In cases where the metacarpophalangeal joint is stable after closed reduction, non-operative treatment yields the favourable functional results (Boland, 1984; Khuri

Fig 3 Intraoperative photograph through the palmar incision. The sheath of the flexor tendon (asterisk) is ruptured and the palmar plate is avulsed from the base of the proximal phalanx (arrow head). The collateral ligaments (small arrows) still attached to the base of the phalanx are also torn.

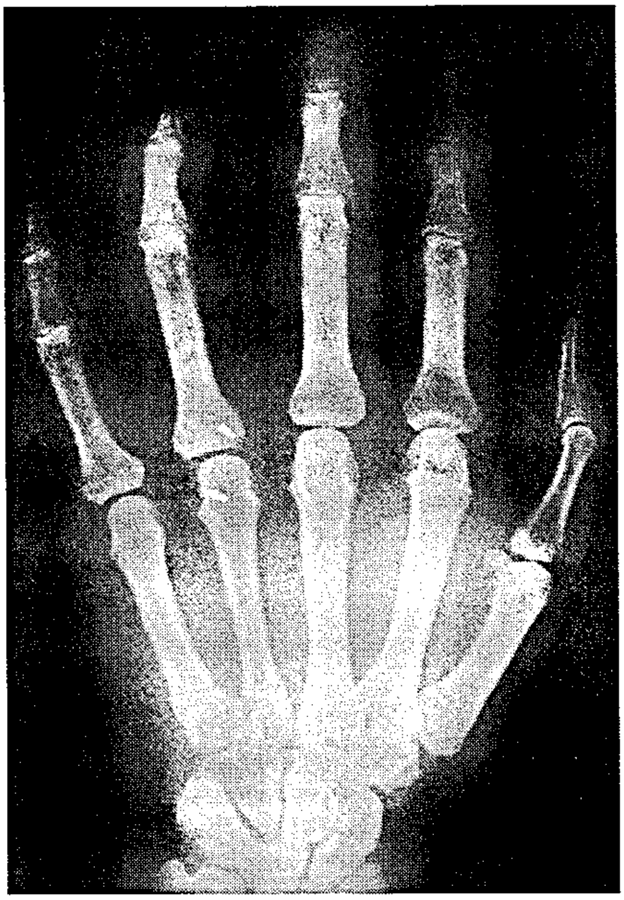

Fig 4 Both of the collateral ligaments were repaired using suture anchors.

Table 1——Reported cases

First author	*Age (years)*	*Sex*	*Injured side*	*Injured finger*	*Mechanism of injury*	*Surgery*	*Time from injury to surgery*	*Surgical procedure*	*Articular interposition*	*Final flex/ext arc (degrees)**
McLaughlin (1965)	—	—	—	Middle	—	Yes	—	OR	DC	—
Renshaw (1973)	48	M	L	Little	H.E.	Yes	2 weeks	OR	PP	60
Wood (1981)	17	F	L	Index	H. F.	Yes	9 months	Arthrodesis	DC	0
	20	M	R	Middle	H. F.	Yes	2 weeks	OR + TF	DC	—
	61	F	R	Middle	H. F.	Yes	5 months	Arthroplasty	DC	60
Betz (1982)	70	F	L	Ring	H.E.	Yes	—	OR + repair of UCL, PP	PP, UCL	Full
Moneim (1983)	59	M	R	Little	H. F.	Yes	7 weeks	OR + repair of RCL, UCL, PP, DC + TF	PP	70
Boland (1984)	65	F	L	Ring	H. F.	No	0	—	—	Decreased by 20
Khuri (1986)	31	M	L	Ring	H. F.	No	0	—	—	Full
Hargarten (1992)	66	M	R	Little	H. F.	Yes	4 weeks	OR	—	65
Qui (1992)	20	M	R	Index	H. F.	Yes	3 weeks	OR + TF	PP	20
Mlsna (1993)	68	M	R	Little		Yes	3 weeks	OR + repair of RCL	DC	65
Takami (1999)	20	M	R	Ring	—	No	0	—	—	Full
	60	F	R	Ring	—	No	0	—	—	75
Lam (2000)	44	M	L	Ring	H. F.	Yes	0	OR + TF	PP	80
Present study	52	F	L	Ring	H. E.	Yes	6 days	OR + repair of RCL, UCL	PP	60

Injured side: R, right. L, left. Mechanism of injury: H.E., hyperextension; H. F., hyperflexion. Surgical procedure: OR, open reduction; TF, provisional transfixation with a Kirschner wire. RCL, radial collateral ligament; UCL, ulnar collateral ligament; PP, palmar plate; DC, dorsal capsule; —, not described.

and Fay, 1986; Takami et al., 1999). However, if the instability persists after closed reduction or reduction is impossible, one should not hesitate to carry out an open reduction. Wood and Dobyns (1981) reported a case whose metacarpophalangeal joint redislocated two times after closed reduction, and underwent an arthrodesis 9 months after the initial injury. The results of operative treatment more than 3 months after the injury are generally poor (Qui, 1992; Wood and Dobyns, 1981).

At surgery, if the capsule or the palmar plate are interposed in the metacarpophalangeal joint they should be extracted and the collateral ligaments should be repaired if they are torn. The suture anchor system was useful in our case for repair of the collateral ligaments.

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Capitate-Based Kinematics of the Midcarpal Joint During Wrist Radioulnar Deviation:
An *In Vivo* Three-Dimensional Motion Analysis

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Purpose: The purpose of this study was to obtain qualitative and quantitative information regarding *in vivo* 3-dimensional (3D) kinematics of the midcarpal joint during wrist radioulnar deviation (RUD).

Methods: We studied the *in vivo* kinematics of the midcarpal joint during wrist RUD in the right wrists of 10 volunteers by using a technology without radioactive exposure. The magnetic resonance images were acquired during RUD. The capitate was registered with the scaphoid, the lunate, and the triquetrum by using a volume registration technique. Animations of the relative motions of the midcarpal joint were created and accurate estimates of the relative orientations of the bones and axes of rotation (AORs) of each motion were obtained.

Results: The scaphoid, lunate, and triquetrum motions relative to the capitate during RUD were found to be similar, describing a rotational motion around the axis obliquely penetrating the head of the capitate in almost a radial extension/ulnoflexion plane of motion of the wrist. The AORs of the scaphoid, the lunate, and the triquetrum were located closely in space. In the axial plane the AORs of the scaphoid, lunate, and triquetrum formed a radially and palmarly opening angle of 43° ± 7°, 41° ± 11°, and 42° ± 14° with the wrist flexion/extension axis, respectively.

Conclusions: This study reports the *in vivo* 3D measurements of midcarpal motion relative to the capitate. Isolated midcarpal motion during RUD could be approximated to be a rotation in a plane of a radiodorsal/ulnopalmar rotation of the wrist, which may coincide with a motion plane of one of the most essential human wrist motions, known as the *dart-throwing motion*. (J Hand Surg 2004; 29A:668–675. Copyright © 2004 by the American Society for Surgery of the Hand.)

Key words: Capitate, kinematics, midcarpal joint, motion analysis, wrist.

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Understanding the interactions of the scaphoid, lunate, triquetrum, and the surrounding carpus is the key to how the wrist maintains its stability while allowing a large range of motion.[1] Although the traditional 2-dimensional radiographic studies of the wrist joint have tried to clarify kinematics of the radiocarpal joint,[2–5] kinematics of the midcarpal joint remain obscure. One reason is that it is very difficult to isolate the midcarpal motion radiographically during global wrist motion because the bones of both the proximal row and the distal row move relative to the radius so that one cannot observe the relative motion of the midcarpal joint. Although the previous studies using 3-dimensional (3D) motion analysis reported detailed data on the midcarpal motion,[6–8] most of the descriptions of the relative motion merely included a combination of numeric angles of simple motions based on the anatomic coordinate system, using terms such as *flexion, radial deviation,* or *pronation.* As a result the kinematics of midcarpal motion have remained obscure. It is difficult to assess 3D behavior of the midcarpal joint without visual information, such as 3D animation.

To overcome these problems in kinematic study, descriptions of the 3D carpal motions using computer-aided design models obtained from computed tomography have been developed.[9–11] These motion analysis systems enable the isolation and visualization of any motion of one bone relative to another bone. The 3D animation of the relative motion affords better appreciation of essential 3D kinematics through the visual check of the 3D motion. Moreover recent development of technology now has enabled *in vivo* motion analysis,[12–18] which would be expected to be more physiologic than *in vitro* motion analysis using cadavers. In a previous study we described the technical details of the *in vivo* 3D motion analysis and the kinematics of the triquetrum hamate joint.[18] The current study is a continuation of the previous study and was designed to investigate overall midcarpal kinematics during wrist radioulnar deviation (RUD) with increased number of observations.

Very little motion exists between the 4 bones of the distal row (trapezium, trapezoid, capitate, and hamate)[6,7,19] and that in contrast the 3 bones of the proximal row (scaphoid, lunate, and triquetrum) appear to be less tightly bound to one another.[2,7,20] Traditionally the midcarpal motion has been investigated by using the proximal body (scaphoid, lunate, and triquetrum) as a reference to determine the kinematics of a distal moving segment (the distal row). Although such a method affords detailed information on the relative motion between the distal and proximal rows, it still can be difficult to understand overall midcarpal motion. If the distal row (eg, capitate) is used as a reference to determine the kinematics of a proximal row (eg, scaphoid, lunate, and triquetrum) one can observe all the relative motions at the same time. Such capitate-based motion analysis may offer new information on the midcarpal kinematics. This study investigated the midcarpal motion in 2 ways: (1) the capitate motion relative to the scaphoid, lunate, and triquetrum, and (2) the scaphoid, lunate, and triquetrum motions relative to the capitate.

The purpose of this study was to obtain qualitative and quantitative kinematic information on the midcarpal joint during wrist RUD as well as its role in and contribution to global wrist motion.

Materials and Methods

The *in vivo* kinematics of the midcarpal joint during wrist RUD was studied in the right wrists of 10 volunteers (6 men, 4 women). The average age of the volunteers was 25 years (range, 20–32 y). The lunates were categorized as type 1 or type 2 based on the presence (type 2) or absence (type 1) of the medial hamate facet on the lunate in the midcarpal joint.[14] Whether the lunates were type 1 or type 2 was determined by measuring the coronal width of the hamate facet on the lunate in the coronal plane of the magnetic resonance image of the wrist in neutral position. There were 5 type 1 and 5 type 2 lunates (Table 1). Magnetic resonance images were acquired in 6 positions during RUD from 30° radial deviation to 45° ulnar deviation in 15° increments[18] in 5 wrists and acquired in 3 positions (a neutral position and 2 extreme positions) in the other 5 wrists. The contours of each bone were segmented from magnetic resonance volume images by using a software program (Virtual Place-M software program; Medical Imaging Laboratory, Tokyo, Japan) and surface models of the bones were constructed. The kinematic variables were calculated by registering the bone in one position and comparing it with another. The volume registration technique was used in this study. The iterative closest point algorithm[21] was used for registration in which a set of 3D volume points was registered by finding the best parameters, minimizing the sum of the distance from each 3D volume point. The scaphoid, the lunate, and the triquetrum were registered with the capitate to investigate the directions of the motion of the capitate relative to each of the bones in the proximal row. To compare the lo-

Table 1. Euler Angles of Motion of the Capitate Relative to the Scaphoid, Lunate, and Triquetrum From Ulnar Deviation to Radial Deviation

				Hamate Facet Width of the	Scaphoid			Lunate			Triquetrum		
Case	Lunate Type	Age	Gender	Lunate (mm)	x	y	z	x	y	z	x	y	z
1	1	25	F	0	29.1°	−16.7°	3.1°	28.9°	−24.2°	8.0°	26.8°	−15.2°	8.5°
2	1	26	M	0	40.4°	−42.1°	3.6°	41.5°	−37.4°	5.0°	19.9°	−30.0°	15.7°
3	1	27	M	0	25.2°	−25.6°	−4.0°	38.6°	−28.2°	−3.3°	28.2°	−16.1°	−3.2°
4	1	24	M	0	23.0°	−24.4°	−0.5°	20.4°	−24.0°	−2.3°	9.6°	−21.8°	9.1°
5	1	24	M	0	33.7°	−37.5°	0.3°	36.6°	−33.8°	−0.5°	28.4°	−24.7°	−0.6°
	Average of type 1 lunate				30.3°	−29.3°	0.5°	33.2°	−29.5°	1.4°	22.6°	−21.6°	5.9°
	SD				7.0°	10.3°	3.1°	8.5°	5.9°	4.9°	8.0°	6.2°	7.7°
6	2	20	F	1.7	39.6°	−33.8°	5.8°	30.2°	−34.1°	7.0°	19.2°	−18.3°	16.8°
7	2	21	F	2.0	13.7°	−16.8°	7.2°	16.4°	−23.0°	5.7°	9.2°	−17.9°	10.8°
8	2	24	F	2.6	35.9°	−27.2°	1.7°	44.8°	−28.2°	1.1°	26.3°	−21.0°	−1.9°
9	2	25	M	4.2	28.5°	−32.2°	5.3°	30.6°	−27.9°	8.3°	21.2°	−22.4°	10.7°
10	2	32	M	4.3	26.0°	−23.3°	−7.7°	45.3°	−29.2°	−14.5°	35.0°	−17.5°	−13.2°
	Average of type 2 lunate				28.7°	−26.7°	2.5°	33.5°	−28.5°	1.5°	22.2°	−19.4°	4.6°
	SD				10.0°	6.9°	6.0°	12.0°	4.0°	9.4°	9.5°	2.2°	12.1°
	Total average				29.5°	−28.0°	1.5°	33.3°	−29.0°	1.5°	22.4°	−20.5°	5.3°
	SD				8.2°	8.4°	4.6°	9.8°	4.8°	7.0°	8.3°	4.5°	9.6°

x: +, extension; −, flexion; y: +, ulner deviation; −, radial deviation; z: +, supination; −, pronation.

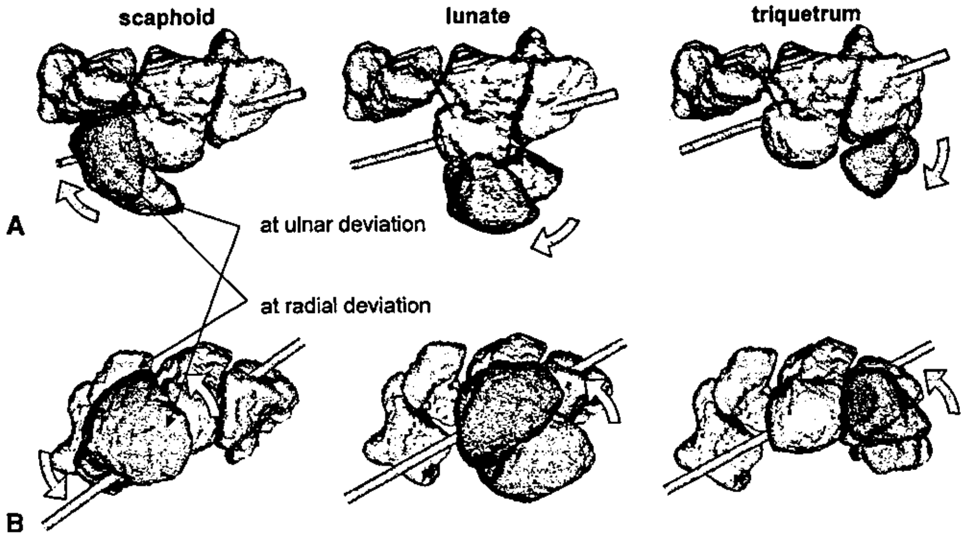

Figure 1. (A) Dorsal view and (B) proximal view of the capitate-based motions of the scaphoid, lunate, and triquetrum and their axes of rotation during RUD of the right wrist.

cation of the axes of rotation (AORs)[22] of the scaphoid, the lunate, and the triquetrum relative to the distal row, the capitate was registered with the scaphoid, the lunate, and the triquetrum. The coordinate system was constructed using bone landmarks in the neutral wrist position: the z-axis was defined as the long axis of the distal part of the radius, which was defined as the principal axis corresponding to the minimum moment of inertia. The x-axis was defined as a line passing the center of the capitate body at right angles to the z-axis and parallel to a line connecting the radial and ulnar styloid. The y-axis was defined as a line perpendicular to the other 2 axes.

Results

The Capitate Motion Relative to the Scaphoid, Lunate, and Triquetrum

From wrist ulnar deviation to radial deviation the capitate rotated radiodorsally relative to the scaphoid, the lunate, and the triquetrum. The converse was true during wrist ulnar deviation. The Euler angles of the capitate motion relative to the scaphoid, lunate, and triquetrum from the wrist ulnar deviation to wrist radial deviation are shown in Table 1. During wrist RUD the capitate angulated 28° ± 8° radially and 30° ± 8° dorsally relative to the scaphoid, 29° ± 5° radially and 33° ± 10° dorsally relative to the lunate, and 21° ± 5° radially and 22° ± 8° dorsally relative to the triquetrum. We could not find any significant difference in the Euler angles of the capitate motion relative to the scaphoid, lunate, and triquetrum between type 1 and type 2 lunates.

The Scaphoid, Lunate, and Triquetrum Motions Relative to the Capitate

On the capitate-based animation the scaphoid, lunate, and triquetrum motions relative to the capitate during RUD were found to be similar to each other, describing a rotational motion in a plane obliquely oriented relative to the coronal plane of the wrist that was almost a radial extension/ulnoflexion plane of the motion of the wrist (Figs. 1, 2A, 2B; video may be viewed at the *Journal's* Web site, www.jhandsurg.org). During wrist radial deviation the proximal portion of the scaphoid, the lunate, and the triquetrum moved radiodorsally and the distal portion of the scaphoid moved ulnopalmarly relative to the capitate. The converse was true during wrist ulnar deviation.

The AORs of the scaphoid, lunate, and triquetrum relative to the capitate were located closely together in space and ran obliquely from the radiopalmar aspect of the distal scaphoid to the ulnodorsal aspect of the hamate, penetrating the neck of the distal scaphoid and the waist of the capitate (Figs. 1, 3). In the axial plane the AORs of the scaphoid, lunate, and triquetrum formed a radially and palmarly opening angle of 43° ± 7°, 41° ± 11°, and 42° ± 14°, respectively, with the x-axis (flexion/extension axis) of the coordinate system (Fig. 3B).

The average range of motion of the scaphoid, the lunate, and the triquetrum around their own axes were 41° ± 10°, 44° ± 10°, and 33° ± 6°, respectively.There were relatively minor intercarpal motions between the scaphoid and the lunate and be-

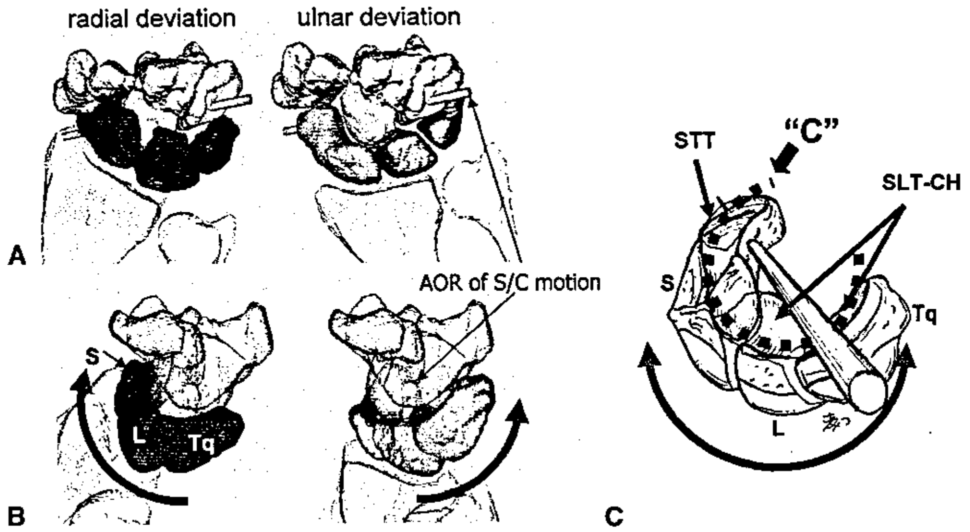

Figure 2. The capitate-based midcarpal motion during RUD. (A) Dorsal view. (B) Ulnodorsal view in which the AOR of the scaphoid-capitate (s/c) motion is perpendicular to the picture. (C) Schema of the ulnodorsal view of the proximal row. The outlines of the surfaces of the STT and SLT-CH joints form a C shape.

tween the lunate and the triquetrum, averaging 8° ± 6° and 16° ± 5°, respectively.

We could not find any significant difference in these AORs and range of motions of the scaphoid, lunate, and triquetrum relative to the capitate between type 1 and type 2 lunates.

Discussion

Current kinematic technique has some limitations. The biggest disadvantage of this technique is that it makes a static rather than dynamic motion analysis. Static measurement does not include any inertial or functional effects that might occur during normal wrist motion. This technique, however, can provide new information regarding *in vivo* midcarpal kinematics.

The midcarpal joint is a major component of the wrist joint and substantially contributes to overall global wrist motion. The scaphotrapeziotrapezoid (STT) joint[10,23] and the triquetrum-hamate (TqH) joint[18] have been studied by one of the current authors (H.M.), both anatomically and kinematically. The studies of the STT joint revealed that the skeletal and ligamentous constraints of the STT joint are very strong and the STT joint essentially has a single degree of freedom. The studies of the STT joint also revealed that the AOR of the STT joint runs obliquely from radiopalmar to ulnodorsal,[10] which is consistent with the current *in vivo* study. The study of the TqH joint revealed that the triquetrum rotated obliquely relative to the hamate during wrist RUD in a radial extension/ulnoflexion plane of motion. This suggests that the TqH motion is similar to the STT motion. The present study suggests that the lunate motion relative to the capitate is also very similar to that of the STT and TqH motions. Collectively this

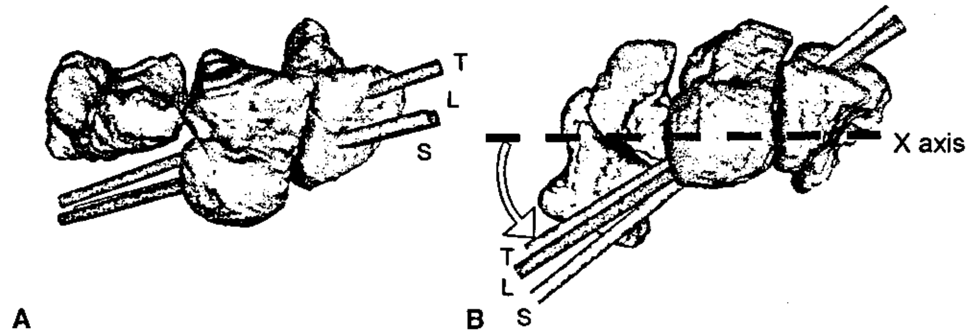

Figure 3. (A) Dorsal view and (B) proximal view of the distal row of the right wrist and the axes of rotation of the scaphoid (s), lunate (l), and triquetrum (t). x-axis, wrist flexion/extension axis.

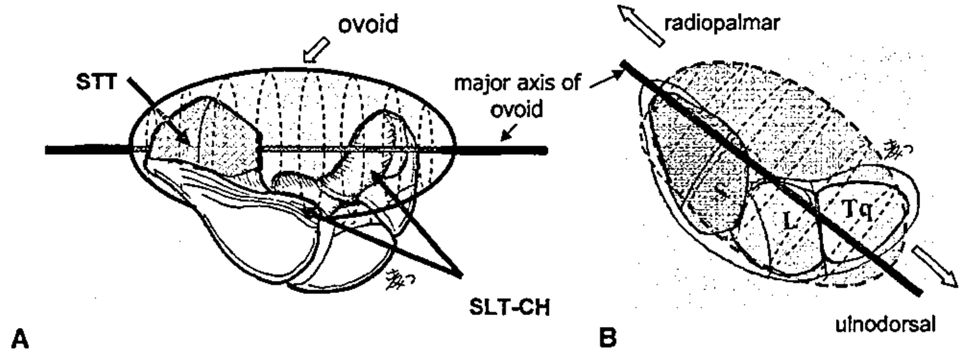

Figure 4. (A) Radiodorsal and (B) distal views of the proximal row and an ovoid. Most of the joint surfaces of the midcarpal joint contact with the imaginary ovoid, whose major axis run obliquely from radiopalmar to ulnodorsal. S, scaphoid; L, lunate.

information implies that the midcarpal motion during RUD is more synchronous than previously reported.

From an anatomic point of view the midcarpal joint may have the most complicated joint shape in the human body. In a broad sense there are 2 articulations: the STT joint and the scapholunotriquetrum-capitate-hamate (SLT-CH) joint. The former is convex proximally whereas the latter is concave. Two-dimensionally these joints form an S shape in a posteroanterior x-ray, which has made the kinematics of the midcarpal joint difficult to understand. Through 3D analysis of the anatomy and kinematics of the midcarpal joint it appears that most of the joint surface of the midcarpal joint forms an ovoid whose major axis runs obliquely from radiopalmar to ulnodorsal (Fig. 4). The STT joint contacts the radiodistal part of the ovoid and the SLT-CH joint contacts the proximal and ulnar parts of the ovoid. Thus the shape of the midcarpal joint allows this joint to rotate smoothly and congruently in an oblique plane of wrist radiodorsal/ulnopalmar rotation around the major axis of the ovoid, which runs obliquely from radiopalmar to ulnodorsal.

The major axis of this ovoid appears to be located closely in space to the AORs of the scaphoid-capitate joint, as determined in this study (Fig. 2). In an oblique view from the dorsoulnar side of the wrist where the AOR of the scaphoid-capitate joint is perpendicular to the picture, the outlines of the surfaces of the STT and SLT-CH joints are seen to form a three-quarter circle or a C shape (Figs. 2B, 2C). The center of the C appears to coincide with the major axis of the ovoid.

Applying this ovoid/C-shaped concept to the kinematics of the midcarpal joint it appears that essentially the kinematics of the midcarpal joint during RUD are a radiodorsal/ulnopalmar rotation around the AOR of the scaphoid-capitate joint, which passes through the center of the C shape of the 3D joint surface contacts of the midcarpal joint (Fig. 2B; video may be viewed at the *Journal's* Web site, www.jhandsurg.org). Therefore we may reasonably conclude that essential kinematics of the midcarpal joint during RUD could be approximated to be a radiodorsal/ulnopalmar rotation around the AOR of the scaphoid-capitate joint along with the C shape of the joint surface of the midcarpal joint.

This radiodorsal/ulnopalmar rotation coincides

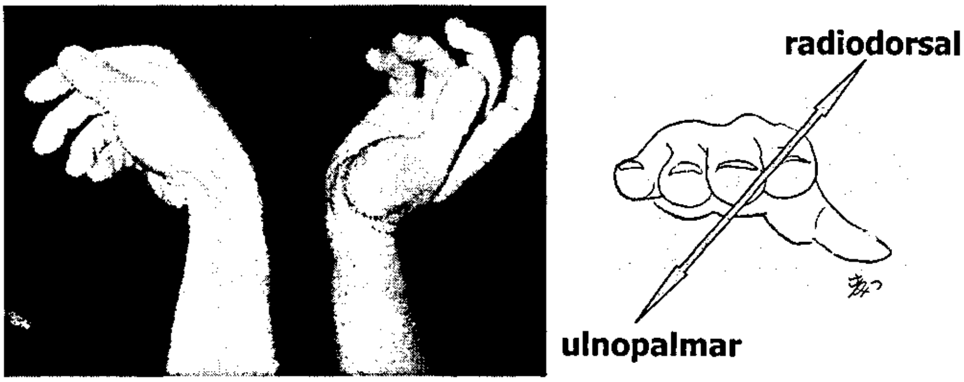

Figure 5. Dart-throwing motion (wrist radiodorsal/ulnopalmar rotation).

radialextension neutral ulnarflexion

Figure 6. The C shape of the outlines of the midcarpal joint surface can be seen radiographically when the x-ray beam is aligned along the radiodorsal/ulnopalmar axis of the dart-throwing motion in the semisupinated view. s, scaphoid; L, lunate.

with the so-called dart-throwing motion[24,25] (wrist radiodorsal/ulnopalmar rotation, Fig. 5), which is one of the most frequently used wrist motions in activities of daily living such as hammering nails, beating a drum, swinging a golf club, or casting a fishing rod. The C shape of the outlines of the midcarpal joint surface can be seen radiographically when the x-ray beam is aligned along the radiodorsal/ulnopalmar axis of the dart-throwing motion in the semisupinated view (Fig. 6). Radiodorsal/ulnopalmar rotation may be the most stable and controllable human wrist motion, which is the main motion plane of the midcarpal joint.

Nakamura et al[26] reported that the kinematics of the type 1 lunate are different from those of a type 2 lunate in 2-dimensional study although we could not find any notable difference in their midcarpal behavior between type 1 and type 2 lunates. We speculate that may be owing to the innate limitation of the 2-dimensional measurements, which are influenced more by the shape of the lunate than our 3D measurement using Euler angle. We probably need to increase the number of subjects, however, to conclude this matter.

This study suggests that the midcarpal joint may be much more important than previously suggested in terms of its contribution to both the stability and mobility of the global wrist joint. Furthermore this raises concern regarding the impact of partial or complete fusion of the midcarpal joint on overall wrist motion and stability. We hope the information and ovoid/C-shape perspective of the anatomy and kinematics of the midcarpal joint will assist the clinician in better understanding the wrist joint and some of its disorders.

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In vivo elbow biomechanical analysis during flexion: Three-dimensional motion analysis using magnetic resonance imaging

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The purpose of this article is to evaluate in vivo 3-dimensional kinematics of the elbow joint during elbow flexion. We studied the ulnohumeral and radiohumeral joint noninvasively in 3 elbows in healthy volunteers using a markerless bone registration algorithm. Magnetic resonance images were acquired in 6 positions of elbow flexion. The inferred contact areas on the ulna against the trochlea tended to occur only on the medial facet of the trochlear notch in all of the elbow positions we tested. The inferred contact areas on the radial head against the capitellum occurred on the central depression of the radial head in all of the tested elbow positions except for 135° flexion, where the anterior rim of the radial head articulates with the capitellum. (J Shoulder Elbow Surg 2004;13:441–7.)

Motion analysis has been widely used to study normal and pathologic kinematics and the effects of reconstructive procedures on pathologic conditions. Kinematic data have been mainly obtained in vitro by a variety of techniques, including bipolar radiography,[11,19,20] electromagnetic sensors,[8] and high-speed video data acquisition systems.[15,18] These methods rely on the assumption that the movement of the markers truly mimics the motion of the bone. These techniques use invasive procedures to mount markers on the bones, such as transcutaneous bone pins or implantable bone markers. As a result, the utility of bone markers is further compromised by mechanical impingement and tethering of soft tissues. Moreover, in vitro experiments cannot completely reproduce the physical muscular force across the elbow. This limitation may alter normal kinematics.

Recently, researchers have been able to measure 3-dimensional (3D) in vivo kinematics using noninvasive techniques. These techniques use surface-based registration of the bones to determine corresponding relationships between images represented at different coordinates via computed tomography (CT) or magnetic resonance imaging (MRI).[1,3] By use of this methodology, in vivo 3D kinematics of the elbow joint can be analyzed noninvasively.

Accurate measurement of the contact areas of the elbow has been extremely difficult, and several techniques have been applied to this highly congruous joint.[21] Silicone casting[4,6] and reversible cartilage staining[7] in studies with cadaveric models have been most commonly used. Again, in vitro experiments cannot reproduce completely the physical muscular force across the elbow, which undoubtedly influences the resulting contact areas. Using a proximity mapping technique,[14] however, we can calculate the in vivo inferred contact area of the elbow joint noninvasively from bone surface models created from CT or magnetic resonance (MR) images. This technique extends our functional understanding of the elbow.

The purpose of this article is to evaluate in vivo 3D kinematics of the elbow joint during flexion motion. We especially focused on the contact areas of the ulnohumeral and radiohumeral joint. In addition, we investigated the pathway of the helical screw axis of motion of the ulna relative to the humerus and the change in the carrying angles with elbow flexion for the ulnohumeral joint.

MATERIALS AND METHODS

We studied the right elbow joints of 3 healthy volunteers (1 woman and 2 men; age range, 24-26 years; mean age, 25.0 years) during elbow flexion motion. The steps in 3D registration are image acquisition, segmentation, and registration. A mathematical description of the motion of individual bones and of their relative motion is derived by

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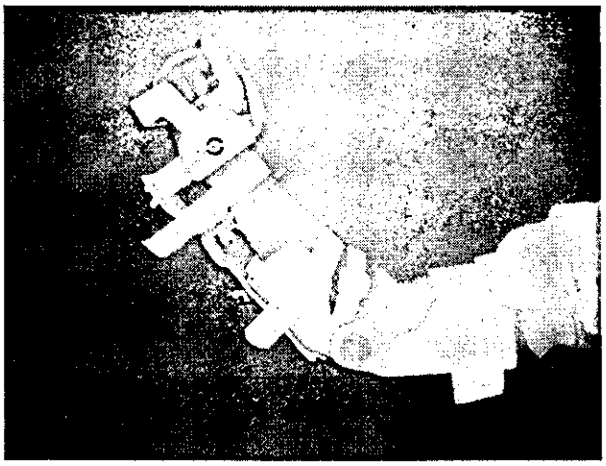

Figure 1 To immobilize the elbow and the wrist at a specific angle during flexion-extension, a special posture device was designed.

computing the rigid transformation required to match the surface models.

Image acquisition

MRI data of the right elbows of volunteers were obtained with a 1.5-T commercial MR system (Magnetom Vision Plus 1.5-T MRI; [Siemens AG, Erlangen, Germany]) in conjunction with a receive-only body-array surface coil. We used a 3D sequence (3dflash) with a TR/TE/flip angle of 2.3 milliseconds/33 milliseconds/45°, a 256 × 200 in-plane acquisition matrix, and a 350-mm field of view and 2.0-mm thickness on a contiguous slice with a pixel size of 0.6 × 0.8 mm. Acquisition of a 3D volume image requires approximately 5 minutes. To immobilize the elbow and the wrist at a specific angle during flexion-extension, a special posture device was designed. During this study of elbow flexion, the forearm was fixed in the neutral position (Figure 1). Each volunteer was positioned in a semiprone position, and images were obtained in 6 positions of elbow flexion (0°, 30°, 60°, 90°, 120°, and 135°).

Segmentation

Segmentation was defined as extracting bone contours and associating each contour with the individual bones. The contours of each bone were segmented from MR volume images by use of the Virtual Place-M software program developed in our laboratory (Medical Imaging Laboratory, Tokyo, Japan). Surface models of the humerus, ulna, and radius were obtained by applying a 3D surface generation of the bones' cortex. By means of the graphics workstation, the 3D geometry of each bone was obtained by connecting the different sections. The software generated 3D surface bone models via the marching cubes technique.[13] Visualization of the geometrical models of each elbow was obtained by use of the software program developed in our laboratory (Division of Functional Diagnostic Imaging, Biomedical Research Center, Osaka University Medical School, Suita, Japan).

Registration

Registration was performed under the assumption that each bone moved independently as a rigid body 3-dimensionally. The kinematic variables were calculated by registering the bone, described by its surface points obtained from segmentation, from one position to another position. We used the iterative closest point algorithm,[1] which is one of the most well-developed methods for surface-based registration. In this method, a 3D surface model and a set of 3D points are registered by starting from initial transformation parameters and finally finding the best parameters while minimizing the sum of the distance from each 3D point to the surface. The humerus was registered with the ulna and the radius. The relative motions between the humerus and the ulna and between the humerus and the radius were determined with this technique.

Motion analysis

This system enables one to view and analyze any bone motion relative to any other bone. Using motion analysis, we calculated several measurements that were hypothesized to characterize elbow motion. The measurements obtained were inferred contact areas with their area centroids, the screw axis of rotation between bones, and the carrying angles. This system serves as a visual check by which to validate the resulting calculated motion of the bones, as well as providing a simple, clear manner by which to display the analyst's conclusions.

Contact area

We measured the inferred contact area of the ulnohumeral and radiohumeral joints using a proximity mapping method[14] during different elbow positions. Proximity mapping to demonstrate distances between 3D surface bone models was accomplished by use of 3D MRI. To determine the interbone distances, a custom program was created. This program used the output file from the solid model formation (3D reconstructions), which gives all vertices positions of the individual surface triangles that form the surface of the reconstructed bone in space. The vertices of the triangles were used as discrete bony landmarks and as a starting point for the minimum distance estimation between bones. From a specific vertex, the algorithm searches all other vertices within a slice and calculates each distance, retaining the minimum distance. If the distance between slices is less than the minimum distance already calculated, the algorithm calculates distances to points in the adjacent slice in search of the minimum; otherwise, that intraslice minimum distance is kept and the next vertex distance is calculated. An output file is created that contains the minimum distance for each vertex and the adjacent bone to which it corresponds. This program was written for the calculation of both the area and centroid of one bone surface with respect to another within a user-specified threshold distance. Proximity mapping is the visual representation of the distance from one bone to the nearest neighboring bone. This method can be used to determine the interbone distances and the centroid of the mapping area. Surface proximity mapping that infers contact area between joint surfaces and their area centroids was calcu-

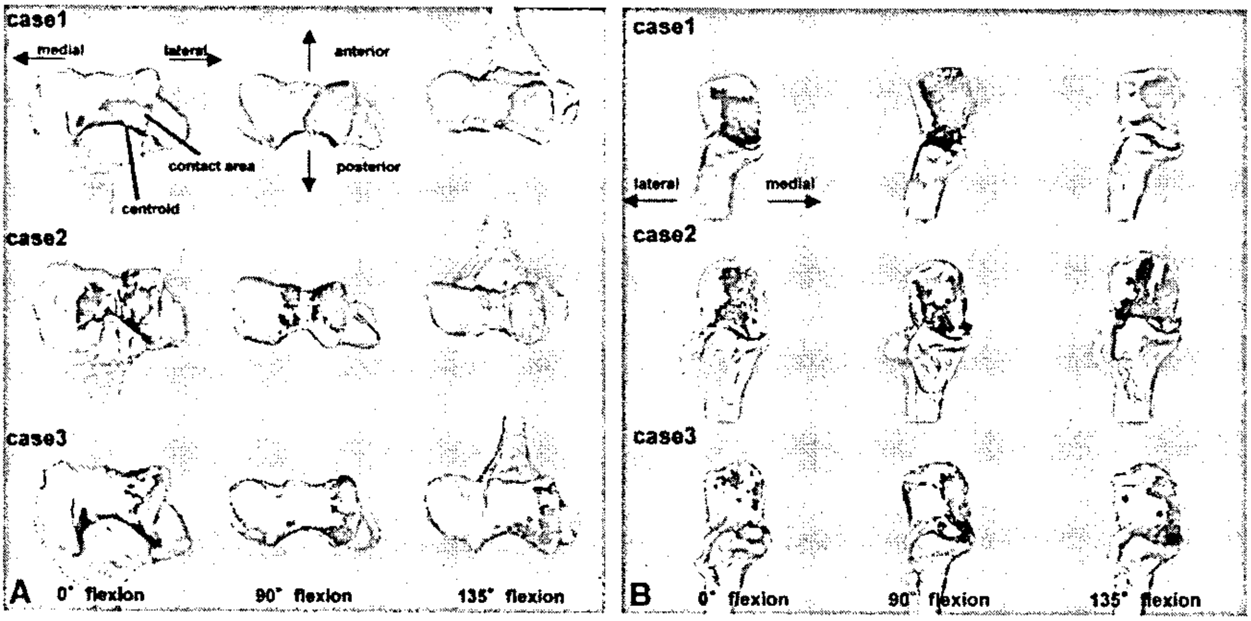

Figure 2 The inferred contact areas of articular surfaces and their centroids of the ulnohumeral joint in 0°, 90°, and 135° flexion. **A**, Contact areas on the humerus. **B**, Contact areas on the ulna.

lated from 3D MR images to visualize the path of motion of the ulna and the radius on the humerus during flexion. The proximity maps were calculated within 2.0- to 3.0-mm distant thresholds according to the size of the individual joint.

Axis of rotation

We expressed the transformations in helical axis parameters, which are defined as a rotation about and a translation along a unique axis.[17] Screw axes of rotation were calculated for each increment of motion. We depicted the configuration and dimensions of these axes. To measure changes of the respective axes, we calculated angular variances from respective subject helical axes in the axial and coronal plane, the minimum distances between the respective axes, and the orientation of the average axis. Screw axes were calculated only for the ulnohumeral joint, because the radiohumeral joint possesses two degrees of freedom of motion (flexion/extension and pronation/supination) and we could not completely exclude pronation/supination motion during an experiment for flexion/extension motion.

Carrying angle

To investigate changes in the carrying angle 3-dimensionally, we defined the carrying angle as the abduction-adduction angle of the long axis of the ulna with respect to the sagittal plane, and we calculated the angle analytically based on the new reference system. The geometrical center of mass and the principal axes of inertia were calculated for each 3D volume of the distal third of the humerus and the proximal third of the ulna. The principal axes of inertia are defined as the long axis, which corresponds to the minimum moment of inertia; the short axis, which corresponds to the maximum moment of inertia; and the medium axis, which is perpendicular to both the long and short axes. The short axes of inertia of the volumes correspond to the anatomic long axes of the humerus and the ulna. The new reference system was defined by use of the principal axes of inertia of the humerus. The sagittal plane was defined as a plane containing the long and short axes of inertia of the humerus. Thus, the precise angle was calculated for each angle of flexion for each elbow.

Validation of registration

The accuracy and consistency of the in vivo methodology described here were determined preliminarily in an in vitro study. MRI scans of a fresh cadaveric arm were acquired three times, changing only the direction of the MR image slices. Reconstructed 3D models of the humerus and radius were created separately from each set of MRI data. The relative position of the radius to the humerus was calculated and was compared among the three MRI slices. It was revealed that our method had a mean rotation error of 0.82° ± 0.38°, a mean translation error of 0.04 ± 0.01 mm, and a mean consistency of 0.32 ± 0.11 mm (root mean square). Therefore, both the segmentation error and the range of MRI acquisition resolutions that might have potentially influenced the results were revealed to be very small.

RESULTS

Contact area

The inferred contact areas of articular surfaces and their centroids of the ulnohumeral joint in 0°, 90°, and 135° flexion are shown in Figure 2. On the humerus, most of the contact areas on the trochlear surface are

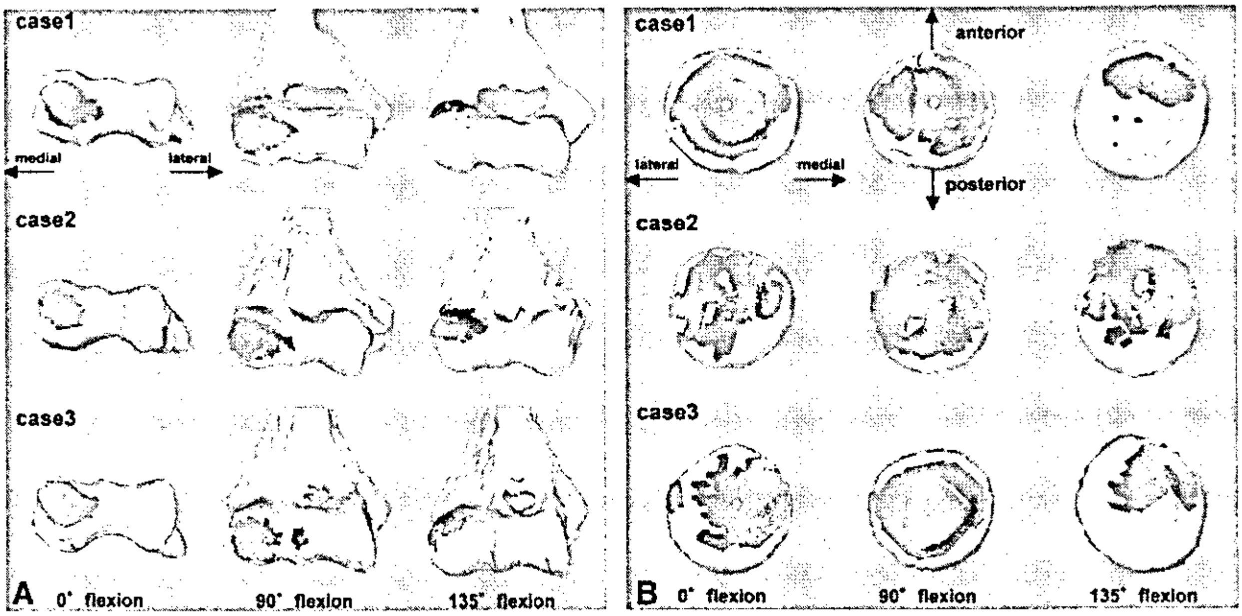

Figure 3 The inferred contact areas of articular surfaces and their centroids of the radiohumeral joint in 0°, 90°, and 135° flexion. **A**, Contact areas on the humerus. **B**, Contact areas on the radius.

situated on the medial facet of the trochlea for any possible elbow position. On the ulna, the contact areas also tended to occur medially in all different elbow positions. The pathway of the area centroids of the contact areas in the ulnohumeral joint during flexion is situated on the medial face of the trochlea just lateral to the sulcus of the trochlear groove.

The inferred contact areas of articular surfaces and their centroids of the radiohumeral joint in 0°, 90°, and 135° flexion are shown in Figure 3. Contacts on the capitellar surface were observed to move linearly from the lower aspect of the capitellum in 0° flexion to the upper aspect in 135° flexion. The inferred contact areas on the radial head against the capitellum occurred on the central depression of the radial head during all different elbow positions except 135° flexion, where the anterior rim of the radial head articulates with the capitellum (Figure 4). The pathway of the area centroids of the contact areas in the radiohumeral joint is situated along a slightly oblique line from the lower medial aspect to the upper lateral aspect on the capitellum with flexion.

Axis of rotation of motion of ulna relative to humerus

The pathway of the screw axis of rotation exhibits a roller configuration tracing the surface of a double conic shape, with the frustum waist being located in the medial portion of the trochlea (Figure 5). The locus of the axis of rotation traced on the surface of the condyles tended to be larger on the lateral side than on the medial side. The locus of the averaged axis of rotation on the lateral condyle showed a counterclockwise circular pattern (Figure 6). The screw axis of rotation varied from 5.67° to 17.23° (mean, 11.02°) in the axial plane and from 7.80° to 19.4° (mean, 11.95°) in the coronal plane. The minimum distances between the respective axes were 0.439 to 0.863 mm (mean, 0.685 mm). All screw axes of

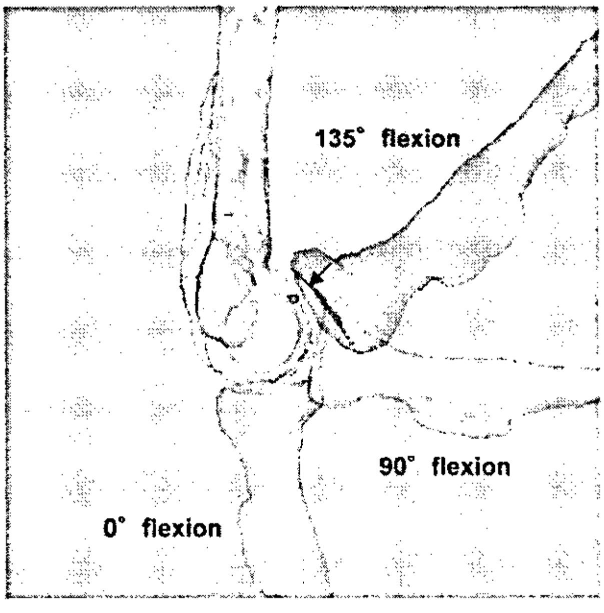

Figure 4 Lateral view of the radiohumeral joint in 0°, 90°, and 135° flexion with their centroids of the contact areas. Note that the anterior rim of the radial head articulates with the capitellum in 135° flexion (*arrow*).

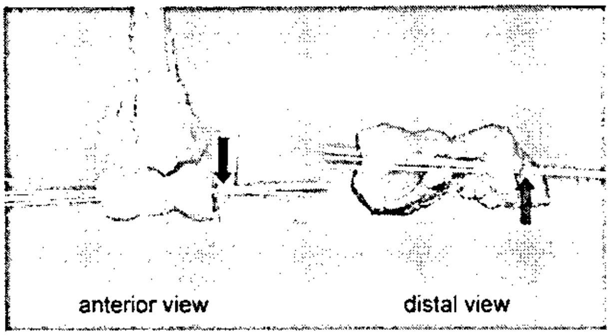

Figure 5 Superimposed images of the instantaneous axes of rotation of the ulnohumeral joint showing roller configuration tracing the surface of a double conic shape, with the frustum waist being located in the medial portion of the trochlea (*arrows*).

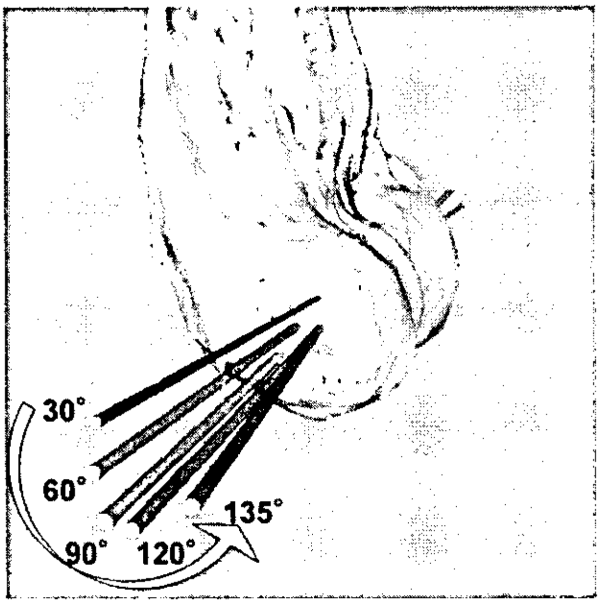

Figure 6 The locus of the averaged axis of rotation on the lateral condyle shows a counterclockwise circular pattern, where it initially moves anteriorly in the range from 0° to 60° flexion and then returns posteriorly.

rotation nearly intersected on the medial facet of the trochlea. The calculated average axis among all positions penetrated the inferior anterior aspect of the medial epicondyle, the center of the trochlea, and the center of the capitellum. In the coronal plane, the average axis formed a proximally and laterally opening angle of 85.46° (SD, 1.55) with the longitudinal axis of the humerus.

Carrying angle

The carrying angle in 0° flexion varied from 16.04° to 22.78° (mean, 18.64°). The pattern of change in the carrying angles with elbow flexion for the ulnohumeral joint was consistent in all elbows. The averaged carrying angle decreased linearly with flexion (Figure 7).

DISCUSSION

This study represents an attempt to analyze 3D motion of the elbow in vivo and noninvasively. We used MRI to avoid radiation exposure from radiographic imaging or CT scanning. Some previous studies were 2-dimensional kinematic analyses, and the importance of documenting 3D kinematics has been noted.[2] In addition, most of the present knowledge about 3D behavior of the skeletal joints has been acquired in studies of cadaveric models using invasive procedures. In vitro studies are also inherently limited because if joint loading with muscular forces is to be accounted for, they must be estimated and simulated. It has been proposed that small changes in joint loading may have profound effects on joint kinematics.[23]

This in vivo analysis offers 3D measurements gathered by use of many different methodologies. With the use of surface registration techniques,[1,3] the 3D quantitative information regarding relative displacement and rotation was acquired in vivo and noninvasively without bone markers. This technique can be used for accurate computer visualization of experimental kinematics by use of the surface models of the bones derived from the MRI data.

The ulnohumeral joint is generally described as a hinge joint.[12] A previous study showed that flexion occurs about a single axis, which passes through the centers of the arcs outlined by the bottom of the trochlear sulcus and the periphery of the capitellum. More recent studies have shown that the elbow joint does not function as a simple hinge joint and that the joint axis translates as well as rotates.[22] The respective axis intersects the trochlear center medially, and the axes translate more at the lateral side than at the medial side.[5] In our studies the results agree well with these findings. These results may suggest the importance of the function of the medial collateral ligament, and they are consistent with the findings about the relatively ambiguous anatomy of the lateral collateral ligament.

The previous studies showed that the change in carrying angle during elbow flexion is linear, being greatest at 0° flexion and diminishing during flexion.[16,24] Our results also agree well with these findings.

A review of the literature has shown that only a few in vitro studies have been performed to obtain data on elbow joint contact. Previous in vitro studies showed that the contact areas on the ulna occurred anteriorly and posteriorly, forming two narrow bands.[4,7] Goel et al[6] reported that in 0° flexion, the contact was observed to be on the lower medial

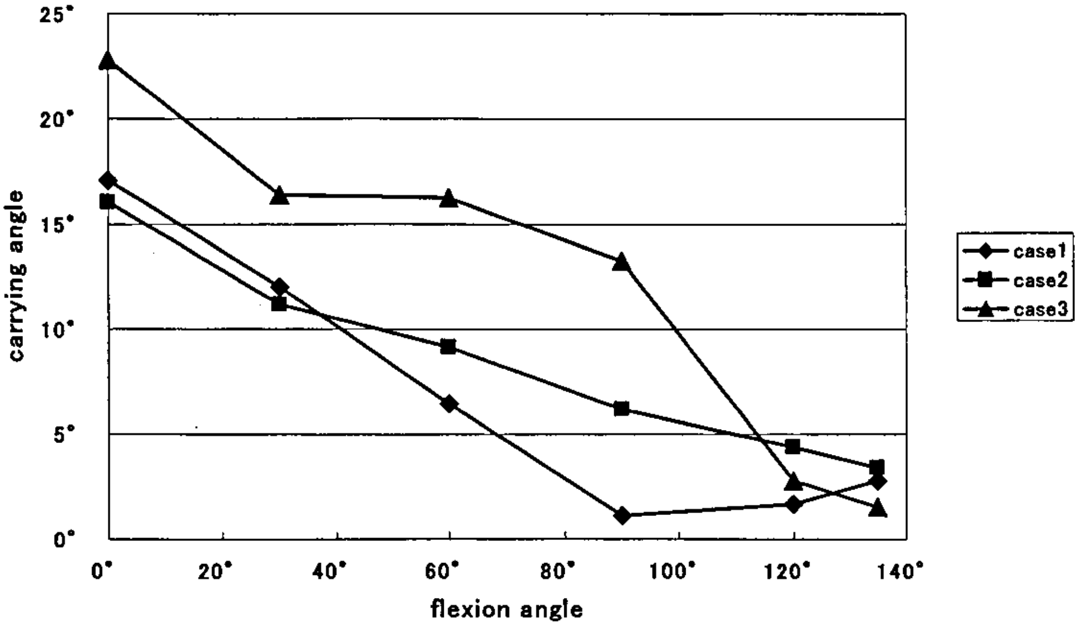

Figure 7 The change in the averaged carrying angle with elbow flexion for the ulnohumeral joint, which decreases linearly.

aspect of the ulna, whereas in other postures, the pressure areas described a strip extending from posterolateral to anteromedial. In our in vivo studies, the pattern of the contact area is different from that observed in the previous in vitro reports. On the ulna, most of the inferred contact areas with the trochlea occurred only on the medial facet of the trochlear notch in all different elbow positions. The path of the centroids of contact areas across the trochlea was revealed to be not on the sulcus but on the medial facet of the trochlea.

Although current techniques provide a detailed analysis of the in vivo kinematics of elbow motion, they have some limitations, with the greatest disadvantage being the use of static motion analysis rather than dynamic analysis, such as instrumented spatial linkages.[9,10] Dynamic kinematic factors such as muscle were not considered in this methodology. The proximity mapping technique has an inherent limitation because of its lack of consideration of thickness of the cartilage. Furthermore, we cannot yet make a definitive statement about elbow kinematics because our database is still small. Additional research is required to build the database.

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関節リウマチの病態におけるマクロファージ遊走阻止因子(MIF)の役割および治療標的因子としての可能性に関する研究

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はじめに

関節リウマチ（以下 RA）は関節滑膜を病変の主座とする疾患であり、滑膜の増生、関節軟骨の破壊、および関節近傍骨組織の萎縮を特徴とする。疼痛と関節の変形は滑膜の存在するあらゆる関節に生じ、痛みと不自由さに由来する患者さんの苦痛は計り知れない。現在日本には約70万人のRA患者が存在するとされ、RAの病態の解明、およびその治療を目標にした研究・開発は急務である。

RAの病態としては、抗原刺激に伴いTリンパ球の滑膜への浸潤とリンホカイン産生が起こり、これら浸潤Tリンパ球と滑膜を構成する繊維芽細胞・マクロファージとの相互作用により関節局所においてサイトカイン・プロスタグランジン・マトリックスメタロプロテアーゼ（以下 MMP）等の産生が亢進して関節破壊に至るとされる。マクロファージ遊走阻止因子（以下 MIF）は近年炎症性サイトカインとして再評価されており、われわれはMIFがRA関節液に高濃度存在すること、MIFがRA滑膜細胞のMMP産生を誘導すること[1)2)]などを報告してきた。さらにII型コラーゲン関節炎マウスに対する抗MIF抗体投与による炎症抑制効果、MIFによるCOX-2転写誘導作用、RA患者におけるMIFプロモーター遺伝子の多型の存在とその疾患重篤性との相関等の報告が相次ぎ、RAの病態におけるMIFの関与が明らかとなってきた。

本研究では、MIFのRA病態における関与をさらに詳細に検討するとともに、MIFをRAの治療のターゲットとしてこの活性を制御することがRAの炎症の制御につながると考え、以下について研究を進めてきた。

方法

1. RA の関節炎において生じる関節腔内好中球浸潤、および好中球走化性ケモカイン動態に対する MIF の役割の *in-vitro* での検討；

1) 関節置換手術時に得られた RA 滑膜組織由来の滑膜細胞にヒト rMIF を添加し、Northern blot および ELISA にて好中球走化性ケモカインである IL-8 を遺伝子・タンパクレベルで定量化した。

2) IL-8 誘導に至る細胞内情報伝達経路を、各種シグナル伝達阻害剤を用いて検討し、IL-1β 誘導に至る経路と比較した。

3) MIF 添加により生じる、核タンパク抽出物の AP-1 および NF-κ B コンセンサスオリゴへの結合活性を EMSA 法により検討した。

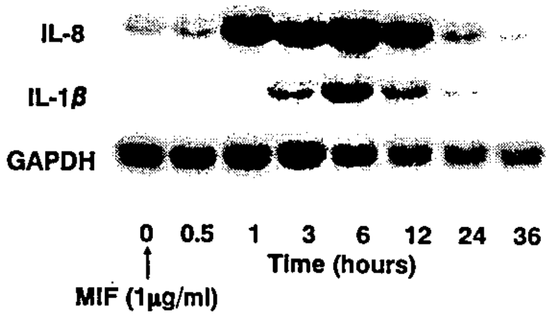
2. 関節炎発症における MIF の意義に関する、マウス抗 II 型コラーゲン抗体カクテル誘発関節炎モデルによる *in-vivo* での検討

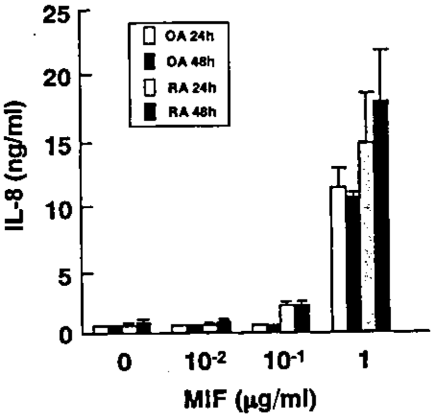
カクテル関節炎の発症の程度に関し、野生型マウス（Balb/c)、抗 MIF 抗体投与マウス、MIF 遺伝子ノックアウトマウスの三群間で比較した。評価は組織学的関節炎スコアを用いた。関節局所における MIF、ケモカイン遺伝子および MMP-１３遺伝子発現も半定量的 RT-PCR により併せて検討した。発症に伴う MIF の局所発現は免疫組織学的にも確認した。

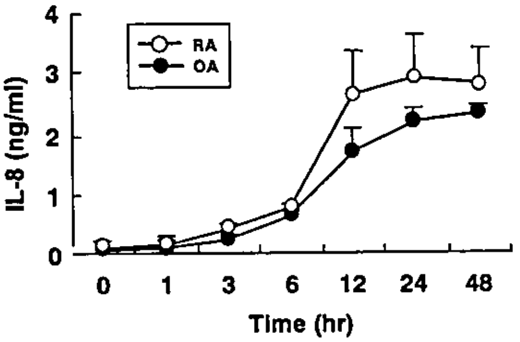
結果

１）MIF は IL-1β および IL-8 の mRNA 発現を誘導し、この程度は mRNA、タンパクレベルいずれにおいても OA より RA 滑膜細胞で強かった（図１)。

図１

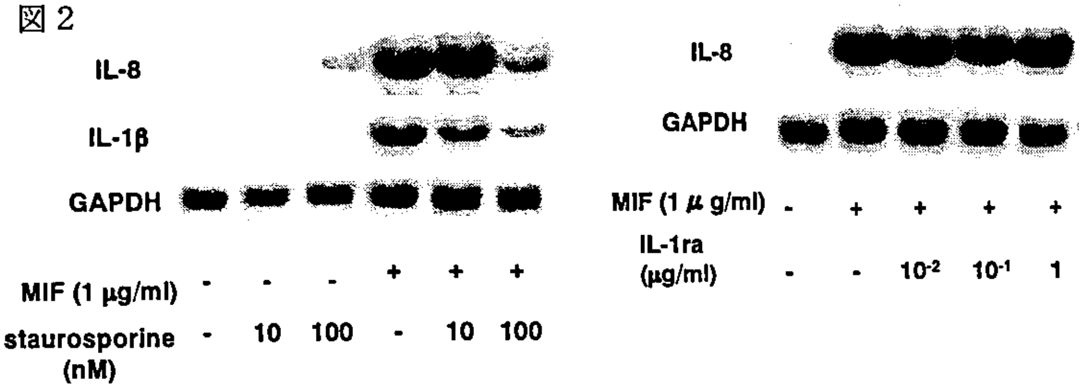






2）チロシンキナーゼ阻害剤、PKC 阻害剤、AP-1 阻害剤の添加により MIF による IL-1β および IL-8 の誘導は阻害された。IL-1β および IL-8 の誘導は NF-κ B 阻害剤によっても阻害された。IL-8 の誘導は IL-1 レセプターアンタゴニストの添加では阻害されなかった（図２　PKC 阻害剤の例として staurosporine）。

図２



3）１μg/ml 以上の MIF 添加により RA 滑膜線維芽細胞抽出核タンパクにおける AP-1 および NF-κ B 結合活性が上昇することが EMSA 法により示された。

図３