Flexafix: The development of a new dynamic external fixation device for the treatment of distal radial fractures
Goslings, J.C.

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Chapter 7

Kinematics of the wrist with the Flexafix device

Submitted for publication.

7.1 Introduction

As described in Chapter 2, various methods have been used in the past to describe the motion of the radius, ulna, carpal and metacarpal bones in relation to each other. In earlier days X-rays were used to study the angles between the bones in different positions of the hand.\textsuperscript{168,169,170} This technique was also used to describe patterns of carpal movement in cineradiographs of the wrist.\textsuperscript{171,172} However, these methods provided indirect information about planar movements. In order to obtain more direct information about the three-dimensional aspect of wrist motion, carpal bones have been implanted with metal markers after which biplanar radiography was performed.\textsuperscript{173,174,175} With this technique the XYZ-coordinates and thus the position and orientation of the respective bones could be determined. Others have used light emitting diodes or sonic digitizers to analyse the three-dimensional properties of the wrist.\textsuperscript{21,176,177} The techniques mentioned above were based on a sequential static analysis of motion, whereas the dynamic aspect of wrist motion could not be addressed.
At the University of Texas Medical Branch in Galveston (Texas, U.S.A.) a technique for kinematic analysis of the wrist has been developed and validated.\textsuperscript{178,179,180} The technique combines data acquired from high-speed video images and three-dimensional reconstructions of CT-scans, which results in a visual animation of the actual motion pattern. In this way, the motions of the carpal bones can be calculated in a dynamic mode. This method has added to the knowledge of the normal kinematics of the wrist and can be applied to help understand abnormal clinical conditions such as carpal instabilities, degenerative diseases and distal radial fractures.

Until recently, most external fixators for the treatment of unstable distal radial fractures did not allow motion at the wrist. The introduction of dynamic external fixators in 1987 has given the possibility of early functional treatment, i.e. movement of the wrist during the period the fixator is mounted.\textsuperscript{17} Early motion of joints after fracture treatment may facilitate the repair of articular cartilage and could possibly reduce the complications of joint immobilisation.\textsuperscript{10,13} It is important to address attention to the effect of this new treatment modality on the kinematics of the wrist. A dynamic external fixation device for the treatment of distal radial fractures should be kinematically compatible with the joint, allowing unconstrained movement of the wrist. However, Patterson et al. have shown that several commercially available dynamic external fixation devices for the treatment of distal radial fractures do not replicate the normal kinematics.\textsuperscript{167} Any device that does alter normal kinematics brings the risk with it of forcing the carpal bones into an abnormal pattern of movement or displacement of fracture fragments.

Also, distal radial fractures can be accompanied by ligamentous injury. Richards performed arthroscopy in 118 patients with acute, intra- and extra-articular distal radial fractures.\textsuperscript{68} A tear of the scapholunate ligament was present in 22\% of intra-articular fractures and in 7\% of extra-articular fractures. Lunotriquetral ligament injuries were seen in 7\% of intra-articular fractures and in 13\% of extra-articular fractures. Geissler diagnosed scapholunate tears in 32\% and lunotriquetral injuries in 15\% of intra-articular fractures in 60 patients.\textsuperscript{181} However, the effect on carpal kinematics of dynamic external fixation in the case of a distal radial fracture accompanied by ligamentous injury has not been studied.

While most available dynamic external fixation devices have an articulating part that has its centre of rotation in the device itself (i.e. outside the wrist), the Flexafix dynamic external fixator is a new device which permits motion in three planes while the centre of rotation of all the movements is located at a point outside the device.\textsuperscript{17,19,20} During the operation this centre of rotation of the device can be positioned within the anatomic space of the wrist. The aim of this study was to analyse the effect of the Flexafix device on wrist kinematics under various conditions.
7.2 Materials and methods

7.2.1 Specimen preparation
Four fresh frozen cadaver upper extremities without visible or radiographically identifiable abnormalities were used. All specimens (two left arms and two right arms) were from men; the average age was 46 years (range 32 to 56 years). Under image intensifier control triad pins were placed in the radius, scaphoid, lunate, capitate and third metacarpal bones in a way that they would not touch each other during movement of the wrist. Care was taken not to place the pins through tendons or other soft tissues involved in wrist motion to avoid altering or otherwise influencing motion. These rigid pins have three spheres of approximately 5 millimetres in diameter placed in a cruciform arrangement on top. To enhance their reflective properties, the spheres were coated with photoreflective paint.

The flexor carpi ulnaris, flexor carpi radialis, and extensor carpi ulnaris tendons were then dissected and each of their end sutured to form a total of three loops. The extensor carpi radialis longus and brevis were looped together to form the fourth loop. The flexor and extensor tendon loops on the radial side of the wrist were then connected by wires to a free-floating pulley; this procedure was repeated for the loops on the ulnar side of the wrist. These two pulleys were both weighted by 5 lb. (2.27 kg) and allowed the tendon pairs to move synergistically during motion while the weight simulated muscle tone. The upper arm was placed into a jig with the elbow flexed 90° and the forearm in neutral orientation while allowing free wrist motion.

With the help of an aiming device (pointing towards the centre of rotation of the sliding mechanism) and 2.5 mm threaded Kirschner wires the Flexafix dynamic external fixator was applied at the radial side of the wrist with the centre of rotation of the device positioned in the proximal part of the capitate bone. Its position was checked with an image intensifier.

After obtaining normal kinematic data was obtained in all four wrists, in two specimens a scapholunate ligament (SL) injury was simulated. The dorsal capsule of the wrist was opened, the scapholunate ligament was completely transected and the DIC ligament was freed from the lunate (see Figure 5, p.20). After the SL tear was made the dorsal capsule was repaired with a suture.

7.2.2 Three-dimensional carpal bone reconstruction
Transverse images of the wrist and triad pins were obtained with a CT scanner (GE 9800, General Electric Medical Systems, Milwaukee, Wisconsin, U.S.A.) generating slices 1.5 millimetres thick. The 3-D shape of the bones was extracted using a software program developed at UTMB running on a SunSparc 2 workstation (Sun Microsystems...
Inc., Mountain View, California, U.S.A.). In each CT slice, the boundaries of the bones were digitally tracked in an interactive process. The data obtained from all the slices were collected and grouped by the program, after which the boundaries of each bone were assembled as a 3-D model using the Application Visualisation System (AVS Inc., Dallas, Texas, U.S.A.) running on a Graphic Workstation (Evans & Sutherland Corp., Salt Lake City, Utah, U.S.A.).  

### 7.2.3 Kinematic data collection

Each wrist was moved passively through several flexion-extension and radio-ulnar deviation cycles by a Kirschner wire inserted in the third metacarpal bone. Four black and white video cameras (High performance CCD cameras, Cohu Inc., San Diego, California, U.S.A.), arranged around the wrist, tracked the triad pins’ reflective surfaces throughout the motion cycles, creating motion path files. The three-dimensional paths for the triad pins were determined by combining the video data, collected at 60 frames per second (Expert Vision System, Motion Analysis Corp., Santa Rosa, California, U.S.A.). The specimens were tested twice: once in the normal condition and once with the Flexafix device mounted. Two specimen were tested four times: once without the fixator, once with the Flexafix device mounted, once after transection of the scapholunate ligament and once after application of the Flexafix device in the presence of the ligament injury.

### 7.2.4 Animation

The three-dimensional geometric reconstructions and the kinematic path data were combined to create an animation of the actual wrist motion. This provides a visual check to validate the calculated motion of the bones, as well as a simple, understandable way to display the data. From the kinematic analysis, measurements that were hypothesised to characterise carpal bone motion were calculated. These included global wrist angle and Euler angles between the bones. Global wrist angle describes the global motion of the wrist and is measured as the angle between the long axis of the third metacarpal and the long axis of the radius. Euler angles represent the angle of one body to another body during motion in relation to a coordinate system. Of the three resulting Euler angles, only the angles in the plane of the motion that was tested were analyzed.

If mounted on the radial side of the wrist, due to its design the Flexafix device allows more flexion extension than radio-ulnar deviation; in this position the latter is limited to 20 degrees (see Chapter 5). Carpal motions (i.e. radiolunate, capitolunate and scapholunate angles) were analysed between 40° of flexion, 40° of extension, 5° of radial deviation and 15° of ulnar deviation. The data for each position of the hand of
were for the wrists tested averaged (at one degree intervals) and the standard deviation (SD) of these averages was calculated, including minimal and maximal SD. The carpal angles were plotted relative to the position (i.e. global wrist angle) of the hand.

7.3 Results

7.3.1 Flexion-extension
Measurement of the radiolunate angle results in a negative value when the lunate is flexed relative to the radius; a positive value corresponds to extension of the lunate. In a movement of both 40 degrees of flexion and 40 degrees of extension, the radiolunate angle in the normal wrist was $-31.2^\circ$ in wrist flexion and $21.3^\circ$ in wrist extension (mean SD 4.0\(^\circ\), range 2.0\(^\circ\) - 5.8\(^\circ\)). With the fixator, these values were $-29.5^\circ$ and 20.0\(^\circ\) respectively (mean SD 4.3\(^\circ\), range 3.1\(^\circ\) - 6.2\(^\circ\)). The difference in the position of the curves was less than two degrees during the entire range of motion tested (Fig. 46).

When the capitate is flexed relative to the lunate, the capitolunate angle is expressed by a positive value; extension of the capitate relative to the lunate results in a negative value. The capitolunate angle was 12.6\(^\circ\) in wrist flexion and -14.8\(^\circ\) in wrist extension (mean SD 7.5 range 6.4 - 8.4) in the normal wrist compared to 16.6\(^\circ\) and -13.6\(^\circ\) (mean SD 6.5\(^\circ\) range 5.1\(^\circ\) - 8.2\(^\circ\)) after application of the fixator. The curve displaying the wrist with the fixator was situated one to four degrees above the curve for the normal wrist with the most close relation between neutral and 25\(^\circ\) of flexion (Fig. 47).

In the normal wrist the scapholunate angle was 15.2\(^\circ\) in wrist flexion and -2.9\(^\circ\) in wrist extension (mean SD 5.2\(^\circ\), range 4.2\(^\circ\) - 6.4\(^\circ\)) with a positive value representing the scaphoid flexed relative to the lunate and a negative value with the scaphoid extended relative to the lunate. In the wrist with the Flexafix device attached these

![Figure 46. Radiolunate angle during flexion and extension.](image-url)
values were 14.8° and -3.1° (mean SD 7.8°, range 4.7° - 9.2°). The plotted curves were closely together during the range of motion tested with a maximum difference in position between the curves of two degrees (during extension) (Fig. 48).

Figure 47.
Capitolunate angle during flexion and extension.

Figure 48.
Scapholunate angle during flexion and extension.

Table 6 shows the three carpal joint angles in different positions of the hand and the ranges of these angles during wrist motion between 40° of flexion and 40° of extension. The ranges describe the shape of the carpal angle curves rather than the position of the curves relative to each other as described above.

7.3.2 Radio-ulnar deviation
During movement of the hand from 15 degrees of ulnar deviation to 5 degrees of radial deviation the radiolunate angle is negative with the lunate in ulnar deviation relative to the radius and positive with the lunate in radial deviation. In the normal condition, the radiolunate angle was -8.1° in ulnar deviation and 1.4° in radial deviation (mean SD 4.7°, range 3.6° to 7.1°), compared to -9.7° and -0.2° (mean SD 4.6, range 4.2 to 5.8)
Kinematics of the wrist with the Flexafix device

respectively after application of the fixator. The curve of the fixator was consistently approximately three degrees below the normal curve (Fig. 49).

A positive value for the capitolunate angle represents ulnar deviation of the capitate relative to the lunate, a negative value radial deviation relative to the lunate. The capitolunate angle was 5.4° in ulnar deviation and -4.7° in radial deviation (mean SD 4.3°, range 4.0° to 5.5°) in the normal wrist versus 9.6° and -2.8° (mean SD 2.9, range

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-40°/40° range

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-40°/40° range

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Table 6.
Range of carpal motion (in degrees) around X-axis (flexion-extension) during movement from -40° of flexion to 40° of extension. Normal = uninjured wrist; fixator = wrist with Flexafix device applied; sln = wrist with scapholunate ligament transected; slfix = Flexafix device applied to wrist with scapholunate injury. Radlun= radiolunate angle, caplun= capitolunate angle, scalun= scapholunate angle.

Figure 49.
Radiolunate angle during radial deviation and ulnar deviation.
1.3 to 5.1) respectively with the fixator (Fig 50). The difference in position between the curves was less than two degrees except near maximum ulnar deviation tested (four degrees).

The scapholunate angle was not determined during radio-ulnar deviation since out of plane motions for this carpal angle were larger than the motions in the principal plane of motion, caused by flexion-extension movements of the scaphoid.

7.3.3 Scapholunate ligament injury
After transection of the scapholunate ligament (SL) in two wrists, the mean radiolunate angle in a flexion-extension movement (40°/40°) was -20.5° in wrist flexion and 19.0° in wrist extension, which is less than before SL transection (Table 6). Application of the fixator in presence of the SL injury resulted in a radiolunate angle from -22.1° in flexion and 19.4° in extension (Fig. 51).

The mean capitolunate angle was 19.6° in flexion and -20.8° in extension without the fixator; with the fixator the values were 17.9° and -20.5° (Fig. 52). The mean scapholunate angle after transection of the SL ligament was 26.7° in flexion and -6.2° in extension.
without the fixator compared to 25.9° and -5.5° with the Flexafix device (Fig. 53). Both the capitolunate and scapholunate angles were increased compared to the angles prior to SL transection. The difference in the position of the curves for the two conditions (SL injury only and SL injury in presence of the fixator) was less than two degrees for all three angles measured during the entire range of motion tested.

7.4 Discussion

This study was designed to analyse the effect of a new dynamic external fixation device developed for the treatment of distal radial fractures on wrist kinematics. It is important to know these effects because any device which is kinematically incompatible with the wrist could possibly lead to abnormal loading conditions. Of all the available techniques to study kinematics a relatively new method was used because this technique provides information about the dynamic aspect of the motion studied. Other radiographic studies, such as standard X-rays, biplanar X-rays, CT-scans and MRI-scans are limited
to the gross approximation of dynamic motion by repeated static positioning. The present study used reflective triad pins rigidly fixed to the bones and high-speed video data collection of wrist kinematics, combined with 3-D reconstructions of CT images. The forearm was stabilised and the wrist was allowed to move freely. The flexor and extensor tendons were loaded with weights, the wrist was moved passively. Another method could have been to move the wrist by active tendon loading with calibrated springs according to physiological cross-sectional area. Since the aim of this study was to compare several conditions, this would probably not have changed the outcome. The technique used in this study has its limitations; it is performed in vitro and implantation of triad pins could potentially disturb normal motion, although care was taken to avoid this.

The range of motion of the wrists tested was to some extent limited by the Flexafix device. When applied to the radial side of the wrist, the device theoretically allows free flexion and extension and 20 degrees of combined radio-ulnar deviation. The mean range of motion with the device in the wrists tested was 121° (70° of flexion and 51° of extension), which is close to the normal range of motion and more than other dynamic external fixation devices tested previously which showed a ROM varying between 94° and 107°. Also, this range provides most of the range of motion needed to perform activities of daily living.

The main aspect of the study was to determine the effect of the Flexafix dynamic external fixator on carpal bone motion. A change, induced by the device, in the normal angles between the individual bones could result in impingement and/or distraction between the bones in parts of the range of motion. In addition, with the device applied to a forearm with a fractured distal radius, the abnormal kinematics may result in fracture dislocation. Further, abnormal loading conditions have been related to the development of arthrosis. On the other hand, it seems unlikely that this will develop during the four weeks that the fixator is used in the dynamic mode, since most authors start the dynamisation two or three weeks after the operation. Nevertheless, a dynamic external fixator which is to be used in its dynamic mode should allow unconstrained movement of the wrist.

There are several means to interpret the measured angles and the differences between the curves in the conditions tested. The difference in the position of the curves can be caused by the fixator altering the normal position and movement of the carpal bones. The differences found during flexion-extension were generally small with a maximum of 4 degrees. Other possible explanations for a higher of lower position of the curve could be slightly different loading conditions between the normal wrist and after application of the fixator. The fixator was mounted on the wrist in an unloaded state, after which it was loaded for testing.
The pattern of the movements displayed by the carpal bones that were studied was comparable for both conditions as shown by the ranges of the carpal angles during flexion-extension tested. In the limited flexion-extension motion tested (40°/40°), the range of the radiolunate angle was decreased by 3.0 degrees after application of the fixator, whereas the range of the capitolunate angle increased with 2.8 degrees. This phenomenon could be explained by the observation from recent studies that the centre of rotation for flexion-extension migrated through the capitate, whereas the sliding mechanism of the fixator has a fixed centre of rotation in the capitate. During radio-ulnar deviation the differences were slightly more pronounced, especially near the maximum range of radial and ulnar deviation allowed by the fixator. The interpretation of the carpal angles during radio-ulnar deviation is partly impeded by the occurrence of out of plane motions, i.e. motion in the flexion-extension or pro- and supination plane. In contrast, during flexion-extension the out of plane motions were minimal, as was also noted by other authors.

A comparison of the absolute figures with the results obtained with the Orthofix, Clyburn and Agee Wrist Jack dynamic external fixators in a previous report is difficult since the testing circumstances were different with respect to cadaver, loading, type of motion and the range of motion tested. In general however, for flexion-extension the results obtained in this study resemble those earlier results which showed carpal angle differences up to 3 degrees. Radio-ulnar deviation with dynamic external fixators has not been reported previously.

After transection of the scapholunate ligament the lunate tended to flex less during flexion compared to normal, whereas during extension the change was small. The 40°/40° range was 39.5° after transection vs 52.5° in the normal wrist. The contribution of the capitolunate angle to flexion increased as a compensation for the reduced flexion of the lunate (27.4° normal vs 40.4° after transection of the SL ligament). The gradual increase in scapholunate angle was also more pronounced in flexion while the 40°/40° range increased from 18.1° in the normal wrist to 32.9° after SL transection. From these results it seems that during flexion of the hand after transection of the scapholunate ligament, the lunate remains in a relatively extended position while the scaphoid flexes, thereby increasing the scapholunate angle. During extension, the scaphoid comes back to the lunate and thus decreases the scapholunate angle to (near) normal values.

The data obtained in the experiments confirm the results of the biomechanical investigations with the Flexafix device described in Chapter 6 in which pin loads were measured during motion with two different types of dynamic external fixators. Apart from biomechanical considerations related to the offset centre of rotation in devices with one or more ball joints, a possible advantage of the device tested in this
study is that in addition to a considerable range of flexion-extension a small amount of radio-ulnar deviation ($20^\circ$) is also permitted by the device. This could allow for a more normal wrist motion since active flexion and extension are accompanied by radio-ulnar deviation respectively. Future studies could focus on the events occurring in the fracture area at the distal end of the radius during movement of the hand in presence of a dynamic external fixator. The theoretical advantage of early motion for fracture treatment by means of dynamic external fixation can only be confirmed in clinical studies. However, clinical results obtained with dynamic external fixators can only be expected to be good if the design of the device that is used is sufficiently compatible with the wrist.

7.5 Conclusion

In this cadaver study the kinematical properties of the Flexafix dynamic external fixator designed for the treatment of distal radial fractures were studied. The device influenced carpal kinematics to a limited extent. In presence of a scapholunate ligament injury the altered kinematics were the same with and without the fixator applied to the wrist. Compared to other types of dynamic external fixators the new device showed a similar kinematic pattern. Additional research is needed to determine the effect of dynamic external fixation with a simulated distal radial fracture. Clinical studies will have to elucidate a presumed beneficial effect over other methods of treatment for distal radial fractures.