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Kinematics of the Wrist

I. An Experimental Study of Radial-Ulnar Deviation and Flexion-Extension*†

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ABSTRACT: **The kinematics of the wrist during radial-ulnar deviation and flexion-extension were studied in several ways. In six fresh cadaver wrists, the forearm was fixed in full pronation, each motion was constrained to one plane, and two metal markers were placed in each of the finger metacarpals, as well as in the radius and all of the carpal bones except the pisiform and greater multangular. Radial-ulnar and flexion-extension movements in these wrists were studied roentgenographically. In the wrists of six normal volunteers, a similar roentgenographic analysis was carried out and the trajectories of wrist motions also were studied using light-emitting diodes. Finally, roentgenographic measurements were made on 100 wrists of normal subjects. From these studies, it was concluded that: (1) during each of these motions, rotation occurs about a fixed axis located within the head of the capitate, and the location of each axis is not changed by the position of the hand in either plane; (2) the distance from the base of the third metacarpal to the distal articular surface of the radius (the carpal height), measured along the proximally projected axis of the third metacarpal on posteroanterior roentgenograms, is constant throughout radial-ulnar deviation of the normal wrist and can be used as a measure of carpal collapse; and (3) the perpendicular distance of the fixed axis of rotation for radial-ulnar deviation from the distally projected longitudinal axis of the ulna can be used as a quantitative measurement of the amount of translation of the carpus in pathological conditions.**

Appreciation of the integrated function of the wrist and hand recently has stimulated interest in the correlation of pathological processes involving the hand and those affecting the wrist [1,4,7,11,15,16].

Review of the literature shows that there were identifiable trends during the evolution of our knowledge of the kinematics of the wrist. The study of wrist motion began in 1896 after the discovery of x-rays [3]. The initial study and subsequent works [5,6,8,19] covered many significant aspects of normal wrist movement.

Efforts subsequently were made to analyze the motion of the wrist using various techniques such as stereoscopic [18,19] and plain roentgenograms [3], plaster molds and dissections [8], cineradiography [1,2], and simple anatomical dissection [10]. Experiments were done restraining the forearm with clamps [12] and other devices, but the details given were quite sketchy. In the experiments in which pins in the various bones [19] were used, projecting long pins were favored with the ligaments left intact so that angular changes could be determined.

In 1941, MacConaill, and more recently Arkless [1,2], bridged the gap between normal and abnormal kinematics of the wrist. MacConaill, using cadaver specimens and roentgenograms, studied normal kinematics and suggested a method to reduce dislocations of the lunate based on his observations. Arkless described cineradiographic findings during wrist motion in normal persons and in patients with rheumatoid arthritis, Kienböck's disease, and other disorders. More recently, others [7,12,15] have attempted to quantitate the pathological changes.

Thus, a firm foundation of qualitative observations of

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the anatomy of the normal wrist and its kinematics was established early in this century, while more recently the thrust has been toward making quantitative measurements of pathological changes.

Unfortunately, there has been no unanimity among the authors who described the normal kinematics of the wrist. For example, the center of motion of the wrist during radial and ulnar deviation has been reported to be in the body[9], head[17], and neck[11] of the capitate, and also was reported to translate during this motion[12]. In addition, quantitative measurements of wrists with pathological processes have been useful but fraught with problems. For example, the normal scapholunate angle as seen on lateral roentgenograms of the wrist has been described[12] as 46 degrees with a range of 30 to 60 degrees, but our attempts to measure so-called wrist collapse[7] in terms of this angle yielded results that were dependent on the position of the hand.

In an effort to reconcile these differences, we performed a two-phase study. In Part I, we focused on a kinematic analysis of the normal wrist and attempted to evolve normal quantitative relationships. In Part II, we applied the methods and measurements evolved in Part I to patients with certain wrist lesions. This paper reports on the Part-I studies; the clinical study will be reported in a later paper.

In Part I, we determined the following: (1) the loci of the centers of rotation in the planar movements of radial-ulnar deviation and flexion-extension motion; (2) the motions of the proximal and distal carpal rows, each row being considered as a unit during radial-ulnar deviation; (3) the relationships of individual carpal bones on posteroanterior roentgenograms during radial-ulnar deviation; and (4) the relationships of the capitate, lunate, and radius on lateral roentgenograms made during flexion and extension.

The following assumptions were made for the study of the cadaver specimens.

1. Every bone is a rigid body and the carpal bones are linked together by ligaments as kinematic chains.
2. Active wrist motion can be simulated by pulling on the extensor carpi ulnaris, extensor carpi radialis longus, extensor carpi radialis brevis, flexor carpi ulnaris, and flexor carpi radialis.
3. Passive wrist motion can be simulated by moving a Steinmann pin that is rigidly fixed in the long axis of the third metacarpal.
4. The kinematics of the carpal bones are essentially the same in fresh (unembalmed) cadaver specimens as in normal living subjects.

Materials and Methods

In this kinematic investigation of the wrist joint we used both cadaver specimens and live volunteers.

Six fresh forearms and hands from cadavera of two middle-aged men and one middle-aged woman were studied. There was no anatomical or roentgenographic evidence of abnormality in any specimen. Forearm rotation was eliminated by transfixing the radius and ulna with two Steinmann pins while the forearm was in full pronation, and by mounting the specimens in a rigid holding device secured to an x-ray table with suction cups (Fig. 1). A planar-motion constraint device (Fig. 1) was used to constrain the hand so that it moved in a purely planar fashion during radial-ulnar deviation and flexion-extension. This device was a semicircular plate of Plexiglass mounted on a frame whose position and height were adjustable. The Steinmann pin projecting from the third metacarpal glided on this plate during radial-ulnar and flexion-extension motion.

By dissection, two fine metal markers were embedded in each selected bone. To avoid confusion in interpreting the roentgenograms, a variety of different-shaped markers were used, such as fine Kirschner wires, dental screws, and watch parts. Great care was taken not to compromise the intracapsular ligament structures of the wrist[14]. The markers were embedded in each finger metacarpal, in the radius and ulna, and in all of the carpal bones except the pisiform and the greater multangular. These two were not marked because the pisiform is a sesamoid bone of the

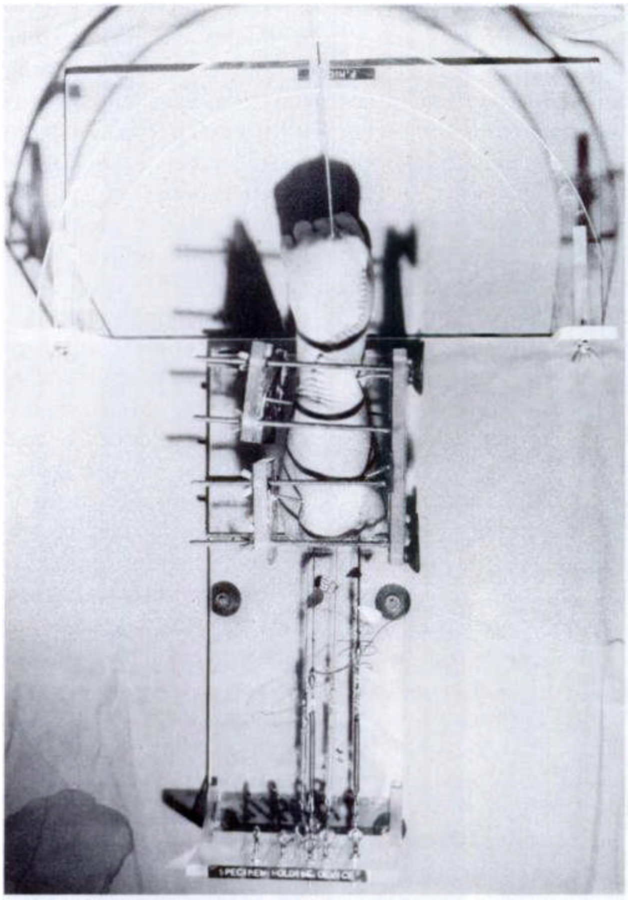

FIG. 1

Prepared specimen mounted in forearm-holding device with the semicircular Plexiglass planar-motion constraint device in position for radial-ulnar deviation. For flexion-extension, the holding device and forearm were rotated 90 degrees about the long axis of the forearm.

flexor carpi ulnaris and is not relevant to this study, and the greater multangular is intimately involved in the motion of the thumb and is the subject of a separate study.

After the markers had been placed, roentgenograms were made to ensure that the markers were not overlapping or otherwise obscured as seen on the posteroanterior and lateral roentgenograms. Three non-collinear points are required for a three-dimensional analysis of motion. However, in an analysis of two selected constrained planar motions as in this study, two points are sufficient for the graphical method used.

The tendons of the five major muscles moving the wrist (the flexor and extensor carpi ulnaris, the flexor carpi radialis, and the extensor carpi radialis longus and brevis) were then isolated proximal to the wrist and a silk suture was placed in each tendon. The sutures were passed subcutaneously and proximally to be brought out through the proximal end of the specimen. By pulling on these sutures and through them on the tendons, active motions could be simulated. For radial-ulnar deviation, the forearm-holding device was adjusted as shown in Figure 1 (with the midpoints of the distal ends of the radius and ulna in the same plane as that of the Plexiglass plate). For flexion-extension, the forearm-holding device was rotated 90 degrees without changing the position of the Plexiglass plate. Passive motions were reproduced by moving the Steinmann pin (fixed in the third metacarpal) along the Plexiglass plate. A thirty-five-millimeter cineradiographic machine and high-resolution film (Kodak XX negative) were used to make cineradiograms of each motion at the rate of thirty-two frames per second as the wrist was moved slowly through each arc of motion. The time required to complete an arc of motion was between four and five seconds.

While the results obtained for radial-ulnar deviation in the posteroanterior projection using the cineradiographic technique were very useful, difficulty in resolution was encountered in the lateral plane. Therefore, in addition, the Schonander apparatus was used to study motion in both planes. With this device we obtained twelve to fifteen roentgenograms, 30.5 by 35.5 centimeters, during the four to five seconds required to complete each arc of motion. The definition of these roentgenograms was very good and allowed accurate measurements to be made.

The cineradiograms and roentgenograms thus obtained were analyzed graphically. A Recordak microfilm reader with a magnification factor of forty was used to project each cineradiogram frame onto a digitizing platen. No special instrument except a normal viewbox was needed for the analysis of the roentgenograms obtained with the Schonander equipment.

In the reduction of the data all of the Schonander roentgenograms and every fifth frame of the cineradiographic film were traced for one full arc of radial-ulnar deviation and of flexion-extension. The outlines of the bones and the precise positions of the metal markers were recorded on tracing paper. The graphic method illustrated in Figures 2 and 3 was employed to determine the center of rotation.

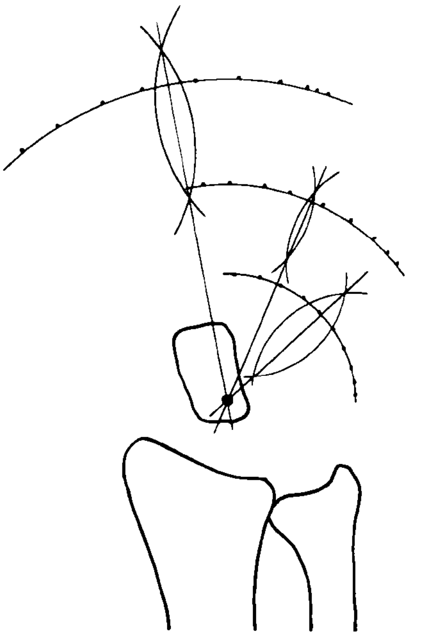

FIG. 2

The center of rotation during radial-ulnar deviation of a representative specimen. The dots show the successive positions of the representative metal markers embedded in the second and third metacarpals. The center of rotation of the wrist determined graphically as shown is located in the head of the capitate.

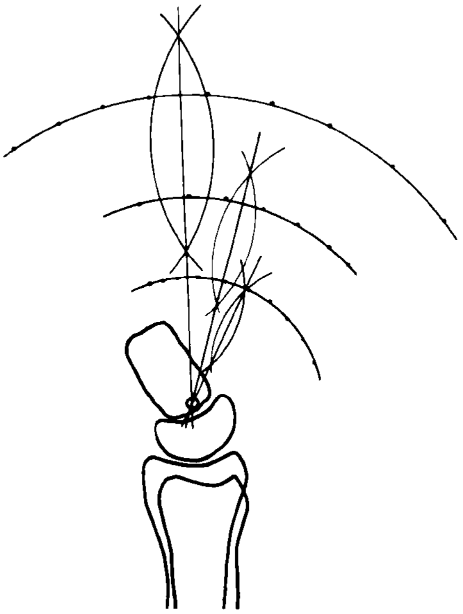

FIG. 3

The center of rotation during flexion-extension of a representative specimen is located in the proximal part of the head of the capitate near the lunate.

To compare the measurements obtained in the cadaver specimens with those in the wrists of normal subjects, roentgenograms were made of six hands of normal young men using the Schonander technique. To reduce radiation hazards the exposure time was restricted to three seconds, with nine roentgenograms obtained during each arc of motion. For these studies one of us restrained the volunteer's forearm in mid-pronation during active motion constrained in the planes of radial-ulnar deviation and of flexion-extension by the Plexiglass plate.

A multinotched Kirschner wire was taped tightly to the dorsum of the hand along the axis of the third metacarpal. Its distal end projected beyond the tip of the extended long finger. Three arbitrary collinear points were located on the Kirschner wire, the bone prominences on the heads of the second and third metacarpals, and the cortical outlines of the distal ends of the radius and ulna. These points were used to establish the necessary points for the subsequent graphic analysis, which was conducted in the same fashion as the analysis of the cadaver specimens.

Finally, posteroanterior roentgenograms of both wrists of fifty normal young women were analyzed by applying measurements derived from the cadaver study (to be described) to delineate normal quantitative relationships of the carpus to the metacarpals and forearm bones.

To establish the characteristic trajectory of the hand during radial-ulnar and flexion-extension motions, both the six cadaver and the six normal hands were studied in a dark room using light-emitting diodes and long exposures on both Polaroid film and thirty-five-millimeter slides. For the cadaver wrists, two diodes were screwed into the dorsum of the third metacarpal on its longitudinal axis. Two diodes were fixed similarly on the longitudinal axis of the distal part of the radius. Each specimen was mounted on the forearm-holding device and the planar constrained motion experiments were repeated in a darkened room with the camera recording the tracks traced by the pulsating lights of the diodes.

The same experiments were performed on six living subjects. The diodes were taped tightly to the hand and to the distal part of the forearm in positions comparable to those in the cadaver experiments. The forearms of the living subjects were restrained by Velcro straps in a specially designed forearm-holding apparatus. This gutter-type device was fixed securely to the experimental table. The subjects performed active radial-ulnar deviation and flexion-extension, being careful to move the hand only in the plane of the planar constraint device.

After the experiments were completed, roentgenograms were made of the hands of the cadavera and of the living subjects with the diodes still attached. From these roentgenograms the relationships of the diodes to the skeleton were established for use in subsequent analysis.

Results

Center of Rotation of the Wrist

This was determined for the two constrained planar motions (radial-ulnar deviation and flexion-extension) using the tracings of the cineradiograms and of the serial roentgenograms. Despite variability in the size and shape of the different capitates and some inherent inaccuracy in the curve-fitting graphic method, the different positions of the metal markers in the second and third metacarpals of the six cadaver hands studied described almost perfect arcs of circles during radial-ulnar deviation and flexion-extension. The centers of these circles (Figs. 2 and 3) were in the head of the capitate and represented the centers of rotation for these two motions. The center of rotation for flexion-extension was slightly more proximal (nearer the lunate) than was the center for radial-ulnar deviation.

When the loci of the two metal markers in the capitate were used in the same way to determine the centers of rotation (Fig. 4), the centers again were shown to be in the head of the capitate. The Schonander study of live volunteers showed similar results. The centers of rotation determined in this study were located consistently in the head of the capitate.

In the light-emitting diode experiment, the trajectories traced by the two diodes located on the third metacarpal of the six cadaver specimens and the six live volunteers were circular (Fig. 5). The results in the six liv-

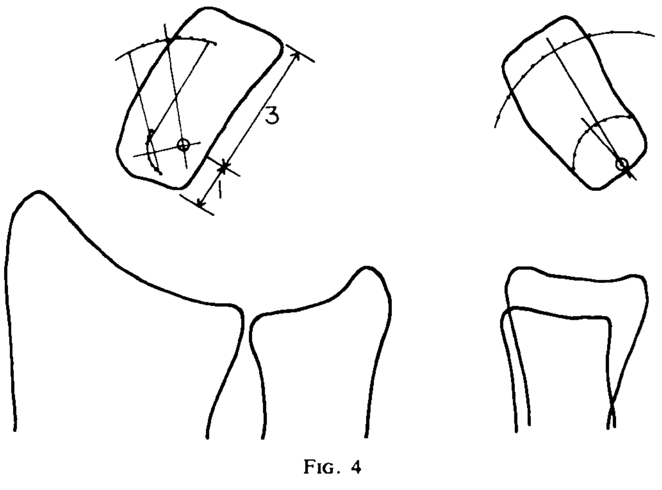

FIG. 4

The location of the center of rotation during ulnar deviation (left) and extension (right), determined graphically using the two metal markers embedded in the capitate. Note that during radial-ulnar deviation the center lies at a point in the capitate situated distal to the proximal end of this bone by a distance equivalent to approximately one-quarter of its total longitudinal length. During flexion-extension, the center of rotation is close to the proximal cortex of the capitate.

FIG. 5

Tracks of the diodes located over the third metacarpal and over the radius of a living subject during radial-ulnar deviation (left) and flexion-extension (right). In both pictures the oval lower dots represent the diodes over the constrained radius. The upper curved arcs show the trajectories of the hand during these two motions.

ing subjects showed minor imperfections caused by movements of the skin to which the diodes were attached. However, in general, the results with the diodes confirmed those obtained roentgenographically.

From these experiments we established a useful rule of thumb for locating the centers of rotation. On posteroanterior roentgenograms the center of rotation for radial-ulnar deviation is slightly to the ulnar side of the longitudinal axis of the capitate at a point located at one-quarter of the total length of the capitate distal to its proximal end. The center of rotation for flexion-extension motion on the lateral roentgenogram is on the longitudinal axis of the capitate just distal to its proximal cortex (Fig. 4).

Carpal Height

Carpal height, the term we use to designate the distance between the base of the third metacarpal and the distal articular surface of the radius measured along the proximal projection of the longitudinal axis of the third metacarpal, was determined on posteroanterior roentgenograms made during radial-ulnar deviation. In each of the six cadaver wrists and in the six normal living subjects, this measurement was constant in all positions (Figs. 6, 7-A, and 7-B) even though the actual length varied from wrist to wrist depending on the size of the hand. The mean angle formed by the longitudinal axes of the third metacarpal and of the capitate as seen on the posteroanterior roentgenograms was 170 ± 5 degrees (Fig. 7-B). It is because of this angle that the lines representing the carpal heights as shown on Figure 7-A do not intersect at the center of rotation of the wrist.

An interesting additional finding was that when the lines representing the carpal heights in different positions of radial-ulnar deviation were bisected and perpendicular lines were drawn at these mid-points, these perpendicular lines intersected at the previously determined center of rotation in the capitate (Fig. 8), thus further confirming the location of the center of rotation for radial-ulnar deviation.

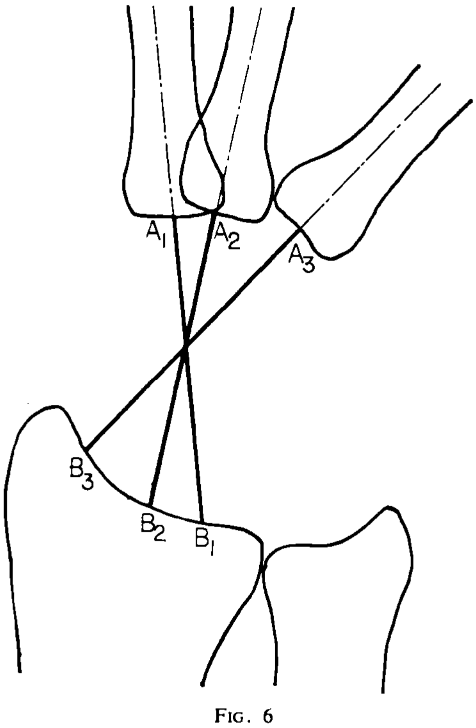

FIG. 6

The carpal height in a normal hand remains the same in all positions of radial-ulnar deviation. The projection of the axis of the third metacarpal during radial-ulnar deviation of the normal wrist lies within the margins of the articular surface of the radius. Note that the lengths of A_1B_1, A_2B_2, and A_3B_3 are equal.

From the measurements of carpal height taken from the roentgenograms of all the hands studied, a consistent ratio was derived. For these hands the average ratio of the carpal height to the length of the third metacarpal was 0.54 with a standard deviation of ± 0.03 (Fig. 9).

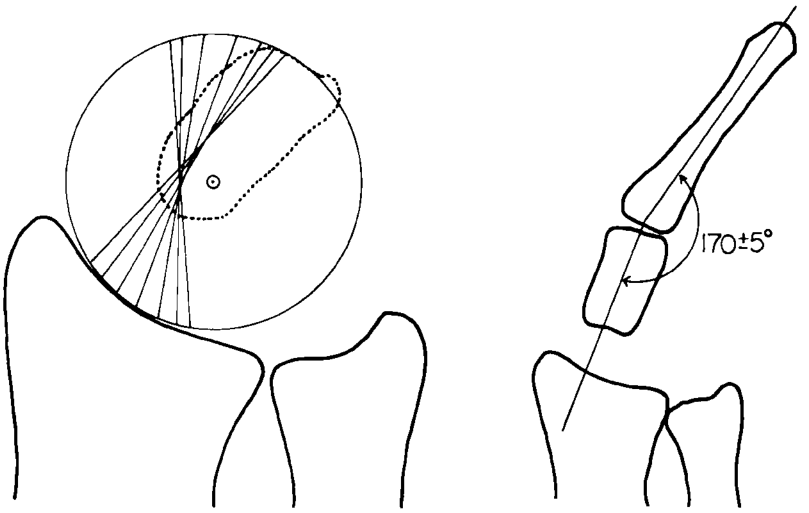

FIG. 7-A FIG. 7-B

Figs. 7-A and 7-B: The carpal height remains constant during circular motion of radial-ulnar deviation of the wrist joint.

Fig. 7-A: Note that the lines representing the carpal heights do not intersect at one point because the longitudinal axes of the third metacarpal and of the capitate are not parallel.

Fig. 7-B: The axes form an angle of 170 ± 5 degrees.

This ratio can be used clinically to develop a quantitative assessment of the loss of carpal height seen in pathological conditions involving the wrist. We term this change carpal collapse. This expression can be calculated by subtracting the carpal height ratio in the abnormal wrist from the corresponding normal ratio, determined from the roentgenograms of the same wrist made before the pathological changes developed or from the roentgenograms of the opposite wrist if it is normal. Average normal values can also be used successfully for comparison. By expressing carpal collapse as a ratio, problems related to magnification, size of the hand, and differences in roentgenographic technique are eliminated.

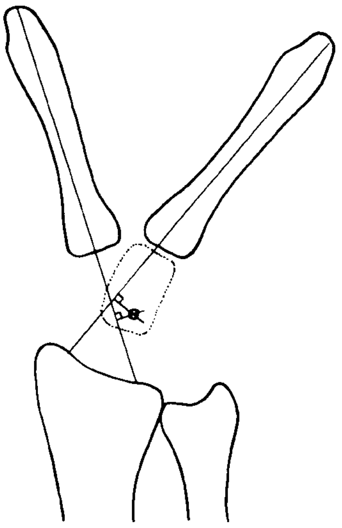

FIG. 8

Because the carpal height is constant in all positions of the wrist, the center of rotation of the wrist during radial-ulnar deviation can be obtained graphically as shown. The perpendicular lines that bisect the carpal heights intersect at the center of rotation for radial-ulnar deviation.

Carpal-Ulnar Distance

The perpendicular distance from the center of rotation for radial-ulnar deviation of the wrist to the longitudinal axis of the ulna projected distally was measured on the posteroanterior roentgenogram and defined as the carpal-ulnar distance. Since the location of the center of rotation is constant and is located in the head of the capitate, carpal translation can be determined in quantitative terms by measuring the carpal-ulnar distance (Fig. 10). In all the hands studied, this distance remained constant in all positions of radial-ulnar deviation and the average ratio of this distance to the length of the third metacarpal was 0.30 ± 0.03.

This carpal-ulnar distance can be used clinically to

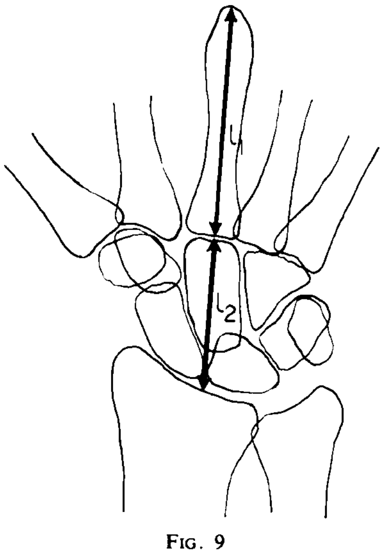

FIG. 9

The carpal height ratio can be calculated as l_1/l_2 where l_1 is the length of the third metacarpal and l_2 is the carpal height. In the normal wrist this ratio is 0.54 ± 0.03.

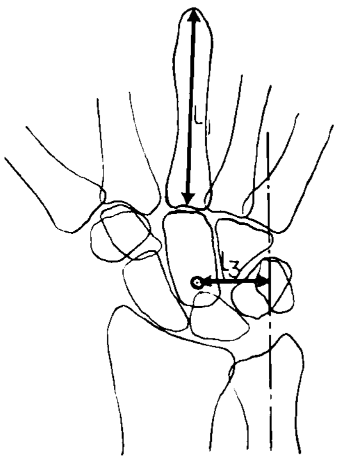

FIG. 10

The carpal-ulnar distance ratio can be calculated as l_3/l_1, where l_3 is the carpal-ulnar distance and l_1 is the length of the third metacarpal. In the normal wrist this ratio is 0. 3 ± 0.03.

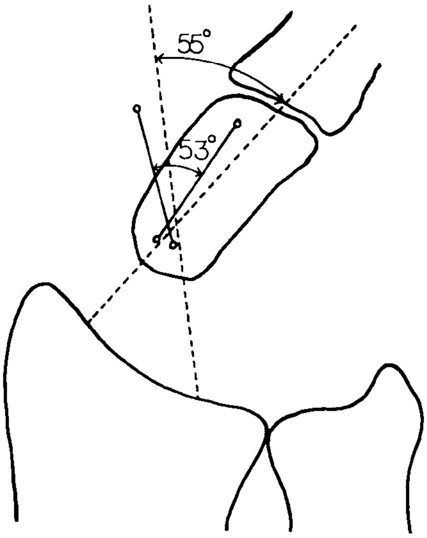

FIG. 11

The so-called fixed unit hypothesis as illustrated by the movements of the capitate and third metacarpal during radial-ulnar deviation. Note that the capitate and the third metacarpal traverse nearly equal angles. The solid lines represent the positions of the capitate and the broken lines show the positions of the third metacarpal.

obtain a quantitative expression of ulnar shift of the carpus in pathological states of the wrist. We term this change carpal translation. By subtracting this ratio in the abnormal wrist from the same ratio in the normal wrist, as determined from roentgenograms of the same wrist made previously or of the contralateral normal wrist, a quantitative value for carpal translation can be obtained.

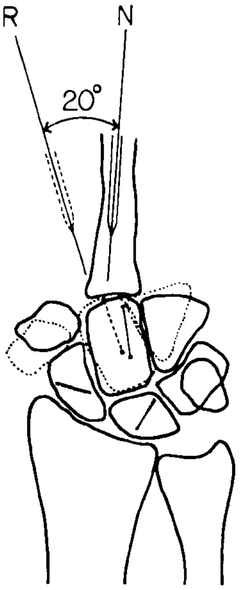

FIG. 12

Movements of the capitate, scaphoid, and lunate from neutral to 20 degrees of radial deviation. The neutral positions are represented by solid lines and 20 degrees of radial deviation is shown by dotted lines. The proximal carpal row does not move during radial deviation, showing that this motion occurs at the intercarpal joint.

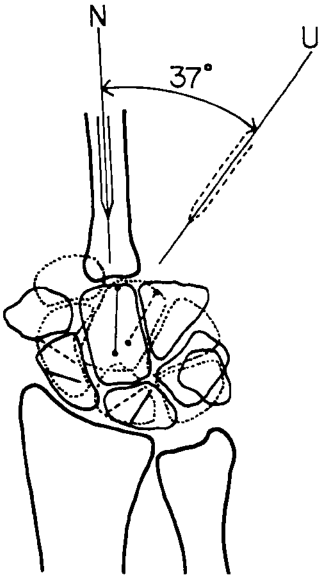

FIG. 13

Carpal movements from neutral to 37 degrees of ulnar deviation. The neutral positions are represented by solid lines and 37 degrees of ulnar deviation is shown by dotted lines. The bones in the proximal and distal rows all move appreciably, showing that ulnar deviation occurs at both the radiocarpal and the intercarpal joints.

Verification of the Fixed Unit Hypothesis

It has long been stated that the second and third metacarpals together with the capitate and lesser multangular move as one fixed unit. In order to verify this so-called fixed unit hypothesis, we reviewed the posteroanterior and lateral roentgenograms obtained in this study of wrist motion. By means of the two metal markers located in each of the four bones, angular changes in position were measured in both planes. Figure 11 shows that the capitate and third metacarpal moved a maximum of 2 degrees in relation to each other. The relative motion between the other two bones was comparable. In addition, there was no detectable motion between the capitate and the lesser multangular. The motions between the four bones that com-

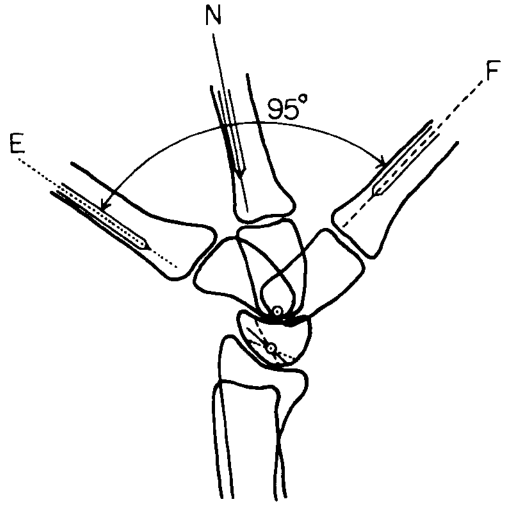

FIG. 14

Movements of the lunate, capitate, and third metacarpal during flexion-extension. For clarity the lunate is traced only in neutral position, but its positions in neutral and in maximum flexion and extension are indicated by the solid, broken, and dotted lines, respectively. The capitate and third metacarpal are traced in all three positions. Note that both radiocarpal and intercarpal motion occur during flexion-extension.

prise the so-called fixed unit were negligible throughout the 55 degrees of radial-ulnar deviation in the six specimens studied, and the fixed unit hypothesis therefore was verified.

Since the wrist motion study was done with both simulated active and passive motions, an opportunity was provided to determine whether the bones of the fixed unit moved differently in these two experiments. The maximum angular change between the components of the fixed unit was 2 degrees during simulated active motion. When passive motion was produced by pushing forcefully on the Steinmann pin in the third metacarpal, this maximum angular change was increased to 4.5 degrees. We believe that this limited additional motion was produced by deformation of the soft tissues.

Over-All Motions of the Carpus

The over-all motion of the carpal bones, considered as a unit, represents the summation of the movements of each individual bone. This motion was analyzed by determining the motions of each carpal bone during both radial-ulnar deviation and flexion-extension. Over-all radial-ulnar deviation of the carpus was measured from the neutral position, which was defined as the position of the hand in which the longitudinal axis of the third metacarpal was parallel to the long axis of the forearm or passed through the navicular-lunate gap.

During passive deviation of the hand from the neutral position to 20 degrees of radial deviation, the motions of the bones of the proximal carpal row (scaphoid, lunate, and triquetrum) relative to the radius were negligible (Fig. 12), as were the motions of these bones relative to one another. Therefore, radial deviation occurred at the intercarpal joint between the proximal and distal carpal rows.

During passive deviation of the wrist from the neutral position to 37 degrees of ulnar deviation, both intercarpal and radiocarpal motion occurred (Fig. 13), indicating that both of these joints contributed to this motion. It is of interest that even though ulnar deviation was nearly twice radial deviation and very different motions of the bones in the proximal carpal row were involved in these two wrist movements, the centers of rotation for radial and ulnar deviation were the same.

Throughout the entire spectrum of 95 degrees of passive flexion-extension motion of the wrist, both the distal and the proximal carpal rows were rotating continually (Fig. 14).

Information derived from a more detailed analysis of the relative motions of the individual carpal bones will be presented in a subsequent publication.

Conclusions

1. The trajectories of the hand during radial-ulnar deviation and flexion-extension, when they occur in a fixed plane, are circular and the rotation in each plane takes place about a fixed axis. These axes are located within the head of the capitate and are not altered by the position of the hand in the plane of rotation.

2. Carpal height, the distance from the base of the third metacarpal to the distal articular surface of the radius, measured on posteroanterior roentgenograms along the projected longitudinal axis of the third metacarpal, is constant in the normal wrist in all positions of radial-ulnar deviation when this rotation occurs in a fixed plane. The ratio of this height to the length of the third metacarpal is 0.54 ± 0.03.

3. Carpal-ulnar distance, the perpendicular distance between the fixed axis of rotation during radial-ulnar deviation of the wrist and the projected longitudinal axis of the ulna, as determined on the posteroanterior roentgenogram, is constant in the normal wrist in all positions of radial-ulnar deviation in a fixed plane. The ratio of this distance to the length of the third metacarpal is 0.30 ± 0.03.

4. Pathological alterations of the wrist associated with carpal collapse and ulnar translation of the carpus can be quantitatively evaluated using the carpal height and carpal-ulnar distance ratios. By using ratios, differences in hand size and roentgenographic magnification are eliminated as variables.

5. The fixed unit hypothesis of the hand, to the effect that the second and third metacarpals in company with the capitate and lesser multangular complex function as a single unit, is confirmed by the findings in this study.

6. Radial deviation of the wrist from the neutral position occurs at the intercarpal joint, while the proximal carpal row does not move. Ulnar deviation from the neutral position, however, is the result of motion in both the intercarpal and the radiocarpal joints.

7. Both the radiocarpal and the intercarpal joints contribute to all phases of flexion-extension motion of the wrist.

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