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Strains and Forces in Selected Carpal Ligaments During In Vitro Flexion and Deviation Movements of the Hand

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Summary: The forces induced in tiny wrist joint ligaments must be estimated in order to understand their role in the mechanism of the joint. We estimated forces in a number of selected ligaments in seven human wrist joint specimens, using a noninvasive method. The method is based on the rationale that the force generated in a ligament depends on its change of length with the joint under load. In vitro length changes of the ligaments were determined during flexion and deviation movements of the hand, using a roentgenstereophotogrammetric analysis technique. Subsequently, bone-ligament-bone (BLB) preparations were dissected from the specimens. From these BLB preparations the zero-force length and the force-elongation relationship were determined in a material testing machine. The forces generated in the ligaments during flexion and deviation were calculated by combining results on the in vitro ligament length changes, the zero-force length, and the force-elongation relationship. Large interspecimen variations of the force patterns were found. Due to this variability, it is not possible to obtain quantitative models for the kinetic behavior of the ligaments. However, qualitative trends could be distilled from the strain and force patterns. It is clear that for most ligaments, the zero-force lengths were not equal to the lengths they possessed in the neutral position of the hand. Furthermore, it could be shown which motions of the hand would most likely strain a particular ligament. It could be shown that the variations in the force patterns originate mainly from variations in the zero-force lengths, and from variations in the force-strain relationship between specimens. These variations might result from real differences between individuals as well as from artifacts introduced by the test method. Uncontrolled effects of frozen storage and unintentional preconditioning might negatively influence the variation. Because these artifacts are present from the initiation of the experimentation, we concluded that, at least in these specimens, the contribution of ligament forces to the kinematics of the wrist joint, which is very consistent between specimens, is of minor importance. **Key Words:** Strain—Forces—Carpal ligament—Hand.

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Not just from a morphological point of view, but with respect to development and evaluation of surgical techniques, and rehabilitation procedures, it is of interest to understand the form of the carpal

joint. To be able to explain the morphology of the ligaments of the carpal joint, insight into their function is required. One might say that the general function of collagenous structures is to transduce forces. However, it is often not clear why these forces arise. To obtain insight into ligament functions, the ligament forces during hand movements should be considered. In the wrist joint, the measurement of forces in ligaments during hand motions has not yet been reported. Nevertheless, many authors have speculated about specific carpal ligament functions. It has been suggested that carpal ligaments can either be considered as structures to stabilize the joint or guide the motions of the carpal bones. That is, they are assumed to either block or limit the movements of the carpal bones and the hand to function as guides or to aid in defining the courses of motion of carpal bones (3,5,6,11,13,25,26). In most cases, functions ascribed to the ligaments are based on qualitative features of carpal bone motions, from which ligament length changes and ligament functions are deduced. The concepts of deduction of ligament function from ligament lengthening and of the deduction of ligament lengthening from carpal motion are questionable; it can also be shown that the intuitive concepts of carpal motion are not in accordance with experimentally determined carpal kinematics (4,7,9,16).

A method widely used to determine forces in ligaments and tendons is the application of buckle-type transducers (1,2,10). However, this technique has the disadvantage of interfering with the course of the ligament, and of possible impingement of the transducer with joint structures. Recently, other methods have been developed without these disadvantages. Xu et al. (28) developed a small force transducer that can be implanted within ligaments. The advantage of this method is that it combines direct measurements, with less influence on the joint motion. However, this method has disqualifying practical implications when applied to the wrist joint: the ligaments in the wrist joint are very small compared with those in the knee joint, for which this implantable force transducer was developed. In addition, the high number of ligaments that must be instrumented makes this method not practicable for the wrist joint. Another method for prediction of forces in knee joint ligaments has been presented recently by Takai et al. (23). Ligament length change was calculated from experimentally determined joint kinematics. Subsequently, after dissecting soft tissue around the knee joint, load-

elongation curves were recorded. In situ loads are calculated by combining load-elongation curves and length data.

It is the aim of this study to determine strains and forces in a selected set of carpal ligaments during in vitro flexion and deviation movements of the hand. The method we developed for estimating strains and forces in carpal ligaments is similar to the one presented by Takai et al. (23), except that the material testing in our method must be performed on ligaments isolated from the wrist joint specimens. Detailed information on the method and its accuracy was reported by Savelberg et al. (18).

METHODS

Material

The wrist joints of seven freshly frozen human cadaver specimens were used in these experiments. Three of the seven joints were obtained from men, the other four from women. Two of the joints were from the same individual. The ages of the donors were 63–78 years (average 68.7 ± 6.3). As far as the record showed, they did not have diseases that would influence the material characteristics or mobility of the joints. The presence of any joint abnormalities was detected by roentgen inspection. The specimens were obtained from autopsy and stored at -20°C until the time of use. Although Matthews and Ellis (12) found that the elastic modulus decreases due to frozen storage, most studies showed that this treatment does not affect the mechanical properties of ligaments (14,24,27). The maximum duration of frozen storage was ~6 months. Approximately 12 h before the start of the experiments, the frozen specimens were slowly thawed at room temperature. During the experiments the specimens remained unfrozen for a maximum of 4 days. During this time they were moistened with Ringer's solution, and when not used were stored in a refrigerator at -4°C . The experiments were performed at room temperature ($\sim 22^{\circ}\text{C}$).

In each specimen, five ligaments were considered (Fig. 1): the palmar radiocapitate ligament (RCP), the palmar radiolunate ligament (RLP), the palmar triquetrocipitate ligament (TCP), the dorsal radio-triquetrum ligament (RTD), and the dorsal triquetro-trapezium ligament (TTD). In the RLP, two parts—a proximal (RLPp) and a distal half (RLPd)—were examined separately. The ligaments were selected because of their relative accessibility,

FIG. 1. The anatomical layout of the ligaments tested. RCP, radiocarpal palmar; RLP, radiolunate palmar, which has been split in the experiments in a proximal and a distal string; TCP, triquetrocapitate palmar; RTD, radiotriquetrum dorsal; TTD, triquetrotrapezium dorsal.

and because their recruitment patterns and mechanical behavior had already been documented (19,20). The recruitment of a carpal ligament has been defined (20) as the length change of a ligament relative to the length of that ligament when the hand is in the so-called neutral position.

Experimental Procedure

By means of a three-step procedure, the forces in the selected ligament or ligament part were determined during *in vitro* flexion and deviation movements of the hand. Subsequently, the ligament length change patterns, the zero-force length, and the force-elongation relationship of a ligament were determined. This method has been described in detail by Savelberg et al. (18).

Determination of the In Vitro Carpal Ligament Length

Radioopaque tantalum pellets (0.5 mm diameter) were glued to the ligaments under consideration in such a way that a string of four or five pellets represented the course of a fiber along the middle of the ligament (8,20). The origin and insertion pellets were attached to the bones. The length of a ligament was computed as the sum of the interval distances between adjacent pellets. After this preparation, the specimen was positioned in a motion-constraining device (9) by which flexion and deviation of the hand could be applied. For flexion, the hand was moved from the neutral position (that position in which radius and third metacarpal are parallel) to sites at 10, 20, 35, 50, 65, and 84° palmarly, as well

as dorsally. For deviation, it was moved to 10, 20, 30, 40, 50, 60, and 70° ulnarly, and to 10, 20, and 30° radially. The positions at 84° palmar and dorsal flexion, and 70° ulnar and 30° radial deviation, represent the maximal excursions for the motions in the respective planes. At each of these positions, a pair of stereo radiographs was obtained so that the three-dimensional (3-D) location of the markers in the ligaments could be reconstructed by means of roentgenstereophotogrammetric analysis (RSA) (21). From the 3-D marker locations, the ligament lengths in each position could be determined.

In three of the seven specimens, stereo radiographs were only made in the neutral position and in the four positions corresponding to each maximal excursion in each direction. In these cases, the ligament lengths in the intermediate positions were obtained by interpolation. This procedure was determined to be valid, based on earlier results of carpal ligament recruitment (8,20).

Determination of the Zero-Force Lengths of Ligaments

After obtaining the ligament length data, bone-ligament-bone (BLB) preparations containing the marked ligaments were isolated (19). These BLB preparations were placed in a material testing machine in a slack position. From this state, the ligament was elongated until a load cell (MTS, Berlin, Germany) to which it was connected registered 0.25 N force. The ligament length corresponding to this force was defined as the zero-force length of the ligament. This length was then measured by RSA with the ligament (which still contained the tantalum markers) in the material testing machine.

Determination of the Force-Elongation Relationship

The final step in the experimental procedure was the determination of the force-elongation relationship. The ligament was strained 15% at a rate of 66%/s of its initial length. Simultaneously, the force developed in the ligament was sampled at 200 Hz. This part of the experiment immediately followed the zero-force length determination; the ligament was not removed from the material testing machine. The ligaments were not preconditioned. The consequences of this are discussed later.

The initial length of each ligament was determined by a pair of Vernier callipers before the lig-

ament was positioned in the material testing machine. It was measured to estimate the maximal strain and the strain rate to be applied to the ligament.

Data Processing

For each position of the joint in the RSA experiment, the amount of strain in a ligament was calculated according to the following equation:

$$\epsilon(p) = \frac{L(p) - L_{ZF}}{L_{ZF}} \quad (1)$$

where $\epsilon(p)$ is the amount of strain with the hand in position p , $L(p)$ is the ligament length (mm) with the hand in position p (as determined in the RSA experiment), and L_{ZF} is the zero-force length (mm) of the ligament. Plotting these strains against the motion of the hand results in strain patterns.

The force-elongation relationship of the ligament was assessed by fitting a second-degree polynomial equation to these data:

$$F = aL^2 + bL + c \quad (2)$$

where F is the ligament force (N); a , b , and c are constants determining the force-elongation relationship, and L is the elongation (mm) of the ligament.

From the actual ligament length $L(p)$ in a given position of the hand, the amount of lengthening that contributes to force development in the ligament or the effective elongation can be calculated by subtraction of the zero-force length:

$$EL(p) = L(p) - L_{ZF} \quad (3)$$

where $EL(p)$ is the effective elongation of a ligament with the hand in position p .

The force developed in a ligament in a certain position of the hand, $F(p)$, is given by substituting the amount of effective elongation in that position for the variable L in Eq. 2. Plotting these forces against the position of the hand results in the ligament force patterns.

Accuracy

In an earlier study (18), we showed that the measurement error for the force estimation depends on the errors made in the determinations of the effective elongation and the current stiffness of a ligament, which, in the nonlinear part of the force-

elongation curve, also depends on the effective elongation. For ligament strains of $\sim 15\%$ of the zero-force length, it was found that the standard error of the force determination was $\sim 5\%$ of the force estimated. The measurement error for the determination of the effective elongation is only dependent on the error made in the RSA experiment. It was shown that this error will be < 0.078 mm (18).

Nine of 42 ligament strings in the seven specimens were not evaluated: three RLPp ligaments, three RLPd ligaments, two TCP strings, and one TTD ligament. There were two reasons for discarding these data. First, some reconstructions of the ligament strings in the RSA evaluations could not be performed because of obvious errors in the pellet identification. Second, some pellets were lost in the BLB preparations.

RESULTS

In most of the ligaments the strain patterns displayed similar tendencies over the specimens tested. However, a large variation between actual strain values of corresponding ligaments over the specimens was found. Figure 2 shows how the magnitude of this variation varies over the different aspects of the measurement method. This variation was as high as 15% of the zero-force length between the most strained and the least strained ligaments at a particular flexion or deviation angle of the wrist joint. Compared with the variation in the recruitment patterns (Fig. 2A), the variation in the strain patterns is considerably higher (Fig. 2B). The variations of the recruitment patterns resemble those reported by de Lange et al. (8) and Savelberg et al. (20). The differences between the most recruited and the least recruited ligaments were maximally 5% of the length in the neutral position of the hand. The variations in the force patterns were even higher than those in the strain patterns (Fig. 2D). The difference between the highest and the lowest force in ligaments was as much as 70 N in the same hand position.

Deviation

In deviation, the RCP ligament lengthened when the hand was moved ulnarly (Fig. 3A). The position in which the zero-force length was reached in different specimens ranged from 20 to 70° ulnar deviation. In maximal ulnar deviation, the strain varied by 0–10%. The variation in the force patterns

FIG. 2. The increasing variability of the patterns from different specimens, when subsequent recruitment patterns (A), strain patterns (B), and force patterns (D) are determined. The variability of the force-strain relationship over the RTD ligaments tested (C).

amounted to 60 N maximally in extreme ulnar deviation of the hand (Fig. 3B). Of the seven specimens tested, the RCP ligaments were loaded in only three.

Contrary to the general trend, the strain patterns of the RLPp ligaments during deviation of the hand were consistent (Fig. 4A). During deviation movements of the hand, the strains in the RLPp ligament changed minimally. For the ligaments tested, the strain varied by 5–10%, and the length of each ligament was always larger than the zero-force length. The force patterns demonstrated a greater variation (Fig. 4B). At maximal radial deviation, the forces ranged from 5 to 35 N. The data of three of the seven RLPp ligaments were not taken into consideration because of artifacts in the ligament length or zero-force length measurements. These artifacts were caused by loosening of the origin or insertion

pellet. Only when a ligament marker was no longer present on a radiograph or when the trend of the recruitment pattern was contrary to patterns known from previous experiments (8,20) were the data of the ligament concerned discarded.

Due to artifacts, the RLPd strain and force patterns of only four specimens were included. The ligament was minimally strained in most of the wrist joints. In two of the four remaining ligaments, some forces were developed. However, their patterns were inconsistent.

During deviation, the TCP ligaments were minimally strained. Consequently, the forces generated in the ligaments were also very small or zero. All TCP ligaments tested displayed a tendency to lengthen when the hand was moved from maximal ulnar deviation to the neutral position. During neutral to radial deviation, the length changes leveled

FIG. 3. The strain (A) and force patterns (B) for the RCP ligaments in the seven specimens tested during deviation of the hand.

off. The dispersion between the strain patterns of most and least strained ligaments was $>10\%$ of the zero-force length.

All RTD ligaments elongated when the hand was moved radially from an ulnarly deviated position (Fig. 5A). Between 20° ulnar deviation and maximal radial deviation the ligament length changed minimally. The hand position in which the zero-force length was reached varied from 40 to 0° ulnar deviation. In one of the specimens tested, the zero-force length was not reached at all. The RTD ligament in another was constantly strained by about 10% . The force patterns were consistent in six of the seven specimens tested (Fig. 5B). They showed maximal values of $5\text{--}7\text{ N}$ between 20° ulnar deviation and the neutral position of the hand.

The length changes in the TTD ligaments were small in deviation of the hand, $\sim 2\%$ of the zero-force length. The ligaments became longer when the hand was ulnarly deviated. The ligaments were almost constantly strained. The variation over the

specimens amounted to $\sim 10\%$ between the most and least strained ligaments. Although variation existed in the strain patterns, the force patterns were similar. The force values were very small: 2 N maximally in ulnar deviation.

Flexion

During flexion, the RCP ligaments were elongated when the hand was moved dorsally (Fig. 6A). The elongation was as much as 20% of the zero-force length over the entire flexion movement; that is, from maximal palmar to maximal dorsal flexion. For the specimens tested, the positions of the hand where the zero-force lengths were reached were between 15 and 80° dorsal flexion. The maximal strains varied by $0\text{--}18\%$. In the force patterns, similar large differences were found. In maximal dorsal flexion, the force values ranged from 0 to 60 N (Fig. 6B). However, the force patterns were similar.

The variation in the strain patterns of the RLPP

FIG. 4. The strain (A) and force patterns (B) for the RLPP ligaments in the seven specimens tested during deviation of the hand.

FIG. 5. The strain (A) and force patterns (B) for the RTD ligaments in the seven specimens tested during deviation of the hand.

ligament during flexion of the hand was $\sim 10\%$ of the zero-force length. The flexion angle of the hand at which the zero-force length was reached varied from 15° dorsal flexion to 70° palmar flexion. The force patterns show that the ligaments were loaded during a large part of the movement range in some of the specimens, whereas in other specimens the ligaments were hardly strained or loaded.

The strain and force patterns of three of the four RLPd ligaments tested were similar. They reached their zero-force length close to the neutral position of the hand (Fig. 7A). The fourth ligament specimen was strained throughout the entire motion. All four specimens were lengthened when the hand was moved dorsally from any position. The force patterns of those three specimens with similar strain patterns also closely resembled each other (Fig. 7B). During the greater part of the motion, no forces or only small forces were generated; however, when the hand was moved close to its maximal dorsal position, the ligament forces began to increase (up to 15 N). The one ligament that had a deviating strain pattern also displayed a different force pattern.

The TCP ligaments experienced minimal elongation during flexion of the hand. The variation in the strain patterns was $\sim 10\%$. Some of the ligaments were strained constantly at a few percent; others remained unstrained throughout the entire flexion movement. The forces developed were small (< 5 N).

The RTD ligaments became elongated when the hand was moved palmarly (Fig. 2B). The length changes were as much as 20% of the zero-force length. In the specimens tested, the zero-force lengths were reached when the flexion angle was between 50° dorsal flexion and 5° palmar flexion.

The variation in the strain at a particular flexion angle was 5–10% of the zero-force length. The variations of the force patterns were as much as 40 N in maximal palmar flexion. The trends in the force patterns were consistent (Fig. 2D).

The strain and force patterns for the TTD ligament during flexion were similar to those in deviation. Only small forces were generated. The strain patterns over the movement were more or less constant in each ligament, but displayed a variation of 5–10% of the zero-force length over the specimens.

DISCUSSION

Compared with other studies on material characteristics and joint kinematics, this study seems to be based on unconventional choices and surprising results. That is, nonpreconditioned force–elongation relationships were used, and larger excursions could be applied to the specimens. It has been emphasized by some researchers that preconditioning is needed to obtain consistent results from material tests. In fact, preconditioning seems to be an unquestioned feature of material testing procedures. However, in our last study (18) it was shown that when the present method is used to estimate ligament forces, preconditioning affects the outcome. Therefore, we concluded that the effects of preconditioning should be considered for each experiment. Because there was no reason to suppose that the carpal ligaments were preconditioned during the first part of the experiments (when the *in vitro* length changes were determined), the force–elongation relationship of the nonpreconditioned ligaments was used.

Compared with those of other studies on wrist-joint behavior (15,17), the excursions that were ap-

FIG. 6. The strain (A) and force patterns (B) for the RCP ligaments in the seven specimens tested during flexion of the hand.

plied in the present study are extraordinarily large. However, those studies concerned *in vivo* experiments in which subjects were asked to perform tasks relevant for daily living.

Despite the high variability in the ligament forces predicted in this study, some interesting features concerning ligament behavior can be observed from trends in the patterns of our results. For the RCP, RLPP, RLPd, and TTD ligaments during deviation, and the RCP, RLPP, TCP, RTD, and TTD ligaments during flexion of the hand, it can be concluded that their lengths in the neutral position of the hand do not equal the zero-force lengths. The RCP ligament seems to be unloaded in the neutral position of the hand. When the hand is moved ulnarly or dorsally, this ligament is strained. The ulnar deviation or dorsal flexion angle at which this occurs is variable. The RLPP ligament seems to be loaded when the hand is in the neutral position. The effect of ulnar or radial deviation on the amount of loading is small, at least for the excursions studied

here. Dorsal flexion seems to result in higher loads, whereas palmar flexion unloads this ligament. The behavior of the RLPd ligament during deviation of the hand is unclear. In flexion, it is likely that this ligament becomes loaded when the hand is moved dorsally from the neutral position. For the RLPd ligament, the length in the neutral position of the hand seems to correspond to the zero-force length. The strain and force patterns of the TCP ligament, both for flexion and deviation of the hand, cannot be interpreted unequivocally. The RTD ligament likely becomes loaded during deviation of the hand, when the hand is close to the neutral position. Ulnar deviation unloads this ligament; radial deviation will not affect the load. During flexion of the hand, the RTD ligament becomes loaded when the hand is moved palmarly. The dorsal flexion angle at which this occurs is variable and small. In the neutral position, the ligament is loaded. The strain and force patterns for the TTD ligament suggest that this ligament becomes loaded only when extreme dorsal

FIG. 7. The strain (A) and force patterns (B) for the RLPd ligaments in the seven specimens tested during flexion of the hand.

flexion or ulnar deviation positions are reached; however, the forces generated are small.

A major point of interest is the high interspecimen variability in the force patterns generated in these experiments. The three major factors contributing to this interspecimen variability are (a) variability in carpal kinematics, reflected in ligament length patterns during motions; (b) variability in the zero-force lengths; and (c) variability in the force-elongation relationships. When the recruitment, strain, and force patterns are considered, it appears that a major increase in variation occurs between recruitment and strain patterns (Fig. 2A and B). The variation in the force patterns (Fig. 2D) is partly the reflection of these variable strain patterns. Another factor in the variation in the force patterns appears to have its origin in the variability of the force-strain relationships (Fig. 2C). Hence, these experiments suggest that a larger part of the interspecimen variation in the force patterns can be attributed to variations in the material characteristics between specimens; that is, the zero-force lengths and the force-strain relationships.

The variations in ligament forces may reflect either real interindividual differences as just discussed, or may be due to artifacts introduced by the measurement procedure, or by measurement errors.

The contribution of measurement errors has been discussed by Savelberg et al. (18). The errors introduced by inaccuracies in the 3-D marker reconstruction and polynomial fitting of the force-elongation samples were small compared with the variation between the specimens found in the present study. They amounted maximally to ~5% of the forces estimated.

One causative factor of artifacts could be the method of specimen storage. There is consensus in the literature that frozen storage does not significantly affect the biomechanical properties of connective tissue (12,14,24,27). Certainly the collagenous fibers keep their properties, which is reflected in the unchanged elastic components of the tissue behavior reported in most of these studies. However, Woo et al. (27) suggested that the cells and the ground substance might be affected. This could change the fluid movements (22) and influence the nonlinear, viscoelastic behavior of the ligaments. Hence, primarily the toe regions of the force-elongation curves could be affected. Therefore, it is not unlikely that a portion of the experimental variability in the zero-force length determination is

caused by the effects of frozen storage because the zero-force length is based on an extremely small force threshold of 0.25 N.

The susceptibility of the force-elongation curves and the zero-force lengths to preconditioning can be another source of artifacts. It is not unthinkable that some of the isolated ligaments, although treated with care, were accidentally subjected to minor strains while mounting them to the tensile testing machine. This may have affected the zero-force lengths in particular (18), but probably to a lesser extent than other sources.

The alignment of the wrist joint specimens to the RSA setup, and that of the isolated BLB preparation of the tensile testing machine, are a third and fourth potential cause of the artifacts to be considered. Slight rotations of the joint specimens around their longitudinal axes would result in slightly different recruitment patterns. However, the recruitment patterns for different specimens are similar (Fig. 2A). Therefore, it can be concluded that the influence of such an artifact would be small. The same is true for the alignment of the BLB preparations. Proper alignment is achieved by selecting the best of three independent trials. Furthermore, in a previous study the tangent moduli of the wrist joint ligaments were determined in a similar way (19). In that study, no extraordinarily large variations among the specimens were found. It was concluded that the method was accurate.

This leads to the conclusion that the variability may be explained by artifacts affecting the zero-force lengths of the ligaments, with freezing and unintentional slight preconditioning as the main causative factors. However, other potential artifacts are not likely to have major effects. On the one hand, the results of the length patterns are consistent among the specimens tested, as well as with previous studies (7,8,20). On the other hand, the force patterns are highly variable. Because the main artifacts, effects of freezing and unintentional slight preconditioning, are already present from the first moment of experimentation, this leads to the conclusion that, at least in these specimens, the wrist behaves kinematically consistent, but kinetically variable. This implies that mechanical behavior of the wrist is predominantly determined by articular geometry, and not by ligament constraints.

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