LECTURE

Dynamic carpal stability

Ronald L. Linscheid and James H. Dobyns

Department of Orthopedics, Mayo Clinic, Rochester, MN, USA

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Abstract. The term carpal instability is commonly used, but what carpal stability actually is has not been defined. Much of the mechanically complex wrist's versatility is due to the intercalated three bone proximal carpal row. Landsmeer described the collapse tendency associated with intercalated segments. The factors which provide static stability are the oblique alignment of the scaphoid, the obliquely aligned dorsal and palmar ligamentous complexs, the intrinsic perilunate ligaments, the transiting transcarpal tendons and the negative intraarticular pressure. The proximal carpal row adjusts its posture on the counterbalancing flexion/pronation torque exerted by the scaphoid and the extension/supination torque exerted by the triquetrum. The dynamic factors are the compressive force exerted across the joint acting on the joint surfaces and the effect of the bowstringing force provided by the flexor carpi radialis acting at the scaphoid tuberosity. The proximal carpal row has a tendency to translate ulnarly along the ulnarly sloped radial articular surface while the distal row has a tendency to slide radially on the radially sloped lunatatotriqueteral distal articular surface. This activity produces differential tension in the ligaments attaching to the triquetrum which effects an extension/supination stance of the triquetrum. The force couple acting on the scaphoid effects the flexion tendency of the scaphoid. The bowstringing of the flexor carpi radialis also counteracts scaphoid flexion. Alterations in any of these factors may upset the delicate mechanical balance of the joint. (Keio J Med 51 (3): 140–147, September 2002)

Key words: wrist, carpus, kinematics, stability, dissociation

Introduction

The condition of carpal instability with several of its clinical manifestations was described by Destot over a century ago.[1] Renewed interest in the subject developed more recently when the term was introduced by Dobyns in 1967.[2–5] Carpal instability is at present best described as a wrist unable to support physiologic loads have altered kinematics or as is usually the case both conditions.[6] What actually constitutes carpal stability has not been defined or well described. What is appreciated is the fact that the wrist joint from a mechanical standpoint is very complex.[7] It allows a wide range of motion in two major planes and with its adjacent radioulnar joint permits a substantial arc of rotation around the longitudinal axis of the forearm. There is also a considerable allowance for stress absorption built into its ligamentous constraints.

Much of the reason for the wrist's versatility is the intercalated three bone system that constitutes its proximal carpal row. This also represents the Achilles' heel of the wrist because of its tendency to undergo a mechanical collapse when ligamentous or bony constraints are interrupted. Landsmeer[8] has described in detail the consequences of a biarticular system that does not have one or more dynamic stabilizers for the intercalated segment.

From an evolutionary viewpoint minimizing muscle bulk acrally allows the benefit of the mass moment of inertia to be located more proximally in the upper limb. That there are no direct tendinous attachments into the proximal carpal row is therefore not surprising but begs the question, how is carpal stability maintained.[9]

Static Stabilizing Factors

The factors that we recognize as contributing to carpal stability are the shapes of the articular surfaces, the constraints of the ligamentous systems, the oblique positioning of the scaphoid lying athwart the midcarpal

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Reprint requests to: Dr. Ronald L. Linscheid, Department of Orthopedics, Mayo Clinic, 200 SW First Street, Rochester, MN 55905, USA

joint, the tendons surrounding the joint on their distal passages and the other soft-tissue investments.[10]

Articular surface morphology

Radius: The shape and alignment of the distal radial articular surfaces has changed little in comparison to hominid fossils and modern apes. The scaphoid fossa is a shallow concavity with a palmar angulation of approximately 10° and an ulnar angulation of 30°. The lunate fossa is defined by the interfossal ridge radially and the attachment of the TFC ulnarly. It has a 12° palmar tilt and an ulnar angulation of 10°. The inclination of these surfaces relative to the axially directed forces we believe plays a dynamic role in carpal stability.

Proximal carpal row: The radii of curvature of the proximal surfaces of both scaphoid and lunate are slightly less than that of their corresponding fossae on the radius so that congruency in the joints is limited. This allows for considerable translation as well as rotation during movement at the radiocarpal joint.[11]

The midcarpal surface of the scaphoid is angled ulnarly and palmarly with respect to the head of the capitate, while the midcarpal surface of the lunate is angled radially with respect to the capitate. The wedge shape of the lunate in the frontal plane is of interest when assessing dynamic factors in carpal stability because of the effect on translation of the surfaces. There is a distinct hamatal facet for the ulnar aspect of the lunate in approximately one third of the population.[12]

The triquetro-hamatal joint has a semihelicoidal articular arrangement which is most congruent with ulnar deviation and mild extension of the wrist.[13]

Ligamentous constraints

Intrinsic ligaments: The two primary intrinsic ligaments of the proximal carpal row (PCR) are the scapholunate and lunatotriquetral interosseous ligaments (SLIL and LTIL). These constrain the scaphoid, lunate and triquetrum to act somewhat in concert under alternating forces acting on their surfaces during the various motions of the wrist. Both have a C shaped sagittal contour due to their origin around the convex proximal perimeters of the bones. The SLIL has a central portion composed of fibrocartilage that merges with the articular cartilage of either bone. The dorsal and palmar components are collagenous with the former being shorter, thicker and stronger than the latter. The movement of the two bones tends to pivot largely about the dorsal component. The LTIL allows smaller arcs of motion between lunate and triquetrum. It also has a fibrocartilagenous central aspect, but the palmar component is the stronger of the two collagenous components.[14,15]

Extrinsic (*capsular*) *ligaments*: The arrangements of the ligaments of the wrist and their functions have received increasing scrutiny. The trajectories of the fibers follow oblique courses to the two major planes of motion thus allowing the movements somewhat analogous to a universal joint. The dorsal capsule contains two major ligamentous inclusions that form a vee shape. The proximal radio triquetral (RTL) component arises distal to Lister's tubercle and passes at an angle of approximately 20° to the lunate fossa to insert on the triquetrum.[16] The distal component, dorsal carpal ligament (DCL), passes over the neck of the capitate to insert on the dorsodistal aspect of the scaphoid and trapezium.

The palmar capsule consists of two major ligamentous inclusions.[17,18] Both arise from a roughened area on the palmar aspect of the radial tuberosity. The radiolunate component, radiolunate ligament (RLL), is the deeper of the two and passes at an angle of approximately 15° to the lunate fossa on to the palmar pole of the lunate before reassembling as the strong palmar aspect of the lunato-triquetral interoseous ligament (LTIL). This then intersects into the ulnolunate and ulnotriquetral ligaments passing to the insertions into the ulnar fovea and styloidal base (Fig. 1).

The more distal and superficial component is often referred to as the deltoid ligament. Radially the distal aspect passes to the palmar ridge of the capitate with a partial insertion to the palmar aspect of the scaphoid waist. The ulnar reappearance passes from the ulnar aspect of the capitate ridge to insert on the palmar aspect of the triquetrum and then continues to the ulnotriquetral ligament. The proximal aspect of the deltoid ligament passes over the capitate head and proceeds to the thick confluence of the two systems on the triquetrum.[18]

Scaphoid alignment

The scaphoid is aligned at an angle of approximately 45° to the proximal and distal carpal rows in the sagittal plane when the wrist is in a neutral position. We previously described this arrangement of the scaphoid and its stabilizing attachments as analogous to a "slider crank mechanism" which imparted an oblique stabilizing support across the mid-carpal joint.[5] Taleisnik suggested that the scaphoid may rock back and forth over the radiocapitate ligament (RCL) at its waist and there is much evidence to suggest that the alternating tension betwen the proximal and distal elements of the ligament affects scaphoid angulation.[17] The Proximal pole of the scaphoid articulating with the scaphoid fossa is

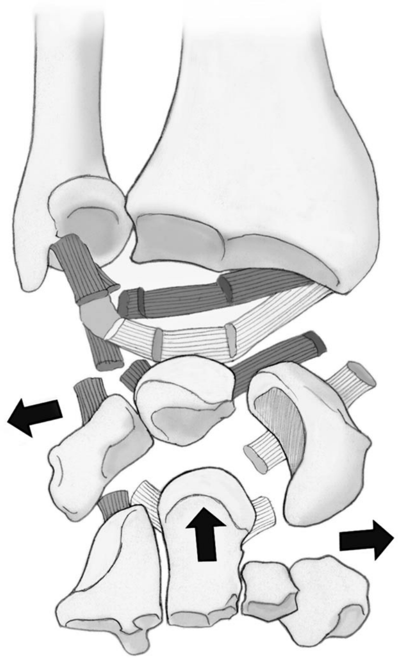

Fig. 1 Exploded schematic representation of the wrist as seen from above. The palmar capsular ligaments are represented as seen first at the radius, then beneath the proximal carpal row (PCR) and lastly at the distal carpal row (DCR). The proximal ligamentous arch is darker than the distal arch (deltoid ligament). Differential tensions may be induced in the ligaments by translations occurring between the PCR and DCR. (lateral arrows). Vertical arrow represents joint compression force.

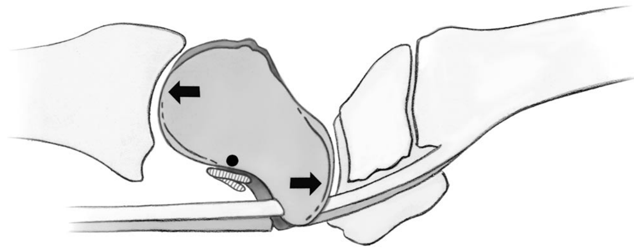

Fig. 2 Schematic sagittal representation of the radio-scapho-trapezial complex and the position of the flexor carpi radialis. The cut end of the radiocapitate ligament is seen beneath the scaphoid waist where it acts like a fulcrum about which the scaphoid may pivot. The scaphoid inherently seeks to rotate into flexion due to the force couple represented by the dorsal arrow at the radioscaphoid joint and the palmar arrow at the scaphotrapezial joint. These forces induce a clockwise torque around the pivot point over the scaphoid waist. The variable tension within the flexor carpi radialis (FCR) may be divided into an axial component ($\cos\vartheta$) and a perpendicular component ($\sin\vartheta$). The latter balances the flexion tendency by supporting the scaphoid tiberosity.

dorsal to the RCL fulcrum while the distal scaphoid articulates with the trapezium palmar to the fulcrum. This arrangement may be considered a ''force couple'' that inherently induces flexion of the scaphoid[10] (Fig. 2).

Proximally the scapholunate interosseous ligament (SLIL) provides a pivot point for the scaphoid through a very strong attachment on the dorsal pole of the lunate.[15] This connection influences the angulation of the lunate in the sagittal plane. Distally the scaphoid is supported on its palmar aspect by the strong vee-shaped palmar scapho-trapezial ligament (STL).[19] On the ulnopalmar aspect of the scaphoid tuberosity there is also a strong attachment for the tendon sheath of the flexor carpi radialis (FCR), which supplies a dynamic stabilizing force.[20,21] See below.

Transcarpal tendons and soft tissue investments

The tension in the tendons on either side of the wrist which are held in close association to the radius by the dorsal and palmar retinacula provide some support to the capsule as to a les ser extent does the rest of the soft tissue investment. Subatmospheric intraarticular pressure may also help stabilize the joint.

Dynamic Factors in Carpal Stability

Ulnar translation

The compresive forces acting across the wrist are well distributed in the neutral position. At the radiocarpal level approximately 80% of the axial joint compressive force is directed onto the scaphoid and lunate fossae of the radius and 20% onto the ulnocarpal joint.[22] When forces are measured directly in the cadaver radiocarpal joint by means such as Fuji film inserts this distribution of force in the scaphoid fossa averages about 60% and that of the lunate fossa 40% of the measured force on the radius.[23] More proximally at the midcarpal joint the scaphoid is considered to transmit approximately 40% and the capititohamate block 60% of the axially directed force.[24] This leads to some confusion because the distribution of compressive forces follows the bony columns. As the angular position of the wrist changes the force distribution will also vary.

Forces acting on oblique surfaces may be decomposed into vectors normal to or tangential to the joint surface. In the frontal plane the compressive force acting on the wedge shaped lunate devolves into an ulnarly directed tangential force on both its distal and proximal surfaces which favors ulnar translation, of the lunotriquetral block. The tangential component of force acting on the capitohamate block however is opposite in direction and causes the capitate to slide radially and intrude into the scapholunate space.[24–30] The proximal scaphoid trapped between the capitate and scaphoid fossa of the radius is therefore under additional stress normal to its surfaces.

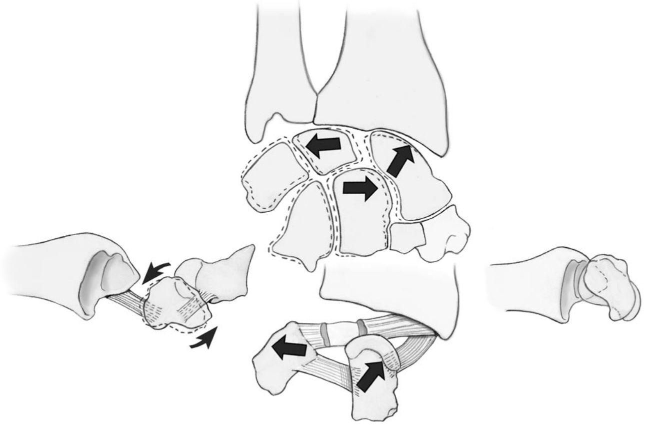

Fig. 3 Top: Frontal schematic wrist joint. Dotted lines represents the initial condition of the wrist at rest. Solid lines represent the wrist under increased compressive force. The lunato-triquetral block is displaced ulnarward and the DCR radialward. This reenforces scaphoid compression., bottom: Ulnar translation of the triquetrum increases tension in the radio-lunate ligament. Radial translation of the capitate relaxes the radio-capitate ligament (RCL) and tensions the triquetro-capitate ligamenrt (TCL). left: TCL tension extends and supinates triquetrum. right: Capitate action on the scaphoid induces flexion/pronation.

As the capito-hamate block translates radially on the distal surface of the lunato-triquetral block it has a tendency to reduce tension in the radio capitate ligament and increase tension in the capito-triquetral ligament. The former, as it relaxes, allows increasing scaphoid flexion and the latter induces lunatotriquetral extension. Differential tensioning of the carpal ligaments is obviously affected by the force applied by the transcarpal tendons. Movements of the wrist also alter the interligamentous tensions (Fig. 2).

The lunate is very unstable. Its rotational moment depends to a large extent on the points of contact between the capitate on its distal surface and the lunate fossa on its proximal surface. The capitate contact tends to lie slightly below the equator of the lunate when the wrist is in a neutral position inducing the lunate to mildly flex relative to the capitate.

Dynamic effect of the FCR

In a series of MRI images taken with the wrist in neutral flexion, extension and both radial and ulnar deviation the angle subtended by the bowstringing of the FCR depending on wrist position varied from 25 to 45° as it passed the scaphoid tuberosity. A vector distribution of the tension in the tendon suggests the dorsally directed component accounts for 40% to 70% of the total tension. By virtue of the bow stringing effect on the scaphoid tuberosity the FCR is capable of helping to dynamically stabilize the wrist by supporting the distal pole of the scaphoid and resisting the innate tendency of the scaphoid to collapse in flexion under load[21] (Fig. 3).

In this connection the action of the FCR is analogous to that of the posterior tibial tendon at the foot where its tension protects the integrity of the plantar "spring" ligament. The overall action of the transcarpal tendons acting on the flexed scaphoid induces a palmodorsal translatory force on the PCR.

The persistence of the 12° palmar slope of the distal radial articular surface acts to resist this dorsal translatory tendency of the PCR.

Relevance to Carpal Kinematics

The gross motions of the wrist are a composite of the individual motions of the eight carpal bones. It is commonly recognized that the scaphoid tends to induce flexion of the PCR while the triquetrum is responsible for a counterbalancing extension effect.[31] The exact mechanisms by which these tendencies effect carpal kinematics is unclear.

The bones of the distal carpal row are articulated with flattened congruent surfaces held together by both short intrinsic and extrinsic ligaments, allowing but a few degrees of motion.[10,11,18,32–34] The proximal row by contrast allows considerable scapholunate movement and modest lunotriquetral motion. In flexion and extension motion (FEM) the angulation at the midcarpal and radiocarpal joints occurs concurrently and in a nearly equiangular fashion. The scaphoid by necessity of its length must angulate further than either row.[10,32]

In radioulnar deviation (RUD) the intercarpal motions are more complex. The distal row supinates several degrees with radial deviation while the proximal row pronates. The reverse is true on ulnar deviation.[35,36] The proximal row also undergoes a conjunct rotation flexing approximately 15–20° on radial deviation (RD) and extending 15–20° on ulnar deviation (UD). It is readily seen that the scaphoid must flex some 30° to 40° during radial deviation to effectively shorten its intercarpal length. This rotation is transmitted to the lunate largely through the dorsal aspect of the SLIL. Additionally increasing tension in both the PCL and RTL occurs dorsally as the distal scaphoid flexes and the triquetrum displaces ulnarly. This encourages lunotriquetral flexion as well.

In ulnar deviation (UD) the proximal carpal row extends. The reason the lunate and triquetrum extend has been the subject of much debate. The partial helicoid surfaces of the triquetrum and hamate approach each other in a very congruent match at full UD. Weber described a low and high position of the hamate as being responsible for the alternate flexion and extension of the triquetrum.[13] He felt displacement of the

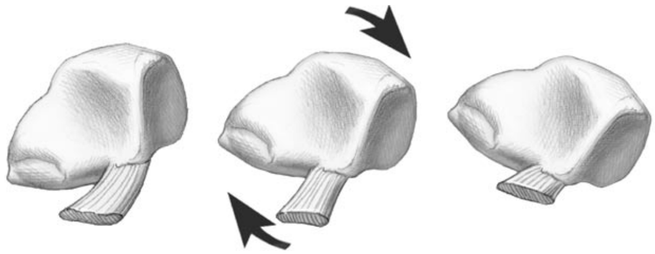

Fig. 4 The triquetrum is seen from its radial aspect with the TCL attached to its palmar surface. The cut end would be attached to the palmar ridge of the capitate. left: The TCL appears slack and the triquetrum is relatively flexed., middle: The TCL under increased tension has slightly extended the triquetrum., right: The TCL is taut and the triquetrum is extended and supinated.

contact area between the triquetrun and hamate ulnovolarly imparted an extension moment to the triquetrum (low position) during UD whereas the triquetrum was in a high position during radial deviation (RD).

Using the description of dynamic carpal stability dependent on differential tensioning of the ligamentous components under the influence of ulnar translation cited above, it seems reasonable to offer a further explanation of the conjunct flexion and extension of the proximal row.

Radial deviation consists of simultaneous but independent radial angulation of both the distal and proximal carpal rows. The instantaneous center of rotation (COR) for the composite movement is represented by tightly grouped foci in the neck of the capitate.[28,35] The PCR angulates radially while also flexing and pronating. This is due to the compression of the scaphoid between the scaphoid fossa of the radius and the STT joint. This movement is transmitted to the lunate and triquetrum through the SLIL and LTIL. At the same time the radial angulation of the DCR on the PCR relaxes the TCL, while dorsally increasing tension in the RTL. This favors triquetral flexion as well. The DCR supinates slightly on the PCR.

On ulnar deviation both the distal and proximal row angulate ulnarly around the COR that lies in the capitate neck. The radial displacement of the lunate reduces tension in the RLL; but tension in the RCL, particularly in its distal aspect, increases as its capitate insertion moves ulnarly. This also increases the support of the RCL under the scaphoid waist. At the same time the tension in the TCL increases as the capito-triquetral distance increases. The tension in the TCL produces an extension supination moment on the triquetrum. This in turn extends the lunate on the head of the capitate carrying the capitate contact dorsally on the distal facet of the lunate. The tension in the RTL dorsally is relaxed, so as not to inhibit the motion (Fig. 4).

Both major palmar ligament complexes merge and insert into the triquetrum proximoradially to its articular surface for the pisiform. These insertions may be thought of as the ‘‘triquetral force nucleus’’, an analogy to the metacarpophalangeal joint ‘‘force nucleus’’ of Zancolli.[37] The tension in the TCL is adjusted by the relative translation of the PCR on the DCR. When the TCL is tensed it induces an extension/supination moment on the triquetrum.

Relevance to the Common Wrist Instabilities

The positions seen in the common wrist instabilities give some suggestions as to what dynamic factors may provide stability in the normal wrist. If one considers the angulations in the sagittal plane that occur in the major so called instability problems as dorsiflexed intercalated segment instabilities (DISI) or volarflexed intercalated segment instabilities (VISI) some clues to understanding the deformities are provided.

DISI conditions

Scapholunate dissociation (*SLD*): In SLD lunate extension and scaphoid flexion give rise to the increased scapholunate angle. This is accompanied by an increased flexion of the capitolunate angle (CLA) which is seen as a DISI posturing of the wrist. A less recognized dorsal translation of the distal carpal row often occurs with the angulation. This dorsal translation pushes the proximal pole of the scaphoid against the dorsal rim of the radius.[5,38–40] This dorsal translation of the capitate is likely augmented by the bowstringing action of the FCR. The capitate contact area shifts dorsally on the distal surface of the lunate aggravating extension in the lunato-triquetral block.

A more important factor in inducing lunatotriquetral extension is probably the increased ulnar translation of the lunato-triquetral block relative to the triquetrocapitate block.[17] This may be seen as an extended scapholunate gap and is due to the release of the SLIL. The net result of these motions is to increase the tension in the triquetro-capitate ligament (TCL) which in turn induces an extension/supination moment in the lunatotriquetral segment of the proximal row (Fig. 4).

Scaphoid non-union and malunion: A similar angular deformity is seen at the capitolunate area in non-unions and malunions of scaphoid waist fractures. An apex dorsal angulation at the fracture site and dorsal translation of the distal on the proximal fragment is often readily observable on tomographic studies. This deformity often progresses with time as the palmar cortices of the fragments erode. The mechanism of deformity is the same as it is in SLD.[5,41–46]

Scapho-trapezio-trapezoidal degenerative joint disease (*STT-DJD*): A third DISI type deformity associated with isolated degenerative arthritis of the scapho trapezio trapezoidal (STT) joint is less commonly recognized and seems counterintuitive to the expectation that the scaphoid inherently tends to undergo flexion when destabilized. In this condition however the scaphoid length is slowly dimished as the articular cartilage in the STT joint is eroded. The scaphoid increasingly adopts an extension stance as the STT component of the scaphoid force couple is diminished. The additional dynamic factor is the dorsal displacement the bowstringed FCR tendon effects on the scaphoid tuberosity. Over time this induces lunate extension as well.[20,21]

VISI conditions

Lunatotriquetral dissociation: If the destabilization of the scaphoid is responsible for DISI deformities it seems reasonable that destabilization of the triquetrum is responsible for VISI deformities. Lunatotriquetral dissociation (LTD) and carpal instability nondissociative (CIND) believed to be on the basis of congenital ligamentous laxity are the prime examples of this.[47] The key injury in the former is the ligamentous failure of the lunato-triquetal interosseous ligament (LTIL) particularly the strong palmar fibers which are no longer able to transmit an extension moment from the triquetrum to the lunate. In the well delineated LTD the intact scapholunate component of the proximal row flexes as one while the triquetrum extends and appears to displace proximally. The triquetro capititate fibers may be torn as well in those instances when there is a prominent carpal supinatation as well. Prominence of the ulnar head dorsally is often an associated finding. The dorsal radiotriquetral ligament may be responsible for the proximal migration and extension of the triquetrum.[48–53]

In the CIND condition a clue to the mechanism of deformity may be noted in the so-called ''catch-up clunk''. This occurs in the transition of the wrist from ulnar to radial deviation or vice-versa. During this motion under the image intensifier the lunate is seen to hesitate and then instananeously jerk onto the lunate fossa while flipping from its extended position in ulnar deviation to the flexed position of radial deviation. This conjunct rotation normally occurs as a smooth integrated motion rather than an unpleasant catastrophic jerk. If gentle pressure is applied to the triquetrum to radially displace the proximal row a more normal motion may be obtained.[54,55] This observation also led to noting that an ulnar minus status of the distal ulna may be an etiologic factor in some cases. The laxity of the RLL may allow the lunate to slip far enough ulnarly that it edges off the lunate fossa and sinks proximally onto the soft TFCC. When the wrist is ulnarly deviating the lunate must then be lifted over the edge of the lunate fossa to slide radially. It is at that point that the ''catch-up clunk'' occurs.[55,56]

Carpal Ulnar translation: This condition emphasizes the inherent tendency of the carpus to ulnarly translate. This occurs when the radial ligamentous attachments at the radial styloid or the capitate are lost. The entire carpus slides ulnarly down the radial slope producing a gap in the radioscaphoid fossa and translation of the lunate onto the triangular fibrocartilage (TFC).[57] The midcarpal joint may collapse into either a VISI or DISI posture.

Adaptive carpus: One further condition that has received much attention and a much more aggressive treatment strategy is the carpal deformity seen in radial malunions and often referred to as the adaptive carpus.[58,59] The distal fragment of the radial metaphysis is dorsally and radially angulated. The greater the angulation the more severe is likely the result. The dorsal angulation of the radial articular surface induces the carpus to translate dorsally. To compensate for the radial angulation the wrist is positioned in ulnar deviation. As this occurs primarily at the midcarpal joint the natural tendency for the lunate and triquetrum to extend occurs and the captitate displaces dorsally on the lunate. The palmar carpal ligaments become taut holding the deformity in place. This precludes any effective dynamic restitution beyond osseous realignment.

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