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CT-based three-dimensional kinematic comparison of dart-throwing motion between wrists with malunited distal radius and contralateral normal wrists

S. Lee [a], Y.S. Kim [b], C.S. Park [b], K.G. Kim [b], Y.H. Lee [c], H.S. Gong [c], H.J. Lee [c], G.H. Baek [c,*]

[a] *Department of Orthopedic Surgery, Sanggye Paik Hospital, Inje University, Seoul, South Korea*
[b] *Biomedical Engineering Branch, Division of Convergence Technology, National Cancer Center, Goyang, Gyeonggi-do, South Korea*
[c] *Department of Orthopedic Surgery, Seoul National University College of Medicine, Seoul, South Korea*

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AIM: To compare motion of the capitate, scaphoid, and lunate in wrists with a malunited distal radius and contralateral normal wrists during dart-throwing motion (DTM) by three-dimensional kinematic studies using computed tomography (CT) images.

MATERIALS AND METHODS: CT was performed simultaneously on both wrists in six patients with a unilateral distal radius malunion at three stepwise positions simulating DTM. Using volume registration technique, the kinematic variables of helical axis motion of the capitate, scaphoid, and lunate were calculated and compared between both wrists. The helical motion of the capitate was also evaluated in a scaphoid- and lunate-based coordinate system.

RESULTS: Among the average rotation and translation of the scaphoid, lunate, and capitate during DTM, only the average rotation of the capitate was significantly different between the uninjured (88.9°) and the injured (70°) wrist ($p = 0.0075$). Rotation of the capitate relative to the scaphoid (26.3° versus 37.8°, $p = 0.029$) or lunate (39.2° versus 59.3°, $p = 0.028$) was smaller in the malunited wrist. The centres of helical axis motion of the three carpal bones were located more dorsally and radially in the injured wrist.

CONCLUSIONS: The present study showed that decreased DTM in wrists with a distal radius malunion resulted from decreased midcarpal motion. The present study of the capitate, scaphoid, and lunate in wrists with distal radius malunion might be the first to present a 3D kinematic analysis of the effect of distal radius malunion on the carpal bones.

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Introduction

There have been reports suggesting that long-term outcomes of conservative treatment for distal radius fractures are favourable.[1] However, a number of patients experienced some impairment several years after the trauma, including limited range of motion, and the severity of fracture

* Guarantor and correspondent: G.H. Baek, Department of Orthopedic Surgery, Seoul National University College of Medicine, 101 Daehak-ro, Jongno-gu, Seoul 110-744, South Korea. Tel.: +82 2 2072 2367; fax: +82 2 764 2718.

E-mail address: ghbaek@snu.ac.kr (G.H. Baek).

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displacement seemed to influence the clinical outcome by altering wrist mechanics.[2–6] Carpal malalignment is seen in some wrists with a dorsally angulated distal radius, and is accepted as an inevitable response, resulting in abnormal overload of the joint and causing ligament attenuation, synovitis, and progressive dynamic instability.[7,8] A corrective osteotomy in the malunited distal radius is usually recommended to relieve symptoms in the wrist and to correct the carpal malalignment.[9] However, consensus has not been reached regarding the amount of acceptable deformity and the indications for corrective osteotomy of distal radius fractures.[10–13] Park et al.[8] recommended that dorsal angulation $\geq 15°$ and the amount of midcarpal flexion of the dorsal intercalated segmental instability should be the determining factors to perform corrective osteotomy.

As dart-throwing motion (DTM) is known to be important in manual occupations as well as activities of daily living, and therefore, evaluation of the range of motion of the wrist can be performed using a DTM. Midcarpal motion is known to be the mainstay of DTM and is difficult to analyse using two-dimensional imaging. Development of three-dimensional (3D) imaging techniques and computerized analytic technologies has enabled non-invasive *in vivo* motion analysis of the wrist joint.[14–17] *In vivo* kinematics of the midcarpal joint have been investigated using a non-invasive bone registration technique,[18–21] which found the angular deviation of the DTM plane[20] and the average contribution of the radiolunate joint to global wrist motion.[18] Werner et al.[22] demonstrated that during intermediate motions of DTM, scaphoid movement was as little as 26% of overall wrist motion, and lunate movement as little as 22%. Regarding minimal scaphoid motion, the DTM plane was aligned 45° from the sagittal plane. Crisco et al.[23] identified scaphoid motion approaching zero in a DTM plane approximately 45° from the sagittal plane, and there was minimal lunate motion in a plane approximately 30° from the sagittal plane.

The aim of the present study was to investigate whether there was a significant difference in the kinematics of the capitate, scaphoid, and lunate between wrists with distal radius malunion and the contralateral uninjured wrists during DTM using computed tomography (CT) images.

Materials and methods

Patients

Six patients, four men and two women, who had unilateral distal radius malunion (four left wrist), were recruited. Informed consent was obtained and the study was approved by the institutional review board. The average age was 64 years (range 49–81 years). The patient volunteers were screened for history of wrist trauma, and bilateral anteroposterior, lateral, and billiard views (partially supinated postero-anterior with ulnar deviation)[24] were obtained to exclude contralateral wrist injuries such as fixed intercarpal ligament injuries or the scaphoid nonunion and to confirm dorsal tilt $>10°$, radial inclination $<10°$, or radial shortening >5 mm in the affected wrist. The average volar tilt of the unaffected side was 13° (range 10–17°) and average dorsal tilt of the affected sides was 19° (range 10–25°). The mean radial inclinations were 24° (range 20–29°) and 14° (range 8–25°), respectively.

Exclusion criteria were any history or findings of any wrist disease or injury, any neurological deficit, and stiffness in the wrist or hand. Five of the six patients were right handed and one patient with left distal radius malunion was ambidextrous. The average interval between trauma and CT was 10 months (range 8–13 months).

CT

CT (Aquilion 64 CT System, Toshiba Medical Systems Corporation, Otawara, Japan; 120 kVp, 250 mA, 0.5 s) was performed simultaneously on both wrists of all patients with an image section thickness of 1 mm. Patients were placed in a prone position on the CT table with the forearm extended, and gripped a custom-designed wrist-positioning jig as they simulated DTM (Fig 1). Scans were acquired at three stepwise positions from full radial extension to full ulnar flexion[1]: maximum radial extension[2]; neutral; and[3] maximum ulnar flexion.

Bone segmentation and reconstruction

Digital models of the bone were generated from the CT DICOM files with Analyze (Mayo Clinic Foundation, Rochester, MN, USA) software (window level/width = 300/2000, thresholding value = 300). Manual intervention was occasionally necessary to define the bone contours and to eliminate contour breaks. The contours were then stacked, and grouped into a voxel model using MATLAB (MathWorks, Natick, MA, USA), which was converted into a volume model by flood-fill operation. The left wrists were converted to the right wrists to simplify the kinematic analysis.

Reference coordinate system

The carpal bone motions were described in relation to an anatomically based reference coordinate system constructed in the distal radius, which was similar to that of Moritomo et al.[20] The z-axis was set parallel to the longitudinal axis of the radial shaft ($+z$ was distal). The x-axis was along the bisecting line of the sigmoid notch to the radial styloid tip and perpendicular to the z-axis ($+x$ was radial). The origin in this coordinate system was set as the intersection of the x-axis with the interfossa ridge on the radial articular surface. The y-axis was aligned perpendicular to both the z-axis and x-axis ($+y$ was dorsal).

Kinematic analysis

The volumes of all carpal bones at three positions in the same wrist were calculated and all three volumes of each bone at different positions were compared to determine the accuracy of the registration technique by the average and

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