In Vivo Assessment of Articular Contact at Radiocarpal Joint during Dorsal/Palmar Flexion and Ulnar/Radial Deviation

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Abstract: The radiocarpal joint transfers loads from the forearm to the hand, and facilitates fine tasks of the hand and fingers by providing a considerable degree of stability. Investigations of in vivo articular contact behavior at the radiocarpal joint are important for understanding the biomechanical functions under physiological loading. Further, knowledge about the biomechanics of the radiocarpal joint would provide a useful clinical indicator for assessing the joint instability and diagnosing osteoarthritis. The objective of this study was to assess in vivo articular contact behavior between the radius and scaphoid and between the radius and lunate using a two-dimensional (2D) to three-dimensional (3D) image matching technique. Four wrist joints of four normal male subjects were enrolled in this study. Biplanar X-ray images were taken during dorsal/palmar flexion and ulnar/radial deviation of the wrist joint. The articular contact was estimated from the joint space distance smaller than the mean cartilage layer thickness measured using an MRI scanner. The distributions of estimated contact area and the contact point locations varied markedly with wrist positions. The present result would be able to provide a fundamental knowledge about the biomechanics of the wrist joint.

Keywords: Biomechanics, Radiocarpal joint, Articular contact, In vivo assessment, Image matching

1. Introduction

The wrist joint complex consists of the articulations of the eight carpal bones with the distal radius, the radioulnar disk, and the metacarpals. The eight carpal bones are divided into the proximal and distal rows. The bones of the proximal rows, the scaphoid, lunate, and triquetrum, form a relatively flexible structure, but at the same time provide a stable basis for the fingers. The convex proximal surfaces of the scaphoid and lunate articulate in part with the concave ones of the distal radius and the articular disk. This articulation is called the radiocarpal joint [1]. The fundamental movements that occur at the radiocarpal joint are dorsal/palmar flexion (or flexion/extension), ulnar/radial deviation, and circumduction. With the coordination of forearm axial rotation (pronation and supination) and the finger flexion and extension, the radiocarpal joint plays the key role to accomplish the hand function that is indispensable for our activities of daily living. Also, the radiocarpal joint transfers loads from the forearm to the hand. Clinically, wrist dysfunction is often caused by sprains or injuries resulted from sudden loading. Moreover, repetitive stress can lead to degenerative changes [2]. Assessment of the articulating behavior of radiocarpal joint could, therefore, be important for understanding the biomechanical functions under physiological and pathological loading. Further, the quantitative evaluation of cartilage contact would provide useful clinical parameters for diagnosing and treating joint instability and osteoarthritis. However, although many in vivo studies on the kinematics of the radiocarpal joint have been reported [3-5], a few studies have been reported on relative articulating movements of the carpal bones with respect to the radius using magnetic resonance imaging (MRI) [6,7], or computed tomography (CT) scanning [8-10]. Both MRI and CT scanning enable to evaluate relative articulating movements with high accuracy in three-dimension (3D); however, a longer imaging time in MRI and high radiation dose in CT may limit the applicability and usability. Recently, a two-dimensional (2D) to 3D image-matching technique has been used to measure the 3D kinematics of several kinds of joints [11-15]. This technique registers the 3D positions of bone models by matching their projections with radiographic images, and allows shorter imaging time and lower radiation dose. The objective of this study was, therefore, to assess in vivo articular contact behavior between the radius and scaphoid and between the radius and lunate during dorsal/palmar flexion and ulnar/radial deviation using a 2D to 3D image matching technique for fully understanding the physiological motion of the wrist joint. Articular contact was estimated from joint space distance obtained using the Euclidean distances from discrete points covering the entire articular surfaces.

2. Materials and Methods

2.1 Subjects and image data collection

After institutional review board approval and informed consent were obtained for each subject, 4 healthy male subjects (29.3 ± 12.5 y.o.) without any wrist and hand pathology participated in the study. No subject was engaged in habitual sports and occupational activities using the upper extremity. Four right-dominant wrist joints were imaged by a CT scanner (BrightSpeed™ Elite SD; GE Healthcare, CT, USA) with slice thickness of 0.63 mm and pixel size of 0.3 x 0.3 mm². The tube current for the CT scan was limited to 20 mA to lower the radiation dose and the Adaptive Statistical Iterative Reconstruction technology [16] was utilized for noise reduction. The CT scan data of each subject were imported into modeling software (ZedView® 9; LEXI, Tokyo, Japan) to create 3D surface bone models of the radius, scaphoid, and lunate with the accuracy and precision of 0.40 ± 0.33 mm. The
accuracy and precision were determined by comparing the dimensions of the surface model with actual values [17]. Then each wrist joint was imaged by a 1.5 T MRI scanner (Healthcare Optima™ MR430s; GE Healthcare, CT, USA) with slice thickness of 1.0 mm and pixel size 0.2 x 0.2 mm² to measure the thickness of the articular cartilage layers covering these three bones. Each subject was x-rayed using a biplanar X-ray system. This system consists of 2 X-ray tubes (RADspeed Pro™ and MobileArt Evolution™; Shimadzu, Kyoto, Japan) to allow frontal and lateral images to be taken with a one-second interval between the two exposures. Two 352 mm x 428 mm imaging plates were used to capture the entire forearm (elbow to wrist) and digitized in 8-bit gray intensity with 0.1 mm resolution (FCR; Fuji, Tokyo, Japan). The subjects were seated and placed their right upper limbs on a radiolucent spacer with 90° of flexion at the shoulder and full extension at the elbow (Fig.1). Biplanar X-ray images were obtained at five wrist positions: neutral, dorsal flexion, palmar flexion, ulnar deviation, and radial deviation (Fig.2). Except for neutral position, each subject bent the wrist to the maximum degree at each of the remaining four positions. To calibrate the biplanar imaging system, an acrylic frame with 37 radiopaque markers was placed over the forearm. Three-dimensional positions of the radius, lunate and scaphoid were determined using the 2D-to-3D image-matching technique. The accuracy of 0.5 mm for translation and 0.6° for rotation was reported based on experiments using femoral and tibial 3D models [18]. The calibrated biplanar imaging system was replicated using custom-made software. The 3D radius, ulnar and scaphoid models were imported into the software to allow them to be matched automatically with the biplanar radiographic images (Figs. 3 (a) and (b)).

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2.2 Estimation of articular contact
To estimate articular contact, the Euclidean distance maps of the scaphoid and lunate bone models were created beforehand using the method presented by Kozinska et al. [19]. Euclidean distance map is in the form of a 3D array whose elements are the norms of 3D vector from the closest point in the reference surface model. Figure 4 shows the Euclidean distance maps of the surface of an arbitrary shape as 2D array for simplicity. The values of elements are set to be positive at the outside of the model while they are set to be negative at the inside. Resolution indicates the element size, or the discretization size of the distance. In this study, resolution was set to be 0.15 mm. If the test model is located near the reference model as

![Fig.1 Subject during biplanar X-ray imaging](image1)

![Fig.2 Five wrist positions to be imaged](image2)

![Fig.3 Result of 2D to 3D image matching](image3)

(a) Biplanar X-ray image at neutral position

(b) Bone models overlaid to the biplanar X-ray image

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shown in Fig.5, the closest distance between the reference and test models can be obtained easily by picking the value of the 2D array element (shown as shaded elements) where the surface of test model intersects. The joint space distances were evaluated between the radius and lunate, and the radius and scaphoid by collecting the closest distance data over the entire bony surfaces facing each other. Articular cartilage was regarded as being in contact if the joint space distance was smaller than the sum of mean thicknesses of two cartilage layers measured using the MRI data. To evaluate the movement of contact region during wrist motion, the centroid of the region was defined as contact point, CP, using the following equation:

$$CP_i = \frac{\sum_{k=1}^{N} p_{ki} \left(1 - \frac{d_i - \text{Min}}{\text{Max} - \text{Min}}\right)}{\sum_{k=1}^{N} \left(1 - \frac{d_i - \text{Min}}{\text{Max} - \text{Min}}\right)}$$  \tag{1}$$

where $k=x, y, z$, $p_{ki}$ the coordinate of $i$-th contact point, $N$ the number of contact point, $d_i$ the joint space distance at $p_{ki}$. Max and Min are the maximum and minimum values of the joint space distance. The range of contact point displacement along the radial and ulnar direction and the dorsal and palmar direction over the five wrist positions were evaluated at both radioulnate and radioscaphoide joints (Fig.6). Differences in the contact area and contact point were analyzed using paired t-tests. The level of significance was set at $P < 0.05$.

![Fig.6 Definition of contact point displacement along the dorsopalmar and radioulnar directions](image)

### 3. Results

The distributions of estimated articular contact area at the radiolunate and radioscaphoide joints of the four subjects were shown in Figs.7 (a) to (d). The cartilage thicknesses of radiolunate and radioscaphoide joints for all subjects are listed in Table 1. The contact area and contact position varied remarkably depending on the subjects and the wrist positions. The contact areas of the radiolunate and radioscaphoide joints at the five positions are compared at Fig.8. The mean ± standard deviation of contact area of the radiolunate joint at neutral position was 50.0 ± 38.5 mm². It increased to 80.3 ± 54.6 mm² at palmar flexion, 141.6 ± 81.5 mm² at dorsal flexion, 94.6 ± 76.1 mm² at radial deviation, and 150.4 ± 52.8 mm² at ulnar deviation. The mean ± standard deviation of contact area of the radioscaphoide joint took its maximal at radial deviation, 201.7 ± 45.3 mm². It decreased to 174.0 ± 49.4 mm² at dorsal flexion, 106.2 ± 39.9 mm² at palmar flexion, 159.8 ± 28.2 mm² at neutral, and 61.0 ± 37.5 mm² at ulnar deviation. The contact area of the radioscaphoide joint tended to be greater than that of the radiolunate joint ($P < 0.05$ at neutral position) except at ulnar deviation ($P < 0.05$). The displacements of contact point at the radiolunate and radioscaphoide joints were compared along the radioulnar and dorsopalmar directions (Fig.9). The radioulnar displacements were similar at radiolunate and radioscaphoide joints (5.5 ± 0.9 mm vs 4.9 ± 1.2 mm). The dorsopalmar displacements differed between the two joints, but not significantly different (4.7 ± 2.3 mm vs 1.7 ± 1.0 mm).

![Fig.4 2D array representing the Euclidean distance map for an arbitrary shape](image)

<table>
<thead>
<tr>
<th>Subject</th>
<th>Radiolunate</th>
<th>Radioscaphoid</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.73 ± 0.24</td>
<td>2.14 ± 0.18</td>
</tr>
<tr>
<td>B</td>
<td>2.14 ± 0.18</td>
<td>2.12 ± 0.19</td>
</tr>
<tr>
<td>C</td>
<td>1.77 ± 0.14</td>
<td>1.69 ± 0.15</td>
</tr>
<tr>
<td>D</td>
<td>2.09 ± 0.13</td>
<td>2.02 ± 0.10</td>
</tr>
</tbody>
</table>

Table 1 The mean ± standard deviation of cartilage thicknesses of radiolunate and radioscaphoide joints for all subjects
Fig. 7 Distributions of contact areas of radiolunate and radioscaphoid joints at five wrist positions.

(a) Subject A
(b) Subject B
(c) Subject C
(d) Subject D

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For example, Sasagawa et al. reported that the mean contact areas were relatively larger than those of these previous reports by Pillai et al. [6] and Sasagawa et al. [7]. However, the present study investigated a small number of normal healthy male subjects. However, the contact pattern may be affected by sex, age, and ethnicity of the subject. The present result, therefore, may have a certain bias and variation. Increasing the sample size as well as inclusion of pathological population into the subject group should be needed as further research to gain a comprehensive insight.
4. Discussion
The present study quantified the contact area and contact position at the radiolunate and radioscapoid joints during dorsal/palmar flexion and radial/ulnar deviation of the wrist joint, in an effort to elucidate the relative change in contact area and location with wrist position rather than estimating the true contact area. Overall, the present result showed that the contact area was larger at the radioscapoid joint, and was larger at dorsal/palmar flexion and radial/ulnar deviation when compared with neutral. This tendency was similar to the previous reports [6-10]. However, the present contact areas were relatively larger than those of these previous reports by Pillai et al. [6] and Sasagawa et al. [7]. For example, Sasagawa et al. reported that the mean contact areas of the radiolunate and radioscapoid joints at neutral position were $14.3 \pm 16.5 \text{ mm}^2$ and $43.6 \pm 13.6 \text{ mm}^2$, respectively. This may be caused by the difference in the measuring method of articular contact where these studies used MR imaging. Fischer et al. [20] validated a MRI-based modeling technique for estimating the contact area by comparing the experimental values obtained by pressure sensitive film and electronic pressure sensors. Thus, MR imaging can be a reliable method among currently available in vivo techniques. Although our technique has an advantage over the MRI in that the time required for imaging is much shorter, further research should be conducted using MRI-based articular cartilage models for evaluating articular contact area with high accuracy.

Similar to the present study, Tang and Chen [8] and Rainbow et al. [9] determined the contact area based on prescribed joint distances, but not the actual cartilage thickness. They both reported the results similar to ours in that the relative change in the contact area of the radiolunate joint with respect to neutral position increased at dorsal flexion. As for the radioscapoid joint, Rainbow et al. showed the decrease in contact area at palmar flexion compared with neutral position, as in the present study. Foumani et al. [10] determined the area of interest using joint distance map based on the parallelism of the opposing subchondral bone surfaces. They showed that the values for the area of interest at the static positions were 66 mm$^2$ for the radiolunate surface and those were 89 mm$^2$ for the radioscapoid surface, both of which were similar to our estimated contact areas.

Variations of the contact point with the wrist position were similar to the results of Tang and Chen [8] and Rainbow et al. [9]. Both of them showed that the contact point displacement was greater along the dorsopalmar direction. The larger contact point displacement may indicate rolling between the joint surfaces resulting from the wrist motion and at the same time, the smaller displacement may indicate sliding. This behavior should be investigated in detail to reveal the process of degenerative change in articular cartilage as the damage to cartilage could be caused by sliding in addition to contact pressure.

The present study utilized the 2D-to-3D image matching technique that has been applied to evaluate the 3D joint kinematics [11-14] and articular contact behavior [15]. This technique can reduce radiation dose considerably compared with CT-based kinematic analyses [3-5, 8-10]. In addition, the time required for imaging is much shorter than that by an MRI-based method as mentioned above. However, detection of bony edge points at X-ray image would be a laborious task for the lateral view of the wrist as the carpal bones overlap each other. This should be resolved by improving the process of image acquisition.

The present study has several limitations worth noting. First, the result obtained was limited primarily by the accuracy (0.5 mm for translation and 0.6$^\circ$ for rotation) of the bony position data collection tools employed. Second, the present study investigated a small number of normal healthy male subjects. However, the contact pattern may be affected by sex, age, and ethnicity of the subject. The present result, therefore, may have a certain bias and variation. Increasing the sample size as well as inclusion of pathological population into the subject group should be needed as further research to gain a comprehensive insight in the articular contact behavior. Finally, omission of the time-dependent deformation characteristics of articular cartilage could have affected the estimation of contact area. This could be resolved by future development of a high-speed 3D imaging technique with high resolutions.

5. Conclusions
The present study estimated articular contact area and contact position at the radiolunate and radioscapoid joints during dorsal/palmar flexion and radial/ulnar deviation of
the wrist joint of normal subjects. The contact area of the radioscaphoid joint was greater than that of the radiolunate joint at neutral position, while at ulnar deviation the contact area of the radioscaphoid joint was smaller than that of the radiolunate joint. There was no significant difference in the displacement of contact point along the radioulnar and dorsopalmar directions at the five wrist positions for both the radiolunate and radioscaphoid joints.

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References


