In Vivo 3-Dimensional Analysis of Stage III Kienböck Disease: Pattern of Carpal Deformity and Radioscaphoid Joint Congruity

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Purpose To examine 3-dimensional carpal alignment and radioscaphoid joint (RSJ) congruity among normal wrists and those with Lichtman stage III Kienböck disease or scapholunate dislocation (SLD).

Methods We conducted 3-dimensional analysis based on computed tomographic data to compare 10 wrists of stage III Kienböck disease (5 IIIa and 5 IIIb) with 5 normal wrists and 3 wrists with SLD. A markerless bone registration technique was used to investigate the 3-dimensional position of the scaphoid relative to the radius. To evaluate RSJ congruency, the inferred contact area between the scaphoid proximal pole and the distal radius was calculated from 3-dimensional bone models.

Results The scaphoid position was not significantly different from normal wrists in stage IIIa Kienböck disease. Stage IIIb Kienböck disease was meaningfully associated with a flexed scaphoid and proximal translation of the centroid, but not dorsal translation of the scaphoid proximal pole, where RSJ congruity was preserved. With SLD, the scaphoid flexed to the same extent as that in stage IIIb Kienböck disease, and the proximal pole translated dorsally together with the capitate, producing RSJ incongruity.

Conclusions The patterns of carpal collapse differed between stage IIIb Kienböck disease and SLD in terms of RSJ congruity. Our study showed that stage IIIb Kienböck disease did not involve dorsal subluxation of the scaphoid proximal pole and that RSJ congruity was retained, unlike SLD.

Clinical relevance Our results suggest that carpal collapse in Kienböck disease is not associated with RSJ incongruity, which may explain why there are asymptomatic patients with Kienböck disease and carpal collapse. *(J Hand Surg Am. 2015;40(1):74–80. Copyright © 2015 by the American Society for Surgery of the Hand. All rights reserved.)*

Type of study/level of evidence Diagnostic II.

Key words Kienböck disease, scaphoid rotatory subluxation, scapholunate dissociation, 3-dimensional analysis.

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According to the Lichtman classification scheme, carpal collapse and osteoarthrosis gradually develop as Kienböck disease progresses.[1] With progression in Kienböck disease, the symptoms gradually worsen. In stage I, the symptoms are often indistinguishable from those of a wrist sprain. In stage II, wrist pain worsens and swelling appears (caused by reactive synovitis). In stage III, wrist stiffness appears. In stage IV, there is wrist pain and swelling aggravated by activity and a permanent loss of wrist motion caused by degenerative changes in the wrist joint.[2] Clinically, however, some patients with Kienböck disease can be asymptomatic.[3]

To prevent disease progression, Kienböck disease can be treated by various surgical procedures.[4−17] Watson et al[18,19] treated stage III Kienböck disease by scaphotrapeziotrapezoid arthrodesis because they considered that the radioscaphoid joint (RSJ) incongruity involving dorsal subluxation of the scaphoid proximal pole accompanying scaphoid rotatory subluxation, which produced synovitis and early joint destruction, was a cause of many symptoms. However, it was not clear from their study if carpal collapse in Kienböck disease actually involved dorsal subluxation of the scaphoid proximal pole.

Taniguchi et al[20] have reported patients with asymptomatic stage IV Kienböck disease that was associated with remarkable carpal collapse, and their RSJ space was retained. In contrast, it was revealed that wrists with scapholunate dissociation (SLD) had RSJ incongruity caused by dorsal subluxation of the scaphoid proximal pole,[21,22] and the incongruity caused osteoarthrosis in RSJ.[21] Therefore, we hypothesized that deformity pattern of SLD would be different from that of stage IIIb Kienböck disease and Kienböck disease would not have RSJ incongruity.

In this study, we examined 3-dimensional carpal alignment in stage IIIa and IIIb Kienböck disease to determine if RSJ incongruity involving dorsal subluxation of the scaphoid proximal pole was present. These results were compared with those for normal wrists and wrists with SLD and RSJ incongruity involving scaphoid rotatory subluxation.

MATERIALS AND METHODS

Eighteen subjects, including 5 with normal wrists, 10 with symptomatic stage III Kienböck disease, and 3 with SLD, were examined. The subjects with normal wrists (4 right, 1 left) included 1 woman and 4 men (mean age, 43 y; range, 31−59 y). All subjects with normal wrists initially presented at our hospital with contralateral wrist disorders, including malunion of the distal radius and scaphoid nonunion. Bilateral computed tomography (CT) scans were obtained for comparison, and the CT data of the normal sides were used in this study. Subjects with stage III Kienböck disease included 5 men (mean age, 31 y; range, 22−38 y) with stage IIIa Kienböck disease (1 right, 4 left) and 5 men (mean age, 51 y; range, 22−73 y) with stage IIIb Kienböck disease (4 right, 1 left) diagnosed by posteroanterior and lateral radiographs based on the Lichtman classification system.[1,23] Patients with collapse of the lunate and a radioscaphoid angle of 60° or less (mean angle, 49°; range, 31°−55°) were classified as stage IIIa and patients with collapse of the lunate and a radioscaphoid angle greater than 60° (mean angle, 71°; range, 65°−76°) were classified as stage IIIb. The subjects with SLD (1 right, 2 left) included 1 woman and 2 men (mean age, 45 y; range, 28−54 y) diagnosed by posteroanterior radiograph, showed widening of the scapholunate gap[24] (mean gap, 7.5 mm; range, 6.3−8.9 mm), and all had signs of the dorsal intercalated segment instability, including a lunate extension identified with a radiolunate angle greater than 15° (mean angle, 30°; range, 21°−40°) or a scaphoid flexion identified with a scapholunate angle greater than 70° (mean angle, 76°; range, 72°−83°) on lateral radiographs.[25] All of them were classified as stage IV scapholunate instability[25] and had type I lunates.[26] These subjects did not have secondary SLD following distal radius fracture but rather had isolated SLD, and a complete scapholunate interosseous ligament tear was confirmed during surgery. CT scans of the affected side were performed in subjects with stage III Kienböck disease and subjects with SLD. There were small differences in sex, side, and age among these groups of subjects; *P* values (all *P* values in the chi-square test were $> .1$) suggested that these differences were insignificant. Our institutional review board approved this study.

Low-dose radiation CT scans (scan time, 0.5 seconds; slice thickness, 0.625 mm; 10 mA; 120 kV; LightSpeed Ultra16; General Electric, Waukesha, WI)[27] of the wrists were performed by using 1/30th of the normal radiation dose. During image acquisition, the wrists were bandaged to carefully maintain a neutral position with the axes of the third metacarpal and forearm in neutral rotation. Data were saved in the Digital Imaging and Communications in Medicine format (DICOM; Peabody, MA) and stored in a computer. Contours of the radius, ulna, and carpals were segmented on the computer; consequently, 3-dimensional surface wrist models of all 13 subjects were constructed 1 by 1 on the basis of 3-dimensional surface generation of the bone cortex[28] by means of a visualization toolkit-based original computer program (VTK; Kitware Inc., Clifton Park, NY). These wrist models were visualized by using software (Orthopedics Viewer; Osaka University, Osaka, Japan) with which the digital 3-dimensional measurements were available regardless of the view on the computer.

Measurement of carpal position

First, the orthogonal reference system of the radius originally advocated by Belsole et al[29] (Fig. 1) was determined as follows: the y axis, indicating the

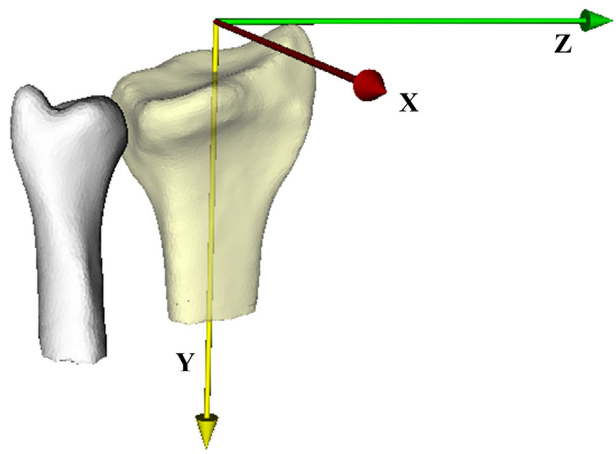

FIGURE 1: The orthogonal reference system for the radius originally was advocated by Belsole et al[29] and is described in the text.

proximal (+)/distal (−) direction, was defined as the longitudinal radial axis. The z axis, indicating the radial (+)/ulnar (−) direction, was defined as the line passing through the top of the radial styloid process perpendicular to the y axis. The x axis, indicating the palmar (+)/dorsal (−) direction, was defined as the line perpendicular to the yz plane. Rotation around the z axis produced flexion (+)/extension (−), rotation around the y axis produced pronation (+)/supination (−), and rotation around the x axis produced ulnar (+)/radial (−) deviation.

Next, the local orthogonal coordinate systems for the scaphoid and capitate were determined using the anatomical features described by Belsole et al[30] (Fig. 2). The position of the volumetric centroid of each bone was calculated from the CT data as the origin of each local orthogonal coordinate system. The x axis of the scaphoid was defined as its principal axis, calculated as the line passing through the centroid with the smallest moment of inertia. The z axis was defined as the line passing through the dorsal ridge of the scaphoid perpendicular to the x axis, and the y axis was the line perpendicular to the xz plane. The y axis of the capitate was defined as its principal axis, and the z axis was defined as the line passing through the dorsal joint ridge of the capitate-hamate joint perpendicular to the y axis. The x axis was the line perpendicular to the yz plane. These orthogonal coordinate systems and the Euler angle method were used to calculate 3-dimensional positions of the scaphoid and capitate relative to the radius with 6 degrees of freedom using translation parameters (Δx, Δy, Δz) along and rotation parameters (φx, φy, φz) around the orthogonal coordinate axes.[31,32] The analyzed positions of each bone with stage III Kienböck disease were compared with those of normal and SLD wrists. All data are expressed as means and SD.

Evaluation of RSJ congruency

To evaluate RSJ congruency, a proximity mapping method, which could measure the inferred contact area from 3-dimensional bone models,[33,34] was used. We used a previously described custom computer program that automatically visualizes the region of one bone surface with respect to another within a user-specified threshold distance as a proximity map.[33] Moore et al reported that the cartilage thickness of the scaphoid is 0.8 mm[35] and Pollock et al reported that of the scaphoid fossa is 0.7 mm.[36] Therefore, the distance threshold was determined to be 1.5 mm, the sum of the thicknesses of both cartilages. The area within the radius, where the distance to the scaphoid was below the threshold, was regarded as the inferred contact area. The analyzed proximity maps were compared among the groups.

Statistical analysis

Post hoc Tukey tests were performed to evaluate the differences in carpal position among the groups. A *P* value of less than .05 was considered statistically significant.

RESULTS

Although the carpal alignment in stage IIIa Kienböck disease was the same as normal, scaphoid flexion was observed in stage IIIb disease. In addition, normal RSJ congruity of both stage IIIa and IIIb Kienböck disease was retained. Conversely, in SLD, the scaphoid flexed to the same extent as in stage IIIb Kienböck disease but also shifted dorsodistally, producing RSJ incongruity, with a dorsal shift of the capitate different from that of stage IIIb Kienböck disease.

Carpal position

In stage IIIa, there was 1.2-mm proximal translation of the centroid of the scaphoid; however, it was not significantly different from the normal scaphoid position. Compared with the normal scaphoid, the scaphoid with stage IIIb Kienböck disease significantly flexed to 26° ($P = .006$), and the centroid of the scaphoid significantly translated 2.7 mm in the proximal direction ($P = .04$) (Fig. 3). Compared with the scaphoid with stages IIIa and IIIb Kienböck disease, the centroid of the scaphoid with SLD significantly translated 4.1 mm ($P = .03$) and 4.9 mm ($P = .001$) in the dorsal direction, respectively, and significantly translated 3.5 mm ($P = .02$) and 5.0 mm ($P = .002$) in the distal direction, respectively (Fig. 3). Table 1 contains the rotational alignments for the 3 wrist conditions.

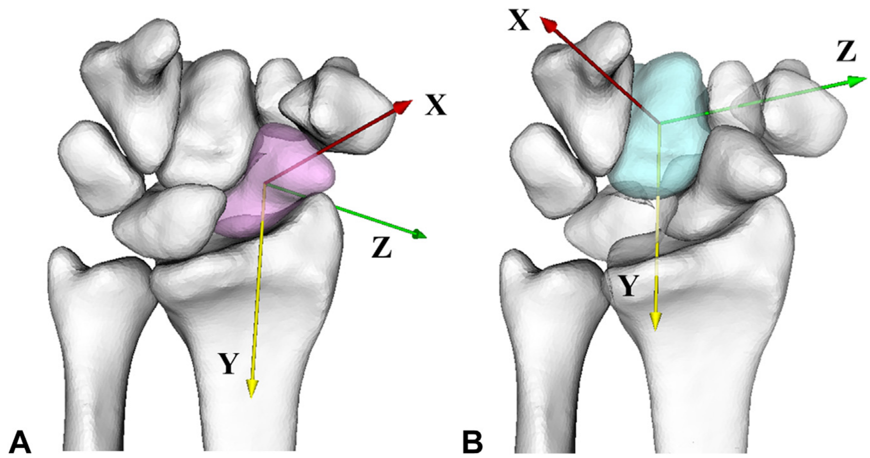

FIGURE 2: The local orthogonal coordinate system as applied to the scaphoid **A** and the capitate **B**, according to Belsole et al[30] and described in the text.

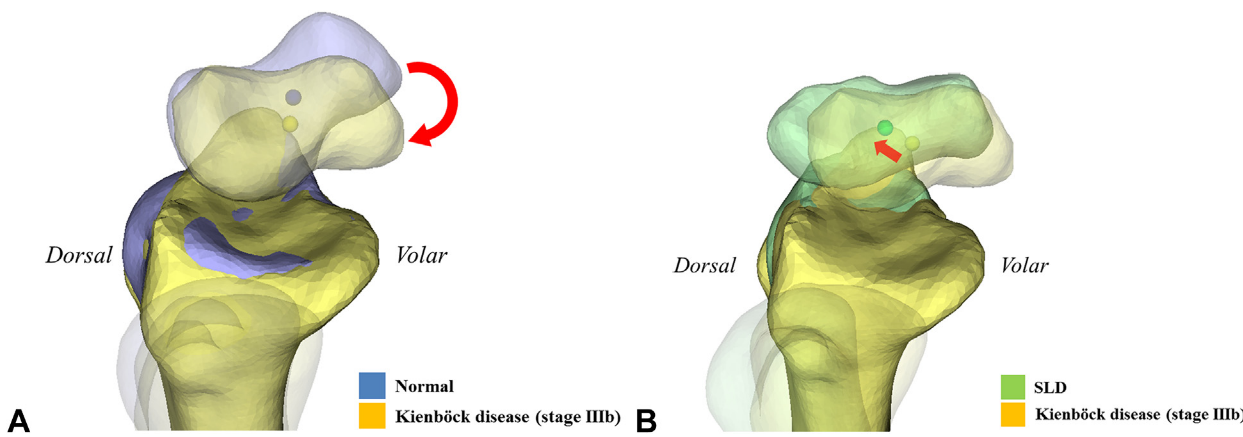

FIGURE 3: The bone models are superimposed with reference to the orthogonal reference system of each radius. The similar color points represent centroids of each scaphoid. **A** Compared with the normal scaphoid, the scaphoid in stage IIIb Kienböck disease shows significant flexing and the centroids are located proximally. **B** Compared with stage IIIb Kienböck disease, the centroid and the proximal pole of the scaphoid with SLD show significant translation in the dorsodistal direction.

The centroid of the capitate in stages IIIa and IIIb Kienböck disease were not significantly different from the capitate in the normal wrists. Compared with the capitate in stage IIIb Kienböck disease, the centroid of the capitate with SLD significantly translated 5.2 mm in the dorsal direction ($P = .03$) (Fig. 4). The rotational parameters of the capitate were not significantly different among the groups (Table 2).

RSJ congruency

The inferred contact areas between the scaphoid proximal pole and the distal radius in the RSJs of normal and stages IIIa and IIIb Kienböck disease were similar and their RSJ congruency was retained. In contrast, the inferred contact areas in the RSJs of SLD shifted dorsally toward the dorsal rim of the distal radius, producing RSJ incongruity (Fig. 5).

DISCUSSION

Some surgeons consider that pain in stage III Kienböck disease is caused by carpal collapse and RSJ incongruity involving dorsal subluxation of the scaphoid proximal pole.[18,19] However, it was not clear whether scaphoid rotatory subluxation with stage IIIb Kienböck disease actually involved dorsal subluxation of the scaphoid proximal pole. Therefore, we examined 3-dimensional carpal alignment and RSJ congruity in stage III Kienböck disease and compared it with those in the normal wrists and wrists with SLD.

Our study has some limitations. First, the sample size was small. If a statistically sufficient number of subjects had been studied, the results might have been different. Second, the character of each group of subjects was heterogeneous. There were fewer subjects in the SLD group than in the other groups

TABLE 1. Position of the Scaphoid

	Rotation (°)			Translation (mm)		
	φx	φy	φz	Δx	Δy	Δz
Normal	−7*	−23	−34	5*	−3	2
Kienböck disease (stage IIIa)	12	−27	−28	4*	−1*	1
Kienböck disease (stage IIIb)	5	−23	−8†	5*	0*†	2
SLD	24†	−23	−19	0†	−5	6

φx, ulnar (+) and radial (−) deviation; φy, pronation (+) and supination (−); φz, flexion (+) and extension (−); Δx, volar (+) and dorsal (−) translation; Δy, proximal (+) and distal (−) translation; Δz, radial (+) and ulnar (−) translation.
*Significant difference compared with SLD.
†Significant difference compared with normal, $P < .05$.

TABLE 2. Position of the Capitate

	Rotation (°)			Translation (mm)		
	φx	φy	φz	Δx	Δy	Δz
Normal	20	35	−13	1	−12	−9
Kienböck disease (stage IIIa)	28	28	−22	1	−8	−10
Kienböck disease (stage IIIb)	19	38	−14	3*	−9	−9
SLD	13	29	−16	−3	−12	−4

φx, ulnar (+) and radial (−) deviation; φy, pronation (+) and supination (−); φz, flexion (+) and extension (−); Δx, volar (+) and dorsal (−) translation; Δy, proximal (+) and distal (−) translation; Δz, radial (+) and ulnar (−) translation.
*Significant difference compared with SLD.

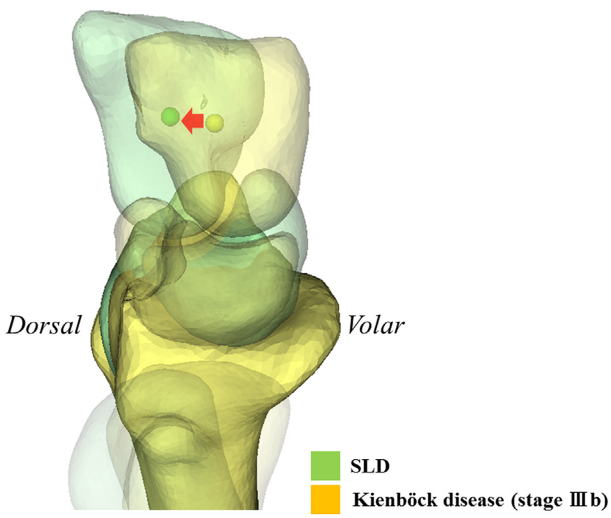

FIGURE 4: The bone models are superimposed with reference to the orthogonal reference system of each radius. The similar color points represent centroids of each capitate. Compared with stage IIIb Kienböck disease, the centroid of the capitate with SLD shows significant translation dorsally.

because there were only 3 patients with SLD whose CT data were available. The groups were not completely matched for sex and age. Third, we did not consider variations of carpals and RSJ morphology, which may have influenced the results. Werner et al[37] reported that the wrists with a deep scaphoid fossa, greater volar tilt, or larger scaphoid curvatures tended not to have dorsal subluxation of the scaphoid proximal pole. Fourth, we did not examine the laterality of carpal position and RSJ incongruity because CT scans were performed only on the affected side. Finally, we assessed the wrists only under static condition.

The wrist position during CT scanning was an important factor in this study because the rotational position of the scaphoid is significantly affected by wrist position. The scaphoid motion follows the wrist motion during wrist flexion and extension and correspondingly flexes and extends during wrist radial and ulnar deviation.[38,39] Although it is common that the wrist position is represented by the relationship between the third metacarpal and radius, the capitate can be used as a substitute for the third metacarpal[38] because the capitate and third metacarpal rotate together as a single unit during wrist motion.[40,41] The results of the rotational parameters of the capitate indicate that the wrists were not in an absolute neutral position during CT scanning. However, these parameters were not significantly different among the groups, which means that the wrist position during CT scanning was fairly uniform among the subjects.

Our study revealed that the pattern of carpal collapse was different between stage IIIb Kienböck disease and SLD in terms of RSJ congruity. Stage IIIb Kienböck disease demonstrated a flexed scaphoid and proximal translation of the centroid but not dorsal translation of the scaphoid proximal pole, so RSJ congruity was preserved. In contrast, the scaphoid in SLD flexed and the proximal pole translated dorsally together with the capitate, producing RSJ incongruity, as Omori et al[22] reported. Understanding the mechanism producing RSJ incongruity is important in dealing with carpal instability. When the scaphoid flexes in normal wrists, this flexion moment is constrained by the extension moment of the triquetrum, and stable equilibrium is achieved via the lunate as a bony link.[37,38] If the link is broken, such as in SLD, the scaphoid flexes and the lunate and triquetrum extend. Simultaneously, the capitate translates in the dorsal direction because of lunate extension, and the scaphoid translates dorsally as well

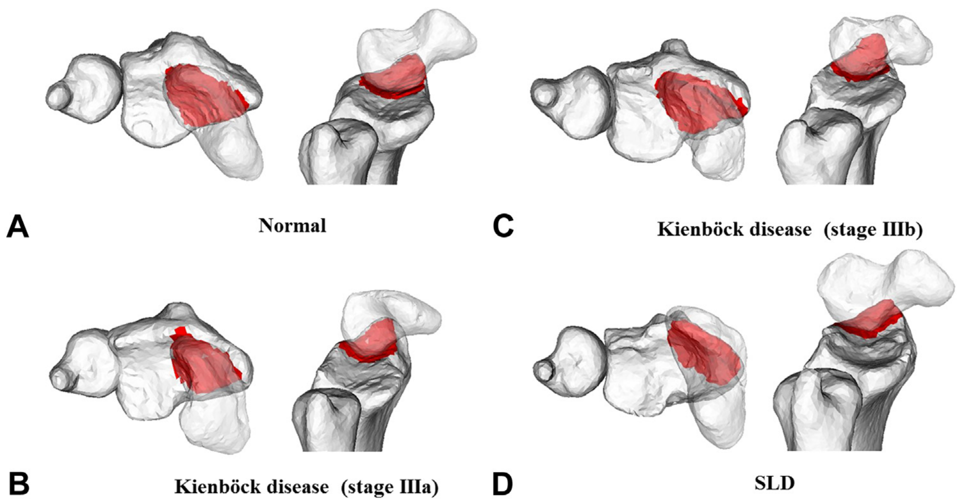

FIGURE 5: Inferred contact areas of the articular surface of the RSJ. A typical example of each joint is shown. The left illustration of each shows a distal view and the right show the ulnar view. **A–C** The contact areas in the RSJ of normal and stage III Kienböck-disease wrists are similar and congruency is retained. **D** In the RSJ with SLD, the contact area is located on the dorsal side, and there is joint incongruity for dorsal subluxation of the scaphoid proximal pole.

because of strong links between the scaphoid and the capitate via the scaphoid intrinsic ligaments.[22,32,42] Subsequently, dorsal translation of the scaphoid proximal pole produces RSJ incongruity. In Kienböck disease, the scaphoid flexes because the lunate collapses and cannot work as a bony link for stable equilibrium of proximal carpal row. In addition, the capitate is not affected by the lunate because the extension moment deriving from the lunate will not occur for necrosis of the lunate. Therefore, the scaphoid and capitate do not translate dorsally in Kienböck disease. Compared with the scaphoid in stage III Kienböck disease, the scaphoid in SLD showed distal translation of the centroid, which was because the scaphoid proximal pole was over the dorsal rim of the radius with the dorsal translation.

There are multiple described surgical treatments for stage III Kienböck disease. Watson et al[18,19] selected scaphotrapeziotrapezoid arthrodesis because of their notion that the cause of many symptoms was RSJ incongruity involving dorsal subluxation of the scaphoid proximal pole accompanying scaphoid rotatory subluxation. However, Kienböck disease treated by scaphotrapeziotrapezoid arthrodesis often has postoperative radial styloid impingement[19,43] or osteoarthrosis of the RSJ.[44] In contrast, stage III Kienböck disease has been successfully treated by resection of the lunate alone,[4,8] radial shortening,[45,46] or capitate shortening[16,47] without the complications developing in the RSJ. Moreover, Taniguchi et al[20] treated stage IV Kienböck disease by cast immobilization and reported that the joint space of RSJ was retained even in the stage that should have shown osteoarthrosis. We think that these observations of previous reports are compatible with our result showing preservation of RSJ congruity in advanced Kienböck disease, which may explain why patients with Kienböck disease and carpal collapse can be asymptomatic.

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