In-vivo dynamic and static three-dimensional joint space distance maps for assessment of cartilage thickness in the radiocarpal joint

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1. Introduction

It is of clinical importance to diagnose cartilage injuries in the wrist at an early stage before more severe osteoarthritis has occurred that cannot be treated without residual problems in joint function (Haims et al., 2004). A non-invasive image-based measurement method for assessing cartilage thickness is the preferred method to more invasive techniques such as wrist arthroscopy.

Cartilage degradation is reflected on radiographs as a reduction of the distance between the adjacent subchondral bone surfaces, called "joint space narrowing". Plain radiographs may be misleading as the two-dimensional (2D) projection can only show joint space thickness for a small part of the articular surfaces. Moreover, the diagnosis of cartilage degeneration is hampered by the anatomical complexity of the wrist in combination with overlapping of the anatomic structures on the radiographic images. Plain radiographs have therefore a limited value for the evaluation of degenerative joint disease in the wrist (Peh et al., 1999). Consequently, a three-dimensional (3D) distribution of joint space thickness is required for a full evaluation of cartilage damage in the wrist.

A 3D imaging method that allows analysis of joint space thickness of the wrist is computed tomography (CT). For measuring joint space thickness, CT scans are often acquired with the wrist in a neutral position. A general drawback is that joint space thickness measured in one position may not be representative for the overall joint space for all possible wrist positions over the entire articulation during motion. The joint space thickness can therefore be overestimated in regions where cartilage adjacent surfaces are not in contact.

A second disadvantage of CT scans is that standard axial, sagittal and coronal reconstructions of image slices from CT scans are not precisely perpendicular to a joint gap which makes the clinically measured joint space thickness less accurate. Finally, the joint space thickness is often measured manually by clinicians and is therefore subject to observer errors.

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In contrast to CT, where cartilage layers are not visible in the acquired images, magnetic resonance imaging (MRI) is a reliable clinical method to detect cartilage layers in larger joints and to diagnose cartilage injuries with high degrees of sensitivity and specificity (Bredella et al., 1999; Potter et al., 1998). However, contrary to the knee joint, which has thick cartilage layers, the measurement of submillimeter cartilage layers of the wrist still remains a challenging task. Due to resolution issues, Haims et al. (2004) and Mutimer et al. (2008) suggested that MRI was not sensitive or accurate enough for diagnosing cartilage defects or cartilage thinning in the wrist, where the cartilage is thinner than 1 mm. If MRI is combined with the use of invasive contrast material, Haims et al. (2004) found that this did not improve the sensitivity, specificity or the accuracy when diagnosing cartilage degradation of the wrist. Recent improvements in MRI techniques are however more promising. The delayed gadolinium-enhanced MR imaging and sodium 23 \(^{23}\text{Na}\) MRI have promising advantages over conventional MR imaging methods for investigation of cartilage quality in larger joints (Shapiro et al., 2002; Welsch et al., 2008). However, their usage in the carpal joint is not investigated and their diagnostic benefits in submillimeter range cartilage levels must still be proven.

The purpose of this study is to adapt a newly developed CT-based imaging method for measuring in-vivo three-dimensional kinematics of the carpal bones during motion (Carelsen et al., 2009; Fournani et al., 2009). The essence of the method is to calculate the joint space thickness using dynamic distance maps during different wrist motions instead of calculating the joint space thickness from a static CT scan (Marai et al., 2006).

A dynamic distance map gives for every point on a subchondral bone surface the shortest distance to the opposing subchondral bone surface within a set of different joint poses. The method enables a non-user-dependent in-vivo quantification of the joint space thickness during motion. We hypothesize that the measure of joint space thickness during wrist motion is smaller than the joint space thickness measured in one single 3D CT scan acquired in a neutral position, giving less over-estimation of the joint space thickness.

The starting point for our distance map generation is the method described by Marai et al. (2006) who used static CT scans to calculate the joint space thickness (JST) in the wrist joint by using a pre-defined threshold distance to select areas on the cortical surface where bones articulate near each other. In contrast to Marai et al. (2006) who used a single distance threshold to define the joint contact areas a second criterion was introduced to define the articulation areas based on the parallelism of the opposing subchondral bone surfaces. We extend the method introduced by Marai et al (2006) by using dynamic distance maps of the radiocarpal joint that are obtained from wrist joint motion patterns in-vivo, acquired by a 4-dimensional X-ray imaging system (4D-RX) (Carelsen et al., 2009; Fournani et al., 2009). These dynamic distance maps are compared to 3D static distance maps acquired from a single CT scan. Subsequently, the diagnostic potential of the distance maps are illustrated by comparing distance maps from wrists with osteoarthritis of the radiocarpal joint with those from normal joints. In our experiments, distance maps were calculated for the radiocarpal joints since it is the most affected articulation of the wrist joint in osteoarthritic wrists (Watson and Ballet, 1984).

2. Methods

2.1. Participants

The right wrists of 10 healthy subjects (5 female and 5 male, average age 37.6 years, range 27–48 years old) and affected wrists of 3 individuals (42 year old male, 53 year old male, 76 year old male) with clinically proven radiocarpal osteoarthritis (OA) due to a scapho-lunate ligament disruption were scanned for this study. The healthy subjects had no history of wrist injury. This study was approved by the Medical Ethical Committee of our hospital and informed consent was obtained from each subject.

2.2. Image acquisition and wrist motion

For reconstruction of the bone geometry, CT images of the wrist were acquired while the hand was in a neutral position. The images were acquired on an Mx8000 Quad CT scanner (Philips Medical Systems; Best; The Netherlands). The acquisition parameters were: collimation 20.5 mm, tube voltage 120 kV, effective dose 150 mAs, rotation time 0.75 s, pitch 0.875; the scans were made in ‘ultra high resolution’ mode (i.e. small focal spot size). Reconstructions were made with convolution kernel E, a field of view of 150 mm, a slice increment of 0.3 mm and a matrix of 512 × 512 pixels. The voxel size was 0.3 × 0.3 × 0.3 mm. Subsequently, dynamic images were acquired by the previously described 4-dimensional rotational X-ray (4D-RX) imaging method by using a modified rotational 3D-RX system (BV Pulsera, Philips Healthcare, The Netherlands) (Carelsen et al., 2009; Fournani et al., 2009). For acquiring 4D-RX scans, 975 projection images were made during a cyclic motion of the wrist from which a set of 20 volume reconstructions were obtained. Each volume reconstruction belongs to a certain pose of the hand during dynamic motion.

The cyclic motion was achieved by using a mechanical device, called handshaker, that consists of a detachable drive unit and a framework in which the drive unit is placed to impose flexion–extension, radio-ulnar deviation and dart throwing motion on the hand (Carelsen et al., 2009; Fournani et al., 2009). The forearm was placed in the handshaker with the elbow flexed 90°. To allow the hand to follow the movements of the handshaker, the participants were asked to grasp the hand piece. To prevent a locked wrist, the forearms were placed in an axial sliding table allowing a free motion of the wrist in the desired direction.

Scans were acquired during a comfortably achieved extension to maximum flexion and back. For radio-ulnar deviation, images were acquired during a dynamic motion from radial deviation to ulnar deviation and back. For the dart throwing motion the hand was moved from radial extension to ulnar flexion.

2.3. Estimation of translations and rotations of individual bones from acquired datasets

The segmentation of the carpal bones, radius and ulna from the CT images was performed by a region growing algorithm (Carelsen et al., 2009). To estimate the 3 translations and 3 rotations of each individual bone relative to those in the neutral position, the segmented boundary voxels of each carpal bone were registered to the corresponding bones in each of 20 volume datasets for each dynamic scan (4D-RX) (Carelsen et al., 2009; Fournani et al., 2009). Custom made software packages were developed in C/C++ and Matlab. The kinematic data as well as the relative positions of the surface points for all bones were calculated for flexion–extension, radioulnar deviation and the dart-throwing motion.

2.4. Calculation of static and dynamic distance maps

For each point on a bone of interest, the smallest distance to the opposite bone is determined (Van de Giessen et al., 2009a, 2009b). The set of points with a distance smaller than 4 mm defines the first estimate of the area of interest on the bone surface. A parallelism criterion was applied similar to van de Giessen et al. (2009a, 2009b). As a result, a point on the bone surface is included in the final area of interest if the angle between its normal vector (i.e. a vector perpendicular to the bone surface for the surface point under consideration) and the normal vector of the closest point of the opposing bone surface deviates less than angle α (0 to 30°) from 180° (Fig. 1). The collection of points on the final area of interest, with associated distances to the opposite bone surface is referred to as a distance map. The static distance map (SDM) is a distance map generated from a single CT-scan in the neutral position. A dynamic distance map (DDM) is generated from the collection of 60 distance maps of all poses of the hand from the 4D-RX acquisitions.
compared to the JST from the DDM for different values of \( \alpha \) for the healthy individuals the JST based on the SDM was the average size of the \( \alpha \) angles of fit estimated. The static 

The mean and standard deviation of the final area of interest used for the calculation of JST measured in 10 healthy individuals using different parallelism criterions. DDM: dynamic distance map; SDM: static distance map.

2.6. Reproducibility analysis

For determining the reliability of the JST calculation method a repeated measurement reproducibility test was applied by computing the root mean squared error (RMSE) of 20 JST’s calculated from one single 4D-RX run in one individual with a non-moving wrist.

3. Results

3.1. Reproducibility

The root mean squared errors in the estimation of radio-scaphoid and radiolunate JST’s from a 3D CT image were less than 0.01 mm for all values of the \( \alpha \).

3.2. The effect of the parallelism criterion on the average area size of the selected points in healthy and affected wrists

For the ten healthy individuals, the final area of interest was considerably different between the static distance map (SDM) and the dynamic distance map (DDM) (Fig. 2). The total surface area of the DDM was larger than the surface area of the SDM. The average radioscaphoid area of the SDM for the parallelism criterion \( \alpha \) equal to 15° was 89 mm\(^2\) (std: 26 mm\(^2\)) while the average radioscaphoid area of the DDM was 151 mm\(^2\) (std: 23 mm\(^2\)) (\(P < 0.01\)).

The average radiolunate final area of interest of the SDM for an \( \alpha \) of 15° was 66 mm\(^2\) (std: 25 mm\(^2\)) while the final area of interest of the DDM was 124 mm\(^2\) (std: 35 mm\(^2\), \(P < 0.01\)). Although the final area of interest increases with increasing \( \alpha \), the difference between dynamic and static final area of interest remains similar for both joints.

For the affected wrists, the final area of interest was different between the SDM and DDM in the radioscaphoid and radiolunate joint. Similar to healthy individuals, the total surface area of the DDM was larger than the surface area of the SDM.

3.3. Average joint space thickness in dynamic and in static distance maps: healthy individuals

For the healthy wrists, there was a difference between the statistically determined joint space thickness (S-JST) and the dynamically determined joint space thickness (D-JST) of the radioscaphoid and radiolunate joints (Fig. 3). The D-JST was smaller than the S-JST for

During flexion–extension, radioulnar deviation and the dart throwing motion. The final area of interest of a dynamic distance map is the union of areas of interest of all 60 poses. Within this final area of interest the minimal distance was determined for each point as the minimum distance for all 60 motion phases. The distance maps then represent the collection of minimal distances to the opposing bone within the final area of interest.

2.5. Data analysis

Both for the dynamic- (DDM) and static distance maps (SDM), the mean radioscapoid joint space thickness (JST) was calculated by taking the average of the separately calculated radius-to-scaphoid and scaphoid-to-radius averages of all distances points. The same method was applied to calculate the average radiolunate joint space thickness.

The average JST of a distance map was defined as the primary outcome variable. Since the magnitude of the parallelism criterion influences the final outcome, each analysis was performed for different angles of \( \alpha \) between 5 and 30°, in 5 degree increments. In addition, the average size of the final area of interest of all individuals was also estimated. The static final areas of interest were compared to the dynamic final area of interest for different values of \( \alpha \).

To compare the dynamic- (D-JST) and static joint space thickness (S-JST) for the healthy individuals the JST based on the SDM was compared to the JST from the DDM for different values of \( \alpha \). To summarize the presented data, only the outcomes for an \( \alpha \) value of 15° were presented. A Student’s \( t \)-test was used to determine the statistical significance of the difference of the JST between two methods for the healthy individuals. Wilcoxon/Mann–Whitney statistical test or two-sample \( t \)-test was used for both dynamic and static distance maps to compare the joint space between healthy individuals and patients with osteoarthritis.
all values of $\alpha$. The radioscaphoid D-JST in healthy individuals for $\alpha$ equal to 15° was 0.91 mm (std: 0.32 mm) while the S-JST was 1.37 mm (std: 0.37 mm. $P < 0.01$). The corresponding radiolunate D-JST (1.17 mm (std: 0.36 mm)) was significantly different from S-JST (1.48 mm (std: 0.33 mm)). For both joints, the value of $\alpha$ did only marginally influence the difference between the two methods.

3.4. Average joint space thickness in dynamic and in static distance maps: affected wrists

Similar to our findings in the healthy wrists, in affected wrists the D-JST was smaller than the S-JST. However, there was only a small difference between the D-JST and the S-JST for the radioscaphoid joint. The difference of the radiolunate D-JST and S-JST in affected wrists was however more distinct (Fig. 4).

3.5. Average joint space thickness in dynamic and in static distance maps: healthy individuals vs. affected wrists

The JST was smaller in all pathological wrists ($n = 3$) compared to the average value in healthy wrists (Fig. 5). This is most prominently seen in the radioscaphoid joint and less in the radiolunate joint. This difference was observed for the JST from the DDM and for the SDM. The average radioscaphoid D-JST of pathological wrists was 0.44 mm (std: 0.22), which was significantly smaller in respect to D-JST of healthy individuals (0.91 mm, std: 0.32, $P < 0.05$). The S-JST of the radioscaphoid joint space in pathological wrists was 0.49 mm (std: 0.20), which was significantly smaller, then the S-JST in healthy individuals (1.37 mm, std: 0.37 mm, $P < 0.01$). In contrast to the findings in the radioscaphoid D-JST, the average radiolunate D-JST and S-JST were not significantly different between healthy individuals and pathological wrists.

4. Discussion

The assessment of the JST is essential for diagnosing cartilage degeneration in arthritis of the wrist joint. The goal of the study was to evaluate the differences between calculated JST of radiocarpal bones acquired during wrist motion and JST acquired from one single CT scan in a neutral pose in healthy individuals. The repeated measurements to determine the reproducibility of the JST method show small deviations, which render the method sufficiently precise for further clinical research purposes. In healthy wrists, DDM provide a smaller value of JST compared to SDM. During motion, a larger area of the articulation surface is comprised within the DDM.

In the osteoarthritic wrists, radioscaphoid joint degeneration was reflected by a reduced JST while the radio-lunate joint was more preserved. This is in agreement with the clinical findings of Watson and Ballet (1984) based on their clinical observations. Moreover, in contrast to the healthy wrists, in affected wrists the S-JST and the D-JST were not considerably different in the radioscaphoid joints. As a possible explanation we hypothesize that affected joints have a higher level of conformity due to an increased friction over a longer period. As a result, a more rigid situation is established which thwarts the free motion between the joint parts.

It was found that in healthy wrists an increase of $\alpha$ affects the magnitude of the area of interest, as more points on the distance maps are included. However, in healthy wrists, the extent of the area of interest does not affect the average JST considerably. The difference between the D-JST and S-JST also remains constant if more points are included by an increase of $\alpha$. Therefore it can be confirmed that the value of $\alpha$ is not critical if comparing the JST between healthy individuals.

This study reveals that in individuals without any pathology of the wrist the JST calculated from dynamic distance maps are smaller than the statically acquired distance maps. This implicates that the joint

![Joint Space Thickness](image-url)
space thickness is overestimated if one static CT scan is acquired and therefore the dynamic distance maps provide a better reflection of the functional joint space thickness.

It is important to realize that the calculation of the average JST as one single numerical parameter is a method to simplify and summarize the information from an extended amount of available data, which is useful for scientific purposes and statistical calculations. However, since the calculated JST reflects the average amount of cartilage thickness across the entire articular surface it is understandable that more localized cartilage damages cannot be evaluated by using this parameter. Therefore, a visual approach to present the data (e.g. Fig. 6) is a more informative way to understand the outcomes and place them in relation to their anatomical localization. This visual approach to link the minimal distance maps to their 3-dimensional anatomical counterparts is a powerful instrument that has potential clinical benefits that covers both diagnostic and therapeutic purposes. The role of the DDM for detection of smaller localized cartilage wear is an issue that deserves more attention in subsequent clinical experiments.

The 4D-RX method to acquire in-vivo kinematical information is used to calculate the JST that is a labor-intensive method. It can be anticipated that advances in CT technology with faster temporal resolution and wider detector coverage will facilitate dynamic joint studies in larger patient groups. Due to the small number of patients with osteoarthritis in this study no general conclusions could be derived from our findings in this group of patients since it was not within the scope of this experiment to perform a diagnostic accuracy study. Further research is required to investigate the benefits of dynamic assessment of the joint space thickness in early stages of arthritis and in more patients.

Conflict of interest statement

None of the authors has a financial interest or business relationship posing a conflict of interest concerning the research described in this paper.

References


Fig. 5. Radius–scaphoid and radius–lunate joint space thickness compared between 10 healthy and 3 affected wrists for both dynamic and static minimal distance maps. Outcomes are given for the parallelism criterion of 15°. Error bars represent the 95% confidence intervals.

Fig. 6. Joint space thickness of 2 typical examples, a healthy wrist (A,B) and from an affected wrist (C,D, patient 2), acquired from a single CT scan (A,C) and from dynamic images (B,D). For the parallelism criterion α, the value of 15° was chosen.


