学 位 論 文 内 容 の 要 旨

博士の専攻分野の名称　博士（工学）　氏名　欧　亜非

学 位 論 文 題 名

Automatic Joint Space Narrowing Quantification in Radiographic Images with Sub-pixel Accuracy for Rheumatoid Arthritis

（関節リウマチ診断に向けたX線画像における関節狭小化の自動定量化）

Rheumatoid Arthritis (RA) is a chronic autoimmune disease characterized by synovitis that primarily affects peripheral synovial joints, like fingers, wrists, and feet. The major radiographic changes on hand, wrist, and feet joints are cartilage damage and bone destruction (like bone erosion and Joint Space Narrowing (JSN)). Those damages and destruction typically lead to painful joints, progressive joint destruction, and deformity, followed by functional limitation and severe disability. There are substantial evidence that RA can be managed in a low level of disease activity and clinical remission with disease-modifying antirheumatic drugs. Early diagnosis by precise quantification of subtle radiographic changes is essential for successful treatment, as it can improve outcomes and effectively manage the progression of RA. Radiology plays a critical role in the diagnosis and monitoring of RA. Clinical radiologist/rheumatologist can assess the radiographic progression of RA by using the Sharp/van der Heijde (SvdH) scoring method. This method relies on scoring the radiographies by subjectively assessing JSN and bone erosion of 38 hand or foot joints. The joint space is one of the most important indicators for the diagnosis and monitoring of RA, and it has attracted the extensive attention of many researchers resulting in great efforts to study the automatic quantification of joint space in RA. According to the methodology and its output metric, those previous works on joint space quantification in RA can be grouped into two frameworks, classification based SvdH scoring method, and margin detection based Joint Space Width (JSW) quantification method.

However, classification based SvdH scoring method has only five levels, which limits the sensitivity and timeliness of the tool. Whereas, the margin detection based JSW quantification works can achieve only pixel-level accuracy. Limited by the current spatial resolution of radiographic imaging, JSN progression of RA can be less than one pixel per year with universal spatial resolution. Insensitive monitoring of JSN can hinder the radiologist/rheumatologist from making a definitive and timely clinical judgment.

In this thesis, we propose a novel and sensitive framework which aims to automatically quantify JSN progression in the early RA. The proposed framework implements fully automatic quantization of JSN progression in RA, which can be broadly grouped into two parts, joint position detection, and JSN progression quantification. For joint location detection, we propose and compare two methods, a classification based joint location detection method and a key point detection based joint location detection method. The two joint location detection methods show different strengths and weaknesses in our experiments. For joint space quantification, we proposed a new framework by calculating the relative widths of the joint space based on an image registration method. Take a Metacarpophalangeal

(MCP) joint as an example, our methodology can be understood in four steps. (i) Segment the proximal phalanx bone and metacarpal bone based on gradient information. (ii) Combining Discrete Fourier Transform (DFT) and the joint segmentation curve, segment the proximal phalanx bone and metacarpal bone in the phase spectrum. (iii) Measure the movement of the proximal phalanx bone and metacarpal bone between baseline and follow-up radiographs respectively by using the image registration algorithm. (iv) Calculate the displacement difference between the proximal phalanx bone and metacarpal bone to get JSN progression.

Also in this thesis, we have improved Full Image Phase Only Correlation (FIPOC) by adding a phase spectrum segmentation step, so that it can measure the displacements of multiple regions at the same time. We named the improved FIPOC algorithm as Partial Image Phase Only Correlation (PIPOC). As an image registration algorithm, PIPOC is used in JSN progression quantification. Compared with FIPOC, PIPOC can effectively avoid the impact of the segmentation and in-painting process and reduce the phase dispersion in the phase difference spectrum. In our phantom study, PIPOC has a much lower mean error than FIPOC. This work aims for computer-aided monitoring and diagnosis of RA. Our work measures JSN progression between a baseline and its follow-up finger joint images by using the phase spectrum in the frequency domain. In our phantom studies, and experiments using clinical dataset our algorithm can measure the displacements of upper and lower bones with sub-pixel accuracy. The measured mean error of our algorithm is in range of 11.9% - 35.0% in comparison to manual measurements using radiographic phantom datasets, in range of 6.0% - 16.1% when using tomosynthesis phantom datasets, and with a Standard De- viation (SD) of 0.0519 mm when using radiographic clinical dataset. Considering that previous works can best achieve only pixel-level accuracy, our extensive experiments demonstrate that the proposed image registration based JSN progression quantization framework promises high precision monitoring when compared to two mainstream related works; the margin detection based JSW quantification framework and image classification based SvdH scoring framework.

These advantages indicate that our proposed framework can fill the gap in monitoring the JSN progression with high sensitivity. Thereby it has a broad application prospect in the monitoring of RA. With the sub-pixel accuracy far beyond usual manual measurements, we are optimistic that the proposed work is a promising scheme for automatically quantifying JSN progression. Currently, Machine Learning (ML) is applied to difficult tasks in medical image analysis. We anticipate future studies in this direction. Our experiments in this study have shown the superiority of image registration based JSN progression quantification framework in RA monitoring compared to the current most popular classification based SvdH scoring framework, and the margin detection based JSW quantification framework. Those ML-based image registration algorithms can be used for JSN quantization in RA. To address the posture (finger movement) related constraints and inconsistent joint angle which is likely to result in mismatched registration. Given the advantages of ML, it may be possible to achieve higher robustness (lower mismatching ratios) at the expense of a small amount of accuracy. Furthermore, we can quantify JSN by ML using the image features extracted by our work, this can improve the overall performance of the algorithm.