlation, the angle difference θ_i can be easily calculated. Next, the corrected phase spectrum of upper bone of follow-up radiography $\hat{g}_i'(x,y)$ can be represented as follow.

$$\hat{g}_i'(x,y)=\hat{f}_i'(x+\alpha_i,y+\beta_i) \quad (6)$$

The normalized cross phase spectrum $\hat{R}_i(u,v)$ of $\hat{g}_i'(x,y)$ and $\hat{f}_i(x,y)$ with Fourier transform can be defined as Equation (7).

$$\hat{R}_i(u,v)=\mathcal{F}\left(\hat{f}_i(x,y)\right)\overline{\mathcal{F}\left(\hat{g}_i'(x,y)\right)}\Big/\left|\mathcal{F}\left(\hat{f}_i(x,y)\right)\overline{\mathcal{F}\left(\hat{g}_i'(x,y)\right)}\right| \quad (7)$$

Therefore, the location of the peak of Dirac delta function δ in the phase difference spectrum can be determined as

$$\left(\alpha_i', \beta_i'\right) = \arg\max_{(x,y)} \mathcal{F}^{-1}\left(\hat{R}_i\left(u,v\right)\right) \tag{8}$$

The least-square fitting method is employed to estimate the displacement $\left(\alpha_i, \beta_i\right)$ around the maximum peak $\left(\alpha_i', \beta_i'\right)$. Therefore, the JSN_{fg} between image $f\left(x,y\right)$ and image $g\left(x,y\right)$ can be quantified as Equation (9).

$$JSN_{fg} = \beta_0 - \beta_1 \tag{8}$$

2.2. Measurement Reliability Quantification

In this section, we propose a metric to quantify the reliability of the JSN progression quantification with joint angle correction. This metric can be used to evaluate the probability of mismatch. This reliability metric is determined based on phase dispersion.

According to the experiments in [5], changes in bone contours can affects the accuracy of JSN progression quantification, and result in phase dispersion in the phase difference spectrum. This phase dispersion appears as multiple low peaks in the phase difference spectrum instead of a single Dirac delta function. This phase dispersion can affect the Dirac delta function position quantization and cause measurement errors or even mismatches. **Figure 2** shows two 3D graph of the phase difference spectrum for the clinical images, and the maximum peak value for each spectrum is normalized as 255.

By comparing the phase difference spectrums in **Figure 2**, we can easily observe that the phase dispersion of a mismatch case is clearly higher than that of the success case. In this study, the phase dispersion is used to represent a confidence index using standard deviation. For the normalized image, to suppress the influence of the main Dirac delta function, the standard deviation of the entire image is obtained by setting the 3 × 3 pixels around the peak as 0, and the sum of the upper and lower bones are used as the confidence index.

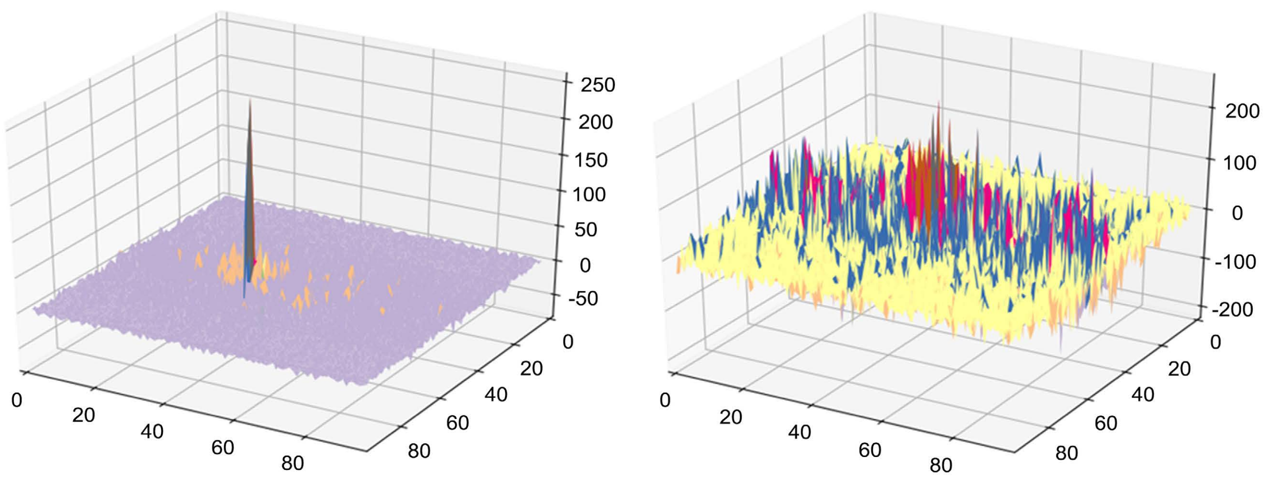

Figure 2. The difference between measurement mismatch and success on 3D graph of the phase difference spectrum. The left spectrum is a successful measurement, and the measurement on the right is mismatched. Successful measurement has lower phase dispersion, which manifests as sharper Dirac delta function peak, and higher signal-to-noise ratio (the ratio of the main Dirac delta function peak to other peaks).

3. Experiments

3.1. Dataset

We used the dataset from *Sagawa Akira Rheumatology Clinic* (Sapporo, Japan), *Sapporo City General Hospital* (Sapporo, Japan) and *Hokkaido Medical Center for Rheumatic Diseases* (Sapporo, Japan). The dataset contains 1120 hand posteroanterior projection radiographic images from patients in the early stages of RA [5].

The radiographic imaging device used in preparing this dataset is *DR-155HS2-5* from *Hitachi* Corporation, with 1.5 mm X-ray aluminum filter thickness. The centering point of the X-ray beam is the MCP joint of the middle finger. Digital imaging and communications in medicine (DICOM) standard is used in preparing and managing this dataset. The size of each image is 2010 × 1490 pixels, the spatial resolution is 0.175 × 0.175 mm, and the bit depth is 12 bits. The tube voltage of X-ray is 42 kV, the tube current is 100 mA. The exposure time of image is 20 msec, and the distance between the X-ray source and the image is 100 cm.

3.2. The Reliability Analysis of Joint Space Narrowing Progression Quantification with Joint Angle Correction

For the confidence index, the mean value for the measured clinical image dataset is 40.83, whereas the mean for the 10 pairs of images with confirmed mismatches are 79.42. **Figure 3** shows an example of the joint images that are measured and their confidence levels respectively. The standard deviation with no rotation is 22.12, while the standard deviation with rotation is 50.82, indicating that the standard deviation increases as the mismatch probability increases.

We invite one radiologist and one radiological technologist in our experiment. According to the confidence index, we divide the JSN progression quantitative results into high index group (mismatch group) and low index group (success group). Both the radiologist and the radiological technologist find that the JSN progression quantitative results in the low index group are more consistent with the trends they assessed.

Figure 3. The confidence index of a successful case (left: 22.12) and a mismatch case (right: 50.82).

In the literature, there are no means to discriminate the mismatch of a successful case in phase only correlation. But the proposed confidence index can help joint space narrowing progression quantification algorithm to be applied in clinical environment, and improve the accuracy of the measurement by giving a reference for the reliability. In addition, the best quantization result can be selected from multiple quantization results according to the confidence index, which will result in higher accuracy.

4. Discussion

In the available literature, the joint space quantification methods for rheumatoid arthritis can be grouped into three groups, margin detection based joint space width quantification framework, machine learning image classification based SvdH [4] scoring framework and the image registration based joint space narrowing progression quantification framework. The experiments show that image registration based joint space narrowing progression quantification framework has the potential for higher sensitivity when compared to other two frameworks. And it has a great potential in monitoring and diagnosing rheumatoid arthritis.

Recently, we proposed a frequency domain analysis-based image registration method named partial image phase-only correlation to quantify joint space narrowing progression of rheumatoid arthritis patients [5] [6] [8]. Partial image phase-only correlation can calculate the displacements of multiple areas with sub-pixel accuracy. The proposed joint space narrowing progression quantification method exhibits a great potential in monitoring and diagnosing the rheumatoid arthritis. Partial image phase-only correlation shows promising potential for high-precision quantization of the joint space narrowing progression, which can help the rheumatologists to make timely judgments on rheumatoid arthritis diagnosis and prognosis.

However, partial image phase-only correlation requires high consistency in hand posture. Experiments illustrate that an inconsistent angle between the upper and lower bones of joint can affect the accuracy of joint space narrowing quantification, and can lead to mismatches. In this work, we introduce a rotation invariant phase only correlation based joint angle correction in the joint space narrowing progression quantification. Our work can manage the mismatch of phase only correlation due to joint rotation. In this method, the rotation can be represented as translation displacement in polar coordinates, and the rotation is compensated by using displacement quantification by full image phase only correlation. The measurement is robust against rotation, which is a major weakness of conventional phase only correlation algorithms.

We propose a confidence index for joint space narrowing progression quantification base on partial image phase only correlation. The confidence index is defined by using the standard deviation for the phase difference spectrum of phase only correlation. By focusing on each mismatch factor, we focus on the characteristic that the phase only correlation output is not a Dirac delta function but an output with many low peaks due to pattern matching failure, and use the standard deviation, which is a variability index, as a measurement reliability index.

5. Conclusion

This work approaches the issue of phase only correlation based joint space narrowing quantification in radiographic images with inconsistent joint angles. Our objective is to further improve the accuracy and the robustness and resolve these issues and make the algorithm suitable for clinical applications. The original contribution of this work is threefold: 1) We introduce rotation invariant phase only correlation in joint space narrowing quantification for joint angle correction. 2) We propose a new metric to quantify the reliability of phase only correlation based on phase dispersion. 3) Our proposed work can greatly improve the detection success rate when the algorithm encounters an inconsistent joint angle.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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