Wrist-joint ligament length changes in flexion and deviation of the hand. An experimental study

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Wrist-Joint Ligament Length Changes in Flexion and Deviation of the Hand: An Experimental Study

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Summary: A method to study ligament-length patterns in situ with roentgenstereophotogrammetry, using strings of glued tantalum markers, was developed. The method was tested against a bone-to-bone marking method in five carpal ligaments in three specimens, whereby the hand was moved through dorsopalmar flexion and radioulnar deviation. The "glued-string" marking method was found to be superior to the bone-to-bone marking method. The length patterns obtained were found to be reproducible in the specimens and different from earlier expectations presented in the literature. The radiocapitate ligament seems to limit the displacements of the capitate in both radial and ulnar deviation, and dorsal flexion. The radiolunate ligament has the same effect for the lunate. Both the dorsal radiotriquetrum and the palmar triquetrocapitate ligaments seem to play a stabilizing role in the neutral position of the hand, whereas the radiotriquetrum ligament also has a function in palmar flexion and the triquetrocapitate ligament functions in dorsal flexion, ultimately resisting these excursions. These findings require confirmation in more extensive experiments, whereby the relationship between ligament length patterns and carpal motion axes is investigated. **Key Words:** Wrist joint—Human ligaments—Human joint kinematics—Stereophotogrammetry.

The human carpus consists of seven carpal bones and enables the hand to perform relatively large motions. The passive stability is ensured by capsule, ligaments, and the geometry of the carpal bones. In the clinical literature, carpal instabilities are usually related to lesions of the ligamentous structures (11,18). Based on anatomical dissection and conventional roentgenography, functions of various wrist ligaments in relation to carpal motions were qualitatively described (1,5,6,12,19). Mayfield et al. (12) reported strains at failure for various wrist ligaments. Logan et al. (10) described the rate-dependent viscoelastic behavior of the scapholunate interosseous ligament.

We studied a method to evaluate in-vitro and in-situ the relative length changes of various ligaments during flexion and deviation of the hand. The methods reported in the literature for studying ligament function in general include bone-to-bone ligament marking with tantalum pellets (3,4), photographic techniques with landmarks on the ligaments (16), direct measurements of strains using mercury strain gauges (14), and direct measurement of ligament forces using buckle transducers (9). In the present study, tantalum pellets and a roentgenstereophotogrammetric system was used to quantitate the carpal bone motions and the relative length changes in ligaments. Results describing the individual carpal

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bone motions were presented earlier (8). This article reports on the accuracy and applicability of a method developed to measure the relative strains in the ligaments of the wrist during hand motions. The results of a pilot study relative to five ligaments in three specimens are presented.

MATERIALS AND METHODS

Three fresh human wrist joints were obtained from autopsy. They were kept frozen until the time of use. Two were a bilateral pair from a 42-year-old man (specimens 4 and 5), one was a left hand from a 68-year-old man (specimen 6). The specimens were radiographed and examined for abnormalities. During preparation and experimentation, the specimens were at room temperature and were kept moist with Ringers' solution.

Skin incisions were made proximal to the wrist joint to isolate the tendons of the extensor digitorum, extensor carpi ulnaris, extensor carpi radialis longus and brevis, extensor pollicis longus and brevis, abductor pollicis longus, flexor digitorum superficialis and profundus, and flexor carpi ulnaris and radialis. These muscles were transsected in their tendinous regions. Four to six tantalum pellets (0.5–1.0-mm diameter) were then inserted in the seven carpal bones, in the radius and in the ulna, using a special spring-actuated syringe. The pisiform was excluded from the experiments. After this procedure, the retinacula at the palmar and dorsal sides of the wrist joint were divided in the longitudinal direction and the tendons of the muscles were temporarily moved laterally to reach the ligament system. The ligaments were approximately parallel fibered. However, in particular on the palmar side, identification of separate ligamentous bands was sometimes difficult. A selection of five ligaments was made. This limitation was merely related to problems in the data acquisition: Identification of the roentgen images would be difficult when more ligaments were to be represented by landmarks. The five ligaments chosen were the radiocapitate, radiolunate, lunatotriquetrum, and the triquetrocapitate, all on the palmar side, and the radiotriquetrum ligament on the dorsal side (Fig. 1). The palmar ligaments were previously described by Taleisnik (17,19).

Using 0.5-mm tantalum pellets, two different methods were applied to represent the ligament fibers. The first method accounted for the actual courses of the fibers by gluing tantalum pellets

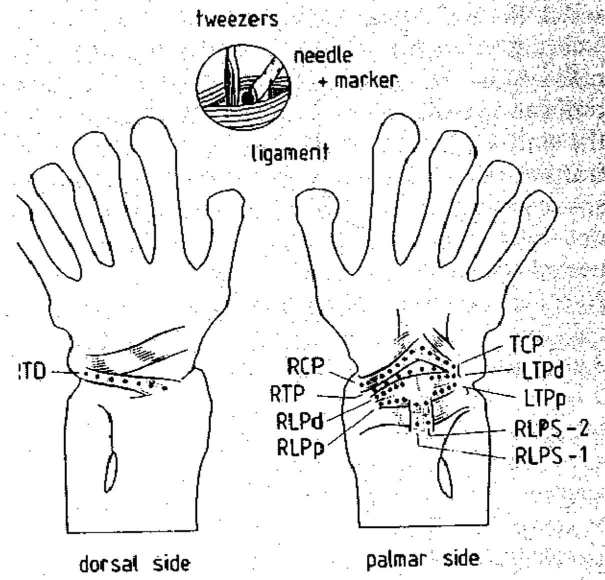

FIG. 1. Schematic illustration of the tantalum pellet positions relative to the ligament system in the wrist joint in dorsal (left) and palmar (right) views. In the method for marking ligament fibers, at intervals a tiny incision along the fiber is made and kept open, until a tantalum pellet provided with glue is embedded (inset). Abbreviations: palmar side—RCP, radiocapitate ligament; RLPp, radiolunate ligament, proximal part; RLPd, radiolunate ligament, distal part; LTPp, lunatotriquetrum ligament, proximal part; LTPd, lunatotriquetrum ligament, distal part; TCP, triquetrocapitate ligament; dorsal side—RTD, radiotriquetrum ligament. The indicated ligaments RTP, RLPS-1, and RLPS-2 are not considered here.

along the fiber bundles over the ligament length. The course of a fiber bundle between the insertion areas was identified using a microscope with a magnification factor of 40. Just next to the fiber bundle under investigation, at intervals of 3 mm, a tiny incision was carefully made and kept open by a pair of tweezers, and a tantalum pellet provided with glue (Histoacryl, B. Brown AG, Melsungen, FRG) was embedded (Fig. 1).

With the second method, the distances between origin and insertion of the ligaments were measured only, using one pellet on either side.

Because of their width, two fiber bundles instead of one were marked in the radiolunate and the lunatotriquetrum ligaments (Fig. 1). In these ligaments, the fibers lying centrally and superficially in the outer one-third of the ligament width were chosen, whereas in other ligaments the most central fiber bundle in the superficial layer was represented (Fig. 1).

After marking the ligaments, the retinacula and the skin were closed by suturing. Each of the upper-extremity specimens was positioned into a fixture in which the radius was fixed (Fig. 2). The specimen was aligned with respect to the laboratory coordinate system. Through this alignment procedure, coordinate systems were introduced in the radius, in the ulna and in the carpal bones, in such a way that translations and rotations more or less corresponded with the anatomical terminology. The tendons of the muscles crossing the wrist were connected to stainless-steel wires, each loaded by a 20-N constant force spring. These loads were meant only to simulate the stabilizing activities of the tendons acting on the wrist joint. The hand was moved subsequently through a dorsopalmar flexion cycle and a radioulnar deviation cycle, starting from the neutral position (in which the long axis of the third metacarpal is parallel to the radius) in angular steps of approximately 8°. These experiments were performed in both the fully pronated and supinated positions of the hand. These two positions were secured each time by Steinmann pins, drilled transversely through the radius and the ulna for stabilization.

After each step, stereoroentgen exposures were made. After the experiments, the joint was dissected at the radiocarpal joint and an additional tantalum marker was placed approximately in the center of the distal area of the radius. One more double exposure was made including this marker and was used to define the origin of the coordinate system of the radius. The roentgenographs were measured on a two-dimensional digitizer and the 3D positions of the landmarks were determined using stereophotogrammetrical principles (15).

From the landmark configurations in the carpal bones, their Euler rotations and translations were determined using principles of rigid-body kinematics (8). For each position of the hand, the total length of each ligament fiber represented was calculated as the sum of the lengths of the (subsequent) marker intervals according to (Fig. 3):

$$L(p) = \sum_{i=0}^{n-1} | x_{i+1}(p) - x_i(p) | \quad \text{for method 1} \tag{1}$$

and

$$L^c(p) = | x_n(p) - x_0(p) | \quad \text{for method 2} \tag{2}$$

where $x_i(p)$ = the position vector of the ith fiber marker of a ligament, measured in position p of the hand; $L(p)$, $L^c(p)$ = the total length of the ligament fiber in position p of the hand, for methods 1 and 2, respectively; i = marker number ($0 \leq i \leq n$); and p = position number ($0 \leq p \leq m$).

For each motion cycle, the relative length change of each fiber was calculated as the elongation of that fiber after each motion step, relative to its initial length in the neutral position of the hand:

$$\epsilon(p) = \frac{L(p) - L_0}{L_0} \quad \text{for method 1} \tag{3}$$

$$\epsilon^c(p) = \frac{L^c(p) - L_0^c}{L_0^c} \quad \text{for method 2} \tag{4}$$

where L_0, L_0^c = the total length of the ligament fiber in the neutral position of the hand, for methods 1 and 2, respectively; and $\epsilon(p)$, $\epsilon^c(p)$ = the relative length change of the fiber.

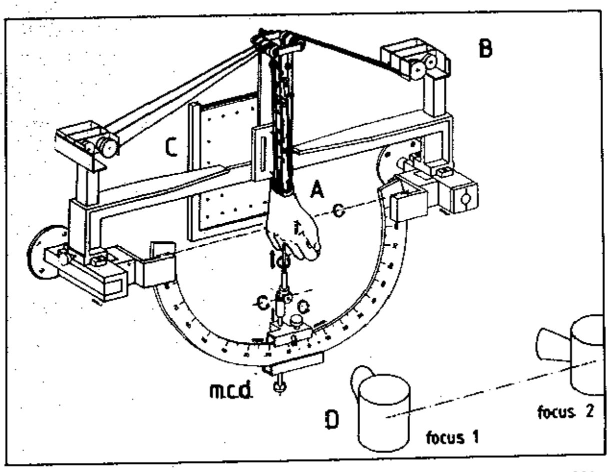

FIG. 2. Experimental setup. The wrist-joint specimen (A), placed in front of the filmholder with reference plate (C). Hand movements were prescribed by using the motion-constraint device (m.c.d.). During the experiments the tendons of the muscles were loaded by 20-N constant force springs (B). The specimen was exposed by two roentgen tubes (D).

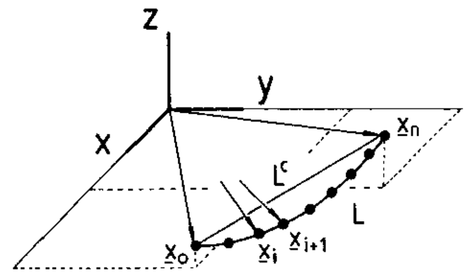

FIG. 3. Method for representing the length of a fiber in a wrist ligament.

We emphasize that L_0 is not defined as the length of a fiber in the unstrained ligament, because the stress in the ligaments was not measured. In addition, for each fiber represented, the maximal relative length change was calculated according to

$$\epsilon_{max} = \frac{L_{max} - L_{min}}{L_0} \quad \text{for method 1} \quad (5)$$

$$\epsilon^c_{max} = \frac{L^c_{max} - L^c_{min}}{L^c_0} \quad \text{for method 2} \quad (6)$$

where $L_{max} = \max\{L(p)\}$, $L^c_{max} = \max\{L^c(p)\}$; $L_{min} = \min\{L(p)\}$, $L^c_{min} = \min\{L^c(p)\}$.

All carpal rotations and relative length changes of the ligament fibers were evaluated as functions of the flexion or deviation angles of the hand, using the rigid-body motions in terms of Euler rotation angles of the capitate as a reference (8).

The accuracy of the experimental method is influenced by several error sources, including the quality of the digitizer, the experience of the operator, and bending effects of the image planes in the cassettes. The error dependency of the first two error factors were quantified by remeasuring the roentgenograms of four subsequent positions of the hand (three motion steps) during deviation, and by repeatedly calculating the length of three ligaments and the kinematic parameters of four carpal bones (repeated reconstruction test).

To investigate the effects of image-plane flatness, an additional test was performed with specially constructed "ideally" flat image planes. In 12 subsequent positions (11 motion steps) of the hand during flexion, the specimen was exposed on both the flat image planes and the conventional image planes. The kinematic parameters of four carpals and the lengths of three ligaments, marked by pellets glued into the structure, were calculated for both series.

In each of these two tests (repeated reconstruction and flat/bent image planes), the results of the two data files were compared by calculating standard errors according to ref. 13:

$$SE = \left\{ \frac{\sum_{i=1}^{n} (P_{i1} - P_{i2})^2}{2n} \right\}^{1/2}$$

in which SE = standard error, P_{i1} = result of first measurement, P_{i2} = result of second measurement, and n = number of duplicate values.

Finally, to study the reproducibility of the results, one experiment was repeated. The specimen remained in the fixture between the initial and the repeated test. The hand was moved from neutral position to maximal radial deviation, further to maximal ulnar deviation, and back to the neutral position.

RESULTS

The SEs for the kinematic parameters and relative length changes for the precision tests are given in Table 1. Those for the repeated reconstruction give an estimate for the precision of the roentgen-stereophotogrammetric system (with conventional cassettes). Evidently, the use of conventional cassettes resulted in a 0.3% SE in the relative length patterns as compared with the test in which new, almost ideally flat roentgen plates were applied. In the latter case, the reconstruction of spatial coordinates of the pellets was performed with an estimated error of <50 μm (SD). The x coordinate, which is directed toward the roentgen tubes, is less precise (50 μm SE) in comparison to the y and z coordinates (30 μm SE each). Using conventional image planes, the errors were approximately 100, 30, and 40 μm for the x, y, and z coordinates, respectively. Inspection of these casettes revealed that their central image areas were slightly bent toward the foci. As a consequence, systematic errors were introduced in the spatial reconstruction of the landmarks, through which the landmark positions were determined closer to the roentgen cassette (into the x direction). The magnitude of these systematic errors depends on the positions of the landmark images on the film. Because the 3D position information of the landmarks was used in relative terms, the influence of the errors in the length patterns was only small (Table 1: 0.3% length change, bent versus flat).

TABLE 1. *SE of the Euler rotations and the relative ligament length changes for the precision tests (repeated reconstruction and routine versus specially made cassettes)*

	Repeated reconstruction (n = 12)	Flat/bent image planes (n = 44)
Flexion (degrees)	0.36	0.33
Deviation (degrees)	0.20	0.39
Pronation/supination (degrees)	0.22	0.44
Rel. length change (%)	0.1	0.3 (n=36)

In the repeated-experiment test, maximal differences were measured <1.0% in the relative length and <1° in the Euler rotation angles. An example of this repeated test, relative to the triquetrocapitate ligament, is shown in Fig. 4. The curves for the two tests are very similar; some hysteresis between the motions toward and from the end positions is in evidence.

For the relatively short ligaments (radiolunate, lunatotriquetrum, triquetrocapitate, and radiotriquetrum) the two representation methods resulted in equal tendencies, although quantitative differences occurred (Fig. 5A). The bone-to-bone representation method tends to slightly overestimate the relative fiber length changes.

For the relatively long radiocapitate ligament, the ligament length patterns obtained with the "string" method were not similar to those from the bone-to-bone method (Fig. 5B).

When using the glued-string representation method, reproducible length patterns in all ligaments of the three specimens were obtained. Figures 6 and 7 present a comparison between the bilateral pair (specimens 4 and 5) in flexion and deviation, respectively. In dorsal flexion of the hand (Fig. 6), the palmar radiocapitate, triquetrocapitate, and radiolunate ligaments increased in length, and in palmar flexion they decreased. The dorsal radiotriquetrum ligament showed the opposite behavior. The lunatotriquetrum ligament remained practically unchanged. For all ligaments represented, the ligament length patterns were not altered by changing the position of the hand from the pronated to the supinated position.

With some exceptions, similar trends were also found in the length patterns during hand deviation for all three specimens, and in both supinated and pronated positions of the hand (Fig. 7). Both in radial and in ulnar deviation the radiocapitate ligament increased whereas the triquetrocapitate and the dorsal radiotriquetro ligaments both decreased in length. The distal part of the radiolunate ligament decreased in length from ulnar to radial deviation in all specimens. During the same hand motion, the proximal part showed an increase in two specimens, whereas in the right hand of the bilateral pair a decrease was observed (Fig. 7). The proximal part remained practically unchanged in the left hand of the bilateral pair, but increased in the right one (Fig. 7) and decreased in the third specimen, in radial deviation. Also in deviation the length patterns were not altered by changing the hand from the pronated to the supinated position.

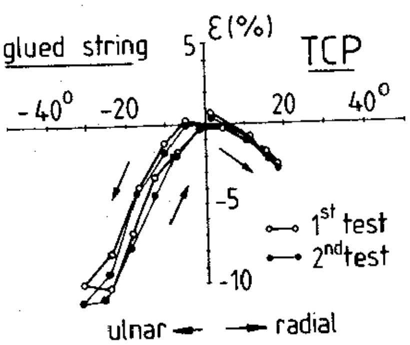

FIG. 4. Relative length changes of the triquetrocapitate (TCP) as a function of hand deviation, measured in the initial and repeated experiment.

In flexion of the hand, maximal length changes (relative to the neutral position) up to 27% occurred (Fig. 8A). In deviation of the hand, maximal length changes of 13% were not exceeded (Fig. 8B).

DISCUSSION

A number of factors limit the accuracy and precision of the results of experiments of this kind. Deviations in flatness of the films in routine roentgen cassettes resulted in errors in relative length changes (0.3%) and in the Euler rotations (0.5°). Hence, the construction and application of special cassettes using ideally flat glass plates must be advised.

Another factor of imprecision was the variability in the alignment procedure, whereby the specimens were fixed in the test apparatus. Small differences between the initial (reference) positions of the specimens were unavoidable.

Variations in size and attachment sites of the ligaments were observed. The marking of representative points of the attachment areas was sometimes difficult. The location of the attachment marker is a variable that may have affected the results.

Different fibers of the same ligament may produce different length patterns. Therefore, the more fibers are included in the marking procedure, the better the behavior of a ligament is represented. Due to the relatively small size of the wrist ligaments and their close-packed locations, only two fiber bundles in two ligaments and only one in the other three ligaments could be represented.

Relatively long ligaments may be bent by surrounding bony structures. For these ligaments, the bone-to-bone fiber representation method then is not sufficient to obtain reliable information on

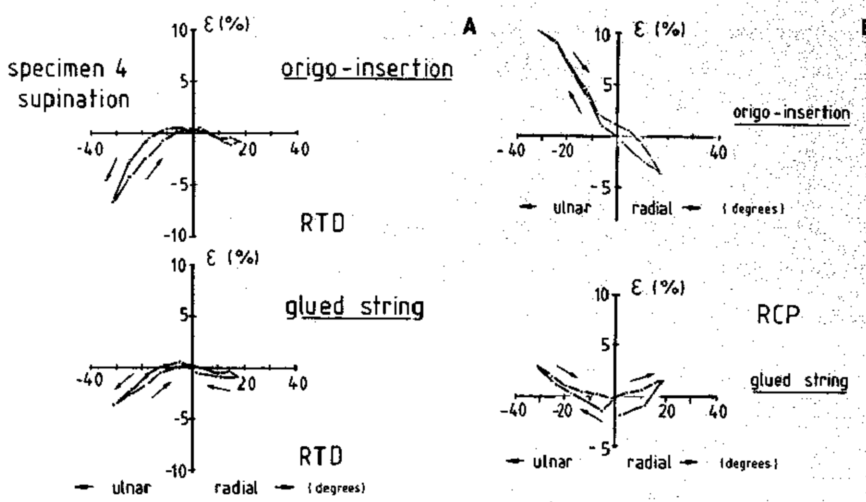

FIG. 5. Relative length changes of the dorsal radiotriquetrum ligament (RTD) **(A)** and the radiocapitate ligament (RCP) **(B)** as functions of hand deviation, comparing the glued string versus the bone-to- bone representation methods.

length patterns. To overcome this problem, a string of markers in the fibers was used. This idea is not new. Stokes and Greenapple (16) measured the length of ligaments connecting motion segments of the spine under various loads, using small markers glued on the ligaments and a stereophotogrammetric technique. Others used India ink to measure local and overall strains in ligaments (20). By gluing tantalum pellets in the ligaments, the mechanical properties of the ligamentous material may be affected locally. However, the amount of glue used was very small.

In view of the precision established for the glued-string measuring method, the length changes of the ligaments found may be judged accurate within a 2% range. The hysteresis found in some cases could be explained by inaccuracies within this margin. However, its consistency suggests it to be a realistic phenomenon. It is probably caused by slightly different 3D motion pathways of the individual carpals when the hand is moved toward and back from the end positions.

In the functional behavior of the ligaments, the fiber length patterns, together with the unstrained length L_0, determine the ligament strain pattern. The forces exerted by the ligaments depend on the strains, as related through ligament geometry and material properties. Although information about length changes were obtained, information about the forces is actually needed to evaluate ligament functions. Hence, in interpreting the length patterns in terms of ligament functions, care must be taken because several deterministic aspects, such as unstrained length and material properties of wrist ligaments, are unknown. The freezing procedure has no effect on ligament mechanical properties or on ligament cross-sectional areas (21).

The present results suggest that the radiocapitate ligament resists the displacements of the capitate in dorsal flexion and in radioulnar deviation of the hand. The stretching of the radiocapitate ligament may be related to the movements of the scaphoid relative to the capitate and to the radius (8). The radiocapitate ligament, crossing the scaphoids waist at the palmar side, will be pushed palmarly by the scaphoid. This results in stretching of the radiocapitate ligament. Hence, it helps to resist palmar flexion of the scaphoid during radial deviation of the hand. This effect is analogous to a boxer falling in the ropes, by which his motion is arrested. Taleisnik (19) hypothesized that during radial deviation the scaphoid rotates around this ligament and creates a situation analogous to ". . . a gymnast balances on a horizontal bar when executing a hip circle," which is not similar to the present description.

The radiolunate ligament resists the lunate motions in dorsal flexion and in radioulnar deviation of the hand. Because both the radiocapitate and radiolunate ligaments are located in front of the proximal pole of the scaphoid, we may speculate that both ligaments assist the scaphoid in keeping its place during these displacements of the hand.

During radioulnar deviation, both the dorsal radiotriquetrum and the triquetrocapitate ligaments reach their maximal length when the hand is in neutral position. Hence, they seem to play a stabilizing role in this hand position. In addition, the dorsal

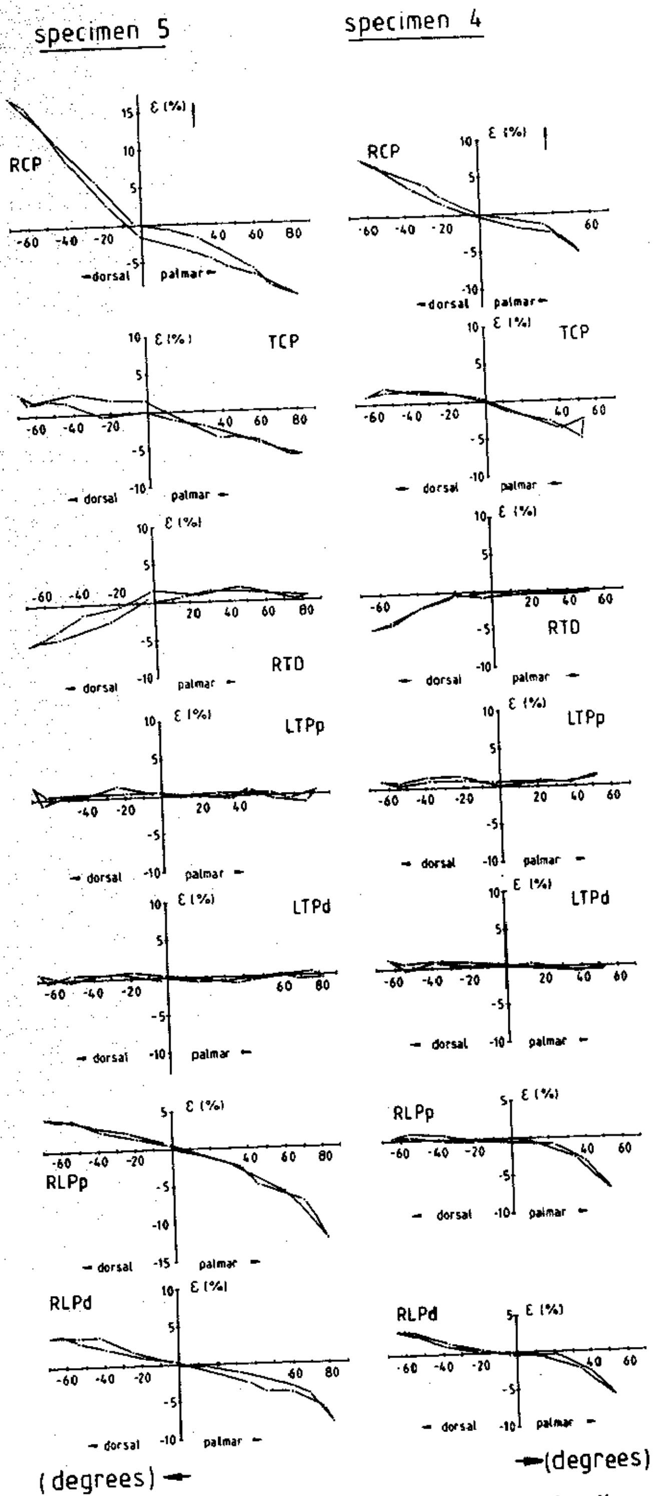

FIG. 6. Relative length changes (vertical axes) as functions of hand flexion (horizontal axes) of seven marked ligament fibers of the two bilateral specimens (4 and 5), with the hand in supination (see Fig. 1 for abbreviations). Similar patterns were found in specimen 6.

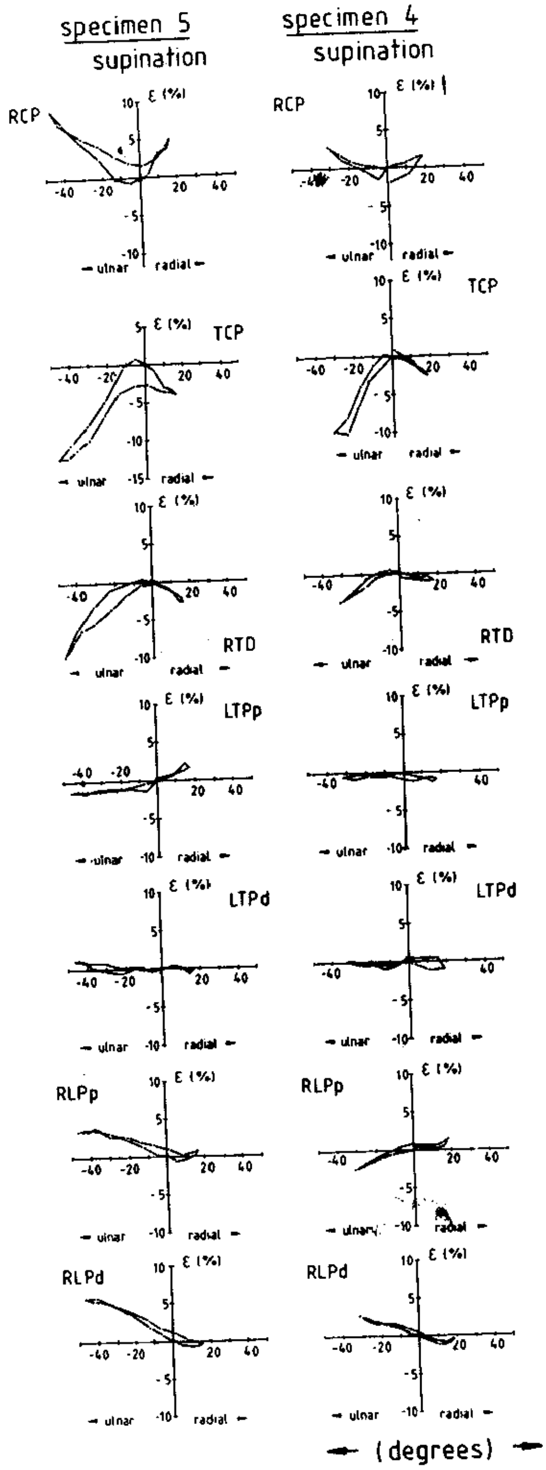

FIG. 7. Relative length changes (vertical axes) as functions of hand deviation (horizontal axes) of seven marked ligament fibers of the two bilateral specimens (4 and 5); hand in supination (see Fig. 1 for abbreviations). Similar patterns were found in specimen 6.

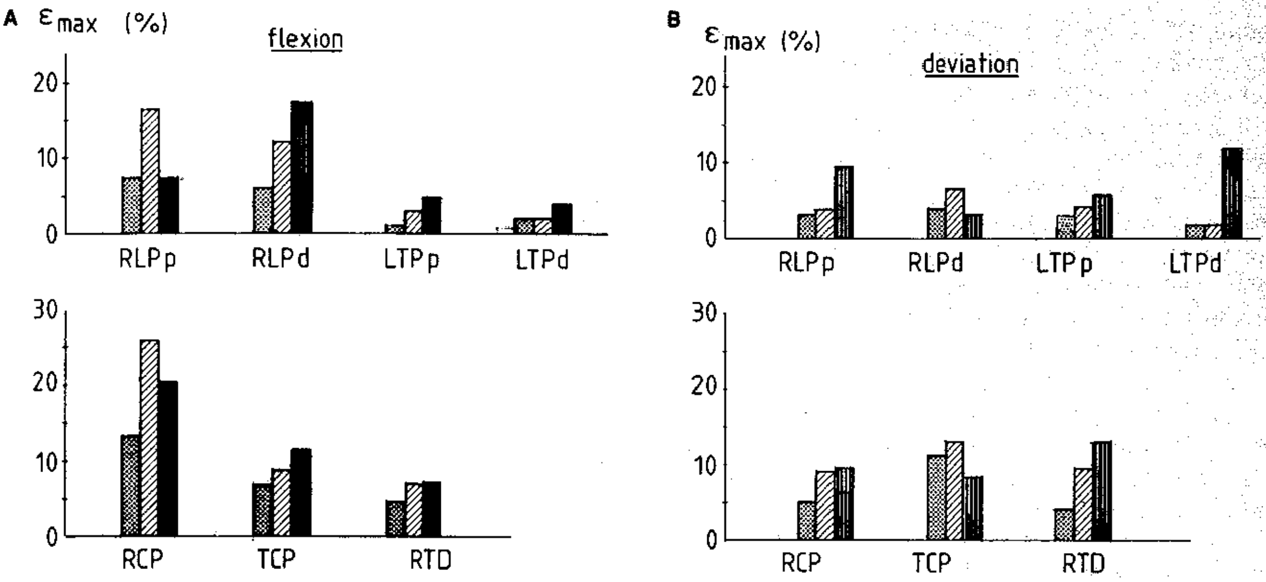

FIG. 8. Maximal relative length changes (ϵ_{max}) relative to the lengths in neutral position of seven marked fibers of five ligaments in the three specimens [4 and 5 (bilateral) and 6, from left to right] as obtained with the glued-string method. (**A**: Flexion; **B**: deviation; see Fig. 1 for abbreviations).

radiotriquetrum ligament also has a function in palmar flexion of the hand and the triquetrocapitate ligament functions in dorsal flexion of the hand, helping ultimately to resist these motions.

In flexion, the lunatotriquetrum ligament remained practically unchanged in length, although movements between the lunate and the triquetrum were observed (8). Apparently, these movements did not produce significant length changes. For deviation, no conclusions can be made concerning the function of this ligament because different results were obtained. Possibly these differences may be related to different markings of the fibers, as previously mentioned.

We found that the measured length patterns as well as the individual carpal bone displacement patterns were not influenced by the supination or pronation position of the hand in the forearm. It has to be noted, however, that in this study only length patterns were determined of ligaments not originating from the ulna. Different results may be found for ligaments originating from the ulna toward the carpus. In this respect, it has been emphasized (7) that the ulnar styloid changes in position relative to the radius and the carpus, when changing the position of the hand in the forearm.

It has been suggested in the literature that nonuniform strains in ligaments occur with maximal values near the attachment areas, at least in the knee joint (2). This was tested here in the ligaments described with the glued-string method, by which the strain distribution over each fiber could be calculated. However, the above suggestions could not be confirmed.

In the literature, speculations about ligament length behavior in the wrist have been reported (1,12). For flexion of the hand these are supported by the present findings. However, for deviation of the hand, they are not. It was thought that from neutral to radial deviation, the triquetrocapitate ligament would be increasingly stretched, whereas the radiocapitate ligament would relax. These expectations were contradicted by the present results. It was also speculated that, from neutral to ulnar deviation, a stretching of the radiocapitate ligament and a slackening of the triquetrocapitate ligament would occur. These predictions are in agreement with the present results. The differences between expected and actual behavior are probably caused by invalid assumptions about carpal bone motion axes. The hypotheses assume rotation axes, fixed in the head of the capitate. As indicated by earlier motion studies, these assumptions may not be realistic (8).

In the clinical literature, it is often reported that in wrist-joint injuries in which the wrist joint is extensively hyperextended in combination with ulnar deviation, ruptures of the radiocapitate and the radiolunate ligaments occur (11). In the present investigation, indications for such a mechanism are found. Of all positions of the hand, these ligaments are maximally stretched in full dorsal flexion and full ulnar deviation of the hand.

It is concluded from this study that the glued-pellet string method developed for measuring ligament length patterns in situ, in combination with roentgenstereophotogrammetry, is precise and adequate for its purpose. In particular for relatively long, bent ligaments, the use of bone-to-bone evaluation techniques must be discouraged. They can be inaccurate even in a qualitative sense.

In three wrist-joint specimens, the general behavior of five ligaments in deviation and flexion motions of the hand was found to be reproducible. In many respects, the length patterns were very different from those suggested in the literature, probably as a result of previous invalid assumptions about carpal relative motions. Confirmation of these findings in a more extensive study, in which ligament patterns are directly related to carpal motion axes, is justified.

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REFERENCES

1. Bonjean P, Honton JL, Linarte R, Vignes J: Anatomical bases for the dynamic exploration of the wrist joint. *Anat Clin* 3:73–85, 1981
2. Butler DL, Stouffer DC, Wukusick PM, Zernicke RF: Analysis of nonhomogeneous strain response of human patellar tendon. In: *1983 Biomechanics Symposium*, AMD vol. 56, FED vol. 1, ed by SL Woo, RE Mates, The American Society of Mechanical Engineers, pp 109–112, 1983
3. Dijk R van, Huiskes R, Selvik G: Roentgen-stereophotogrammetric methods for the evaluation of the three-dimensional kinematic behaviour and cruciate ligament length patterns of the human knee joint. *J Biomech* 12:727–731, 1979
4. Huiskes R, Blankevoort L, Dijk R van, Lange A de, Rens ThJG van: Ligament deformation patterns in passive knee-joint motions. In: *Advances in Bioengineering*, ed by RL Spilker, New York, The American Society of Mechanical Engineers, pp 53–54, 1984
5. Kauer JMG: The interdependence of carpal articulation chains. *Acta Anat (Basel)* 88:481–501, 1974
6. Kauer JMG: Functional anatomy of the wrist. *Clin Orthop* 149:9–20, 1980
7. Kauer JMG: Comparative aspects of the ulnar articular disc. *Fortschr Zool* 30:77–79, 1985
8. Lange A de, Kauer JMG, Huiskes R: Kinematic behavior of the human wrist joint: a roentgen-stereophotogrammetric analysis. *J Orthop Res* 3:56–64, 1985
9. Lewis JL, Lew WD, Schmidt J: A note on the application and evaluation of the buckle transducer for knee ligament force measurement. *J Biomech Eng* 104:125–128, 1982
10. Logan SE, Nowak MD, Gould PhL, Weeks PM: Biomechanical behavior of the scapholunate ligament. *Biomed Sci Instrum* 22:81–85, 1986
11. Mayfield JK: Wrist ligamentous anatomy and pathogenesis of carpal instability. *Orthop Clin North Am* 15:209–216, 1984
12. Mayfield K, Johnson RP, Kilcoyne RG: The ligaments of the human wrist and their functional significance. *Anat Rec* 186:417–428, 1976
13. Mikhail EM: *Observations and Least-Squares*. New York, Dun-Donnelley, 1976
14. Monohan JJ, Grigg P, Pappas AM, Leclar WJ, Marks T, Fowler DP, Sullican TH: In-vivo strain patterns on the four major canine knee ligaments. *J Orthop Res* 2:408–418, 1984
15. Selvik G: A roentgenstereophotogrammetric method for the study of the kinematics of the skeletal system [Thesis]. University of Lund, Sweden, 1974
16. Stokes I, Greenapple DM: Measurement of surface deformation of soft tissue. *J Biomech* 18:1–17, 1985
17. Taleisnik J: The ligaments of the wrist. *J Hand Surg* 1:110–118, 1976
18. Taleisnik J: Post-traumatic carpal instability. *Clin Orthop* 149:73–82, 1980
19. Taleisnik J: The ligaments of the wrist. In: *The wrist*, ed by J Taleisnik, Edinburgh, Churchill/Livingstone, pp 13–38, 1985
20. Woo SLY, Gomez MA, Seguchi Y, Endo CM, Akeson WH: Measurement of mechanical properties of ligament substance from a bone-ligament-bone preparation. *J Orthop Res* 1:22–29, 1983
21. Woo SLY, Orlando CA, Camp JF, Akeson WA: Effects of post mortem storage by freezing on ligament tensile behavior. *J Biomech* 19:399–404, 1986