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Digital image analysis protocol for determining the radiocarpal joint space in the rheumatoid arthritic wrist

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ABSTRACT

This paper describes a simple protocol for measuring the joint space of the rheumatoid arthritic (RA) wrist from projection radiographs. The protocol is implemented using a computer algorithm based upon the Interactive Data Language platform. The computerized algorithm features a user-friendly graphical interface to aid the operator to measure joint space parameters, namely distance and area, of the wrist vertebral morphometry at the radiocarpal region. Dual-energy X-ray absorptiometry (DXA) radiograph of a standard hand and wrist phantom was evaluated using the measurement protocol to determine the accuracy and precision of the protocol. The accuracy, parameterised by the systematic error, returned a mean of 5.20% for distance and is equal to 3.49% for area measurement. The precision of the measurement protocol, parameterised by the coefficient of variation (CV), for distance returned a mean of 1.96%; the CV for area measurement equals 2.1%. Three observers participated to investigate the repeatability (intra-observer) and reproducibility (inter-observer) of the measurement protocol, parameterised by the CV, using DXA radiographs from a healthy volunteer and a RA patient. The inter-observer repeatability for distance measurement for the respective observers returned mean values of 10.9%, 7.7% and 11.4% for the healthy wrist. However, the results revealed improved repeatability for the RA wrist; the CV for the respective observers returned mean values of 7.7% 7.1% and 10.0%. The inter-observer repeatability for area measurement for the respective observers returned mean values of 10.2%, 7.1% and 10.1% for the healthy wrist. However, the results revealed improved repeatability (in two out of the three observers) for the RA wrist; the CV for the respective observers returned mean values of 6.8% 6.5% and 10.8%. Student's t-test analysis of the intra-observer repeatability revealed that the measurements of distance and area were generally not intra-observer sensitive. On the other hand, student's t-test analysis of the inter-observer reproducibility revealed that half of the distance measurements were inter-observer sensitive; whereas the remaining were not. Similar findings were obtained for area measurements. Overall the results reveal that the variabilities in accuracy and precision tests and the repeatability and reproducibility tests were typically 10% or less. These findings, in addition to the versatility and simplicity of the digital image analysis protocol, lend to the potential of using the protocol to complement the acquisition of bone mineral density data derived from DXA for diagnosing the progression of RA in patients.

1. Introduction

Rheumatoid Arthritis (RA) is a chronic progressive disease resulting in joint inflammation, and consequently extreme discomfort and pain. RA typically starts in the membrane surrounding the joint (the synovium), which then thickens and fills the joint space (JS). The joint function deteriorates further with age [1]; RA is more common amongst women over 50 years of age than any other demographic [2]. Radiography plays an important role in the diagnosis of RA as the features associated with the pathology of the diseases can be visually assessed [3]. Protocols for radiologic assessment of RA can be broadly classified into: (1) scoring system; and (2) quantitative radiography. The “gold standard” has been the scoring systems initially proposed by Kellgren and Lawrence [3] and this has been discussed extensively in several studies

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[4–7]. However, a major limitation of any scoring system is that it is qualitative and hence inherently subjective [4]. It is for this reason that quantitative radiography has been proposed as an alternative since it aims to measure the distribution and size of each radiographic feature accurately and precisely [8]. Quantitative radiography to assess radiographic structural changes, such as JS narrowing at the peripheral JS of RA patients, is intended to measure cartilage loss from erosion effects [4]. Typical measurement parameters for quantitative radiography are distance [4] and area [9] and these parameters may be evaluated directly from the radiograph [10] or from computerized image analysis of digitized x-ray films [9]. However, the accuracy and precision of the diagnosis depends very much on the measurement protocol [4,9,11].

Additionally, poor contrast and resolution in conventional x-ray systems have hindered their usefulness in quantitative radiographic assessment despite their low-cost, ease of interpretation and ability to provide a permanent record which can be assessed at any stage of the disease [8]. Alternative systems have been proposed and developed. Buckland-Wright [12] developed a microfocal radiographic system capable of producing high-definition images, resolution and have applied the system to both knee and hand [11]. Harvey et al. [13] employed a second generation dual-energy x-ray absorptiometric (DXA) scanner to achieve high contrast in radiographs of bone and used interactive computerized image analysis technique for accurate delineation of bony margin in the hip joint for distance measurement. DXA belongs to a family of multi-energy imaging techniques that are designed to acquire radiographs containing energy-independent information free from artifacts caused by x-ray attenuation as seen in conventional x-ray radiography [14–16].

More important, DXA scanners are used for measuring bone mineral density (BMD) to assist in the diagnosis of bone deterioration and loss [17–20] that could be linked to RA [13,18]. To this end, this paper proposes a computerized image analysis method for the assessment of JS in the wrist of RA patients using digital radiographs acquired based on existing imaging protocols. A computer algorithm (known as 'WRISTJS') was developed to implement the digital image analysis protocol. To measure the radiocarpal JS of the wrist from radiographic images, the proposed measurement protocol involved evaluating distances and areas within the JS. The distance parameter measures the separation between joint margins, and provides a measure of JS narrowing at specific sites along the radius and carpal bones of the wrist. The area parameter measures compartmentalized areas of the JS of the respective radius and carpal bones of the wrist to facilitate overall assessment of the degree of JS narrowing at these sites. The protocol for the JS measurement of joint space is driven by the need to avoid excessive and complicated procedures. Here, each stage of the protocol is executed independently; this reduces the potential effects of sequential systematic error. It is envisaged that such a method to acquire data related to distances and areas with the joint space of the RA wrist could be used to complement the BMD results obtained from the same DXA images for diagnosing the progression of the disease.

2. Materials and methods

2.1. Reference locations

A fundamental approach in the quantitative radiographic measurement of the wrist JS is the use of reference locations to achieve precision [11,21] or the use of landmarks identified by active shape models [21]. In this study the focus is on manual identification of reference locations using anatomical landmarks (ALs).

Ideally, the reference locations must be radiographically visible at any stage during the period of study of the disease. These reference locations (or landmarks) play an important role in ensuring that: (1) the same observer will obtain consistent repeated measurements performed on the same region; (2) different observers will obtain measurements from the same image with minimal variability; (3) temporal changes in any radiographic feature are detectable. In this study, six ALs along the bony margin in the radiocarpal JS have been identified for the measurement protocol. These ALs are indicated in the schematics in Fig. 1. The observers were instructed on the arguments underpinning these ALs; this would help them make informed decision when identifying and marking them digitally during the image analysis process.

Two ALs, namely #1 and #2, along the leading bony edge of the radius medial and lateral ends have been designated as the radius "tangential" locations (Figure A). As the name suggests, they have been defined such that if a straight line is drawn passing through them, the line should just rest on the bony margin. Another two ALs (#3, #4) along the bony margins of the scaphoid and lunate have been designated as the carpal "tangential" points (Fig. 1 A)—if a straight line is drawn passing through them, the line should just rest on the bony margin of both scaphoid and lunate.

The last two ALs, i.e. #5 (along the medial scaphoid) and #6 (along the lateral lunate carpal) have been designated as the carpal "end" location (Fig. 1 A). AL #5 has been defined on the scaphoid bony margin by the intersection point of the carpal bone with the radius leading edge. Although AL #6 could be defined by the intersection point of a straight line (drawn perpendicular to the bony margin where AL #2 is located) with the lunate bony margin, in some cases it was more appropriate to define AL #6 as an intersection point of the carpal bone with the radius leading edge. This is for when it was more feasible to detect the overlapping projected images of the radius and carpal bones.

After the ALs were identified and registered into WRISTJS, the radiocarpal JS would be compartmentalized into the radioscaphoid and radiolunate region to facilitate independent assessment of RA. The anatomical locations (#1, #2, #5 and #6) on the carpal and radius bone defined the horizontal bounds of each compartment; the curves outlined by the bony margin define the vertical bounds of the compartments.

2.2. Distance and area measurement

As mentioned in section 1, the two quantities used for JS measurement are distance and area. For the purpose of illustrating how WRISTJS executes the distance measurement, consider the radioscaphoid compartment (Fig. 1). Here, WRISTJS has been programmed to divide the horizontal (with respect to the image axes) spatial separation between the anatomical location #1 on the radius bone and the anatomical location #3 on the scaphoid bony margin into five equal segments. From these segments four equally spaced (at distance of Δx in the horizontal direction) points along the curve fitted to the radius would be identified. Rudimentary trigonometric methods were used to determine the distances (d1, d2, d3 and d4) between the radius and the scaphoid (Fig. 1 B).

The arguments used to implement the area calculations were more straight-forward: the areas of interest were the regions enclosed by the radiolunate and radiocarpal compartments. The areas of regions A_{MRS} and A_{LRL} were taken as the sum the areas constrained by d1 to d4 between the radius and scaphoid; and d5 to d8 between the radius and lunate respectively.

2.3. Measurement protocol

The protocol for measuring the wrist JS involves the following steps: (1) image processing; (2) identifying AL #1 and #2, as well as secondary points along the radius bony margin (for demarcation); (3) identifying AL #3, #4, #5 and #6, as well as secondary points along the carpal bony margin (for demarcation), (4) generating the respective curves that best fit the points found in step 2 and step 4; (4) calculating distance and area.

In step 1, image enhancement was performed using two operations, namely magnification and smoothing; the latter removes pixilation as a result of enlargement. The recommended filter size of 3 × 3 pixels was adhered to [22]. In step 2, prior to the identification of ALs #1 and #2 on the radius bony margin (Fig. 1), the WRISTJS generated a straight line through AL #1 and #2; the line was used as a guide for identifying AL #1