Carpal Biomechanics: Application to Ligamentous Injuries

E. Camus

1 Introduction

Since Destot in 1905, the study of intracarpal injuries has interested many authors who were faced with wrist traumatisms [1–7]. Therefore, the analysis of the sole traumas is not enough to understand carpal biomechanics. Studies have thus been led in different directions to solve injuries' mechanism.

Imaging studies dealt with the radiography of healthy subjects [8–17], with the in vitro measure of intracarpal movements [18–27] and then in vivo by CT scan [28–40]. The radiographic studies of healthy subjects enabled to measure the shift of the bones that could be seen on front and profile views. But the bone superposition and the out-of-the-radiographic-plane position of some bones do not allow to measure all the displacements. Cadaveric studies allowed researchers to fix markers on carpal bones to differentiate them better and measure their movements. The authors of these studies mostly resorted to metallic markers, which shifting was recorded by stereoradiography. Yet, the necessary surgical approach to introduce the markers and their presence inside the wrist involve a doubt on the similarity in between in vivo results [23, 28, 29]. Recent CT scan studies measured in vivo the in-plane and out-of-plane movements of the bones [28, 29, 36, 38–40]. These studies enabled to draw an accurate view of carpal biomechanics.

In vitro studies on carpal ligament sections were useful to start some ligamentous traumatic sequences. Several carpal restraints are thus described [7, 41–50].

Works on forces transmission enabled to explain the different strains applied to the moving wrist [51–58].

As the study and the diagnosis of carpal ligamentous injuries are difficult, it seems necessary to present a biomechanical synthesis of the available data on the topic.

E. Camus
Hand Surgery Unit, SELARL Chirurgie de la Main,
Polyclinique du Val de Sambre,
162, route de Mons, 59600 Maubeuge, France
e-mail: ejcamus@wanadoo.fr, emmanuel.camus@wanadoo.fr

E. Camus, L. Van Overstraeten (eds.), *Carpal Ligament Surgery*,
DOI 10.1007/978-2-8178-0379-1_2, © Springer-Verlag France 2013

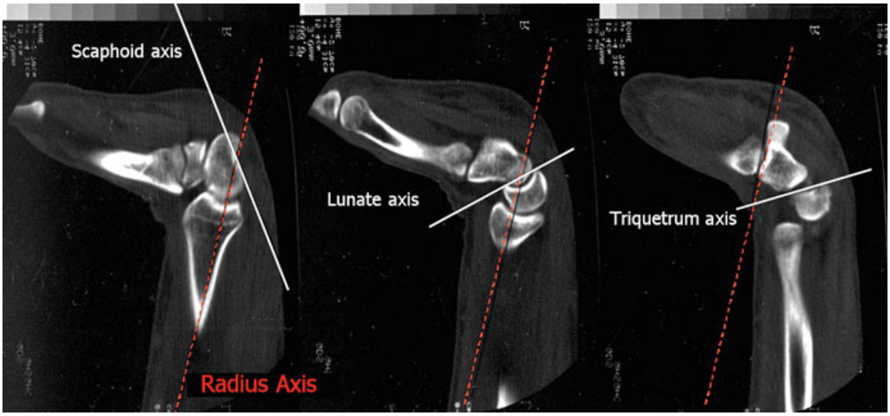

Fig. 1 Sagittal section of the extended wrist column by column. *Red* radius axis, *Black* wrist bone axis

2 Kinematics of the Wrist

2.1 Flexion and Extension of the Wrist

Under the action of carpal flexor or extensor tendons, both carpal rows flex or extend jointly, with varied ranges of motion [29, 40]. As the movements of both rows have the same direction in the sagittal plane, the ranges of motions add up. The tilting movements in the frontal plane are not important [29, 40]. Usually, it is said the radiocarpal space is mainly mobilized during flexion and the mediocarpal space during extension [59]. In fact, thorough CT scan studies prove this is oversimplified [40, 60] (Fig. 1). Flexion is predominant in STT, radiolunar and ulnotriquetral spaces (Fig. 2). Extension is predominant in radioscaphoid, lunocapital and triquetrohamate spaces (Fig. 3).

The main flexion and extension lines of the wrist are thus described. These lines represent the space which is the most mobile in each motion. The scapholunate ligament is where those lines cross and reverse (Fig. 4).

2.2 Radial and Ulnar Deviation of the Wrist

Both carpal rows deviate in the same direction in the frontal plane. The radial or ulnar deviation of both rows adds up [17]. But in the sagittal plane, different movements coexist.

During radial deviation, the proximal row (R1) flexes, and the distal row (R2) extends. With such inverse movements, one neutralizes each other and this allows to

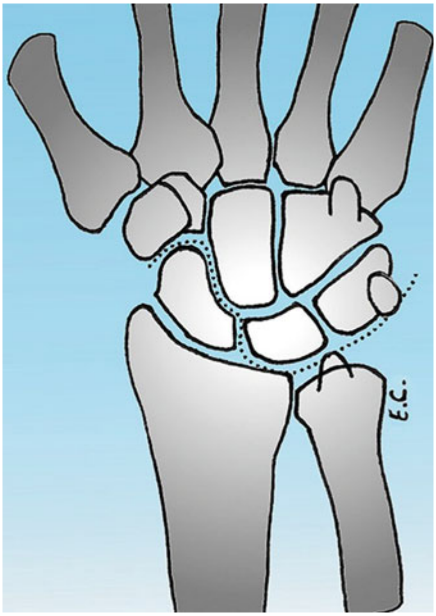

Fig. 2 Wrist main flexion line

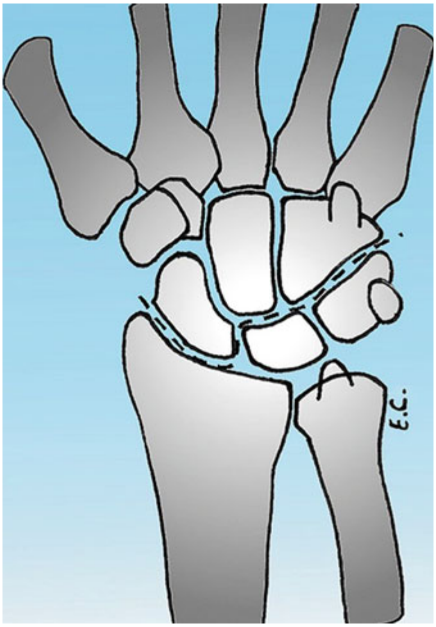

Fig. 3 Wrist main extension line

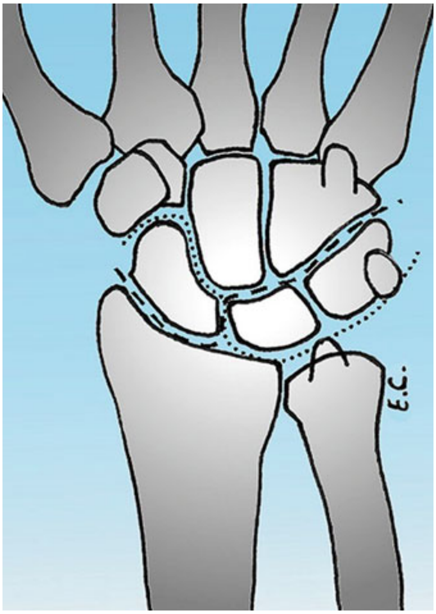

Fig. 4 Junction of the of flexion and extension main lines within the scapholunate ligament

maintain the hand in the frontal plane. On the radial side of the wrist, the flexion of the scaphoid comes with an apparent shortening of the scaphoid's height and consequently of the radial column's height, and on the ulnar side of the wrist, an uplifting of the triquetrum on the hamate engenders a lengthening of the ulnar column's height [17, 40].

During ulnar deviation of the wrist, a reversal of the rows' movements is noticed; there is an extension of the proximal row and a flexion of the distal row. The lengthening of the radial column goes with a vertical position of the scaphoid, and the ulnar column's height shortens as the triquetrum crosses palmarly ahead of the hamate [17, 40]. Seen in the frontal plane, those movements can be compared with the mobilization of a double cup (Fig. 5) [17]. In the sagittal plane, the shearing of both carpal rows following the radial deviation can be compared to the closing of scissors (Fig. 6a) and the ulnar inclination to the opening of these scissors (Fig. 6b) [40].

Two variants which differently combine flexion-extension and radioulnar deviation of the proximal row of the carpus have been described. Some wrists show a proximal row flexion-extension movement that prevails on the radioulnar motion. They are called column wrists [14]. At first sight, these wrists belong to so-called lax subjects [15]. On the contrary, some subjects have a wrist with a proximal row which does not flex or extend much; they are called row wrists. They usually refer to rigid wrists. The influence of gender on both these biomechanical variants is still under consideration [14, 16].

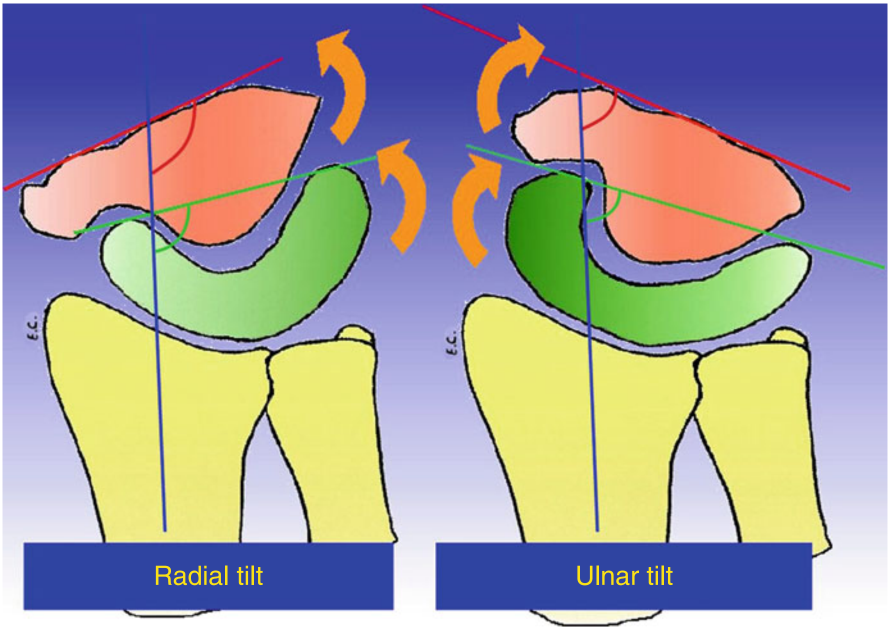

Fig. 5 Pattern of both carpal rows mobility following the double-cup description. *Blue* radius axis, *red* distal row transverse axis, *green* proximal row transverse axis

3 Actions of the Ligaments and Peripheral Tendons

3.1 Ligaments

Ligaments are passive brakes which authorize movements inside and between the rows and maintain the spacial coherence of the carpus [61]. They allow intra-row movements, which are adaptative for congruence movements, and inter-row movements which are efficient movements to mobilize the hand [17]. The limit of range depends on their length. For didactic reasons, intrinsic and deep extrinsic ligaments (Fig. 7) and extrinsic superficial ligaments will be separately represented (Fig. 8).

The scapholunate ligament links both bones (Fig. 7-1). The fibres which constitute the ligament are not symmetrically distributed. The dorsal part of the ligament is the most fibrous and thickest and also the most resistant [62]. It is considered as the main stabilizer of the scapholunar couple. It is always injured in scapholunar instability [63–65]. This ligamentous injury involves an increase flexion of the scaphoid from 3° to 6° [47–50, 62, 66], an extension of the lunate of 5° [50] and a dorsal translation of the scaphoid's proximal pole more than 2 mm [62]. Tang also noticed a possible displacement of the rotation centre of the wrist [67].

The radioscapholunate ligament (Fig. 7-2) is thin; it is a neurovascular pedicle [62, 68] and not a real ligament.

The lunotriquetral ligament (Fig. 7-3). Its fibres are asymmetric too. On the palmar part, these fibres are thicker and resist to traction. They lock up the palmar translation of the lunate. Dorsal fibres are the most torsion resistant. They lock up both the lunate's dorsal translation and the torsion by differential flexion-extension between the two bones [41]. When the ligament is injured, it engenders

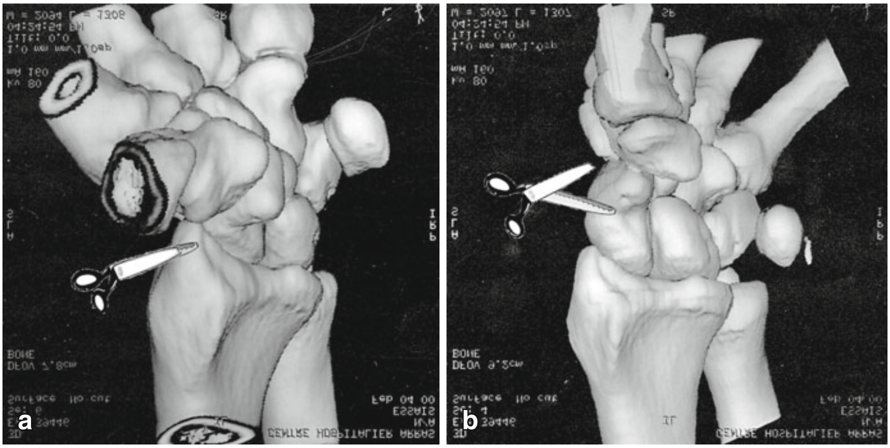

Fig. 6 (**a**) During radial inclination, shearing scissors-like between both proximal and distal carpal rows. Trapezium and trapezoid cross back the scaphoid whose tubercle runs forward (flexion of the scaphoid). (**b**) During ulnar deviation, trapezium and trapezoid run distally to the scaphoid. The distal row flexes when the proximal row extends

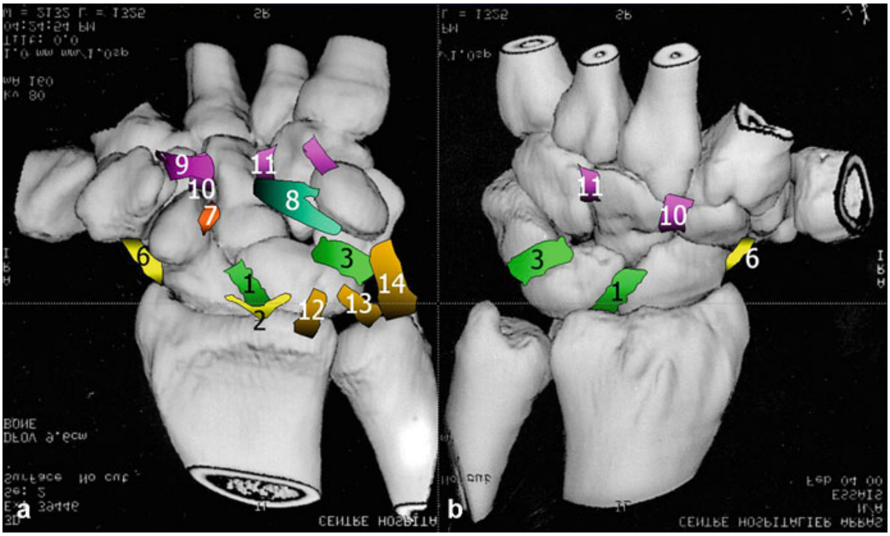

Fig. 7 Intrinsic and deep extrinsic ligaments. (**a**) Palmar view. (**b**) Dorsal view. *1* Scapholunate ligament, *2* Radioscapholunate ligament, *3* Lunotriquetral ligament, *6* Scaphotrapezial ligament, *7* Scaphocapitate ligament, *8* Triquetrohamatocapitate ligament, *9* Capitotrapezial ligament, *10* Capitotrapezoidal ligament, *11* Capitohamate ligament, *12* Short radioulnar ligament, *13* Ulnolunar ligament, *14* Ulnotriquetral ligament

a lunotriquetral instability with VISI and sometimes a gap with supination of the triquetrum [42].

The palmar scaphotriquetral ligament (Fig. 8-4) avoids palmar scaphotriquetral dissociation and indirectly scapholunate dissociation. It probably maintains the head of the capitate when the wrist extends [66].

The radioscaphocapitate ligament (Fig. 8-5) is a powerful palmar ligament ensuring carpal cohesion. It is tensed against the scaphoid tubercle which lifts it in radial inclination of the wrist (Fig. 9). It avoids the dorsal translation of the proximal scaphoid pole and is a secondary stabilizer of the scapholunate couple [63]. If it is injured, it can be responsible for the scaphoid's instabilities with DISI and scapholunar gap [64].

The scaphotrapezial ligament (Fig. 7-6) is V pattern ligament attached to the radial side of the scaphoid, the proximal point and at distal joint on the palmar and radial sides of the trapezium [68]. It is another secondary stabilizer of the scapholunar couple together with the radioscaphocapitate ligament. For Moritomo et al., it is also one of the points where the scaphoid's flexion-extension axis passes through [69] (Fig. 10). The injury of this ligament after that of the scapholunar ligament worsens the instability of the scapholunar space.

The scaphocapitate ligament (Fig. 7-7) is the second element which stabilizes the scaphoid with the distal carpal row [68]. It also plays a part in the materialization of the scaphoid's flexion-extension axis (Fig. 10).

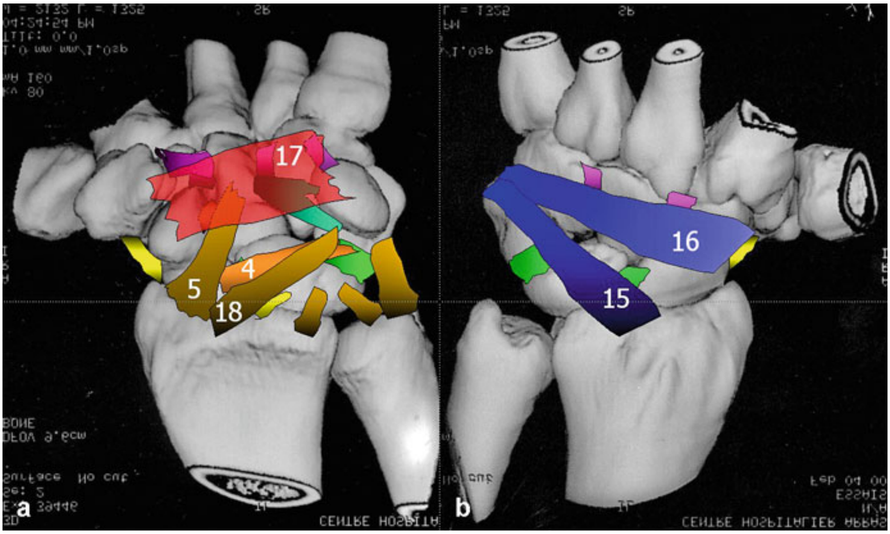

Fig. 8 Extrinsic ligaments. (**a**) Palmar view. (**b**) Dorsal view. *4* Scaphotriquetral ligament, *5* Radioscaphocapitate ligament, *15* Dorsal radiocarpal ligament, *16* Dorsal intercarpal ligament, *17* Carpal anterior annular ligament, *18* Radiolunotriquetral ligament

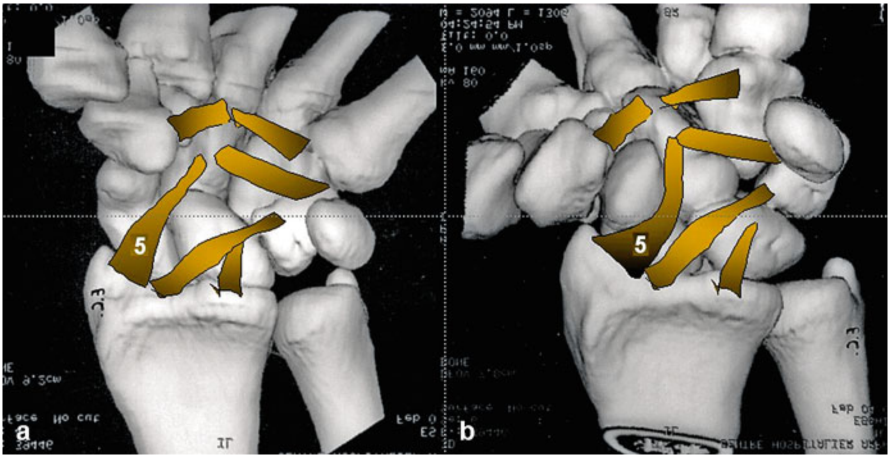

Fig. 9 Lifting of the radioscaphocapitate ligament by the scaphoid tubercle during radial inclination. (**a**) Ulnar inclination. (**b**) Radial inclination. *5* Radioscaphocapitate ligament

The triquetocapitate ligament (Fig. 7-8) is tensed from the radial angle distal from the triquetrum to the ulnar part of the capitate's body [68]. It takes attachment from the hamate bone, and its fibres go to the ulnotriquetral ligament to describe the ulnocapitate ligament. It is the ulnopalmar stabilizer of the mediocarpal space.

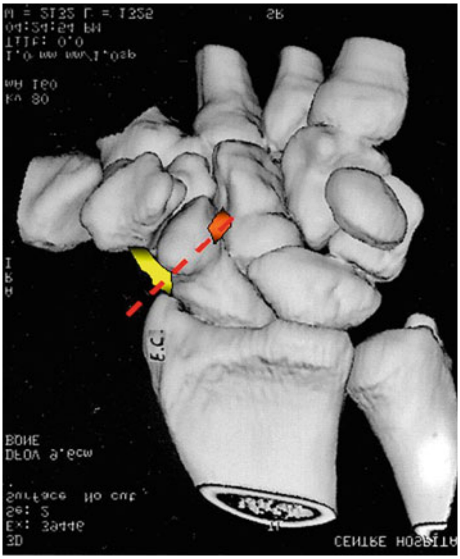

Fig. 10 Materialization of the axis of flexion-extension of the scaphoid. *Orange* scaphocapitate ligament, *yellow* scaphotrapezium ligament, *dotted line* scaphoid's flexion/extension axis according to Moritomo

The long radiolunotriquetral ligament (Fig. 8-18) is the palmar part of Kuhlmann's triquetral sling [8, 61]. It prevents the ulnar translation of the carpal bones. When this ligament is injured, the perilunar region becomes deeply unstable and thus promotes the perilunar dislocation of the carpal bones [7].

The dorsal radiocarpal ligament (Fig. 8-15) is radiolunotriquetral. It is the dorsal part of Kuhlmann's triquetral sling [8, 11, 61]. It is a secondary stabilizer of the carpal bones. When it is injured, it is as destabilizing for the carpus as when the radioscaphocapitate and scaphotrapezial palmar bundles are injured [65]. The dorsal radiocarpal ligament is injured in more than 50 % of the carpal instabilities, often in association with the interosseous scapholunar ligament, but it may be the only ligament to be injured [70].

The dorsal intercarpal ligament (Fig. 8-16) links the triquetrum and the distal scaphoid and continues on the trapezium and the trapezoid in half of the cases. It is the last secondary stabilizer of the carpal bones [65]. For Viegas, this ligament constitutes, together with the dorsal radiocarpal ligament, a dorsal V-shaped radioscaphoidal ligament with a transversal orientation [47]. The resulting length varies, but the ligament is always tensed. A direct radioscaphoid ligament would be either lax, to allow the flexion of the wrist, and inefficient or tensed in a neutral position, preventing flexion and giving stiffness. This transversal V-shaped ligament remains tensed whatever the position of flexion or extension of the wrist thanks to the movement of the branches of the V which modify the angle (Fig. 11) and whatever the radioulnar inclination of the wrist as it goes together with the linked movements of flexion/extension of the scaphoid.

The transverse anterior annular ligament of the carpal bones (Fig. 8-17) completes the system. If it were sectioned, there would be an extension of the scaphoid

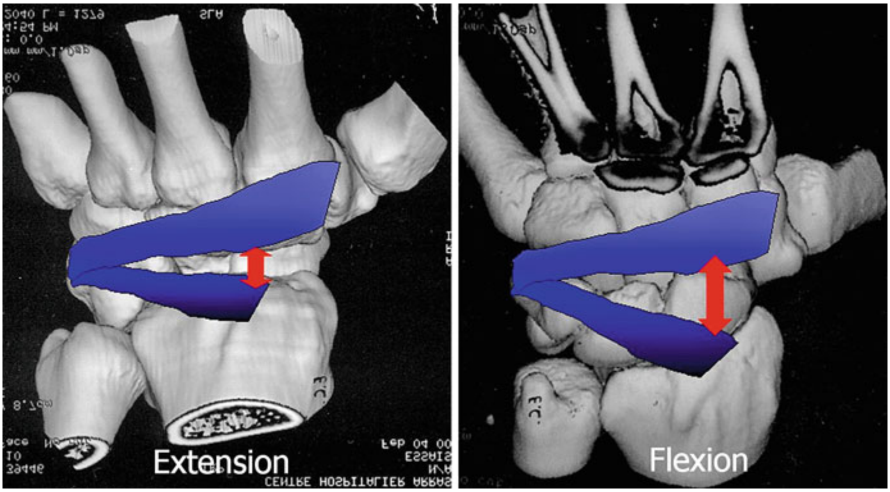

Fig. 11 Opening variation of the angle of the dorsal ligamentous V

of 58 % during the carpal ulnar drift and probably an increase of the restraints on the other ligaments [48].

To sum up, the scapholunar instability is often the result of an interosseous injury. The problem increases if other ligaments, mainly the palmar secondary stabilizers (radioscaphocapitate ligament or scaphotrapezial ligament) or the dorsal secondary stabilizers (dorsal radiocarpal or dorsal intercarpal), are affected [63–65, 71].

If the ligamentous injury starts at the distal pole of the scaphoid and affects the STT ligamentous system, there is also a destabilizing of the scaphoid, what can lead to STT arthritis if no surgical repair is made [72]. This situation of distal scaphoidal ligamentous injury can be compared to the partial osseous resections which are used in scaphotrapezial arthritis [73]. The distal scaphoidal resection separates the scaphoid from the trapezium and the trapezoid. It engenders a DISI in half of the cases [74], but the isolated trapeziectomy does not destabilize the wrist. The injury of the scaphotrapezial ligament only seems to have no impact on the scaphoid's stability. It must be linked with a scaphotrapezoidal ligamentous injury or maybe a scaphocapitate ligamentous injury to produce a scaphoidal destabilization by its distal pole.

The lunotriquetral instability is linked to an injury of the lunotriquetral ligament, the palmar radiolunotriquetral ligament and the dorsal radiocarpal ligament [7, 42]. It is often associated to an ulnocarpal hyper pressure or to an injury of the TFCC. There may be a responsibility of the injured triquetrocapitate and palmar scaphotriquetral ligaments, but this has not been studied yet.

A ligamentous injury is not necessarily unstable at once. If one of the restraints of the different compartments is affected, there is often merely an occult ligamentous laxity, which can only be seen by arthroscopy. However, the repetition of movements in a wrist where there is such a laxity can engender a real instability by

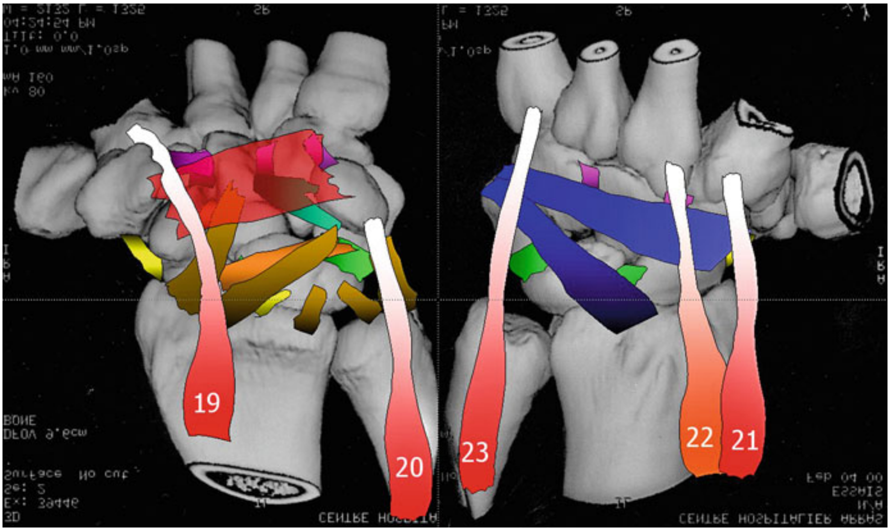

Fig. 12 Motor tendons of the carpus. *19* Flexor carpi radialis, *20* Flexor carpi ulnaris, *21* Extensor carpi radialis longus, *22* Extensor carpi radialis brevis, *23* Extensor carpi ulnaris

the fatigability of previously sane restraints. Berger asserted that carpal destabilization is linked to the number of cycles of movements imposed to the wrist. This assertion is checked for the scapholunar compartment [63–65] and for the lunotriquetral compartment [42].

3.2 Tendons

The peripheral tendons come stabilizing the wrist with the carpal ligaments. The carpal motors muscles and tendons are the flexor carpi radialis and the flexor carpi ulnaris, the extensor carpi radialis brevis and longus and the extensor carpi ulnaris. Their direction is mostly axial (Fig. 12). This layout makes them play a role in the cohesion of the carpal bones. Intracarpal pressures are mainly due to the traction impressed on the hand by the motor tendons. The traction strengths stiffen the tendons which become like the bars of a cage around the carpal bones [51].

Schematically, there are four muscular groups, often contracting two by two, surrounding the wrist [75]. The action of the palmaris longus is insignificant. The radial and ulnar flexors and extensors act two by two and simultaneously, in the elementary movements of the carpus. For instance, the neutral extension of the wrist is the result of the simultaneous contraction of the radial and ulnar carpal extensors (Table 1). The dart thrower's motion (DTM) is produced by the alternative contraction of flexor carpi ulnaris and the extensor carpi radialis longus and brevis [76].

Table 1 Combined action of the carpal motor muscular groups

		Extension		
	ECU		ECRL, ECRB	
Ulnar Tilt		DTM		Radial Tilt
	FCU		FCR	
		Flexion		

ECU extensor carpi ulnaris, *ECRL* extensor carpi radialis longus, *ECRB* extensor carpi radialis brevis, *FCU* flexor carpi ulnaris, *FCR* flexor carpi radialis, *DTM* dart thrower's motion. In this motion, the ECR and FCU tendons do not have a combined but an alternative action (*dotted arrow*)

This tension applied to the tendons makes them become rigid. They are variable brakes of carpal dislocation according to their tension degree. The motors of the fingers have a distinguished action from the motors of the wrist. The extension of the carpus increases the efficiency of the fingers flexors [59]. When the wrist moves, the agonist groups are tense and the antagonist groups are lax. This imbalance of tension of the different groups produces the hand mobilization. On the contrary, in the powerful grasp, the osseous cohesion is possible thanks to the tension of the finger flexors and the wrist extensors. This leads to the tendinous caging of the carpal bones in association with the ligaments to maintain carpal coherence [51].

The flexor carpi radialis stabilizes the scaphoid distal pole. The fibres of its sheath are closely combined to those of the scaphotrapezial capsule [77]. Its role is important since 40–70 % of the tension created by this tendon enables the stabilization of the scaphoid and prevents its collapse by flexion [52]. At the back of the wrist, the extensors carpi radialis longus and brevis stabilize the proximal pole [52, 67]. When the scapholunar ligament is injured, the course of these three tendons, which are necessary to move the hand, is lengthened and requires to develop more strength [67]. Chronicle STT instability can rupture the flexor carpi radialis [78, 79].

4 Absorption and Transmission of Axial Pressures

The pressures going through the carpus originate in the muscular contraction and in the tendinous tension of the motors of the hand. This results in an axial compression which tends to dislocate the carpus. The tenoligamentous system creates cohesion which limits collapse. Axial pressures are normally transmitted to the forearm without carpal exhaustion that give the motor muscles a stable support to move the hand. These pressures are not spread at random. In the neutral position of the wrist, pressure in the radioscaphoid fossa is superior to pressure recorded at the radiolunate or ulnotriquetral spaces [53]. Radioscaphoid pressure represents 45–55 % of total pressure, radiolunar pressure from 30 to 40 % and pressure under TFCC from 9.7 to 22 %. The radius thus receives from 80 to 90.3 % of the total pressure distributed through the carpus [52, 54–57].

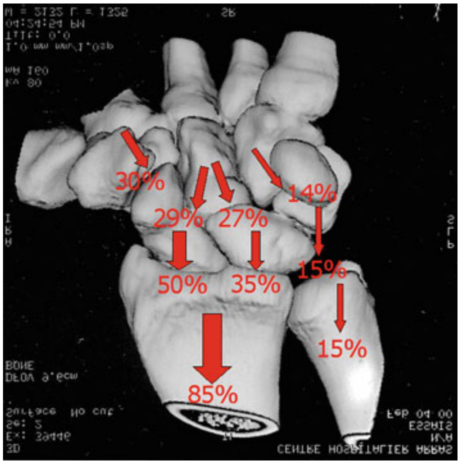

Fig. 13 Distribution of the pressures through the carpus

In the mediocarpal space, the scaphoid receives from 28 to 30.7 % of the total pressure through STT and from 26 to 32 % through the scaphocapitate space. The lunate receives from 26 to 29 % of the pressure through the capitate, and the triquetrum receives from 10.5 to 17 % of the total pressure which is transmitted by the hamate [56, 57] (Fig. 13). According to Schuind, intracarpal pressure is concentrated towards the scaphoid when it is transmitted from the mediocarpal to the radiocarpal spaces [56]. During the contraction of the motors of the hand, tendinous tension and consequently carpal caging increase as laxity decreases. The carpus is in a maximal position of interlocking [51]. Pressure in the different columns of the carpus may vary during motion. It is redistributed towards the scaphoid in radial tilt of the wrist but towards the lunate in ulnar tilt or during a grasp movement [50, 55, 57]. These physiological variations of pressure in the carpus can undergo a post-traumatic evolution. After a scapholunar dissociation, there is a decrease of pressure in the scaphoid fossa of the radius and an increase of pressure in the radiolunar and lunocapital joints [50, 58]. Consequently, the lunate becomes overworked. The scaphoid does not take its responsibility as it is unbolt and escapes from pressure by flexion instead of transmitting it. But when flexion is too important, its proximal pole bumps into the dorsal margin of the radius and engenders a dorsal radioscaphoid hyperpressure. The apparition of carpal arthritis comes as a consequence of this phenomenon [58].

5 Balance of the Carpal Proximal Row

The movements of the proximal row, which automatically associate flexion and radial tilt and extension and ulnar tilt, prove the carpal proximal row is in constant balance. The compaction strengths on the radial column of the carpus flex the scaphoid that drives the proximal row to follow scaphoid in flexion. The compaction

Fig. 14 Carpal proximal row in equilibrium. Scaphoid flexion counterbalances triquetrum extension

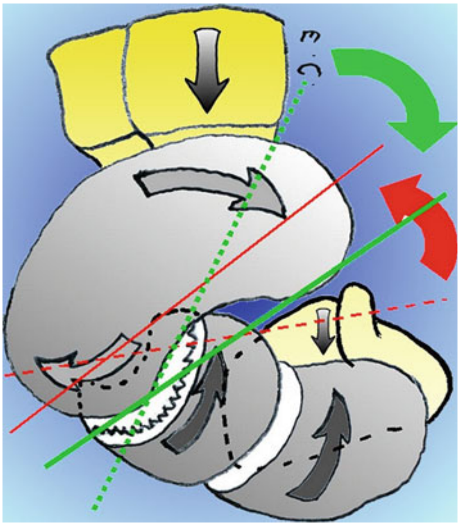

Fig. 15 DISI with scapholunar ligament rupture. The scaphoid flexes (*green axis*) and the lunate (*red axis*) and triquetrum extend

strengths on the ulnar column of the wrist extend the triquetrum which drives the proximal row in the same direction [40].

During the grasp, the compaction strengths of the carpus are global. The radial strengths which flex the proximal row are counterbalanced by the ulnar strengths which extend the proximal row. The carpal proximal row is thus in a state of balance under pressure (Fig. 14). At that stage, the injury of one of the intrinsic ligaments can make the lunate go out from its axis, with DISI (Fig. 15) or VISI (Fig. 16).

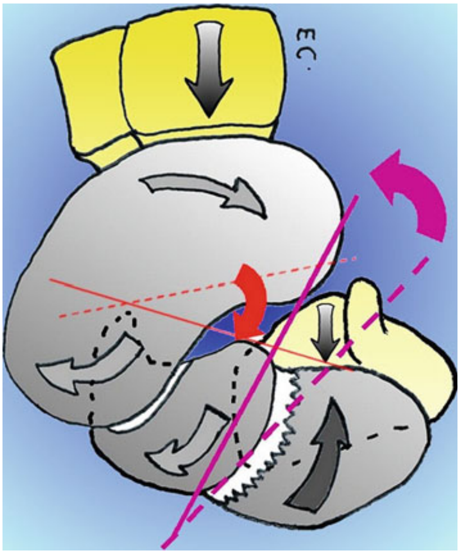

Fig. 16 VISI with lunotriquetral rupture. The scaphoid and lunate (*red axis*) flex and the triquetrum extends (*pink axis*)

6 Particular Factors of Vulnerability of the Scapholunar Ligament

The scapholunar instability is the most frequent of the post-traumatic carpal instabilities [43]. This raises the question of the factors which facilitate this frequent injury.

6.1 The Junction of the Mobility Main Lines

The scapholunar space is the seat of the maximal constraints of movements when the wrist drives from flexion to extension. This is where the main lines of intracarpal mobility cross (Fig. 4). The differential flexion/extension value is about 30° between scaphoid and lunate, absorbed by torsion of the ligament [40].

6.2 The Capitate's Transmitted Pressure

The head of the capitate is just facing the scapholunar ligament in the neutral position and in the ulnar tilt of the carpus. In case of axial load, the head tends to dissociate the scapholunar space as a quoin [80]. This becomes obvious in case of scapholunate collapse with the shortening of the carpal height. The head of the capitate is usually locked in the scapholunar space.

6.3 Concentration and Reverse Absorption of Pressures

The lunate is in equilibrium when it is under pressure (*see above*: *balance of the proximal row*). It remains in a neutral position as it absorbs the flexion constraints transmitted by the scaphoid and the extension constraints transmitted by the triquetrum. Since most of the axial loads are directed towards the radius via the scaphoid, the loads which flex the scaphoid are stronger than the loads of the ulnar column which extend the triquetrum. This should result in an imbalance in flexion of the whole carpal proximal row. But the lunate often has a dorsal horn which is thinner than the palmar horn [81]. The axial pressure transmitted by the capitate thus helps the triquetrum to extend the lunate. The triquetrolunate ligament is not the only piece that maintains the lunate in equilibrium. This ligament is thus less affected than the scapholunar ligament in overload injuries.

7 Conclusion

Because the scapholunar ligament is exposed to axial constraints of mobility and loads, it represents a weak point of the proximal row. But it is protected by quite a complete system of extrinsic ligaments which contribute to unify the wrist. There are a palmar ligamentous plane, a dorsal ligamentous plane and a distal scaphoidal ligamentous complex. The different tendons around the wrist can also have a cohesion effect of the carpus. A ligamentous injury is less likely to happen if the scapholunar ligament is unaffected. In that case, the lunotriquetral ligament is most likely injured. Seldom the extrinsic ligaments can be the only one to be affected, astride on the radiocarpal or the mediocarpal spaces. Once all the biomechanical aspects are put together, it is possible to understand the different mechanisms of the carpal collapse, which result from the application of the mechanical loads to the carpus, badly absorbed or badly redirected, by bones badly locked when they should sustain load. The different ligament injuries explain the varieties of carpal instabilities. Consequently, clinical, paraclinical and arthroscopic exams have to explore those different ligamentous restraints for the best. This aims to enable a ligamentous repair as physiological as possible.

References

1. Destot E (1905) Lésions du poignet et accidents du travail. Vigot, Paris
2. Wagner CJ (1956) Perilunar dislocations. J Bone Joint Surg 38 A:1198–1207
3. Linscheid R, Dobyns JH, Beabout JW, Bryan RS (1972) Traumatic instability of the wrist. J Bone Joint Surg 54-A:1612–1632
4. Meyrueis JP, Cameli M, Pan P (1978) Instabilité du carpe. Diagnostic et formes cliniques. Ann Chir 32:555–560

5. Allieu Y et al (1984) Table ronde sur l'instabilité du carpe. Ann Chir Main 3:277–367
6. Gilula LA, Destouet JM, Weeks PM, Young LV, Wray RC (1984) Roentgenographic diagnosis of the painful wrist. Clin Orthop Relat Res 187:52–64
7. Mayfield JK (1984) Patterns of injury to carpal ligaments. Clin Orthop Relat Res 187:36–42
8. Kuhlmann N (1979) Les mécanismes de l'articulation du poignet. Ann Chir 33:711–719
9. Lanoy JF, Mazas Y, Mazas F, Rengeval JP (1982) Etude radiologique des centres de rotation du poignet. Ann Chir Main 1:227–232
10. Schernberg F, Gérard Y (1983) L'exploration radiologique du poignet. Rev Chir Orthop 69:521–531
11. Kapandji A (1987) Biomécanique du carpe et du poignet. Ann Chir Main 6:147–169
12. Schernberg F (1990) Roentgenographic examination of the wrist. J Hand Surg 15B:210–228
13. Sennwald GR, Zdravkovic V, Kern HP, Jacob H (1993) Kinematics of the wrist and its ligaments. J Hand Surg 18A:805–814
14. Craigen MA, Stanley JK (1995) Wrist kinematics. Row, column or both? J Hand Surg 20B:165–170
15. Garcia-Elias M, Ribe M, Rodriguez J, Cots M, Casas J (1995) Influence of joint laxity on scaphoid kinematics. J Hand Surg 20B:379–382
16. Nuttall D, Trail IA, Stanley JK (1998) Movement of the scaphoid in the normal wrist. J Hand Surg Br 23:762–764
17. Camus EJ, Millot F, Larivière J, Rtaimate M, Raoult S (2008) The double-cup carpus: a demonstration of the variable geometry of the carpus. Chir Main 27(1):12–19
18. Youm Y, Mcmurtry RY, Flatt A, Gillespie TE (1978) Kinematics of the wrist. J Bone Joint Surg 60 A:423–431
19. Kuhlmann N, Gallaire M, Pineau H (1978) Déplacements du scaphoïde et du semi-lunaire au cours des mouvements du poignet. Ann Chir 32:543–553
20. De Lange A, Kauer JM, Huiskes R (1985) Kinematic behaviour of the human wrist joint: a roentgen-stereophotogrammetric analysis. J Orthop Res 3:56–64
21. Ruby LK, Cooney WP, An KN, Linscheid RL, Chao EY (1988) Relative motion of selected carpal bones: a kinematic analysis of the normal wrist. J Hand Surg 13A:1–10
22. Savelberg HH, Koolos JG, De Lange A, Huiskes R, Kauer JM (1991) Human carpal recruitment and three-dimensional carpal motion. Orthop Res 9:693–704
23. Kobayashi M, Berger RA, Nagy L, Linscheid RL, Ushiyama S, Ritt M, An KN (1997) Normal kinematics of carpal bones: a three dimensional analysis of carpal bone motion relative to the radius. J Biomech 30:787–793
24. Berger RA, Crowninshield RD, Flatt AE (1982) The three-dimensional rotational behaviors of the carpal bones. Clin Orthop 167:303–310
25. Berger RA, Blair WF, Crowninshield RD, Flatt AE (1982) The scapholunate ligament. J Hand Surg 7A:87–91
26. Werner FW, Short WH, Fortino MD, Palmer AK (1997) The relative contribution of selected carpal bones to global wrist motion during simulated planar and out-of-plane wrist motion. J Hand Surg 22A:708–713
27. Ishikawa JI, Cooney WP, Niebur G, An KN, Minami A, Kaneda K (1999) The effects of wrist distraction on carpal kinematics. J Hand Surg 24A:113–120
28. Crisco JJ, Mcgovern RD, Wolfe SW (1999) Noninvasive technique for measuring in vivo three-dimensional carpal bone kinematics. J Orthop Res 17:96–100
29. Moojen TM, Snel JG, Ritt MJ, Kauer JM, Venema HW, Bos KE (2002) Three-dimensional carpal kinematics in vivo. Clin Biomech 17:506–514
30. Moutet F, Chapel A, Cinquin PH, Rosepitet L (1990) Imagerie du carpe en trois dimensions. Ann Chir Main Mbre Sup 9:32–37
31. Patterson RM, Nicodemus CL, Viegas SF, Elder KW, Rosenblatt J (1998) High-speed, three-dimensional kinematic analysis of the normal wrist. J Hand Surg 23A:446–453
32. Moritomo H, Viegas SF, Elder K, Nakamura K, Dasilva MF, Patterson RM (2000) The scapho-trapezio-trapezoidal joint. Part 2: a kinematic study. J Hand Surg 25A:911–920

33. Wolfe SW, Crisco JJ, Katz LD (1997) A non-invasive method for studying in vivo carpal kinematics. J Hand Surg 22B:147–152
34. Sun JS, Shih TTF, Ko CM, Chang CH, Hang YS, Hou SM (2000) In vivo kinematic study of normal wrist motion: an ultrafast computed tomographic study. Clin Biomech 15:212–216
35. Patterson RM, Elder KW, Viegas SF, Buford WL (1995) Carpal bone anatomy measured by computer analysis of three-dimensional reconstructions of computed tomography images. J Hand Surg 20A:923–929
36. Feipel V, Rooze M (1999) Three-dimensional motion patterns of the carpal bones: an in-vivo study using three-dimensional computed tomography and clinical applications. Surg Radiol Anat 21:125–131
37. Wolfe SW, Neu C, Crisco JJ (2000) In vivo scaphoid, lunate and capitate kinematics in flexion and in extension. J Hand Surg 25A:860–869
38. Moojen TM, Snel JG, Ritt MJ, Venema HW, Kauer JM, Bos KE (2002) Scaphoid kinematics in vivo. J Hand Surg 27A:1003–1010
39. Moojen TM, Snel JG, Ritt MJ, Venema HW, Kauer JM, Bos KE (2003) In vivo analysis of carpal kinematics and comparative review of the literature. J Hand Surg 28A:81–87
40. Camus EJ, Millot F, Larivière J, Rtaimate M, Raoult S (2004) Kinematics of the wrist using 2D and 3D analysis. Biomechanical and clinical deductions. Surg Radiol Anat 26:399–410
41. Ritt MJ, Bishop AT, Berger RA, Linscheid RL, Berglund LJ, An KN (1998) Lunotriquetral ligament properties: a comparison of three anatomic subregions. J Hand Surg Am 23:425–431
42. Ritt MJ, Linscheid RL, 3rd Cooney WP, Berger RA, An KN (1998) The lunotriquetral joint: kinematic effects of sequential ligament sectioning, ligament repair, and arthrodesis. J Hand Surg Am 23(3):432–445
43. Mitsuyasu H, Patterson RM, Shah MA, Buford WL, Iwamoto Y, Viegas SF (2004) The role of the dorsal intercarpal ligament in dynamic and static scapholunate instability. J Hand Surg Am 29(2):279–288
44. Short WH, Werner FW, Green JK, Weiner MM, Masaoka S (2002) The effect of sectioning the dorsal radiocarpal ligament and insertion of a pressure sensor into the radiocarpal joint on scaphoid and lunate kinematics. J Hand Surg Am 27(1):68–76
45. Larsen CF, Amadio PC, Gilula LA, Hodge JC (1995) Analysis of carpal instability: I. Description of the scheme. J Hand Surg Am 20(5):757–764
46. Hodge JC, Gilula LA, Larsen CF, Amadio PC (1995) Analysis of carpal instability: II. Clinical applications. J Hand Surg Am 20(5):765–776
47. Viegas SF, Yamaguchi S, Boyd NL, Patterson R (1999) The dorsal ligament of the wrist: anatomy, mechanical properties, and function. J Hand Surg 24A:456–468
48. Ishiko T, Puttlitz CM, Lotz JC, Diao E (2003) Scaphoid behavior after division of the transverse carpal ligament. J Hand Surg 28A:267–271
49. Mayfield JK, Johnson RP, Kilcoyne RK (1980) Carpal dislocations: pathomechanics and progressive perilunar instability. J Hand Surg 5A:226–241
50. Short WH, Werner FW, Fortino MD, Palmer AK, Mann KA (1995) A dynamic biomechanical study of scapholunate ligament sectioning. J Hand Surg 20A:986–999
51. Kapandji AI, Martin-Bouyer Y, Verdeille S (1991) Three-dimensional CT study of the carpus under pronation-supination constraints. Ann Chir Main 10:36–47 [French]
52. Linscheid RL, Dobyns JH (2002) Dynamic carpal stability. Keio J Med 51:140–147
53. Koebke J, Fehrmann P, Mockenhaupt J (1989) Stress on the normal and pathologic wrist joint. Handchir Mikrochir Plast Chir 21:127–133
54. Werner FW, Glisson RR, Murphy DJ, Palmer AK (1986) Force transmission trough the radioulnar carpal joint: effect of ulnar lengthening and shortening. Handchir Mikrochir Plast Chir 18:304–308
55. Hara T, Horii E, An KN, Cooney WP, Linscheid RL, Chao EY (1992) Force distribution across the wrist joint: application of pressure-sensitive conductive rubber. J Hand Surg 17A:339–347

56. Schuind F, Cooney WP, Linscheid RL, An KN, Chao EYS (1995) Force and pressure transmission trough the normal wrist. A theoretical two-dimensional study in the posteroanterior plane. J Biomech 28:587–601
57. Genda E, Horii E (2000) Theoretical stress analysis in wrist joint – neutral position and functional position. J Hand Surg 25B:292–295
58. Sato S (1995) Load transmission trough the wrist joint: a biomechanical study comparing the normal and pathological wrist (abstract, art in Japanese). Nippon Seikeigeka Gakkai Zasshi 69:470–483
59. Dufour M, Pillu M (2006) Biomécanique fonctionnelle. Issy-les-Moulineaux/Elsevier, Masson [French], pp 371
60. Kaufmann RA, Pfaeffle HJ, Blankenhorn BD, Stabile K, Robertson D, Goitz R (2006) Kinematics of the midcarpal and radiocarpal joint in flexion and extension: an in vitro study. J Hand Surg 31A:1142–1148
61. Kuhlmann JN (2002) La stabilité et les instabilités radio- et médio-carpiennes. Sauramps Médical, Montpellier
62. Berger RA, Imeada T, Berglund L, An KN (1999) Constraint and material properties of the subregions of the scapholunate interosseous ligament. J Hand Surg 24A:953–962
63. Short WH, Werner FW, Green JK, Masaoka S (2002) Biomechanical evaluation of ligamentous stabilizers of the scaphoid and lunate. J Hand Surg 27A:991–1002
64. Short WH, Werner FW, Green JK, Masaoka S (2005) Biomechanical evaluation of ligamentous stabilizers of the scaphoid and lunate: part II. J Hand Surg 30A:24–34
65. Short WH, Werner FW, Green JK, Masaoka S (2007) Biomechanical evaluation of ligamentous stabilizers of the scaphoid and lunate: part III. J Hand Surg 32A:297.e1–297.e18
66. Sennwald GR, Zdravkovic V, Oberlin C (1994) The anatomy of the palmar scaphotriquetral ligament. J Hand Surg 76B:147–149
67. Tang JB, Ryu J, Kish V (1997) Scapholunate interosseous ligament sectioning adversely affects excursions of radial wrist extensor and flexor tendons. J Hand Surg 22A:720–725
68. Berger RA (2001) The anatomy of the ligaments of the wrist and distal radioulnar joints. Clin Orthop Relat Res Feb (383):32–40
69. Moritomo H, Viegas SF, Elder K, Nakamura K, Dasilva MF, Patterson RM (2000) The scapho-trapezio-trapezoidal joint. Part 1: an anatomic and radiographic study. J Hand Surg 25A:899–910
70. Slutsky DJ (2008) The incidence of dorsal radiocarpal ligament tears in patients having diagnostic wrist arthroscopy for wrist pain. J Hand Surg 33A:332–334
71. Gayet LE, Texereau J, Condroyer A, Duport G, Clarac JP (2000) Modélisation cinématique du carpe et instabilité. Rev Chir Orthop 86(suppl II):87 [French]
72. Sicre G, Laulan J, Rouleau B (1997) Scaphotrapeziotrapezoid osteoarthritis after scaphotrapezial ligament injury. J Hand Surg 22B:189–190
73. Herren DB, Lehmann O, Simmen BR (1998) Does trapeziectomy destabilize the carpus? J Hand Surg 23B:676–679
74. Garcia-Elias M, Lluch AL, Farreres A, Castillo F, Saffar P (1999) Resection of the distal scaphoid for scaphotrapeziotrapezoid osteoarthritis. J Hand Surg 24B:448–452
75. Saffar P, Semaan I (1994) The study of the biomechanics of wrist movements in an oblique plane. A preliminary report. In: Schuind F, An KN, Cooney WP III, Garcia-Elias M (eds) Advances in the biomechanics of the hand and wrist. Plenum Press, New York, NATO ASI Series A: life sciences. Vol. 256: pp 305–311
76. Moritomo H, Apergis EP, Herzberg G, Werner FW, Wolfe SW, Garcia-Elias M (2007) IFSSH committee report of wrist biomechanics committee: biomechanics of the so-called dart-throwing motion of the wrist. J Hand Surg 32A:1447–1453
77. Masquelet AC, Strube F, Nordin JY (1993) The isolated scapho-trapezio-trapezoid ligament injury. Diagnosis and surgical treatment in four cases. J Hand Surg 18B:730–735
78. Cowey AJ, Carmont MR, Tins B, Ford DJ (2007) Flexor carpi radialis rupture reined in! Inj Extra 38(3):90–93 (Elsevier Online)

79. Verkellen K, Dauwe D, Demuynck M, Kestelijn P, Vanden Berghe L (1992) Spontaneous ruptures of the flexor carpi radialis tendon secondary to STT osteoarthritis. Acta Orthop Belg 58:474–476
80. Oberlin C (1990) Carpal instability and desaxations. Anatomical bases. Clinical and Radiologic study. Elsevier – conférence d'enseignement de la SOFCOT. 38:235–50 [French]
81. Watson HK, Yasuda M, Guidera PM (1996) Lateral lunate morphology: an X-ray study. J Hand Surg 21A:759–763

http://www.springer.com/978-2-8178-0378-4

Carpal Ligament Surgery
Before Arthritis
Camus, E.; Van Overstraeten, L. (Eds.)
2013, XXIII, 306 p. 205 illus., 132 illus. in color.,
Hardcover
ISBN: 978-2-8178-0378-4