Human carpal ligament recruitment and three-dimensional carpal motion

DOI:
10.1002/jor.1100090509

Document status and date:
Published: 01/01/1991

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Journal of Orthopaedic Research
9:693–704 Raven Press, Ltd., New York

Human Carpal Ligament Recruitment and Three-Dimensional Carpal Motion

H. H. C. M. Savelberg, J. G. M. Kooloos, *A. De Lange, †R. Huiskes, and J. M. G. Kauer

*Department of Anatomy and Embryology, and †Institute of Orthopaedics, University of Nijmegen, Nijmegen, and *T.N.O. Leather and Shoe Research Institute, Waalwijk, The Netherlands*

Summary: In five fresh human cadaver wrist joints six carpal ligaments and seven carpal bones were marked with small, radio-opaque pellets. Using a roentgenstereophotogrammetric measuring system, the ligamentous length changes and the kinematics of carpal bones were determined in different flexion and deviation positions of the hand. The data generated by this method differ significantly from lengthening data predicted by current concepts on carpal ligament functioning. The motions of carpal bones and the lengthening of the carpal ligaments were related to each other. It appeared that most carpal ligaments lengthen only during one half of a full movement cycle. Hence, ligaments seem to constrain either a dorsal- or a palmar-directed motion of the hand, or an ulnar- or a radial-directed motion of the hand. When the hand is in maximal radial deviation or maximal palmar flexion, none of the ligaments has a greater length than in the neutral situation. The tested parts of the lunatotriquetrum palmar ligament do not lengthen during any movement of the hand. Significant lengthening relative to the neutral situation was found for the radiocapitate palmar ligament (6.5% in maximal ulnar deviation and 11.7% in maximal dorsal flexion of the hand), and for the distal string of the radiolunate palmar ligament (6.4% in maximal ulnar deviation). It was confirmed that the carpals, apart from moving in the plane in which the hand motion takes place, also execute considerable out-of-plane motions during hand motions. The combination of these experimentally and simultaneously determined data on length change and on the movements of carpal bones are found to be necessary in order to give suitable explanations for the observed separate kinematical phenomena. **Key Words:** Carpal motions—Ligament length—Roentgenstereophotogrammetry.

To understand the carpal mechanism underlying the motions of the hand relative to the forearm, information on carpal kinematics and carpal ligament lengthening is required. Carpal kinematics have been studied before (2,10,13). Carpal ligament lengthening is a function of carpal displacement, the material characteristics of the ligaments, and the positions of the ligaments relative to the carpals. Insight into carpal ligament behavior and material characteristics will enable the deduction of forces, generated in the ligaments, by which knowledge on the carpal mechanism can be refined.

Most of the current concepts on carpal ligament length change (4,12,16) are derived from two-dimensional (2-D) radiographs. These concepts are

Received February 6, 1990; accepted January 9, 1991.
Address correspondence and reprint requests to Prof. Dr. J. M. G. Kauer, Department of Anatomy and Embryology, University of Nijmegen, P.O. Box 9101, 6500 HB Nijmegen, The Netherlands.

based on kinematical models of the wrist joint that assume 2-D movements of the carpals in the principal planes only (flexion, deviation), whereby fixed axes of rotation during flexion and deviation are assumed (4,5,11,12,17,18,22). In these studies, usually one fixed axis is assumed for the movement of the whole carpal joint for flexion and one for deviation of the hand. All carpal bones are thought to rotate around these axes when the hand is deviated or flexed. For example, during radial deviation of the hand relative to the forearm, the carpals of the distal row (trapezium, trapezoid, capitate, and hamate) are assumed to rotate around one rotation axis in the capitate head toward the radial side, whereas those of the proximal row (scaphoid, lunate, and triquetrum) are assumed to move ulnarly around the same axis. However, as shown experimentally (2,10,13), carpals also demonstrate considerable out-of-plane motions in planes perpendicular to the one in which the hand moves. Furthermore, these authors (2,10,13) do not find a fixed center of rotation. Hence, for a good comprehension of ligament behavior, it must be studied in three-dimensional (3-D) analysis.

The purpose of the present project was to update the present-day concepts, using precise measurement techniques for ligament lengthening behavior and 3-D carpal motion. These techniques are based on roentgenstereophotogrammetry, whereby markers in bones and ligaments are reconstructed from stereoroentgen images (3,10,14).

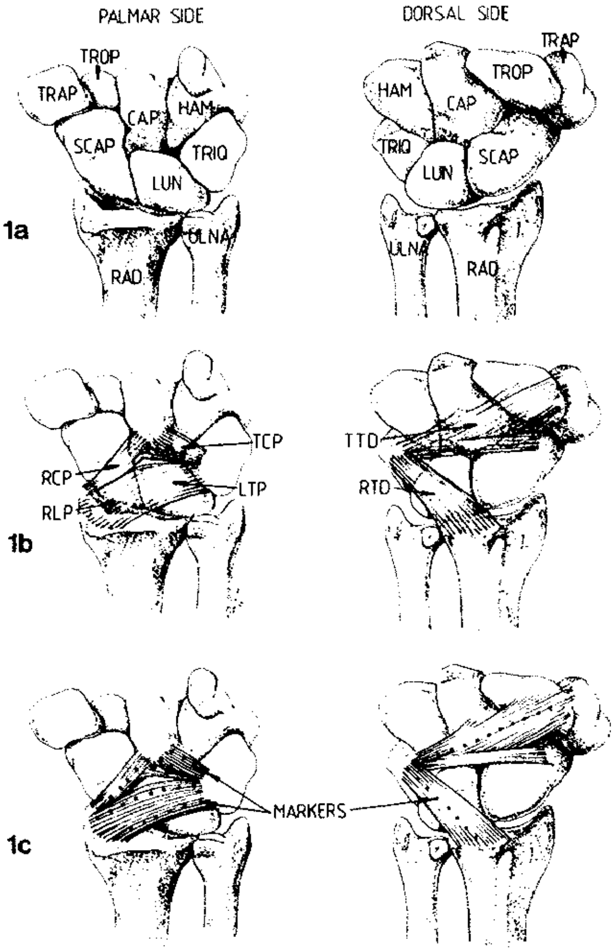


FIG. 1. Schematical view of the tested carpal system. **A:** The carpal bones from the palmar **(left)** and the dorsal side **(right)**. **B:** The tested carpal ligaments from the palmar **(left)** and the dorsal side **(right)**. **C:** The distribution of the radio-opaque markers over the carpal ligament system, left palmar and right dorsal sides. Wider ligament strips are provided with two strings of markers, both proximal and distal. RAD, radius; TRAP, trapezium; TROP, trapezoid; CAP, capitate; HAM, hamate; SCAP, scaphoid; LUN, lunate; TRIQ, triquetrum, RCP, radiocapitate palmar strip; RLP, radiolunate palmar strip; LTP, lunatotriquetrum palmar strip; TCP, triquetrocapitate palmar strip; RTD, radiotriquetrum dorsal strip; TTD, triquetrotrapezium dorsal strip.

METHODS AND MATERIALS

Nomenclature

In this study five fresh human cadaver wrist joints were used, and were kept frozen until time of use. This procedure did not seem to affect the mechanical properties of the ligaments (21). By means of radiographs, each specimen was examined for osseous abnormalities before the experiment.

The superficial ligamentous apparatus of the carpal joint can be characterized as a complex system of interwoven ligament fibers (Fig. 1B), as it is presented, for example, by Williams and Warwick (19), rather than as a system of well-defined ligaments, as some authors suggest (4,12,15). For practical purposes this study is limited to the superficial ligament complex. This system can be reached without inducing functional abnormalities in the carpus as a whole. For this study the complex was subdivided into strips of ligamentous tissue based on the patterns of insertion areas on the carpal bones. In each specimen six such strips were defined (Fig. 1B), four on the palmar and two on the dorsal side. As is customary in the literature (12,16), they were named by their origin and insertion sites, respectively. The following ligament strips were distinguished [Taleisnik's (16) nomenclature between brackets]: radiocapitate palmar (radioscaphocapitate), radiolunate palmar, lunatotriquetrum palmar, triquetrocapitate palmar (volar intercarpal), radio-

triquetrum dorsal (radiotriquetral fascicle of the dorsal radiocarpal ligament), and triquetrotrapezium dorsal (dorsal intercarpal). Because some of these strips were rather wide, differences in length changes between the outermost fibers (distal and proximal parts) can be expected. In these cases both these strip parts were considered.

Surgical Proceedings and Marking of Selected Elements

By a transversal skin incision just proximal to the wrist joint and a longitudinal incision crossing the first one, the joint was approached. The skin of the forearm was opened and the tendons of the mm. flexor carpi radialis and ulnaris, the mm. extensor carpi ulnaris and radialis longus and brevis, the m. extensor digitorum and mm. extensor pollicis longus and brevis, the mm. flexor digitorum superficialis and profundus, and m. abductor pollicis longus were isolated. The longitudinal lesion was extended in the distal direction. Subsequently, the flexor retinaculum was divided so that the tendons could be moved distally and the ligament system exposed. A similar action was undertaken at the dorsal side of the joint.

Four to six tantalum or stainless steel markers [diameter (Ø): 0.5, 0.8, or 1.0 mm] were introduced into each of the seven carpal bones and into the radius. To insert the markers, a special spring-actuated syringe was used (1). Very small incisions were made in each ligament fiber to create envelopes for tantalum pellets (Ø: 0.5 mm), which were to represent the ligament strips. After the markers were placed, these envelopes were covered by a small dot of tissue glue (Histoacryl, B. Brown AG, Melsungen, FRG) to prevent the markers from being squeezed out of the fibers. Because the dots of tissue-glue are rather small relative to the ligament dimensions, their effects on the ligamentous material characteristics are assumed to be negligible. Each strip was represented by at least three markers: one each on the origin and insertion sites, and the third between these two. In most cases a total of four or five tantalum pellets were introduced. Experiments by de Lange et al. (9) showed that this is a reliable and valid method. Care was taken that a string of markers was placed along the same fiber, close to the middle of the ligament. The wider ligament strips (radiolunate palmar, lunatetriquetrum palmar, and triquetrocapitate palmar) were provided with two strings of markers. In these cases the outermost fibers were chosen to represent the ligaments (Fig. 1C). Finally, the retinacula and the skin were closed by suturing.

Experimental Set-up and Data Processing

The specimen was positioned into a motion-guiding system (10). The radius was fixed, and the third metacarpal was connected to a movable carriage by a Steinmann pin, which guided the flexion and deviation movements of the hand. The tendons acting on the hand were loaded by 20N constant-force springs to simulate the assumed stabilizing activity of these muscles. The forearm was supinated. De Lange et al. (6,10) showed that no differences in carpal kinematics occur between pronated and supinated test specimens. Starting from an extreme position (e.g., maximal palmar flexion) the hand was moved in 4° steps to the other extreme (dorsal flexion in this example) and back to the starting position. A similar procedure was followed for motion in the frontal plane, resulting in radioulnar deviation. After each 4° step, a pair of stereoroentgenographs is made by two x-ray tubes. A more detailed description of the experimental set-up is given by de Lange et al. (10) and de Lange (6).

The roentgenstereophotogrammetric experiment resulted in about 80 pairs of stereoroentgenographs for a complete flexion cycle and 40 pairs for a deviation cycle. The markers, representing the carpal bones and ligaments on the roentgenographs, were digitized. Using stereophotogrammetric principles (14) the 3-D positions of the tantalum pellets were reconstructed for each carpal position. The sequential position data were used to determine the 3-D motion characteristics of each carpal, in terms of translation vectors and Euler rotations, or in terms of helical axes (6,7), and the lengths of the carpal ligaments as the sum of distances between subsequent ligament markers (9).

Calculation of the Kinematic Parameters and the Ligament Strains

The total length of a ligament string in a particular position j, L_j, is given by the sum of the lengths of subsequent marker intervals according to

$$L_j = \sum_{i=1}^{n} |x_{j,i} - x_{j,i-1}|$$

where $x_{j,i}$ = the position vector of the i-th marker of

a ligament string, measured with the hand in position j, L_j = the total length of the ligament string with the hand in position j, i = marker number ($1 \leq i \leq n$), and j = position number ($1 \leq j \leq m$).

Furthermore, the relative length change of a ligament string (e_j) is calculated as the length of that ligament string in position j relative to its reference length, which is defined as the length in the neutral position of the hand, when radius and third metacarpal are aligned. This neutral position is determined visually. The reference does not necessarily equal a functional zero-length, a situation in which the ligament force is zero.

The relative length is determined by

$$e_j = (L_j/L_o) * 100\%$$

where L_o = the total length of the ligament string with the hand in the neutral position.

The length changes of the ligament strings are presented as functions of the degree of flexion or deviation of the hand, which is represented by the capitate position (6,10).

Finite helical axes are calculated for the movements of the carpals from the neutral position to the four end positions: radial and ulnar deviation, and palmar and dorsal flexion. These helical axes describe the movement of a particular carpal bone relative to another carpal or to the radius, as a combination of rotation about and translation along the axis. Furthermore, to relate these data to the ligament length change information, finite helical axes for each movement are averaged over the five different experiments. This results in one average finite helical axis, the angular dispersion (X) of the five actual finite helical axes around the average finite helical axis, and the mean and standard deviation for the magnitude of rotation about and translation along the actual finite helical axes for each movement. The direction vector of the average finite helical axis is calculated according to a method minimizing the root mean square (r.m.s.) values of the sines of the angles between the average finite helical axis and the actual finite helical axes (6,7,20). The angular dispersion (X) is defined as the arcsine of the r.m.s. values.

Analysis of Bone–Ligament Interaction

The length of a ligament can be changed by two causes. Firstly, by displacement of the insertion sites of the ligament relative to each other, and secondly when the course of a ligament is changed by an intervening carpal bone. In the latter case, the ligament is forced to bend around a bone. The scaphoid could be such a bone; it demonstrates freedom of movement, and several ligaments cross this bone without attaching to it (radiocapitate and radiolunate palmar strips). The same can be said for the triquetrocapitate palmar ligament and the hamate.

To analyze these interactions for each ligament, 3-D graphs of spatial ligament courses, represented by the marker positions on the ligament as measured in ultimate hand positions, are produced. The positions of the markers in the neutral position and in an extreme hand position are presented. These plots represent the ligament string and show an image of the course of that ligament. The establishment of the changes of these courses and of the marker positions between the neutral and one of the extreme positions of the hand enables a discussion of bone–ligament interaction.

RESULTS

Ligament Length Changes

From the mean ligament length changes it appears that all the ligament strings are recruited during only one direction of a movement (Table 1). They lengthen either when the hand is deviated radially or when it is deviated ulnarly, and either when it is flexed palmarly or when it is flexed dorsally. It can be observed that some elements (proximal and distal lunatetriquetrum palmar) do not show any length change at all, in any of the motions.

In flexion, the maximal length changes for radiocapitate palmar, proximal and distal radiolunate palmar, and radiotriquetrum dorsal strings are significantly higher ($p < 0.0625$, Wilcoxon's test for paired comparison) than in deviation. The other selected elements of the carpal ligamentous system do not show significant differences in maximal length changes between flexion and deviation movements of the hand.

In maximal radial deviation no strings are significantly stretched relative to the neutral situation. The triquetrocapitate palmar strings even shorten significantly ($p < 0.01$, t test) in this situation. In maximal ulnar deviation of the hand, significant ($p < 0.05$) elongations are observed in the radiocapitate palmar, distal radiolunate palmar, proximal tri-

TABLE 1. *Relative length changes of the wrist joint ligaments*

	Deviation				Flexion			
	% Mean ulnar (±SE)	n	% Mean radial (±SE)	n	% Mean palmar (±SE)	n	% Mean dorsal (±SE)	n
RCP	106.5 (2.3)[a]	5	101.1 (2.1)	5	89.0 (6.4)	5	111.7 (4.8)[a]	5
RLPp	102.0 (3.1)	5	100.0 (1.0)	5	89.5 (8.7)	5	103.3 (2.0)	5
RLPd	106.4 (3.4)[a]	5	99.6 (1.0)	5	92.2 (3.4)[a]	5	107.6 (5.3)	5
LTPp	99.2 (1.6)	4	100.0 (1.1)	4	99.5 (2.1)	4	100.9 (0.6)	4
LTPd	100.5 (0.6)	4	98.8 (0.9)	4	98.7 (1.5)	4	100.7 (0.4)	4
TCPp	105.4 (3.1)	2	97.0 (0.6)[a]	3	101.3 (2.5)	3	103.9 (0.9)[a]	2
TCPd	96.5 (0.9)[a]	2	97.4 (0.3)[a]	3	100.6 (2.3)	3	102.6 (3.4)	3
TCP	88.8 (1.8)[a]	2	96.8 (1.1)[a]	2	94.0 (1.4)[a]	2	101.8 (1.1)	2
RTD	95.6 (2.9)	5	98.8 (0.9)	5	105.7 (5.0)	5	95.2 (2.3)[a]	5
TTD	106.4 (4.3)	3	99.2 (0.8)	3	101.9 (6.1)	3	98.7 (2.0)	3

[a] Length changes that differ significantly from 100% (which equals the neutral length), denoting $p = 0.05$ (*t* test).

quetrocapitate palmar, and triquetrotrapezium dorsal strings.

In maximal dorsal flexion of the hand, the radiocapitate palmar, proximal and distal radiolunate palmar, and proximal triquetrocapitate palmar strings are recruited ($p < 0.1$). The radiotriquetrum dorsal string shortens significantly ($p < 0.05$) in this situation. In maximal palmar flexion, no lengthening of ligamentous strings can be noticed. The radiocapitate palmar, distal radiolunate palmar, and triquetrocapitate palmar strings are significantly ($p < 0.05$) shorter in maximal palmar flexion.

The length changes of the strings between the neutral and extreme positions occur gradually in general (Fig. 2). Only in the less stretched situations some wrinkles appear on the curves. In most of the strings, continuous length changes occur from a certain point in the hand position to the extreme of the motion. Some reach a maximum or minimum length before the hand position has reached its extreme value. This phenomenon occurs only in deviation movements for the radiotriquetrum dorsal, and proximal and distal triquetrocapitate palmar strings.

For the wider ligament strips that are represented by two strings of markers (a proximal and a distal one), we can observe in several situations significant differences in the length changes of both these strings (Table 1). In ulnar deviation the distal radiolunate palmar string lengthens, whereas the proximal radiolunate palmar string does not change in length; the distal triquetrocapitate palmar string becomes shorter, whereas the proximal triquetrocapitate palmar string retains its neutral length. In palmar flexion the same trend is shown for both the radiolunate palmar strings; in dorsal flexion a lengthening of the proximal triquetrocapitate palmar string was noticed, whereas the distal string did not change in length.

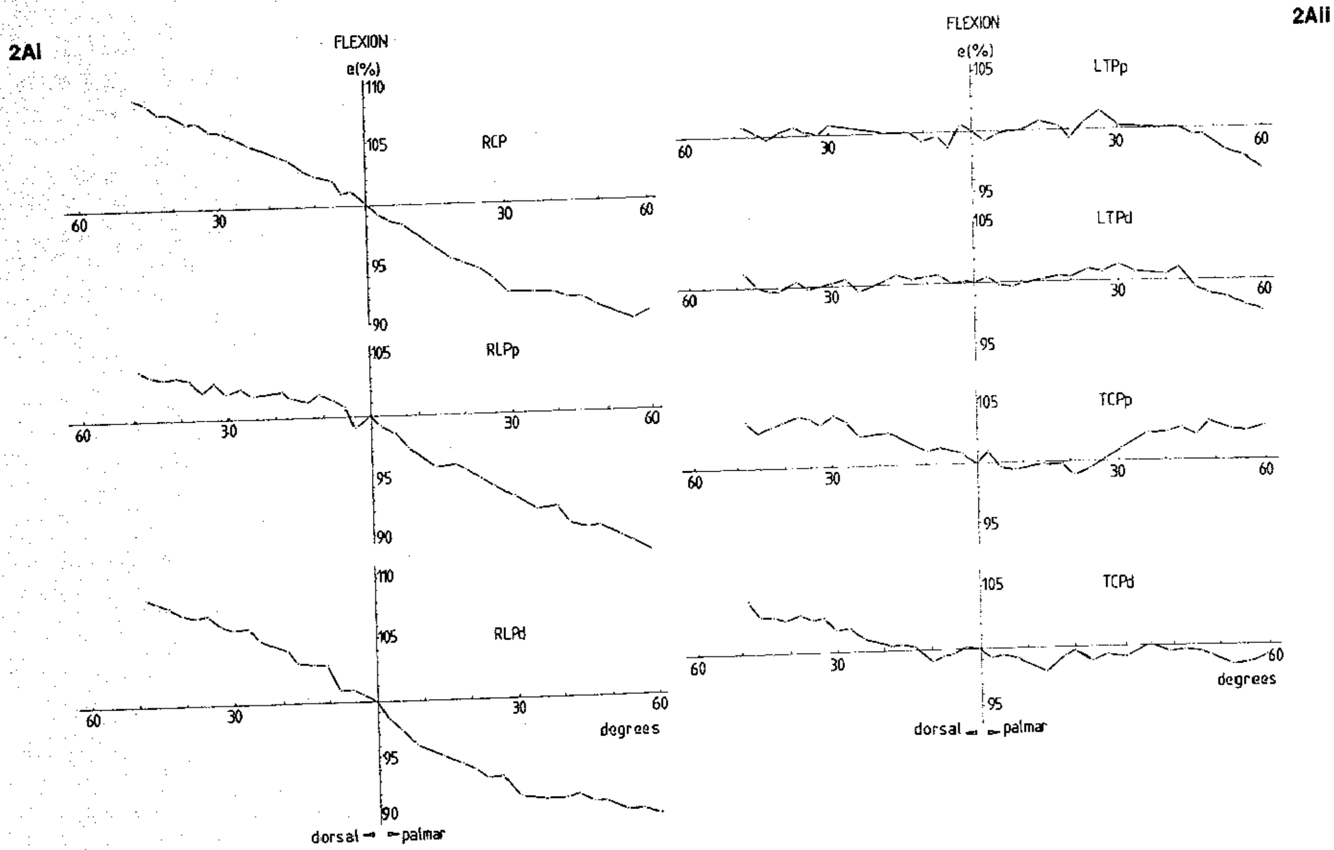
Carpal Motions

The kinematic parameters for the carpal motions show that considerable out-of-plane movements of the carpals occur during flexion and (in particular) deviation of the hand (Table 2). In flexion movements of the hand, the carpal bones usually show only small tendencies to move in other than the flexion plane. But in palmar flexion, out-of-plane motions (ulnar deviation and supination) can be noticed for the movement of the lunate relative to the radius. The out-of-plane movements of the other carpals relative to the radius are only slight. On the other hand, in both ulnar and radial deviation, the movements of the lunate and the scaphoid relative to the radius have a notable out-of-plane component. Here the out-of-plane component, flexion in these cases, is even higher than the planar component. Furthermore, in radial deviation the other (triquetrum, trapezium, trapezoid, capitate, and hamate) carpals, and in ulnar deviation the triquetrum and the hamate, show less pronounced out-of-plane motions, similar to those in palmar flexion.

The excursions of the carpals, i.e., the total rotations about and, to a lesser extent, the translations along the finite helical axis, and more extensive for flexion than for deviation.

Bone–Ligament Interaction

Now that the ligament recruitment patterns (Fig. 2) and the motions of the carpal bones (Table 2) are



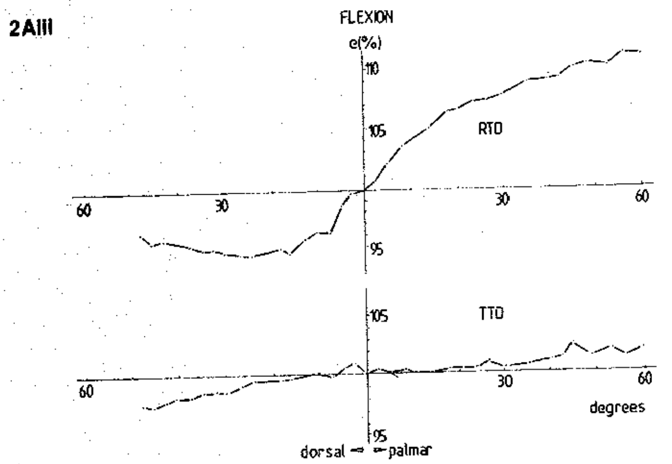
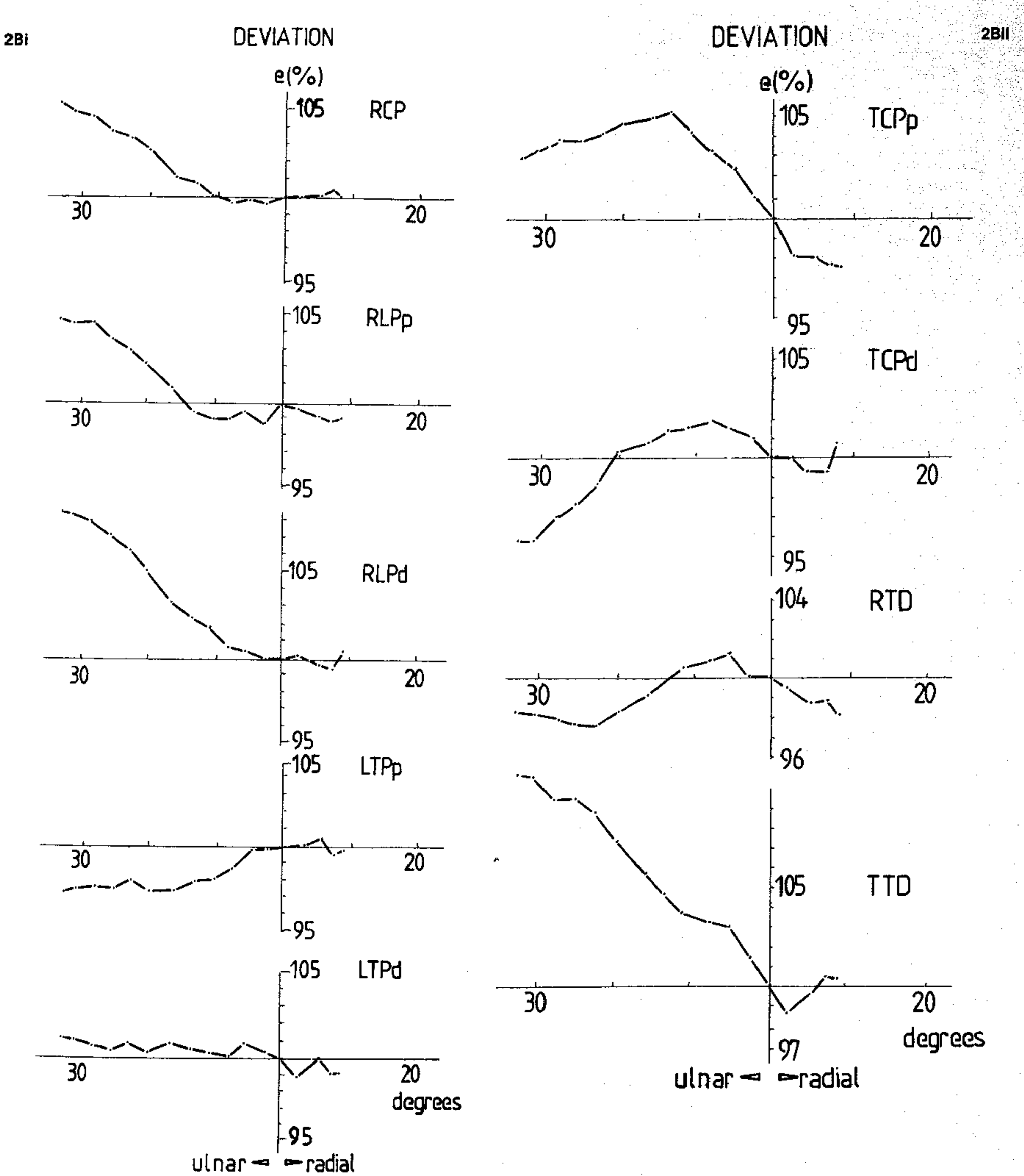


FIG. 2. A: The relative length changes as functions of hand flexion of nine marked ligament fibers in six ligaments of a representative specimen (abbreviations as in Fig. 1). **B:** The relative length changes as functions of hand deviation of nine marked ligament fibers in six ligaments of a representative specimen.

established, we will consider the way the carpal motions influence the ligament length.

Flexion

When the hand is flexed palmarly, the insertion sites of ligaments that run on the palmar side of the hand between the radius and the carpals approach each other and consequently almost all these ligaments become shorter, except the triquetrocapitate palmar and lunatotriquetrum palmar ligaments that retain their lengths. This is illustrated in Fig. 3B for the radiocapitate palmar ligament. In this case there are no effects of an intervening bone measured. The same occurs for the ligaments on the dorsal side of the hand during dorsal flexion of the hand. During dorsal flexion the ligaments on the palmar side all elongate because the distances between their inser-



tion sites increase, except the lunatotriquetrum palmar ligament which does not change. The radiocapitate palmar ligament elongates even more due to an intervening bone, the scaphoid. This is illustrated in Fig. 3C. This ligament not only elongates because of the separation of the radius and the capitate [Fig. 3C and D; the distal marker has mainly moved dorsally (5→5′)], but also because the ligament is

TABLE 2.

	Average finite helical axis unit–vector components			x (degree)	Rotation (degree ± SEM)	Translation (mm ± SEM)
	x	y	z			
Neutral to ulnar deviation						
Lunate to radius	−0.45	−0.89	0.10	10.29	34.2 ± 4.2	−2.1 ± 1.1
Capitate to radius	−0.99	0.01	0.11	10.51	43.6 ± 7.2	−5.6 ± 1.5
Scaphoid to radius	−0.44	−0.89	0.13	8.53	35.3 ± 7.3	−2.0 ± 1.2
Trapezium to radius	−0.99	0.09	0.07	11.91	44.6 ± 9.1	−6.7 ± 2.1
Trapezoid to radius	−1.00	−0.04	0.05	12.61	40.9 ± 7.2	−6.1 ± 1.4
Triquetrum to radius	−0.71	−0.70	0.05	28.50	38.1 ± 10.1	−1.3 ± 1.3
Hamate to radius	−0.95	−0.27	0.18	16.50	39.8 ± 10.8	−3.0 ± 2.1
Triquetrum to lunate	−0.60	0.80	−0.07	25.23	18.4 ± 19.8	−0.2 ± 0.4
Capitate to triquetrum	−0.50	0.78	0.38	27.42	29.5 ± 8.3	−0.1 ± 0.8
Trapezium to triquetrum	−0.43	0.84	0.32	29.31	30.9 ± 11.7	−0.7 ± 0.5
Neutral to radial deviation						
Lunate to radius	0.25	0.96	−0.01	12.10	8.2 ± 2.8	−0.1 ± 0.1
Capitate to radius	0.94	0.12	−0.30	7.78	14.6 ± 2.8	−1.0 ± 0.5
Scaphoid to radius	0.18	0.98	0.01	15.43	9.6 ± 2.8	−0.1 ± 0.2
Trapezium to radius	0.92	−0.09	−0.39	6.21	16.2 ± 2.9	−1.8 ± 0.8
Trapezoid to radius	0.93	−0.04	−0.36	8.01	14.6 ± 2.9	−1.5 ± 0.6
Triquetrum to radius	0.95	0.30	−0.07	40.37	8.8 ± 2.6	−0.2 ± 0.6
Hamate to radius	0.94	0.20	−0.27	11.15	15.2 ± 2.8	−1.0 ± 0.5
Triquetrum to lunate	0.74	−0.62	0.28	42.62	7.6 ± 3.0	−0.4 ± 0.3
Capitate to triquetrum	0.90	−0.38	−0.21	21.30	11.8 ± 5.6	0.1 ± 0.6
Trapezium to triquetrum	0.79	−0.59	−0.20	17.58	14.4 ± 6.5	−0.1 ± 0.7
Neutral to palmar flexion						
Lunate to radius	0.78	−0.45	0.44	9.64	27.1 ± 8.2	0.7 ± 1.5
Capitate to radius	0.95	−0.22	0.21	10.86	69.9 ± 14.5	−0.2 ± 1.0
Scaphoid to radius	0.93	−0.26	0.28	7.96	43.2 ± 7.9	−0.8 ± 1.1
Trapezium to radius	0.94	−0.18	0.28	15.37	61.1 ± 9.7	−0.9 ± 1.7
Trapezoid to radius	0.93	−0.16	0.35	24.42	83.1 ± 34.5	1.6 ± 3.5
Triquetrum to radius	0.92	−0.33	0.20	9.35	35.4 ± 11.3	0.8 ± 1.3
Hamate to radius	0.93	−0.23	0.27	9.75	68.9 ± 13.7	0.2 ± 1.2
Triquetrum to lunate	0.84	−0.45	−0.30	10.27	13.1 ± 8.3	−0.04 ± 0.5
Capitate to triquetrum	0.98	0.05	0.20	16.37	36.0 ± 7.4	0.4 ± 0.8
Trapezium to triquetrum	0.88	0.40	0.24	26.39	30.2 ± 6.5	0.7 ± 1.2
Neutral to dorsal flexion						
Lunate to radius	−0.99	0.04	−0.14	26.58	36.4 ± 11.5	−1.3 ± 0.1
Capitate to radius	−1.00	0.06	0.04	27.67	62.4 ± 6.6	−1.4 ± 0.8
Scaphoid to radius	−0.99	0.09	−0.07	27.01	57.1 ± 9.9	−1.5 ± 0.3
Trapezium to radius	−1.00	0.08	−0.04	27.35	59.4 ± 6.1	−2.0 ± 1.3
Trapezoid to radius	−0.99	0.09	−0.07	26.96	62.5 ± 6.9	−1.8 ± 0.9
Triquetrum to radius	−0.99	0.14	−0.07	28.07	51.2 ± 27.6	−1.0 ± 1.4
Hamate to radius	−0.99	0.09	−0.10	30.06	61.7 ± 6.9	−1.5 ± 0.7
Triquetrum to lunate	−0.98	−0.16	0.10	36.74	10.3 ± 2.6	−0.1 ± 0.1
Capitate to triquetrum	−0.85	0.35	−0.39	32.02	23.5 ± 7.4	0.3 ± 0.5
Trapezium to triquetrum	−0.84	0.32	−0.45	35.63	20.8 ± 7.9	0.1 ± 0.1

The column denoted by x gives the angular dispersion as a measure of the deviation of the actual finite helical axes from the average finite helical axis. For deviation movements of the hand, positive unit-vector components correspond with radial deviation, palmar flexion, and pronation for x, y, and z, respectively. For flexion movements of the hand, positive components of x, y, and z correspond to palmar flexion, radial deviation, and supination, respectively.

pushed away by the scaphoid (Fig. 3C and D; the distal displacement of the middle marker (3→3′)]. The dorsal ligaments elongate in palmar flexion because the distances between their insertion sites increase. The lunatotriquetrum palmar strip is not affected by the flexion of the hand because the lunate and triquetrum, to which it inserts, move more or less similarly.

Deviation

When the hand is moved radially, the lengths of the ligaments are not changed. This is due to the movements of the carpals, which are very small in this case; hence, the insertion sites are hardly displaced. During ulnar deviation the shortening of the radiotriquetrum dorsal ligament is caused by the de-

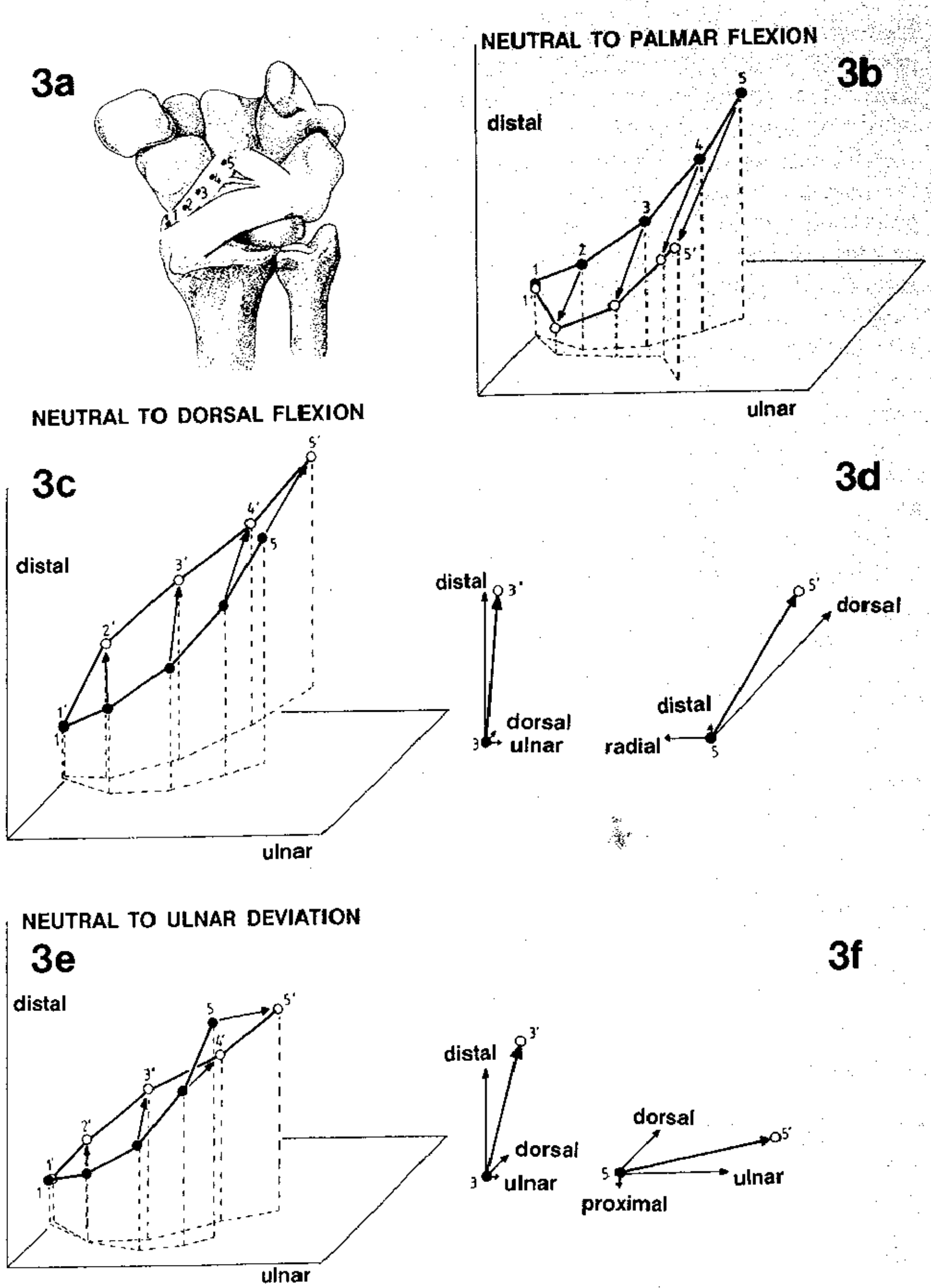


FIG. 3. The 3-D kinematics of the RCP ligament. The positions of the ligament markers and the 3-D course of the RCP ligament are given. **A:** The position of the RCP ligament relative to the other carpal structures. **B:** The position of the markers and the ligament in the neutral position (●) and in the palmarly flexed position (○). The solid lines between the markers in a hand position show the interpolated course of the ligament. The arrows between two positions of a marker in different positions of the hand represent the motions of the markers due to palmar flexion of the hand. The markers are numbered from proximal to distal in increasing order. In the neutral position the markers are primeless, whereas in palmar flexion they are primed. **C:** Similar to Fig. 3B but now for dorsal flexion instead of palmar flexion of the hand. **D:** The displacement of the middle marker (3→3′) and the most distal (5→5′), showing mainly distal displacement denoting the increased curvation of the ligament, and mainly dorsal displacement, representative for the increased distance between origin and insertion. **E:** Similar to Fig. 3B but now for ulnar deviation instead of palmar flexion of the hand. **F:** Similar to Fig. 3D but now for ulnar deviation instead of dorsal flexion of the hand. Again showing increased curvation and distance between origin and insertion.

crease of the distance between the respective insertion sites. The shortening of the triquetrocapitate palmar ligament can also be attributed to the approach of the insertion sites. The movements of the lunate and the triquetrum in ulnar deviation are about equal, so there is no change in the distance between the insertion sites of the lunatotriquetrum palmar ligament and in the length of this ligament. The insertion sites of the triquetrotrapezium dorsal ligament are separated during ulnar deviation; hence the ligament elongates.

The radiocapitate palmar ligament elongates because of the displacement of the insertion sites of the ligament and because of an intervening bone, the scaphoid, which displaces the ligament distally. This is illustrated in Fig. 3E and F for the radiocapitate palmar ligament. The arrow, showing the displacement of the most distal marker (5→5′), denotes dorsal as well as ulnar displacement of the insertion on the capitate. This means that the distance between origin and insertion is increased by the movement of the capitate relative to the radius.

Furthermore, the middle part of the ligament has been lifted distally [Fig. 3E and F; arrow associated with the middle marker (3→3′)], which indicates the intervening effect of the scaphoid.

A hitherto unknown ligament–bone interaction in the carpus is shown in relation to the radiolunate palmar ligament. Although both the distal and the proximal strings of the radiolunate palmar ligament insert to the same bones (radius and lunate), their lengths change unequally during ulnar deviation. The distal radiolunate palmar ligament is elongated because the distance between the insertion sites increases, whereas, the proximal radiolunate palmar ligament shortens due to the approach of its insertion sites to each other. This is illustrated in Fig. 4B and D. The out-of-plane motion of the lunate (dorsal flexion, Table 2) displaces the insertion site of the proximal string distally and somewhat palmarly (Fig. 4B), and as a consequence the distance between origin and insertion decreases. However, the insertion site of the distal string of the lunate is displaced mainly distally (Fig. 4D), due to the same out-of-plane motion, causing an increase of the distance between origin and insertion.

DISCUSSION AND CONCLUSIONS

Assessment of the Measuring Method

For the measurement of ligament length changes, de Lange et al. (9) showed that the method used in this experiment is preferred over determination of ligament length by measuring the origin–insertion interval. The advantages of the present method are the relative noninvasiveness of placing small markers between ligament fibers and the accommodation to fiber curvature without impairing ligament or carpal bone motions. To determine errors due to inaccuracies in data processing, six subsequent pairs of roentgenographs were processed five times. The standard deviations of the string lengths were chosen as a measure for the error. They ranged from 0.005 to 0.055 mm. The standard deviations for the

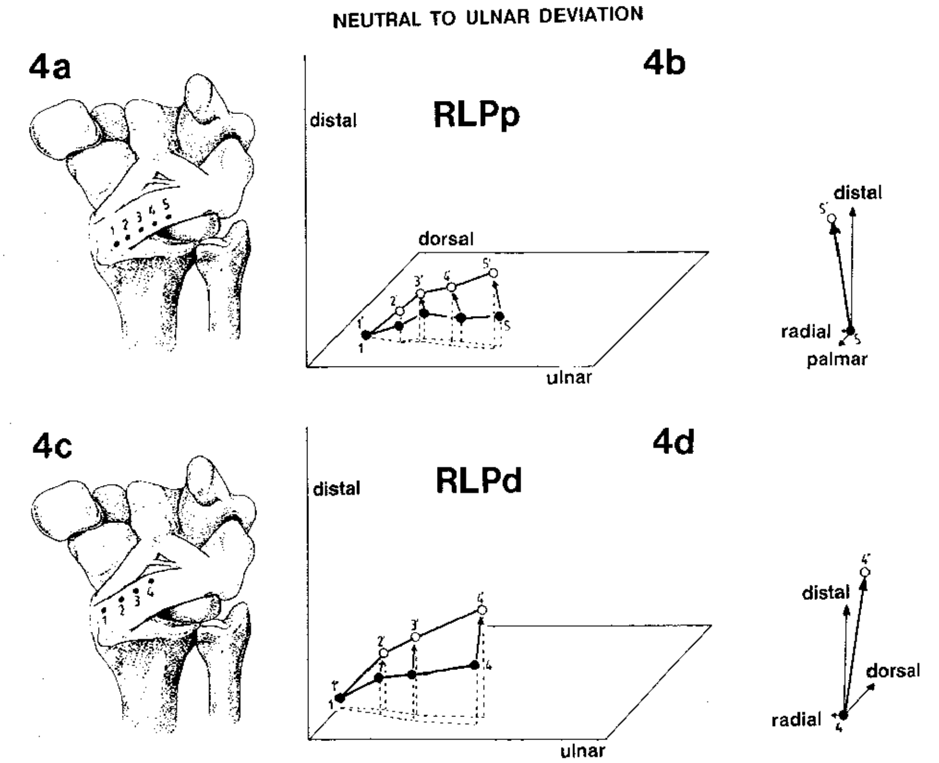


FIG. 4. The 3-D kinematics of the RLP ligament. The positions of the ligament markers and the 3-D course of the RLP ligament are given. **A:** The position of the RLPp ligament relative to the other carpal structures. **B:** The position of the markers and the RLPp ligament in the neutral position (●) and in the ulnarly deviated position (○). The solid lines between the markers in a hand position show the interpolated course of the ligament. The arrows between two positions of a marker in different positions of the hand represent the motions of the markers due to ulnar deviation of the hand. The markers are numbered from proximal to distal in increasing order. In the neutral position the markers are primeless; in ulnar deviation the markers are primed. The displacement of the most distal (5→5′) is considered more in detail. Its displacement vector is resolved in components along the main orientation axes, showing mainly palmar and distal displacement. This results in an approach of the insertion areas to each other. **C:** The position of the RLPd ligament relative to the other carpal structures. **D:** Similar to Fig. 4B but now for the RLPd ligament in the neutral position and in ulnar deviation of the hand. The resolved vector for the displacement of the most distal marker (4→4′) shows mainly dorsal and distal displacement. This results in an increase of the distance between origin and insertion.

relative string lengths ranged between 0.037 and 0.158%.

A similar procedure for the determination of the accuracy of the kinematical parameters was carried out by de Lange et al. (6,8,10). They registered 2.97° for the standard deviation of the direction of the finite helical axis, 0.23° for the standard deviation of the rotation about the finite helical axis, and 0.025 mm for the standard deviation of the translation along the finite helical axis. These errors are small enough not to interfere with our conclusions.

Carpal Kinematics and Ligament Length Referred to Other Studies

The present results on carpal movements are in good agreement with earlier studies (2,10,13). Notably, considerable out-of-plane motions of the proximal carpals) scaphoid, lunate, and triquetrum) are observed in ulnar and radial deviation and, to a somewhat lesser degree, in palmar flexion. Hence, the carpal motions can hardly be described as planar ones.

Discussion of ligament length changes in the literature (4,12,16) were hitherto based on theoretical concepts of carpal kinematics, assuming planar carpal movements in the plane of hand motion around a fixed center of rotation. For deviation, Mayfield et al. (12) thought the strips, which are called radiolunate palmar, lunatetriquetrum palmar, and triquetrocapitate palmar in the present study, would stabilize the movement of the hand to the radial side, whereas the opposite movement, ulnar deviation, was to be constrained by the radiocapitate palmar strip. Because only strained ligaments can stabilize a movement, this means that during those movements these supposed stabilizing ligaments should be strained. Bonjean et al. (4) suggested a similar straining pattern for carpal ligaments during deviation movements of the hand. Although Taleisnik (16) expected out-of-plane movements of some carpal bones in radial and ulnar deviation, he came to the conclusion that in radial deviation the radiolunate palmar and triquetrocapitate palmar strips will be strained. Our studies show that in maximal radial deviation none of the selected ligaments are strained relative to the neutral situation (Table 1). In maximal ulnar deviation, on the other hand we showed that not only is the radiocapitate palmar string strained, as was predicted by Mayfield et al. (12) and Bonjean et al. (4), or the radiolunate palmar and triquetrocapitate palmar strings that Taleisnik (16) considered to be lengthened, but that all three strings—radiocapitate palmar, radiolunate palmar, and the proximal triquetrocapitate palmar string—are strained (Table 1).

For flexion of the hand, dorsal as well as palmar, no such striking differences between speculations in the literature and the results of our experiments are evident. This is caused by the fact that in flexion smaller out-of-plane motions of the carpals occur (hence, the motions are almost planar), and by the fact that the ligamentous structures run almost perpendicular to the plane of movement. Hence, the ligament recruitment patterns are more trivial in this case, and less subtle.

Interaction of Ligaments and Carpals

In this study, ligament lengths and carpal positions have been determined simultaneously in a number of flexion and deviation positions. Subsequently, the ligament length changes and carpal motions for the motion steps between the positions of the hand have been calculated. It has been clarified how ligaments change in length with the changing positions of carpal bones: either insertion areas are displaced relative to each other, or the ligament course is influenced. It is shown that insight into the out-of-plane motion of the lunate is necessary to understand the behavior of the radiolunate palmar ligament. It has been explained why the distal string elongates, while at the same time the proximal one becomes shorter. The effect of the intervening scaphoid on the radiocapitate palmar ligament can only be understood when the 3-D motion of the carpal bones and the 3-D courses of the ligaments are considered.

Acknowledgment: We gratefully acknowledge the cooperation in parts of the experimental procedure by Dr. A. Lemmens, Institute of Radiodiagnostics, University of Nijmegen, Nijmegen, The Netherlands.

REFERENCES

1. Aronson AS, Holst L, Selvik G: An instrument for insertion of radio-opaque bone markers. *Radiology* 113:733–734, 1974
2. Berger RA, Crowninshield RD, Flatt AE: The three-dimensional rotational behaviors of the carpal bones. *Clin Orthop Rel Res* 167:303–310, 1982
3. Blankevoort L, Huiskes R, Lange A de: The envelope of passive knee joint motion. *J Biomech* 21:705–720, 1988

4. Bonjean P, Honton JL, Linarte R, Vignes J: Anatomical bases for the dynamic exploration of the wrist. *Anat Clin* 3:73–85, 181
5. Fisk GR: The wrist. *J Bone Joint Surg* 66-B:396–407, 1984
6. Lange A de: A kinematical study of the human wrist joint. [Doctoral dissertation]. Nijmegen, The Netherlands: University of Nijmegen, 1987
7. Lange A de, Huiskes R, Kauer JMG: Effects of data smoothing on the reconstruction of helical axis parameters in human joint kinematics. *J Biomech Eng* 112:107–113, 1990
8. Lange A de, Huiskes R, & Kauer JMG: Measurement errors in roentgenstereophotogrammetric joint-motion analysis. *J Biomech* 23:259–269, 1990
9. Lange A de, Huiskes R, Kauer JMG: Wrist-joint ligament length changes in flexion and deviation of the hand: an experimental study. *J Orthop Res* 8:722–730, 1990
10. Lange A de, Kauer JMG, Huiskes R: The kinematical behavior of the human wrist joint: a roentgenstereophotogrammetric analysis. *J Orthop Res* 3:56–64, 1985
11. Linscheid RL: Kinematic considerations of the wrist. *Clin Orthop Rel Res* 202:27–39, 1986
12. Mayfield JK, Johnson RP, Kilcoyne RF: The ligaments of the human wrist and their functional significance. *Anat Rec* 186:417–428, 1976
13. Ruby LK, Cooney WP, An KN, Linscheid RL, Chao EYS: Relative motion of selected carpal bones: a kinematic analysis of the normal wrist. *J Hand Surg* 13A:1–10, 1988
14. Selvik G: A roentgen stereophotogrammetric method for the study of the kinematics of the skeletal system. [Doctoral dissertation]. Lund, Sweden: University of Lund, 1974. Reprinted in *Acta Orthop Scand* 60(suppl 232):1–51, 1989
15. Taleisnik J: The ligaments of the wrist. *J Hand Surg* 1:110–118, 1976
16. Taleisnik J: *The wrist*. New York: Churchill Livingston, 1985
17. Volz RG, Lieb M, Benjamin J: Biomechanics of the wrist. *Clin Orthop Rel Res* 149:112–117, 1980
18. Weber ER: Concepts governing the rotational shift of the intercalcated segment of the carpus. *Orthop Clin North Am* 15:193–207, 1984
19. Williams R, Warwick PL: *Gray's anatomy*. Edinburgh, Scotland: Longman, 1973, pp 435–436
20. Woltring HJ: Model and measurement error influences in data processing. In: Berne N, Capozzo A, eds. Biomechanics of human movements-applications in rehabilitation, sports and ergonomics. Worthington: Bertec Corp., 1990: 203–237.
21. Woo SL-Y, Orlando CA, Camo JF, Akeson WK: Effect of postmortem storage by freezing on ligament tensile behavior. *J Biomech* 19:399–404, 1986
22. Youm Y, Flatt AE: Kinematics of the wrist. *Clin Orthop Rel Res* 149:21–32, 1980