Table 1—Patient data

Patient number	*Age in years*	*Hand/dominance*	*Cause of fracture*	*Type of hamate fracture*	*Time from fracture to tendon rupture*	*Cause of tendon rupture*	*Wrist symptoms before tendon rupture*	*Time from tendon rupture to repair*	*Ruptured tendon(s)/ involved finger*	*Repair*	*Graft length (mm)*	*Follow-up*	*Strickland evaluation*
1	58	Right/dominant	Hammering	Middle part	25 years	Lifting	None	4 weeks	FDP/little	Tendon graft	45	13 years, 6 months	54% (fair)
2	63	Left/nondominant	None apparent	Tip	—	Prying off a cover with a screwdriver	None	9 weeks	FDP + FDS/little	Tendon transfer	—	12 years, 11 months	74% (good)
3	35	Right/dominant	Hit with golf club	Middle part	3 years	Hitting a golf ball	Mild pain on playing golf	8 weeks	FDP/little, frayed FDP/ring	Tendon graft	50	1 year, 2 months	97% (excellent)
4	51	Right/dominant	Impact upon a nail	Base	6 months	Spontaneous	Decrease of grip power	5 weeks	FDP/little	Tendon graft	70	1 year, 11 months	54% (fair)
5	55	Right/dominant	Fall	Middle part	10 years	Lifting	None	6 months	FDP/little, frayed FDS/little	Tendon graft	90	7 years, 3 months	74% (good)
6	73	Left/nondominant	None apparent	Middle part	—	Spontaneous	Occasional pain	7 months	FDP/little	Tendon graft, tenolysis	100	6 years, 3 months	74% (good)

patients, with no recollection of obvious injury to the palm or wrist did heavy manual work as either a woodcutter or a farmer.

Radiographic examination of the wrist included posteroanterior and lateral views in all patients, but none was diagnosed with non-union of the hook of the hamate based upon these radiographs. Radiography in an oblique lateral view in supination was performed in four patients, providing a diagnosis of non-union in two. Radiography in a carpal tunnel view, performed in five patients, was diagnostic in all five; the same was true for computed tomography (CT). Conventional tomography was diagnostic in three of four patients so examined; the same was true for magnetic resonance imaging (MRI). In all patients the fragment had a smooth, round surface at the non-union, associated with marginal sclerosis (Figs 1–3). The fragment varied in size, but, in all instances, it was at least 1 mm away from the body of the hook. The fragment was displaced into the carpal tunnel in one patient (case 2). The hook fractures were located on the middle part of the hook in four patients, on the tip in one and on the base in one patient (Stark et al., 1989).

Tendon reconstruction was performed at an average of 13 weeks after tendon rupture. In all patients, a curved and zigzag incision was made on the palm between the distal palmar crease and the wrist. All patients underwent release of the carpal tunnel for exposure of the hook of the hamate, the tendon stump and the pisotriquetral joint. In all patients, the ruptured tendons were identified at surgery. In four of six patients, only the flexor digitorum profundus (FDP) tendon of the little finger was ruptured and the flexor digitorum superficialis (FDS) tendons were intact. In one patient, the FDP tendon of the little finger was ruptured and the FDS tendon of the ring finger was partially frayed. In the remaining patient, both flexor tendons of the little finger were ruptured. The proximal stumps of the ruptured tendons were in the carpal tunnel and the distal stumps were found proximal to the A1 pulley. No tenosynovitis was apparent around either end of any of the tendons. A free tendon graft, using the palmaris longus tendon in three patients and the plantaris tendon in two, was interposed between the proximal and distal stumps in five patients. Tendon transfer of the FDS tendon of the ring finger, with distal attachment to the FDP tendon of the little finger, was performed in the patient with rupture of both FDP and FDS tendons. In each case, the ends of the ruptured tendon were dissected free of adhesions, and the interpositional graft or tendon transfer tendon was sutured to the freshened stump(s) using the interlacing suture method. The junctions of the grafts with the stumps were placed away from the carpal area. The mean length of the interpositional grafts was 66 (range 45–100) mm. Operative findings included loss of periosteum of the hook of the hamate, which is an important structural component of the ulnar side of the carpal

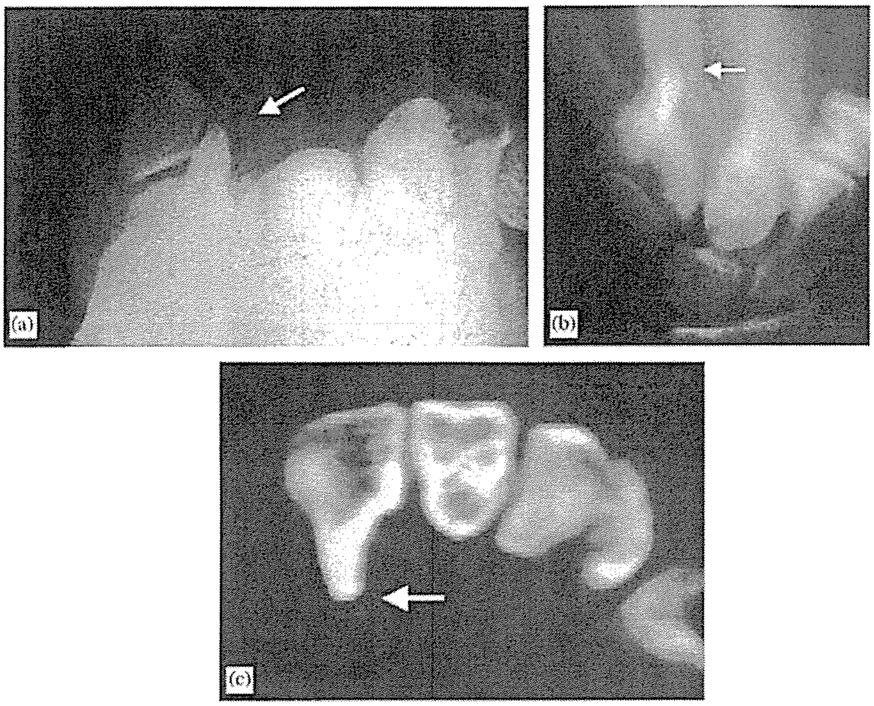


Fig 1 Non-union of the tip of the hook of the hamate bone: (a) on carpal tunnel view X-ray, (b) on tomography, and (c) on CT scan (case 2).

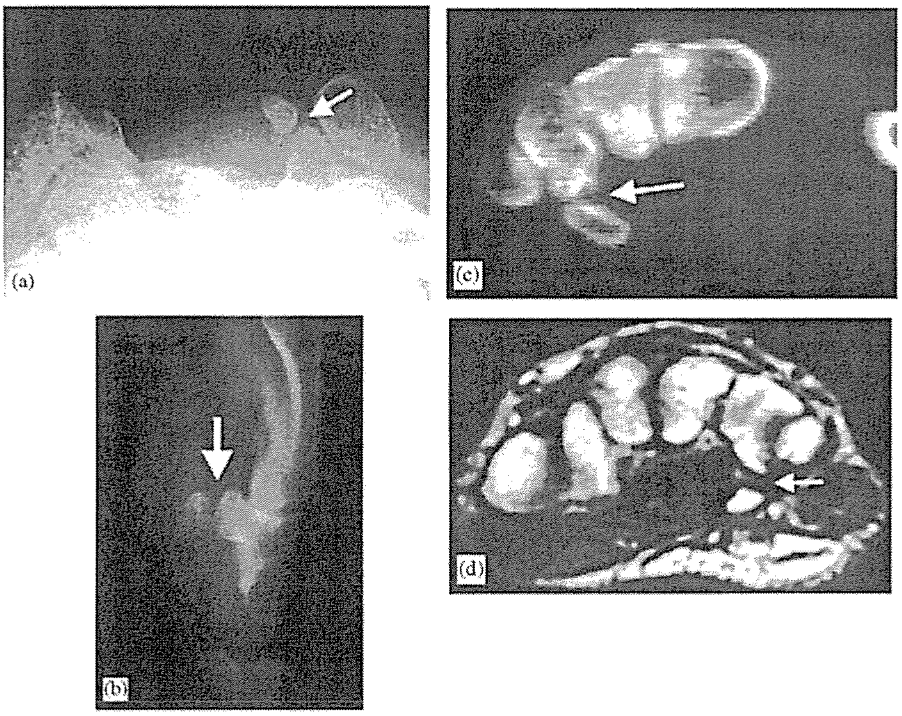


Fig 2 Non-union of the middle part of the hook of the hamate bone: (a) on carpal tunnel view X-ray (case 3), (b) on tomography (case 5), (c) on CT scan (case 1) and (d) on MRI (case 6).

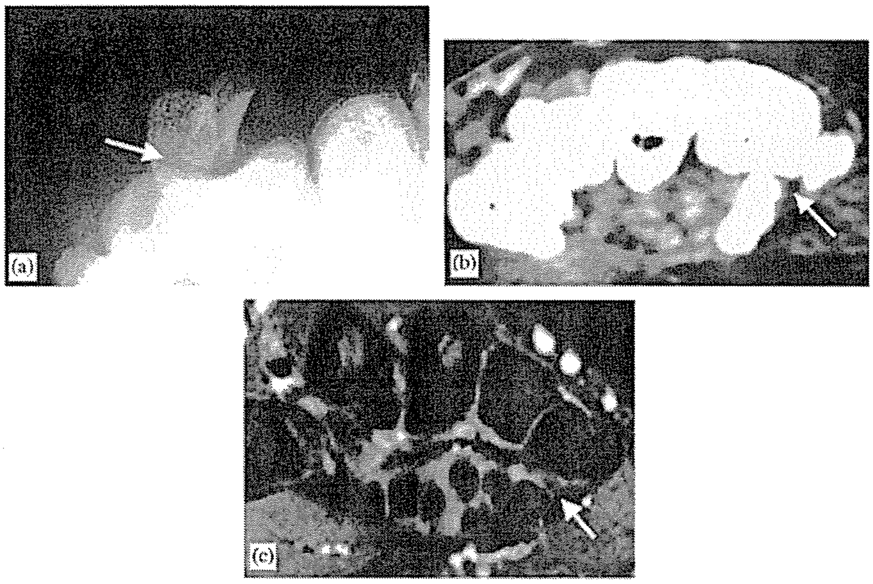


Fig 3 Non-union of the base of the hook of the hamate bone: (a) on carpal tunnel view X-ray, (b) on CT scan and (c) on MRI (case 4).

tunnel. The cortical surface of both the fragment and the basal part of the hook were exposed. The fragments, clearly mobile at the non-union, were removed in all patients. After tendon reconstruction, modified Kleinert mobilization was used for 3–4 weeks. In one patient, tenolysis was performed 14 months after the tendon graft. Follow-up was maintained for an average of 7 years and 2 months (range 1 year and 2 months–13 years and 6 months).

At follow-up, the ranges of active metacarpophalangeal (MCP), proximal interphalangeal (PIP), and distal interphalangeal (DIP) joint motion were measured in all patients and total active range of motion (TAM) was calculated. These findings were also graded according to Strickland's criteria (Strickland and Glogovac, 1980). Grip strength was measured by Smedley's Hand Dynamometer (Sakai Co, Tokyo, Japan) in both hands and grip strength in the affected hand, relative to the contralateral hand, was calculated as a percentage.

RESULTS

Total active range of motion, including MCP, PIP and DIP ranges of motion, averaged 218° (range 185–265°). In full finger extension, the extension deficit at the MCP, PIP and DIP joints averaged 21° (range 5–40°). On average, final grip strength was 86% of the strength of the contralateral hand (range 63–126%). Outcome, as measured by the Strickland's criteria, was excellent in one patient, good in three, and fair in two (Table 2).

All patients were satisfied with the result of tendon reconstruction and all could use the little finger in carrying out activities of daily living, manual labour or sports. All patients returned to their original employment.

DISCUSSION

In all of the patients in our series, symptoms at the wrist from the original fracture had become nil or very mild, until the closed flexor tendon rupture(s) of the little finger occurred. Accordingly, closed flexor tendon injury of the little finger should raise suspicion of non-union of the hook of the hamate. Other causes of tendon injury such as osteoarthritis of the pisotriquetral joint (Saitoh et al., 1997) should be differentiated from non-union of the hook of the hamate by seeking the latter in radiographs from oblique and carpal tunnel views of the wrist, conventional tomography (Murray et al., 1979) or CT (Stark et al., 1989). In three of our patients, MRI was also useful to diagnose non-union of the hook of the hamate.

Stark et al. (1977) reported that 20 of their 62 cases had displaced fragments, fractures having occurred at the base of the hook in 47 cases, in the middle part in eight and at the tip in seven cases. Of 26 cases of closed rupture of the flexor tendon in association with hook of the hamate non-union reported in other papers, the location of the hook fracture was either described, or shown on X-ray, in nine cases, as being at the base in eight cases or in the middle part in one (Foucher et al., 1985; Hartford and Murphy, 1996; Milek and Boulas, 1990; Minami et al., 1985; Takami et al., 1983; Yang et al., 1996). Our cases had fractures at all three sites. The site of non-union appears to have no apparent relationship with the occurrence of flexor tendon rupture.

Murray et al. (1979) pointed out that the ligaments attached to the hook of the hamate transmit intermittent forces that contribute to non-union and irregularity of the fracture margins. From our experience at surgery for painful non-union of the hook of the hamate, the margins of the fragment are sharp and near the basal part of the hook; in contrast, in the present series, the fragments were rounded and fairly distant from the basal portion of the hook, while showing marginal sclerosis at the non-union. This suggests that the tendon abrasion leading to rupture was not caused by a sharp fragment edge at the non-union but by an exposed cortical surface of the non-union that lacked periosteum.

Milek and Boulas (1990) reported surgical results in four patients, three of whom were treated by tendon transfer and one by tendon graft. They attributed variation in quality of the results, largely, to patients' age differences and recommended end-to-side tendon transfer using the FDP tendon of the ring finger. In our series, the mean patient age was 59 years. Although this was relatively high, results were satisfactory and outcome did not depend on patient age or on the interval between tendon rupture and reconstruction. We only had data to show the effectiveness of tendon graft or transfer on grip strength in three patients. To our knowledge, this has not been reported previously. In these three patients (cases 2, 5, and 6) the percentage of the strength of the contralateral hand was 87%, 71%, and 90% pre-operatively and 63%, 79%, and 126% postoperatively. These figures would suggest that tendon reconstruction does not improve grip strength in this situation. This may be because of the presence of an intact FDS tendon in the little finger in five of six of our cases and/or the relatively small contribution of the little finger FDP tendon to entire grip strength, The remaining fully functional fingers of these hands may also have compensated in part for the loss of little finger strength. Use of the FDS tendon of the ring finger as a tendon transfer would seem more likely to compromise not only the function of the ring finger, per se, but also the ability of the hand, as a whole, to compensate for any residual disability of little finger function than restoration of the function of the little finger profundus tendon. Therefore, we believe that free tendon grafting followed by early controlled mobilization is the treatment of first choice for these patients.

References

Andress MR, Peckar VG (1970). Fracture of the hook of the hamate. British Journal of Radiology, 43: 141–143.

Bishop AT, Beckenbaugh RD (1988). Fracture of the hamate hook. Journal of Hand Surgery, 13A: 135–139.

Boulas HJ, Milek MA (1990). Hook of the hamate fractures. Diagnosis, treatment, and complications. Orthopaedic Review, 19: 518–529.

Boyes JH, Wilson JN, Smith JW (1960). Flexor-tendon ruptures in the forearm and hand. American Journal of Orthopedics, 42: 637–646.

Clayton Ml (1969). Rupture of the flexor tendons in the the carpal tunnel (non-rheumatoid) with specific reference to fracture of the hook of the hamate. Journal of Bone and Joint Surgery, 51A: 798–799.

Crosby EB, Linscheid RI (1974). Rupture of the flexor profundus tendon of the ring finger secondary to a fracture of the hook of the hamate. Review of the literature and report of two cases. Journal of Bone and Joint Surgery, 56A: 1076–1078.

Dunn AW (1972). Fractures and dislocations of the carpus. Surgical Clinics of North America, 52: 1513–1538.

Foucher G, Schuind F, Merle M, Brunelli F (1985). Fractures of the hook of the hamate. Journal of Hand Surgery, 10B: 205–210.

Futami T, Aoki H, Tsukamoto Y (1993). Fractures of the hook of the hamate in athletes. 8 cases followed for 6 years. Acta Orthopaedica Scandinavica, 64: 469–471.

Hartford JM, Murphy JM (1996). Flexor digitorum profundus rupture of the small finger secondary to nonunion of the hook of hamate: a case report. Journal of Hand Surgery, 21A: 621–623.

Milek MA, Boulas HJ (1990). Flexor tendon ruptures secondary to hamate hook fractures. Journal of Hand Surgery, 15A: 740–744.

Minami A, Ogino T, Usui M, Ishii S (1985). Finger tendon rupture secondary to fracture of the hamate. A case report. Acta Orthopaedica Scandinavica, 56: 96–97.

Murray WT, Meuller PR, Rosenthal DI, Jauernek RR (1979). Fracture of the hook of the hamate. American Journal of Roentgenology, 133: 899–903.

Saitoh S, Kitagawa E, Hosaka M (1997). Rupture of flexor tendons due to pisotriquetral osteoarthritis. Archives of Orthopaedic and Trauma Surgery, 116: 303–306.

Stark HH, Chao EK, Zemel NP, Rickard TA, Ashworth CR (1989). Fracture of the hook of the hamate. Journal of Bone and Joint Surgery, 71A: 1202–1207.

Stark HH, Jobe FW, Boyes JH, Ashworth CR (1977). Fracture of the hook of the hamate in athletes. Journal of Bone and Joint Surgery, 59A: 575–582.

Strickland JW, Glogovac SV (1980). Digital function following flexor tendon repair in zone II: a comparison of immobilization and controlled passive motion techniques. Journal of Hand Surgery, 5A: 537–543.

Takami H, Takahashi S, Ando M (1983). Rupture of flexor tendon associated with previous fracture of the hook of the hamate. Hand, 15: 73–76.

Teissier J, Escare P, Asencio G, Gomis R, Allieu Y (1983). Rupture of the flexor tendons of the little finger in fractures of the hook of the hamate bone. Report of two cases. Annales de Chirurgie de la Main, 2: 319–327.

Yang SS, Kalainov DM, Weiland AJ (1996). Fracture of the hook of hamate with rupture of the flexor tendons of the small finger in a rheumatoid patient: a case report. Journal of Hand Surgery, 21A: 916–917.

Received: 24 July 2005
Accepted after revision: 30 December 2005

Dr Hiroshi Yamazaki, MD, Department of Orthopaedic Surgery, Shinshu University School of Medicine, 3-1-1, Asahi, Matsumoto City, Nagano, 390-0304, Japan. Tel.: +81 263 37 2659; fax: +81 263 35 8844.
E-mail: h-ymzk@hsp.md.shinshu-u.ac.jp

doi:10.1016/j.jhsb.2005.12.015 available online at http://www.sciencedirect.com

PII: S0021-9290(97)00097-8

J. Biomechanics, Vol. 30, Nos. 11/12, pp. 1183–1186, 1997
© 1997 Elsevier Science Ltd. All rights reserved
Printed in Great Britain
0021-9290/97 $17.00 + .00

TECHNICAL NOTE

FEASIBILITY OF USING A MAGNETIC TRACKING DEVICE FOR MEASURING CARPAL KINEMATICS

Jun-ichi Ishikawa,† Glen L. Niebur,† Shigeharu Uchiyama,† Ronald L. Linscheid,† Akio Minami,‡ Kiyoshi Kaneda‡ and Kai-Nan An*†

† Biomechanics Laboratory, Department of Orthopedics, Mayo Clinic and Mayo Foundation, Rochester, MN 55905, U.S.A.; and ‡ Hokkaido University School of Medicine, Sapporo, Japan

Abstract—While several different methods have been used to measure carpal kinematics, biplanar radiography is generally considered to be the most accurate and popular one. However, biplanar radiography is tedious and so only pseudo-dynamic kinematics can be measured. Recently, magnetic tracking system has been developed for the measurement of joint kinematics which is versatile and easy to use and so the possibility of measuring motions dynamically. In this study, the capability of a magnetic tracking device to accurately measure carpal kinematics was investigated by comparing it with biplanar radiography. The kinematics of the third metacarpal, scaphoid, and lunate in five fresh cadaveric specimens were measured using both methods as the wrists were placed in eight positions. The finite screw rotation of each bone with respect to the distal radius during selecting the seven wrist motions was calculated for both measuring techniques and compared. In general, the kinematics for all three bones measured by using either magnetic tracking device or biplanar radiography was identical and showed no statistical difference. The averaged differences ranged from 0.0 to 2.0°. These differences were due to the potential effect of the weight of the sensors and the interference of the attaching rod to the surrounding tissue. It is concluded that the application of the magnetic tracking device to carpal kinematics is warranted, if proper technical procedures as suggested are followed. © 1997 Elsevier Science Ltd. All rights reserved

Keywords: Magnetic tracking; Biplanar radiography; Wrist; Kinematics; Accuracy.

INTRODUCTION

Biplanar radiography has been used in our laboratory previously to measure the motions of the carpal bones. This technique has been proven to be accurate in several earlier kinematic studies (Garcia-Elias *et al.*, 1989; Horii *et al.*, 1991; Kobayashi *et al.*, 1997; Trocmé *et al.*, 1990), but the technique has two primary drawbacks. First, the method can be quite time-consuming and technically challenging. Second, only static measurements are possible, thereby limiting its usefulness in studies involving dynamic motion of the wrist.

A magnetic tracking device (3Space Tracker, Polhemus, Colchester, VT) has been used in our laboratory to measure joint kinematics both *in vitro* and *in vivo*, and its capabilities and limitations have been reported (Imaeda *et al.*, 1994; Itoi *et al.*, 1992; Jantea *et al.*, 1994). This device uses magnetic field technology to measure the position and orientation of a sensor in relation to a magnetic source up to 60 Hz. This capability to perform dynamic measurements makes this an attractive method to perform studies of joint motion.

Previous studies have shown magnetic tracking to be a viable method for measuring joint kinematics (An *et al.*, 1988; Imaeda *et al.*, 1994; Itoi *et al.*, 1992; Jantea *et al.*, 1994; Luo *et al.*, 1996). In an ideal environment, this magnetic tracking system would have the accuracy of 0.2 mm and 0.5°. However, it has not yet been validated for use in the wrist (Jantea *et al.*, 1994). Joint kinematics are measured by attaching a sensor to the bones of interest, and moving the joint throughout a normal range of motion. Because of the small size of the carpal bones and the highly congruent nature of the wrist joint, it is important to verify that the sensor and associated mounting hardware do not significantly alter the position or normal motion of the bones.

In order to verify that carpal kinematics can be accurately measured by the 3Space, the kinematics of five wrist joints were measured using both the 3Space and biplanar radiography. The measurements by biplanar radiography were considered as the true value for comparison. The results of the two methods were compared by comparing the finite screw rotations and displacements as measured by each method during simulated wrist motions.

MATERIALS AND METHODS

Five fresh frozen cadaveric wrist specimens with a mean age of 76 yr including one pair of wrists were obtained from two males and two females. There were two left and three right-sided specimens. No radiographic evidence of significant degenerative changes was present in any specimens; however, a degenerative tear of the scapho-lunate interosseous ligament (SLIL) was noted in two specimens. The specimens were thawed overnight at room temperature, and were irrigated regularly with saline to prevent drying during the experiment. The protocol of human cadaveric specimens was approved by the institutional review board.

The radius and ulna were fixed in neutral rotation using a Steinmann pin, and the proximal 2/3 were amputated. A longitudinal incision was made over the dorsal side of the wrist, and the extensor retinaculum was cut between the third and fourth compartment. The dorsal radiolunotriquetral ligament was identified, and a small parallel arthrotomy was created through which the lunate and the proximal pole of the scaphoid could be approached. A second incision was created over the anatomic snuff box, where the distal half of the scaphoid could be approached from between the abductor pollicis longus and extensor pollicis longus tendons.

Magnetic sensors were attached to the bones using fiberglass rods press fitted into 2.2 mm drill holes. One rod was inserted into the lunate through the small dorsal arthrotomy and oriented palmarly and 20–30° proximally from the axial plane to prevent impingement between the rod and the dorsal rim of the distal radius during extension of the wrist. The second rod was inserted into the scaphoid through the incision over the snuff box. A third rod was inserted into the shaft of the third metacarpal obliquely so as not to hit the rod inserted into the lunate during extension. Small plastic mounts were attached to the ends of the

---

Received in final form 18 *July* 1997.

* Address correspondence to: K. N. An, Mayo Clinic/Mayo Foundation, Orthopedic Biomechanics Laboratory, Rochester, MN 55905, U.S.A.

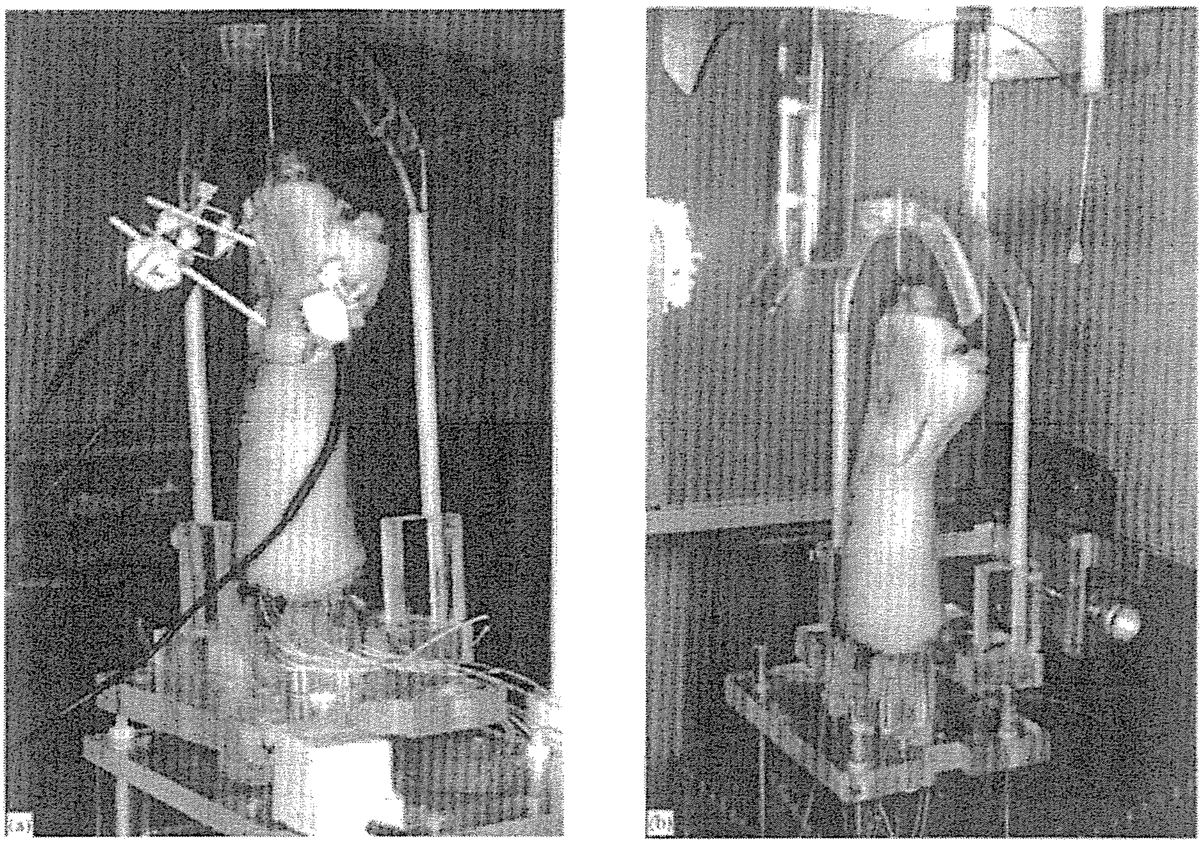


Fig. 1. Experimental setup by using magnetic tracking device and biplanar radiography. (A) magnetic tracking device, (B) biplanar radiography. In both methods the same jig was used to simulate the same eight wrist positions.

rods and sensors were fixed to the mounts with plastic screws. The magnetic source was fixed to the experimental table.

Four small spherical markers for biplanar radiography were embedded into the lunate, the scaphoid and the third metacarpal, as has been described previously (Garcia-Elias *et al.*, 1989; Horii *et al.*, 1991; Kobayashi *et al.*, 1997). Fingers were disarticulated at the metacarpophalangeal joint and a pin for guiding wrist motions was inserted into the third metacarpal.

The specimen was fixed to the experimental table, along with a specially developed jig for positioning the wrist (Fig. 1). The jig allows the wrist to be placed and held in eight positions by fixing the pin inserted into the third metacarpal to a notch in the jig at neutral, 30, and 60° of flexion, 15 and 30° of extension, 15° of radial deviation, and 15 and 30° of ulnar deviation. In this study no loads were applied to the wrist tendons.

Data were collected using the 3Space Tracker with the wrist fixed in each position by the jig. Ten data points were collected at each position and averaged. After collecting the data from the 3Space method, biplanar radiographs were then taken with the wrist fixed in the same positions while using the same jig. The positions of the markers on the radiographs were digitized on an electronic digitizer.

In order to eliminate coordinate system dependence in the kinematic calculations, finite screw displacements (Spoor and Veldpaus, 1980; Woltring, 1994) were used to compare the measurements. Both sets of data were used to calculate the screw axes for the following motions: neutral to 30, and 30–60° of flexion; neutral to 15, and 15–30° of extension; neutral to 15° of radial deviation; and neutral to 15, and 15–30° of ulnar deviation. The measurement based on biplanar radiography was treated as true motion for comparison.

The effect of the wrist position on the error was determined using repeated measurements of one-way analysis of variance (ANOVA). A *post-hoc* two-tailed *t*-test with Fisher PLSD was used to compare between each wrist position. *P* values less than 0.05 were considered significant.

RESULTS

The results of bony movement as measured by these two methods are shown in Fig. 2. In general, the linear relationships were observed. For the third metacarpal, the difference error was 0.1°, ranging from −3 to 5.9°. The difference between the two measurement techniques was not statistically significant for any of the calculated motions (Table 1).

The difference in the measurements of the lunate rotation using two techniques ranged from −4.3 to 4.2°, and averaged 0.3°. For most of the wrist positions the difference was small and showed no statistical difference. However, in moving the wrist from neutral to 15° of extension the mean difference for the five specimens was 2°. This difference was statistically significant with p equal to 0.037. From 15 to 30° of ulnar deviation, the mean difference was 1.6°. This was also significant with p equal to 0.027. The difference in the lunate rotation also showed a dependence on the direction of the wrist motion, with the 3Space overestimating the rotation in radial deviation, and underestimating the rotation in ulnar deviation (Table 1).

The difference in the scaphoid measurements based on the two methods ranged from −4.1 to 7.2°, which is a much larger range than for the lunate and the third metacarpal. The difference was only found to be statistically significant when the wrist was moved from the neutral position to 15° of extension ($p = 0.046$) (Table 1).

The orientations of the screw displacement axes based on the two methods of measurement are almost the same for most of the motions (Table 2).

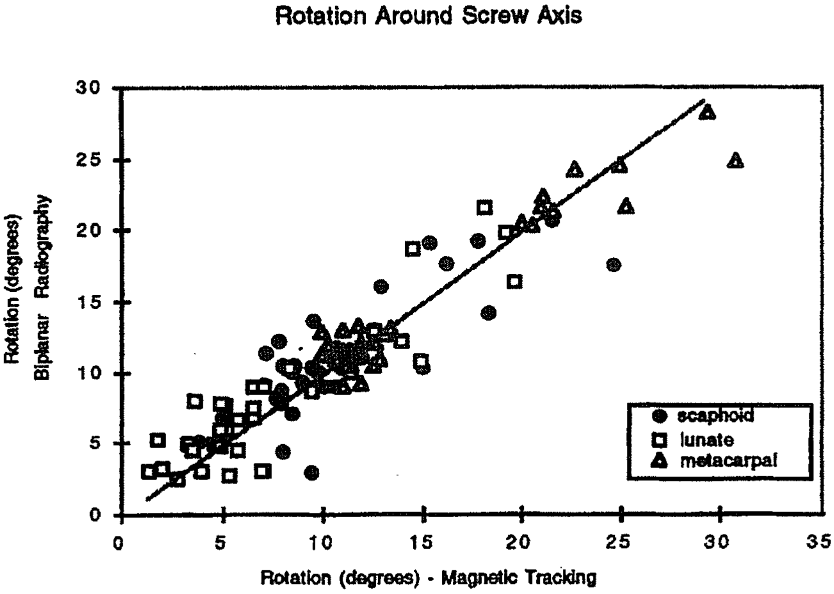


Fig. 2. Rotation of third metacarpal, lunate, and scaphoid, as measured by using magnetic tracking system and bi-planar radiography.

Table 1. Differences of rotation around screw axis between 3Space and biplanar radiographic method

	Metacarpal		Lunate		Scaphoid	
	M	S.D.	M	S.D.	M	S.D.
E15-30	0.4	0.9	−1.1	1.8	−1.6	1.6
N-E15	−0.4	1.5	−2.0*	1.5	−2.0*	1.6
N-F30	0.3	1.9	0.0	3.2	−0.7	2.0
F30-60	1.2	2.9	0.3	2.5	−0.5	5.1
N-RD15	−0.1	2.4	2.0	2.2	1.9	3.3
N-UD15	−0.3	0.6	0.2	0.8	−0.1	1.6
UD15-30	−0.6	0.7	−1.6*	1.1	−0.7	1.3

*Significance difference between methods of measurement, $p < 0.05$

Note: Wrist motion: E15-30 = 15–30° of extension; N-E15 = neutral to 15° of extension. N-F30 = neutral to 30° of flexion; F30-60 = 30–60° of flexion. N-RD15 = neutral to 15° of radial deviation. N-UD15 = neutral to 15° of ulnar deviation; UD15-30 = 15–30° of ulnar deviation M = Mean; S.D. = Standard deviation.

DISCUSSION

Normal kinematics of the wrist were first investigated by Bryce in 1896 (Andrews and Youm, 1979). Since then, numerous investigators using several methods have attempted to determine carpal bone motion as a function of wrist motion. Abnormal carpal kinematics as related to normal kinematics received increased attention after the introduction of the concept of carpal instability (Linscheid *et al.*, 1972).

While several different methods have been used to measure carpal kinematics (Andrews and Youm, 1979; Berger *et al.*, 1982; Youm and Yoon, 1979; Youm *et al.*, 1978), biplanar radiography is generally considered to be the most accurate and popular one. In addition, the technique can be used in a relatively non-invasive manner, resulting in minimal alteration of the carpal kinematics. However, the major drawback for biplanar radiography is that the implantation and digitization of the markers is tedious and time-consuming. Therefore, only static positions can be measured, and pseudo-dynamic kinematics can be determined.

Magnetic tracking has become widely accepted for the measurement of joint kinematics, (Imaeda *et al.*, 1994; Itoi *et al.*, 1992; Jantea *et al.*, 1994). The technique is versatile and easy to use with the capability of measuring motions dynamically.

The difference of rotations of three bones between the two methods was small, and application of the magnetic tracking device to carpal kinematics is warranted by this study. This difference may be due to two factors. The weight of the sensor (17 g) in conjunction with the moment arm provided by the rod may cause some alteration of the kinematics. In addition, the rod itself might interfere with tendons or ligaments during movement, thereby altering the kinematics.

The primary drawback of this experiment was that the measurements were not taken simultaneously for both measurement devices. However, a specially designed jig was used to position the wrist for both measurement techniques, and the wrist remained fixed to the jig in between the data collections. A second drawback was the lack of tendon loading in the experiment. Because there was no tendon loading, there may have been more than the normal amount of wrist laxity during the experiments. This may have caused the sensors to induce more motion in the carpal bones, such that their effect on the kinematics may have been exaggerated.

The measurements of carpal kinematics by using a magnetic tracking device and biplanar radiography were found to be nearly identical. Using a magnetic tracking device for measuring carpal bone kinematics on the basis of this study is reasonable, but some caution must be exercised. The sensors must be attached to the bones in such a way that

Table 2. Unit vector describing the orientation of the screw displacement axis during wrist flexion-extension

	E15-30			N-E15			N-F30			F30-60		
	x	y	z	x	y	z	x	y	z	x	y	z
Third Metacarpal												
3Space	−0.030	−0.999	0.010	−0.102	−0.995	0.010	0.061	0.997	−0.041	−0.072	0.988	0.134
Biplanar	0	−0.999	−0.030	−0.081	−0.996	−0.031	−0.080	0.996	0.040	−0.141	0.980	0.141
Lunate												
3Space	0	−0.999	−0.032	−0.143	−0.990	0	0	0.995	0.104	−0.168	0.905	0.390
Biplanar	−0.116	0.976	−0.186	−0.100	−0.994	−0.040	0.112	0.927	0.357	−0.159	0.864	0.478
Scaphoid												
3Space	−0.133	−0.985	0.113	−0.162	−0.975	0.152	0.061	0.998	0	−0.277	0.882	0.381
Biplanar	−0.133	−0.990	0.051	−0.010	−0.999	0.051	−0.148	0.985	0.085	−0.246	0.870	0.427

Note: Direction: x = proximal; y = radial; z = palmar.

they will have a minimal effect on the kinematics. The rods inserted into the bones should be as small and as short as possible so as to avoid impingement of the rod and to minimize the moment generated by the sensor. At the same time the rods must be placed so as to avoid interference with one another during normal wrist motion. The ability to make continuous measurements of the carpal bones, rather than discrete position measurements, is a distinct advantage.

Acknowledgement—This study was supported by grant AR40242, awarded by the National Institutes of Health.

REFERENCES

An, K. N. and Chao, E. Y. S. (1984) Kinematic analysis of human movement. *Annual Biomedical Engineering* **12,** 585–597.

An, K. N., Jacobsen, M. C., Berglund, L. J. and Chao, E. Y. S. (1988) Application of a magnetic tracking device to kinesiologic studies. *Journal of Biomechanics* **21,** 613–620.

Andrews, J. G. and Youm, Y. (1979) A biomechanical investigation of wrist kinematics. *Journal of Biomechanics* **12,** 83–93.

Berger, R. A., Crowninshield, R. D. and Flatt, A. E. (1982) The three dimensional rotational behaviors of the carpal bones. *Clinical Orthopaedics* **167,** 303–310.

Brumbaugh, R. B., Crowninshield, R. D., Blair, W. F. and Andrews, J. G. (1982) An *in vivo* study of normal wrist kinematics. *Journal of Biomechanical Engineering* **104,** 176–181.

Bryce, T. H. (1896) On certain points in the anatomy and mechanism of the wrist joint reviewed in the light of a series of roentgen ray photographs of the living hand. *Journal of Anatomy and Physiology* **31,** 59–79.

Garcia-Elias, M., Cooney, W. P., An, K. N., Linscheid, R. L. and Chao, E. Y. S. (1989) Wrist kinematic after limited intercarpal arthrodesis. *Journal of Hand Surgery* **14A,** 791–799.

Horii, E., Garcia-Elias, M., An, K. N., Bishop, A. T., Cooney, W. P., Linscheid, R. L. and Chao, E. Y. S. (1991) A kinematic study of luno-triquetral dissociation. *Journal of Hand Surgery* **16A,** 355–362.

Imaeda, T., Niebur, G., An, K. N. and Cooney, W. P. (1994) Kinematics of the trapeziometacarpal joint after sectioning of the ligaments. *Journal of Orthopaedics Research* **12,** 205–210.

Itoi, E., Motzkin, N. E., Morrey, B. F. and An, K. N. (1992) Scapular inclination and inferior stability of the shoulder. *Journal of Shoulder Elbow Surgery* **1,** 131–139.

Jantea, C. L., An, K. N., Linscheid, R. L. and Cooney, W. P. (1994) The role of the scapho-trapezial–trapezoidal ligament complex on scaphoid kinematics. In *Advances in the Biomechanics of the Hand and Wrist,* eds F. Schvind, K. N. An, W. P. Cooney III and M. Garcia-Elias, pp 345–361. NATO AS1 Series A256, Plenum, New York.

Kinzel, G. L., Hall, A. S. Jr. and Hillberry, B. M. (1972) Measurement of the total motion between two body segments—I. Analytical development. *Journal of Biomechanics* **5,** 93–105.

Kobayashi, M., Berger, R. A., Linscheid, R. L. and An, K. N. (1997) Intercarpal kinematics during wrist motion. In *Hand Clinics. Biomechanics of the Hand and Wrist,* ed. D. L. Nelson. W. B. Saunders Co, Philadelphia, PA.

Linscheid, R. L. (1986) Kinematic considerations of the wrist. *Clinical Orthopaedics* **202,** 27–39.

Linscheid, R. L., Dobyns, J. H., Beabout, J. W. and Bryan, R. S. (1972) Traumatic instability of the wrist. *Journal of Bone Joint Surgery* **54A,** 1612–1632.

Luo, Z. P., Niebur, G. L. and An, K. N. (1996) Determination of the proximity tolerance for measurement of surface contact areas using a magnetic tracking device (Technical note). *Journal of Biomechanics* **29,** 367–372.

Ruby, L. K., Cooney, W. P., An, K. N., Linscheid, R. L. and Chao, E. Y. S. (1988) Relative motion of selected carpal bones: a kinematic analysis of the normal wrist. *Journal of Hand Surgery* **13A,** 1–10.

Spoor, C. W. and Veldpaus, F. E. (1980) Rigid body motion calculated from spatial coordinates of markers. *Journal of Biomechanics* **13,** 391–393.

Trocmé, M. C., Sather, A. H. and An, K. N. (1990) A biplanar cephalometric stereoradiography technique. *American Journal of Orthodontic and Dentofacial Orthopedics* **98**(2), 168–175.

Woltring, H. J. (1994) 3-D attitude representation of human joints: a standardization proposal. *Journal of Biomechanics* **27,** 1399–1414.

Youm, Y., McMury, R. Y., Flatt, A. E. and Gillespie T. E. (1978) Kinematics of the wrist. *Journal of Bone Joint Surgery* **60A,** 423–431.

Youm, Y. and Yoon, Y. S. (1979) Analytical development in investigation of wrist kinematics. *Journal of Biomechanics* **12,** 613–621.

The Effects of Wrist Distraction on Carpal Kinematics

Jun-ichi Ishikawa, MD, William P. Cooney III, MD, Glen Niebur, BSME,
Kai-Nan An, PhD, *Rochester, MN,* Akio Minami, MD,
Kiyoshi Kaneda, MD, *Sapporo, Japan*

Changes in carpal kinematics under wrist distraction were studied in fresh cadaveric specimens. A magnetic tracking device measured kinematic motions of the scaphoid, lunate, and third metacarpal relative to the fixed radius in 3 planes of passive motion (coronal, sagittal, and "dart throwers") under progressive distraction loads. The change in percent contribution of the radiocarpal and midcarpal joints was calculated. Radiocarpal motion during extension was decreased as increasing traction was applied, but it increased with flexion. Motion of the scaphoid relative to the lunate was smaller in the oblique plane, resulting in less radiocarpal motion than in the sagittal plane. In the coronal plane, traction had little effect on radial deviation, but ulnar angulation of the scaphoid was greater with ulnar deviation of the wrist. These results suggest that different degrees of tension exist in the palmar and dorsal ligaments with the wrist under traction and during different planes of wrist motion. If wrist motion is desired during fixed traction, such as used clinically with external fixation, the dart-throwers motion (wrist extension with radial deviation and wrist flexion with ulnar deviation) appears to have the least impact on radiocarpal motion. If greater radiocarpal motion is desired, however, such as during postoperative mobilization, flexion-extension and radioulnar deviation will create more radiocarpal motion than the dart-thrower's motion. (J Hand Surg 1999;24A:113–120. Copyright © 1999 by the American Society for Surgery of the Hand.)

Key words: Carpal kinematics, wrist distraction, distal radius fracture.

Normal and pathologic carpal kinematics have received much interest in recent years.[1–7] The relative contributions of articular constraint and ligamentous stability to the control of carpal kinematics are difficult to quantify and evaluate. Detailed studies of the material properties of individual human wrist ligaments have been reported.[8–10] Savelberg et al[9] studied the forces and strains in individual carpal ligaments during wrist motions and concluded that carpal kinematics are controlled by articular geometry more than by ligamentous constraints. It is widely accepted, however, that the tension of carpal ligaments varies with wrist motion and plays a role in stabilizing the wrist joint.[2,3]

It has become increasingly apparent that early motion facilitates joint recovery following fracture but that it may be harmful to fracture healing.[11] Early wrist motion has been suggested in the treatment of intra-articular distal radius fractures and after internal compression screw fixation of scaphoid fractures and nonunions.[12] Distraction of the wrist to reduce loads across the articular cartilage and to prevent load across the fracture fragments is proposed for treatment of many of these conditions.[13,14] The effect of distraction on carpal kinematics is unknown, however, and the effect of continued distraction on treatment programs has only recently been studied.[15,16]

From the Orthopedic Biomechanics Laboratoy, Mayo Clinic/Mayo Foundation, Rochester, NY; and Hokkaido University School of Medicine, Sapporo, Japan.

Received for publication January 15, 1997; accepted in revised form July 13, 1998.

No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

Reprint requests: William P. Cooney III, MD, Department of Orthopedics, Mayo Clinic/Mayo Foundation, Rochester, MN 55905.

0363-5023/99/24A01-0017$3.00/0

Distraction reduction of distal radial fractures is accomplished through ligamentotaxis, which of necessity must alter the articular and ligamentous constraints that act to stabilize the wrist. No reports have addressed kinematic changes of the wrist that occur under traction.

The purpose of this study was to examine wrist kinematic changes under various amounts of traction with varying loads and to determine whether motions of sagittal flexion-extension, radial-ulnar motion, and "dart-throwers" motion could be initiated during the early phase of wrist rehabilitation. The dart-thrower's motion (wrist extension and radial deviation to wrist flexion and ulnar deviation) is used in many activities of daily living. In this study we were interested in determining whether the dart-throwers motion could be the preferred method of early mobilization of the wrist. As an aside, we wished to examine the potential of early wrist motion associated with external fixation of severe wrist injuries (complex distal radius fractures and wrist fracture dislocations) to determine whether distraction plus motion were mutually compatible.

Materials and Methods

Ten fresh-frozen cadaveric specimens with a mean age of 57 years were used in this experiment. No specimens showed significant degenerative changes on radiographic examination.

The specimens were allowed to thaw at room temperature overnight in preparation. The skin of the forearm was excised circumferentially 5 to 6 cm proximal to the wrist. The tendons of the extensor carpi radialis longus and brevis, extensor carpi ulnaris, flexor carpi radialis, flexor carpi ulnaris, and abductor pollicis longus were identified and sectioned proximal to the skin incision. A heavy suture was secured to each tendon for application of load. The radius and ulna were transfixed with a Steinmann pin in neutral forearm rotation and were then transected 15 cm proximal to the capitate head.

A magnetic tracking device (3Space Tracker System, Polhemus, Colchester, VT) was used to record the kinematics (Fig. 1).[1,17,18] This system, with 6° of freedom, allows accurate tracking of the 3-dimentional position and orientation of a sensor in relation to a source. The sensor represents the moving object and the source represents the fixed reference. Although this system may be affected by metallic objects, its accuracy has proved to be high in previous kinematic studies, which was confirmed by comparing it with a biplanar radiographic method in our previous study.[19]

To attach the 3Space sensors, incisions were made

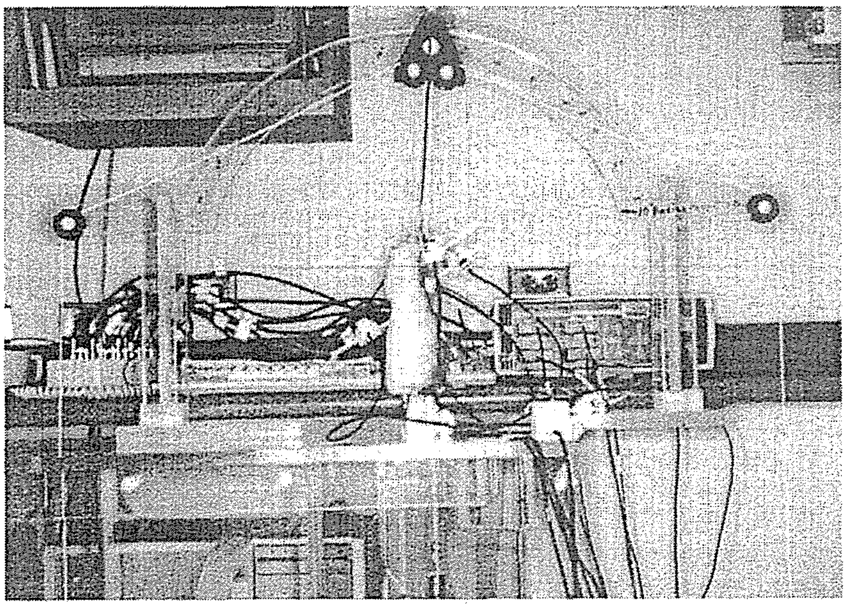


Figure 1. The experiment setup. A magnetic tracking device was used to analyze the carpal kinematics. Traction force was applied through the neck of the third metacarpal.

over the lunate, scaphoid, third metacarpal, and distal radius. The lunate was approached through a longitudinal skin incision over the dorsal side of the wrist. The extensor retinaculum was cut between the third and fourth compartment and the dorsal radiolunotriquetral ligament was identified. A small arthrotomy along the distal edge of this ligament was used to approach the lunate. The condition of the scapholunate interosseous ligament was examined to ensure the ligament was intact. A second small incision was added over the anatomic snuff box and the scaphoid was approached between the abductor pollicis longus and the extensor pollicis longus tendon.

A third incision was made over the distal radius directly over the site for the induced radius fracture. A 0.045-inch (1.1-mm) K-wire was inserted into each bone and its position was confirmed with anteroposterior and lateral x-rays. The K-wires were removed and the drill hole enlarged to 2.2 mm in each bone. Nonmagnetic plexiglass rods were used to mount the sensors. Care was taken not to penetrate the opposite cortex. Small plastic mounts were attached at the end of each rod and the sensors were fixed by plastic screws. A third metacarpal sensor was attached in a similar fashion. Movement of the third metacarpal was used to represent gross (total) motion of the wrist. A rod for guiding wrist motions was inserted longitudinally into the third metacarpal shaft.

All capsular and retinacular incisions were closed with interrupted sutures. Specimens were securely mounted in a special holding device with polymethyl methacrylate. A custom-designed protractor to which the source was fixed was bolted on the experimental table. The different planes of wrist motion were constrained by rotating this protractor. Passive wrist motion was simulated by sliding the pulley attached to the protractor with the third metacarpal rod as a guide.

The planes of wrist motion were sagittal (flexion-extension), coronal (radial-ulnar deviation), and dart-throwers (radial extension-palmar flexion) planes. The latter was at an angle of 23° to the sagittal plane. In these 3 planes, the global flexion-extension and radial-ulnar deviation were constrained by the system, but adjunct pronation-supination motion of the wrist was allowed.

A 10-kg load approportioned to each muscle-tendon unit physiologic cross-sectional area was applied as a preload.[20–23] The preload was used to simulate normal compression across the wrist related to muscle tone. The data were obtained continuously during neutral to 50° of extension, 50° of flexion, 15° of radial deviation, 30° of ulnar deviation, 50° of dart-throwers extension, and 50° of dart throwers flexion.

The data of the relative position and motion of the sensors to the source were calculated as the screw displacement axis.[8] The relative displacement of a moving segment from one position to another can be described in terms of a rotation around and translation along this axis. The coordinate system was constructed on the radius. The x-axis is defined along the longitudinal axis of the radius (pronation-supination) and the y-axis lies in the coronal plane perpendicular to the x-axis (radioulnar deviation). The z-axis was perpendicular to both the x-axis and the y-axis (extension-flexion).

Wrist Motion Measurements

The radiocarpal and midcarpal motions were calculated as the relative motion of the lunate to the distal radius and of the lunate to the capitate and third metacarpal, respectively. The percent contribution at the radiocarpal and midcarpal joints was calculated during motion in each plane. Relative motion of the scaphoid with respect to the lunate was also calculated.

Traction forces of 0 kg, 5 kg, 10 kg, and 15 kg were applied to the K-wire penetrating the neck of the third metacarpal by 2 strong cords tied at either end of the wire. The cords passed around a roller and came down both sides of the table through another pulley system fixed at the ends of the protractor. This allowed the traction force to be applied in line with the third metacarpal during each sequence of wrist motion (Fig. 1). These traction forces represent types of clinically applied wrist distraction that might be used in the reduction of distal radius fractures or carpal dislocations.

The specimens were preconditioned by repeating the motion 5 times before collecting data for each traction force sequence. The change in percent contribution at the radiocarpal and midcarpal joints and the relative motion of the scaphoid to the lunate were statistically analyzed by repeated measurement of ANOVA.

Results

The results are expressed as a percent change in global wrist motion and in the differences of motion between the scaphoid and lunate bones of the proximal row, both as a consequence of wrist distraction.

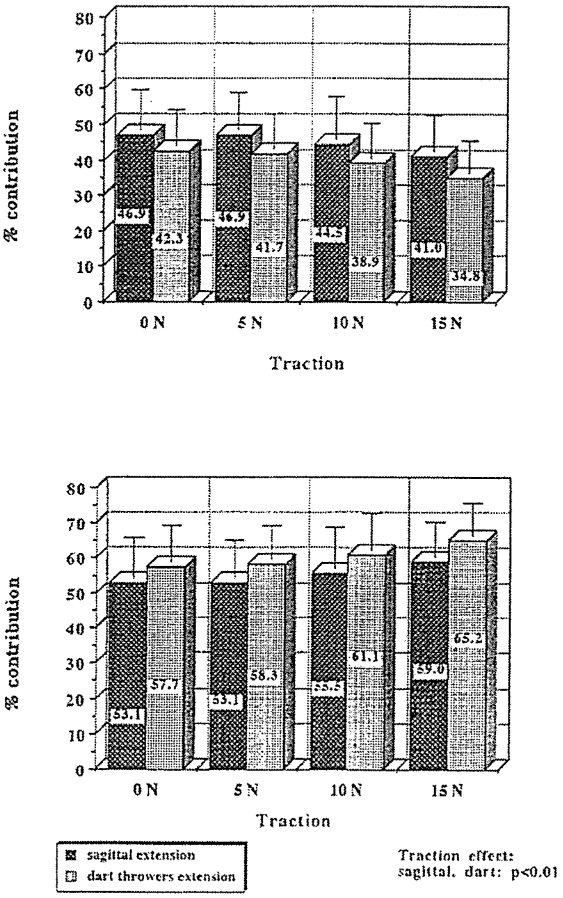


Figure 2. The percent contribution at the radiocarpal (top) and midcarpal (bottom) joints during wrist extension.

Change of the Percent Contribution of the Radiocarpal and Midcarpal Joints to Global Motion of the Wrist

Wrist extension. The percent contribution to wrist extension of the radiocarpal joint decreased; that of the midcarpal increased significantly during wrist distraction. Radiocarpal motion was also smaller and midcarpal motion was larger during dart-throwers extension compared with sagittal extension (Fig. 2).

Wrist flexion. The percent contribution of the radiocarpal joint increased and that of the midcarpal decreased significantly during wrist distraction. Radiocarpal motion was smaller and midcarpal motion was larger during wrist flexion with the dart-throwers motion compared with sagittal plane motion (Fig. 3). During both flexion and extension, the smallest amount of radiocarpal motion occurred with the dart-throwers motion.

Wrist radial-ulnar deviation. The percent contribution of the radiocarpal joint increased and that of the midcarpal decreased significantly under distraction during ulnar deviation motion. There was no important change, however, regarding the percent contribution during radial deviation. Radiocarpal motion was smaller and midcarpal motion was larger during radial deviation in comparison to ulnar deviation during wrist distraction (Fig. 4).

The Change of the Relative Motion of the Scaphoid to the Lunate During Global Motion of the Wrist

Extension-flexion of the wrist. The scaphoid extended relative to the lunate during wrist extension. This motion decreased with traction. The scaphoid flexed more relative to the lunate during wrist flex-

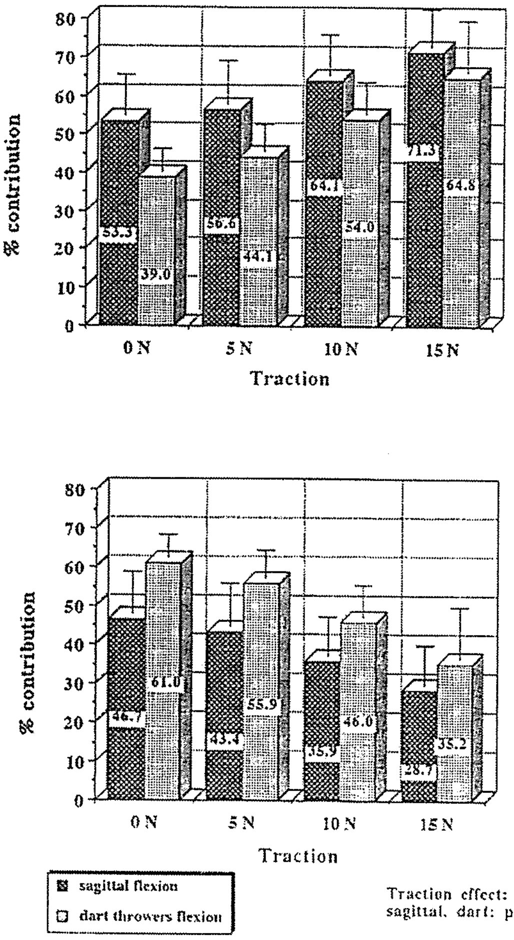


Figure 3. The percent contribution at the radiocarpal (top) and midcarpal (bottom) joints during wrist flexion.

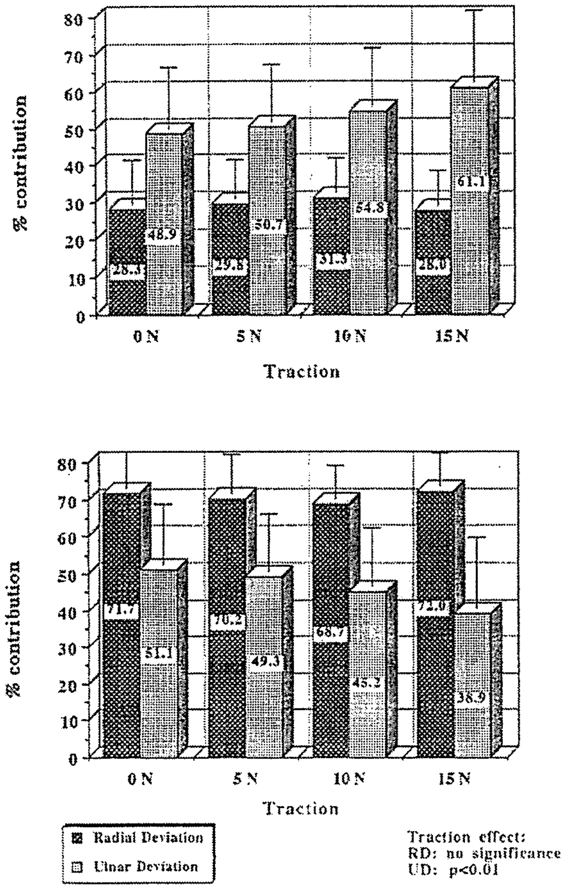


Figure 4. The percent contribution at the radiocarpal (top) and midcarpal (bottom) joints during wrist radial ulnar deviation.

ion. This motion increased with traction. The relative motion of the scaphoid with respect to the lunate was smaller in the dart-throwers plane compared with the sagittal plane (Fig. 5).

Radial-ulnar deviation. The relative motion of the scaphoid with respect to the lunate changed under traction during wrist ulnar deviation. During radial deviation, however, the relative motion of the scaphoid showed no important change (Fig. 6).

Discussion

Several reports using different investigative methods have shown that tension in individual wrist ligaments change during wrist motions.[8-10] Whether these changes in tension control carpal kinematics is not well-known. The distal carpal row is controlled by the extrinsic flexor and extensor wrist tendons, which intiate motion at the midcarpal joint level. The proximal carpal row is considered an intercalated segment whose motion is induced by the distal carpal row and stabilized by the radiocarpal ligaments as well as the geometric constraint of the joint architecture.[21] The scaphoid is considered a mechanical link between the rows.[2,3]

The main ligaments on the palmar side of the wrist are the radioscaphocapitate, long and short radiolunate, and ulnocarpal ligaments. These ligaments become tense during wrist extension and vary in differential tension during radial and ulnar deviation.[2,22]

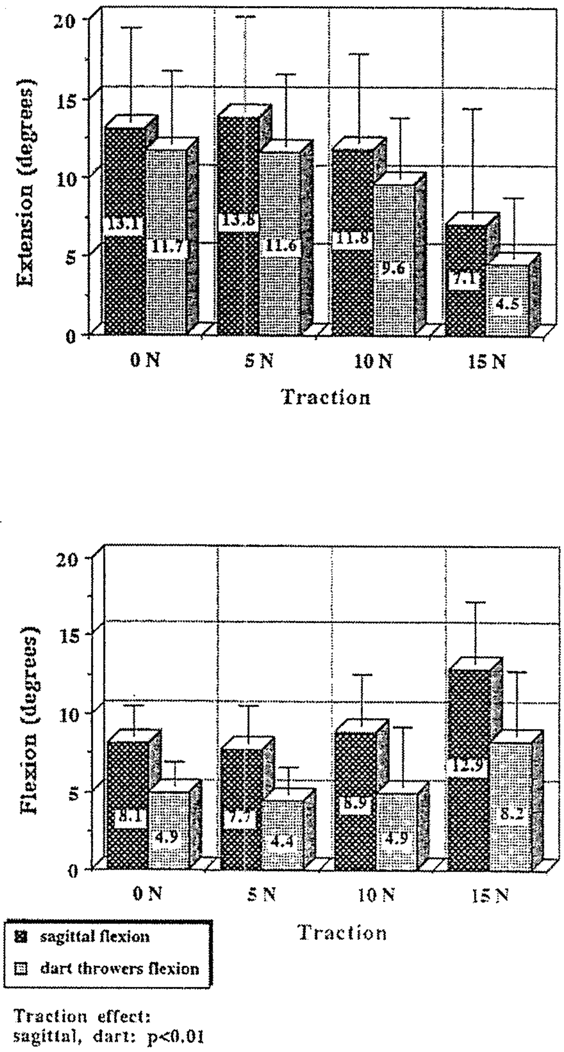
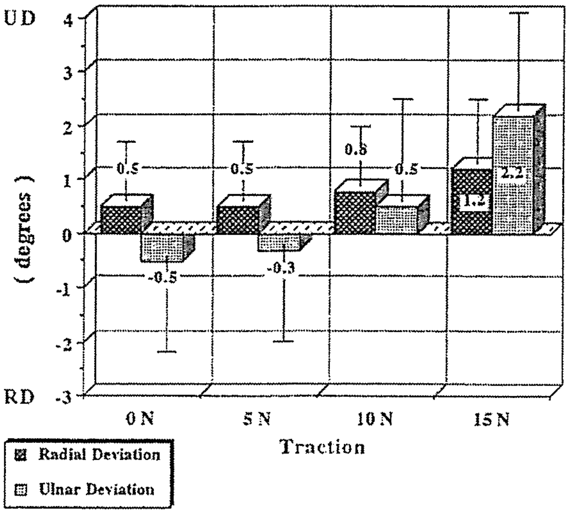


Figure 5. The relative motion of the scaphoid with respect to the lunate during wrist extension (top) and flexion (bottom).



Traction effect:
RD: no significance
UD: p<0.01

Figure 6. The relative motion of the scaphoid with respect to the lunate during wrist radial-ulnar deviation.

The percent contribution of the radiocarpal joint to global wrist motion decreased during wrist extension during distraction (traction); that of the midcarpal joint increased. The differences were statistically significant. These findings suggest a greater effect of traction on the proximal (radiocarpal) palmar ligaments than on the distal (midcarpal) palmar ligaments. The scaphoid extended relative to the lunate during wrist extension, but the degree of scapholunate motion decreased with traction. This observation further suggests that the strong volar radiocarpal ligaments restrict radiocarpal motion more than midcarpal motion with the wrist under traction and that the palmar radioscaphocapitate ligament restricts extension of the scaphoid more than the long and short radiolunate ligaments restrict the lunate.

During wrist extension, we observed that the percent contribution of the radiocarpal joint was smaller and that of the midcarpal joint was larger during dart-throwers extension than during sagittal extension. In addition, the relative motion of the scaphoid with respect to the lunate was smaller during dart-throwers extension than during sagittal extension. These results demonstrate that during dart-throwers motion there was less motion at the radioscaphoid joint than was observed during sagittal plane wrist motion. The proximal carpal row rotated more concentrically (in unison) with dart-throwers motion than during sagittal plane wrist flexion and extension. As a consequence of these observations, dart-throwers motion may represent a more physiologic plane of motion.

Conversely, the percent contribution of the radiocarpal and midcarpal joints to wrist flexion during traction was opposite that of wrist extension. During traction, radiocarpal flexion increased and midcarpal joint flexion decreased. The main dorsal extrinsic ligament of the radiocarpal joint is the dorsal radiolunotriquetral ligament. This ligament elongates in wrist flexion. This increased tension, augmented by traction, appears to have a definite effect on carpal kinematics. Whether this ligament has sufficient strength, however, to restrict radiocarpal flexion to the same extent that the palmar ligaments restrict radiocarpal extension during wrist extension is not known. These findings are consistent with the results from a cadaver study of Kaempffe et al,[16] who stated that dorsal capsular strain was 4-fold that of the volar ligaments.

Scaphoid flexion relative to the lunate during wrist flexion increased under traction. This suggests that the dorsal radiolunotriquetral ligament constraints radiolunate flexion more than the capsular structure constrains radioscaphoid motion. Horii et al[24] noted this fact during studies of lunotriquetral dissociation. A palmar flexed lunate would occur only after division of the lunotriquetral ligament and dorsal radiotriquetral ligament. The percent contribution of the radiocarpal joint was smaller and that of the midcarpal was larger during dart-throwers flexion than during sagittal plane wrist flexion. Again, the scapholunate complex appears to be more unified in motion with dart-throwers flexion-extension than with sagittal plane flexion-extension. The flexion of the scaphoid with respect to the lunate was also smaller during dart-throwers wrist flexion. This indicates that radioscaphoid motion induced by midcarpal motion was less. Lesser tension in the dorsal radiolunotriquetral ligament in the dart-throwers plane than in the sagittal plane of wrist flexion would explain this result.

In the coronal plane of wrist motion (radial-ulnar deviation), the percent contribution of the radiocarpal joint increased and that of the midcarpal decreased during wrist ulnar deviation. Ulnar deviation of the scaphoid with respect to the lunate increased under traction during ulnar deviation of the wrist. These results suggest that midcarpal motion (scaphocapitate, scaphotrapeziotrapezoidal joint) induced the ulnar deviation of the scaphoid, especially under traction during wrist ulnar deviation. Increased tension in the radiocarpal ligaments increases more under traction in ulnar deviation than in wrist radial deviation. There were no significant changes in the percent contribution under traction during radial deviation. The relative motion of the scaphoid to the lunate showed no significant change under traction. This might be explained by the fact that the induced radioscaphoid motion was small during wrist radial deviation, which results in lesser tension in the radiocarpal ligaments compared with wrist ulnar deviation under traction.

Evaluation of carpal kinematics under traction provides useful information about the mechanism of carpal motion. Mayfield et al[26] noted that the proximal carpal row has more ligamentous stabilizers than the distal row. In this study, we did not measure the actual tensions of each carpal ligament. The study clearly suggests, however, that the scaphoid functions as a mechanical link between the distal and proximal carpal rows and that there is an effective change in tension in the radiocarpal ligaments when under traction in different planes of wrist motion.

From a clinical perspective it appears that traction (distraction) changes normal carpal kinematics and that motion of the wrist combined with traction induces abnormal patterns of motion. In the treatment of distal radius fractures, traction may be necessary for fracture reduction, but maintaining excessive traction could affect carpal ligament function and alter carpal kinematics.[25] More importantly, it appears that wrist distraction with external fixation of distal radius fractures is not compatible with wrist motion since the distraction changes carpal kinematics at both the radiocarpal and midcarpal joints.[27,29] Lighter traction would be more preferable to heavy traction[18] and if motion is desired during traction, the dart-throwers motion of wrist extension-radial deviation and wrist flexion and ulnar deviation would effect normal carpal kinematics the least.

References

1. Jantea CL, An KN, Linscheid RL, Cooney WP. The role of the scapho-trapezial-trapezoidal ligament complex on scaphoid kinematics. In: Schuind F, An KN, Cooney WN, Garcia M, eds. Advances in the Biomechanics of the Hand and Wrist. New York: Plenum Press, 1994.345–361.
2. Linscheid RL. Kinematic considerations of the wrist. Clin Orthop 1986;202:27–39.
3. Viegas SF, Patterson RM, Ward K. Extrinsic wrist ligaments in the pathogenesis of ulnar translation instability. J Hand Surg 1995;20A:312–318.
4. Werner FW, Palmar AK, Somerset JH, Tong JJ, et al. Wrist joint simulator. J Orthop Res 1996;14:639–646.
5. Short WN, Werner FW, Fortino MD, Palmar AK, Mann KA. A dynamic biomechanical study of scapholunate ligament sectioning. J Hand Surg 1995;20A:986–999.
6. Ritt MJ, Stuart MJ, Berglund LJ, Linscheid RL, Cooney WP, An KN. Rotational stability of the carpus relative to the forearm. J Hand Surg 1995:20A:305–311.
7. Imaeda T, Niebur G, Cooney WP, Linscheid RL, An KN. Kinematics of the normal trapeziometacarpal joint. J Orthop Res 1994;12:187–204.
8. de Lang A, Huiske R, Kauer JMG. Wrist-joint ligament length changes in flexion and deviation of the hand: an experimental study. J Orthop Res 1990;8:722–730.
9. Savelberg HHCM, Kooloos JGM, Huiskes R, Kauer JMG. Strains and forces in selected carpal ligaments during in vitro flexion and deviation movements of the hand. J Orthop Res 1992;10:901–910.
10. Weaver L, Tencer AF, Trumble TE. Tensions in the palmar ligaments of the wrist. J Hand Surg 1994;19A:464–474.
11. Clyburn T. Dynamic external fixation for comminuted intra-articular fractures of the distal radius. J Bone Joint Surg 1987;69A:248–254.
12. Filan SL, Herbert TJ. Herbert screw fixation of scaphoid fractures. J Bone Joint Surg 1996;78B:519–529.
13. Fernandez DL. Technique and results of external fixation for complex wrist injuries. Hand Clin 1993;9:625–637.
14. Fernandez DL, Flury MC. History, evolution and biomechanics of external fixation of the wrist joint. Injury 1994; 25:502–513 (suppl 4).
15. Kaempffe FA. External fixation for distal radius fractures: adverse effects of excessive distraction. Am J Orthop 1996;25:205–209.
16. Kaempffe FA, Wheeler DR, Paimer CA, et al. Severe fractures of the distal end of the radius: the effect of amount and duration of external fixator distraction on outcome. J Hand Surg 1993;18A:33–41.
17. An KN, Jacobsen MC, Berglund LJ, Chao EYS. Application of a magnetic tracking device to kinesiologic studies. J Biomech 1988;21:613–620.
18. Spoor CW, Veldpaus FE. Rigid body motion calculated from spatial coordinates of markers. J Biomech 1980;13: 391–393.
19. Ishikawa JI, Niebur GL, Uchiyama S, Linscheid RL, An KN. The feasibility of use of magnetic tracking device for measuring carpal kinematics. J Biomech 1997;30:1183–1186.
20. Brand P, Beach PB, Thompson DE. Relative tension and potential excursion of muscles in the forearm and hand. J Hand Surg 1981;6:209–219.
21. Horii E, An KN, Linscheid RL. Excursion of prime wrist tendons. J Hand Surg 1993:18A:83–90.
22. Hara T, Horii E, An KN, Cooney WO, Linscheid RL, Chao EYS. Force distribution across the wrist. Application of pressure sensitive conductive rubber. J Hand Surg 1992; 17A:339–347.
23. An KN, Horii E, Ryu J. Muscle function. In: An KN, Berger RA, Cooney WP, eds. Biomechanics of the wrist joint. New York: Springer-Verlag, 1991:157–170.

24. Horii E, Garcia-Elias M, An KN, et al. A kinematic study of lunotriquetral dissociations. J Hand Surg 1991;16:355–362.
25. Berger RA, Amadio PC. Predicting palmar radiocarpal ligament disruption in fractures of the distal articular surface of the radius involving the palmar cortex. J Hand Surg 1994;19B:108–113.
26. Mayfield JK, Johnson RP, Kolcayne RF. The ligaments of the human wrist and their functional significance. Anat Rec 1976;186:417–428.
27. Ruby LK: Wrist biomechanics. AAOS Instructional Course Lectures 1992;41:25–32.
28. Sommerkamp TG, Seeman M, Sulman J, et al. Dynamic external fixation of unstable fractures of the distal part of the radius. J Bone Joint Surg 1994;76A:1149–1161.
29. McQueen M, Hajducka C, Court-Brown CM. Redisplaced unstable fractures of the distal radius. A prospective randomized comparison of four methods of treatment. J Bone Joint Surg 1996;78B:404–409.

整・災外 47：733—740，2004

特集 RA上肢の手術—最近の動向

RA手関節の手術

石川淳一* 三浪明男 岩崎倫政

要旨： リウマチ手関節では病期の進行に従って特有の変形を呈する。手術方法としては滑膜切除を基本として遠位橈尺関節の破壊に対してはDarrach法，Sauvé-Kapandji法，hemi-resection interposition arthroplastyなどが行われ，橈骨手根関節の破壊に対しては部分手関節固定，全手関節固定，人工関節置換などがある。それぞれ有効な手術法であり，筆者らが行っている方法を中心に詳述した。言うまでもなく関節リウマチは全身性疾患であり，手術治療を考える際は手関節のみの状態にとらわれず，隣接関節をはじめ他の関節の状態を総合的に検討し，患者のADL上の改善が期待される場合のみそれぞれの病期に応じて手術適応，方法を吟味することが重要であると考える。

はじめに

手関節は関節リウマチ(RA)で侵される頻度の高い関節であり，手のかなめ石としての手関節の変形はその末梢のMP，PIP関節の機能および変形の発生にも重要な影響を及ぼす。さらに手関節の伸展，屈曲のみならず遠位橈尺関節の破壊は前腕の回旋運動の障害をもたらす。

RA手関節の初期のX線変化としては骨萎縮像，骨嚢胞の形成などであるが，病期の進行とともに滑膜増殖は手関節を支持する靱帯の破壊，機能消失をもたらし，手関節特有のX線学的変化をもたらす。最も高頻度に滑膜増殖がみられるのは尺側部のいわゆるprestyloid recessといわれる部位であり，この部と遠位橈尺関節での滑膜増殖により尺骨頭の破壊と三角線維軟骨複合体(TFCC)の尺側手根骨の支持機能が失われ，手根骨は回外方向へ回旋し，尺骨頭は背側へ脱臼する。また掌側の橈骨手根靱帯(radiocapitate, radiolunate ligament)の機能消失により舟状骨は掌側回転を生じ，手根骨は橈側へ回転する。舟状月状骨間靱帯の破壊により舟状月状骨間の離開がみられる場合もある。さらに背側の橈骨手根靱帯(dorsal radiotriquetral ligament)の機能不全とあいまって手根骨の尺側偏位および掌側亜脱臼が生じる。また手根骨の橈側回転に伴って中手骨も橈屈することになり，結果としてMP関節での尺側偏位が助長される。

RA手関節に対しては上記の病期の進行によるX線変化に応じて種々の手術的治療が考慮されるが，大きく分けると，(1) 滑膜切除，(2) 尺骨遠位端切除(Darrach法)や遠位橈尺関節(DRUJ)の再建術，(3) 橈骨手根関節の再建術などが挙げられる。以下各手術法の適応および方法について述べる。

I．滑膜切除術

抗リウマチ薬による内科的治療の進歩により滑膜切除術の適応となる例は減少傾向である。しかし，薬物治療や装具療法などあらゆる保存的治療

---

* Jun-ichi ISHIKAWA et al，北海道大学医学部，整形外科学教室

Key words： Surgical treatment, Rheumatoid arthritis, Wrist

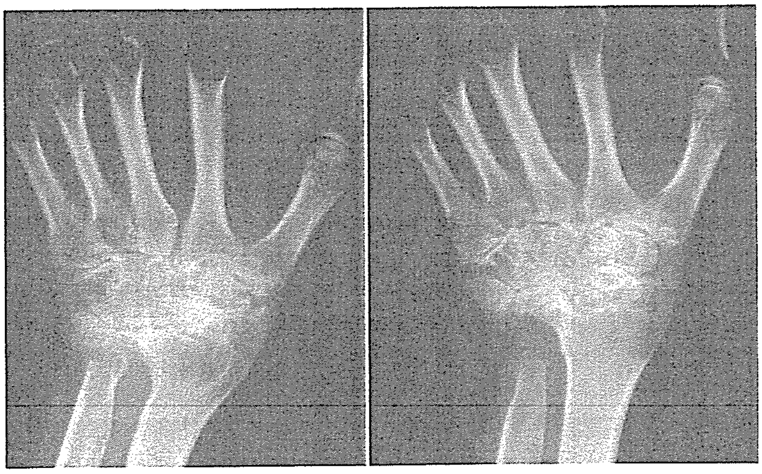


図 1　Darrach 法
71 歳女性，stage Ⅳ。橈骨手根関節は骨性強直であり，手根骨尺側偏位の進行はない。

に抵抗する疼痛のある滑膜炎が 4〜6 カ月以上持続しており，X 線像上関節破壊が進行しておらず関節裂隙が保たれている例では，関節変形の進行防止，除痛効果，伸筋腱断裂の発生防止などの観点より，滑膜切除はなお有効な方法と考えられる。滑膜切除により炎症の場の排除を行うことにより薬物治療の有効性を高めることも期待できる。ほとんどの例では，有痛性の尺骨遠位端背側脱臼，亜脱臼を伴っており，後に述べる尺骨遠位端切除（Darrach 法）を併用して行う。また伸筋腱の皮下断裂を伴う例では伸筋腱の再建が必要となる。

第 2 中手骨基部より手関節中央を通り，尺骨頭の近位尺側 3〜4 cm に至る直線状の皮膚切開を用いる。背側の静脈は術後の腫脹を抑えるため可能な限り温存することが重要である。橈骨神経浅枝，尺骨神経背側枝は術野の橈尺側にてそれぞれ確認しておく。伸筋支帯は第 6 コンパートメント上で縦切し，橈側をベースとしてコの字形に橈側へ反転する。伸筋腱を確認し，腱周囲および腱内への滑膜増生を認める場合滑膜切除を行う。

関節包は H 字状に切開し，橈骨手根関節，手根中央関節，遠位橈尺関節の滑膜切除をマイクロリューエル，関節鏡用パンチなどを用いて行う。特に尺骨手根骨間は滑膜増生が強く，入念に切除を行う必要がある。尺骨頭の不安定性が著明な場合は Darrach 法を合併して行う。駆血帯を解除し，止血操作を丁寧に行った後，関節包を閉鎖縫合する。腱断裂に対する処置を行った例以外，伸筋支帯を腱の下敷きにする操作は行っていない。皮下にドレーンを留置し，皮下，皮膚を縫合する。術後は約 2 週間のシーネ固定の後，手関節の自他動運動を開始する。

小川ら[1]は平均 13 年の長期成績を報告し，無痛は 78%，腫脹の消失は 92%で得られていたが，X 線像上での関節破壊の進行は 81%でみられたとしている。長期での関節破壊の進行は避けられないが，滑膜切除は先に述べた適応症例を厳格に選べば除痛，腫脹の消失において良好な成績が得られると考える。

II．遠位橈尺関節の再建術

1．尺骨遠位端切除（Darrach 法）

遠位橈尺関節の破壊があり，回内外時の疼痛が著明な場合や背側への尺骨頭脱臼により伸筋腱の断裂が存在する場合，滑膜切除と併用して行う。問題点として尺骨遠位切除端の不安定性による痛みや尺側の支持の消失による手根骨の尺側偏位の出現が指摘されている。したがって活動性の低い，

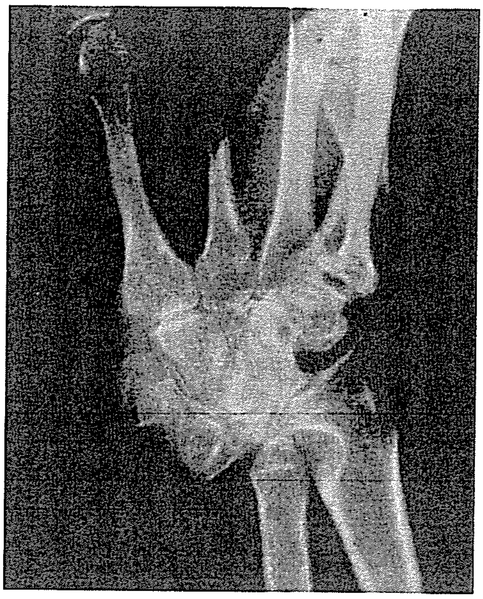


図 2
著明な手根骨の尺側偏位を認め，手根骨は掌尺側へ脱臼している。

図 3 尺骨切除端に対する安定化手術
ECU の半裁腱を，近位を基部として作成し，骨孔を通してもとの腱に縫合する。

比較的高齢者や橈骨手根関節が強直位にある例が最もよい適応となる（図 1）。術前 X 線像にてすでに手根骨の尺側偏位が存在したり，橈骨遠位尺側縁が近位尺側へ傾斜している例では Darrach 法単独は禁忌である（図 2）。

手術方法は先に述べた滑膜切除施行後，尺骨遠位を骨膜下に展開し，遠位尺側から近位橈側へボーンソーを用いて切除する。切除量は回内外にて橈骨とぶつからない程度の最小限（通常 15 mm 程度）でよい。切除端はヤスリにて滑らかにする。近年切除端の不安定性による疼痛が問題点として指摘され，種々の安定化術が報告されている。筆者らは尺側手根伸筋腱（ECU 腱）を用いた再建を行っている[2)]。ECU 腱の遠位橈側に近位を基部とする half slip を作成し，切除端の背側に 3.5 mm ドリルであけた骨孔に通し，反転して最大緊張下に同腱に interlacing 縫合を行う（図 3）。術後は約 2 週間のシーネ固定を行う。

2．Sauvé-Kapandji（S-K）法

DRUJ の破壊により前腕回旋時痛がある例が適応となる。Darrach 法では握力の低下をきたす場合があることと，手関節の横幅が狭くなる点が欠点であり，比較的若年者で活動性が高い場合は S-K 法が選択される。S-K 法後長期経過例では尺骨頭と尺側手根骨が癒合することが多く，手関節の安定性に寄与しうると考えられる。しかしすでに橈骨手根関節が強直位にある場合は S-K 法の必要はない。

DRUJ の滑膜切除を行ったのち，骨膜下に尺骨の骨幹端部を展開する。ボーンソーにて約 15 mm 尺骨頭を残して 10〜15 mm 幅で骨切除する。尺骨頭および橈骨の尺骨切痕を海綿骨がでるまで新鮮化する。先に切除した尺骨を残存する尺骨頭の幅に応じて円盤状に採型し，間に介在するよう移植する。Kirschner wire にて固定したのちキャニュレイテッド海綿骨ネジ 1 本にて固定する（図 4）。尺骨切除部の骨膜は完全に切除し，再癒合を防止する。術後は軽度回外位にて肘上シーネ固定を 2 週間行う。

S-K 法の問題点として Darrach 法と同様に近位端の不安定性によるクリック，疼痛があげられる。不安定性が著明な場合，近位端と橈骨が衝突（impinge）する。筆者らは先に述べた ECU の半裁腱を用いた遠位端安定化術を追加して行っており[2)]，不安定性をきたした例は経験していない（図 5）。

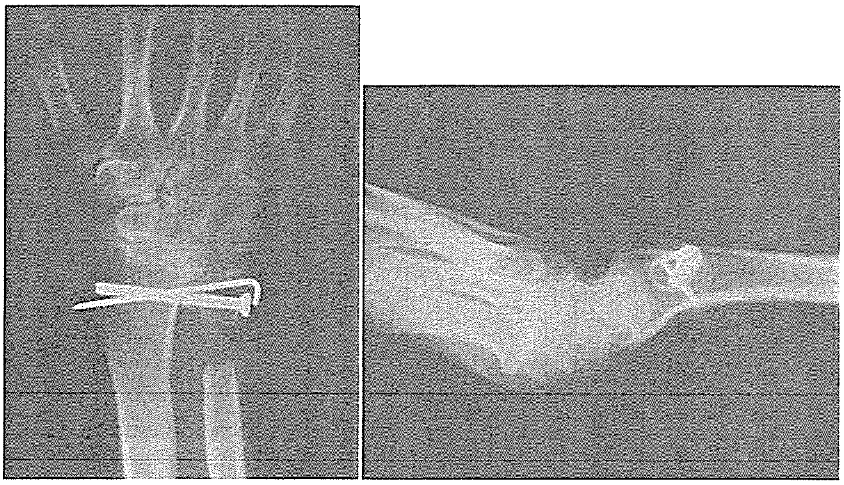


図 4　S-K 法
52 歳女性，stage Ⅲ。術後 2 年。尺側手根骨の支持が得られている。

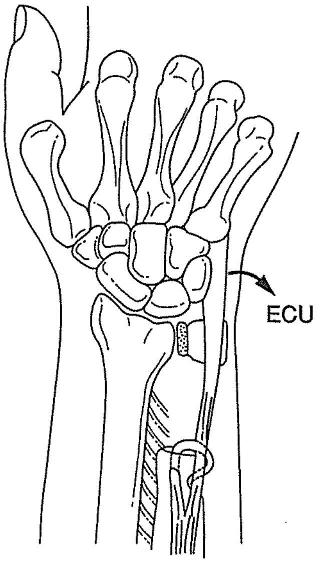


図 5　S-K 法＋ECU tenodesis
ECU の half slip を用いて腱固定を行い，尺骨近位端の安定化を図る。

3．Hemiresection interposition arthroplasty（Bowers 法），Matched distal ulnar resection（Watson 法）

比較的早期の RA で TFCC の機能が温存されているが DRUJ 関節面の破壊による回旋時痛が著明な場合が適応となる。したがって RA に対する適応は極めて少ないと思われる。

手術方法は尺骨の TFCC 付着部を温存して尺骨頭の橈骨との関節面を切除し，切離した関節包および伸筋支帯を尺骨頭の切除面に介在するように縫合する。長掌筋腱の腱球を挿入する場合もある。手技の詳細については他書にゆずる[3]（図 6）。

Ⅲ．橈骨手根関節の再建術

1．橈骨月状骨間固定術

橈骨手根関節の破壊による手関節掌背屈での疼痛が強く，手根中央関節は比較的保たれている例が適応となる。また術前手根骨の尺側偏位や橈側回転がみられる場合に Darrach 法を行う際は手関節のアライメントの矯正と変形の進行を防止する目的で橈骨月状骨間固定を追加する。

手術方法は橈骨月状骨窩および月状骨関節面を海綿骨が露出するまでリューエルで切除したのち月状骨を可及的に解剖学的位置に整復する。手根骨の尺側偏位，橈側回転を矯正するように留意する。腸骨を採取し，ブロック状に橈骨月状骨関節の高さを保持するような形で移植する。内固定として Kirschner wire や Herbert screw，ステープルを用いる[4)5)]（図 7）。術後は 6 週間の外固定を行う。

橈骨月状骨間固定術で最も問題となるのは可動域の減少である。しかし当科で行った 13 例の術後