3 Wrist Biomechanics

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3.1 Introduction

In order to facilitate hand function, the upper limb must be mobile, but also stable. If the proximal articulations of the upper extremity lack mobility, the hand will not be properly positioned where it is needed. If those joints are unstable, the hand will not be able to carry heavy objects. To understand wrist biomechanics, therefore, one needs to learn kinematics (how joints move) and kinetics (how do they resist loads without yielding or suffering injury) [1, 2].

The wrist is often described as the least important articulation of the upper limb; a joint that can be fused without generating great distress to the patient. This is only partly true. Unquestionably, patients with a fused wrist may cope effectively with stressful activities, but they have substantial limitations in daily activities such as washing one's back, turning a door knob, or rotating the steering wheel [3, 4]. Without a mobile wrist, there is no precision in placing the hand where is required to manipulate an object. Without the wrist, the hand is less effective [5]. The wrist, indeed, is an important articulation.

Several mechanical models have been hypothesized to explain wrist function: the wrist as two interconnected rows (proximal and distal), as three interdependent columns (lateral, central, and medial), or as a ring of four linked units (distal row, scaphoid, lunate and triquetrum) [6, 7]. Although certainly useful for teaching purposes, none of these models can fully explain how the wrist is allowed to move and yet be able to transfer substantial amount of loads. Wrist function is not only the result of a perfect mechanical interaction between moving bones and soft tissue constraints (Fig. 3.1), but also the consequence of a complex system of ligament-muscle reflexes mediating its dynamic muscle stabilization [8, 9]. Most of these factors have been largely ignored or underestimated in the past. Furthermore, most descriptions of carpal bone kinematics have been based on observations made on a limited number of specimens or in vivo determinations using 3-D reconstructions of CT scans [10–14]. Being the number of observations small, some perspective may have been lost in terms of individual variations of normality, both in terms of anatomy as in mechanics [15–17]. In short, carpal kinematics is not yet a fully understood issue, and needs more thorough investigations for us to be efficient in coping with its dysfunctions.

The wrist is not only a complicated composite joint allowing large range of motion; the wrist is also a load bearing articulation [18]. The carpus has a self-locking mechanism allowing transmission of large amount of forces [18–20]. Albeit certain wrist positions are better prepared than others to bear loads [21, 22], the normal wrist does not need to be placed in one particular position to grasp, push, or pull an object.

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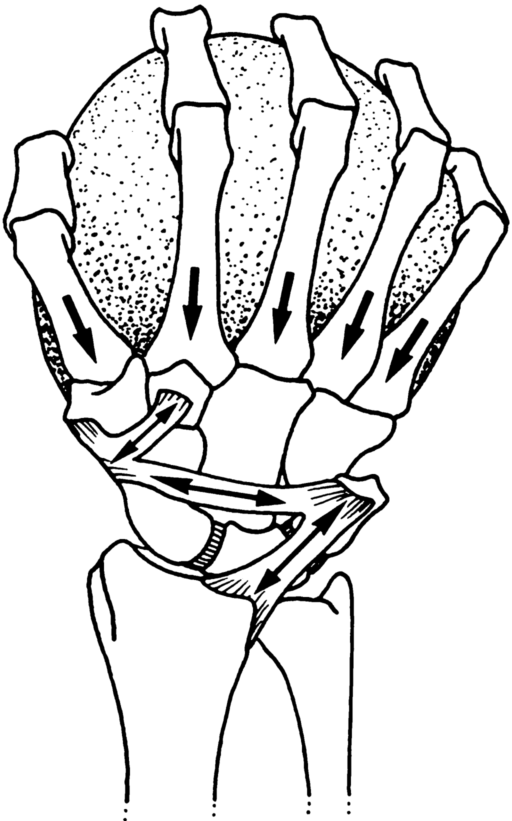

Fig. 3.1 The wrist is a very mobile, load bearing articulation, which stability is based upon an adequate interaction between the different articular surfaces and soft tissue constraints. With permission from [64]

Aside from its role as a mobile self-stabilizing load bearing articulation, the wrist is also an important pulley to enhance finger function [5, 23, 24]. The so called "carpal pulley", which is basically composed of the distal carpal row and their transverse ligament interconnections, can be oriented at will for an optimal finger function. This chapter will analyze the wrist joint and the carpal pulley from a kinematic and a kinetic perspective.

3.2 Carpal Kinematics

Carpal bone motion has been traditionally described as a combination of three rotations (Eulerian angles) and three translations (antero-posterior, mediolateral and proximodistal) around and along three orthogonal axes, taking the distal radius as a reference (Table 3.1). Wrist rotation along the sagittal plane (Y axis) corresponds to flexion–extension, rotation along the coronal plane (X axis) determines abduction (radial deviation) or adduction (ulnar deviation), and rotation along the axial or transverse plane (Z axis) corresponds to pronation-supination. The first and second types of rotation (flexion–extension and radial-ulnar deviation) may be either the result of a passive external force, or be actively contracting the muscles which tendons cross the wrist. Active rotation along the axial plane of pronosupination only happens if the two other rotations (flexion–extension and radio-ulnar deviation) are constrained in neutral position (isometric type of loading); a typical example of this type of rotation is when the hand makes a closed fist: it does not move from a slightly extended position, but it rotates an average 1.9° supination [25].

The unconstrained wrist seldom rotates in a pure flexion–extension or radial-ulnar deviation mode. Most activities of daily living require the wrist to move along an oblique plane, from extension-radial deviation to flexion-ulnar deviation. It is one of the most utilized planes of wrist motion (using a hammer, fly fishing, throwing, pushing or holding a heavy object). Although known by Corson [26] in 1897, the so-called "physiologic flexion–extension" motion was not properly addressed until recently. Fisk [27], in 1980, was the first to use the term "dart throwing " to refer to this type of rotation, and Saffar and Seumaan [28], in 1994, were the first to investigate it from a biomechanical perspective. Since then, multiple studies have emphasized its peculiar kinematics [12, 14, 29].

3.2.1 Flexion–Extension

Wrist flexion is a rotation around the Y axis, located proximal to the head of the capitate, near the lunate, and parallel to the palmar surface of the distal radial metaphysis. Flexion brings the palm towards the volar aspect of the forearm. Extension of the wrist is also a rotation about

Table 3.1 Individual carpal bone rotation (average Eulerian angles) relative to the radius during wrist movements, according to the kinematic study by Kobayashi et al. [10]

	Wrist flexion 60°	Wrist extension 60°	Wrist radial deviation 15°	Wrist ulnar deviation 30°
Scaphoid (n: 22)	Flx 40°, UD 8°	Ext 52°, UD 4°	RD 4°, Flex 8°	Ext 17°, UD 14°, Pron 7°
Lunate (n: 22)	Flx 23°, UD 11°	Ext 30°, UD 4°	RD 2°, Flex 7°	Ext 22°, UD 15°, Pron 4°
Triquetrum (n: 22)	Flx 30°, UD 10°	Ext 39°	RD 5°, Flex 4°	Ext 17°, UD 18°
Trapezium (n: 13)	Flx 54°, UD 3°	Ext 59°	RD 14°, Sup 5°	UD 32°, Flx 10°, Pron 16°
Capitate (n: 22)	Flx 63°, UD 3°	Ext 60°	RD 15°, Sup 4°	UD 31°, Flx 6°, Pron 12°

Flx Flexion, *Ext* Extension, *RD* Radial deviation, *UD* Ulnar deviation, *Pron* Pronation, *Sup* Supination

this axis, but in the reverse direction: the back of the hand approximates the dorsal aspect of the forearm. All tendons located palmar to the Y-axis contribute to wrist flexion, while extension results from contraction of muscles located dorsal to this axis [30]. The most active wrist flexors are the flexor carpi radialis (FCR), the flexor carpi ulnaris (FCU) and palmaris longus, while the extensor carpi radialis brevis and longus (ECRB-L), and extensor carpi ulnaris (ECU) are active extensors. Aside from those, any tendon crossing the wrist to mobilize the fingers also has an influence on the wrist. The mean range of active flexion–extension of normal wrists is 59° and 79° respectively [31].

Regardless the direction of wrist motion, the trapezoid, capitate and hamate bones move synchronously (in about the same direction) as if they were connected by synostoses. In fact, only the trapezium-trapezoid joint exhibits some minor, but detectable mobility [10]. Consequently, the internal dimensions of the carpal tunnel change little during wrist motion [32]. The bones of the proximal carpal row, by contrast, appear less strongly connected to each other. Substantial differences in sagittal rotation exist between the three row bones. For a total 120° of wrist flexion–extension, the average rotation of the scaphoid, lunate and triquetrum are 92°, 53°, and 69° respectively (Table 3.1) [10]. The different radii of curvatures of their proximal convexities explains why the three bones move differently. To coordinate such complex mobility, a complex arrangement of

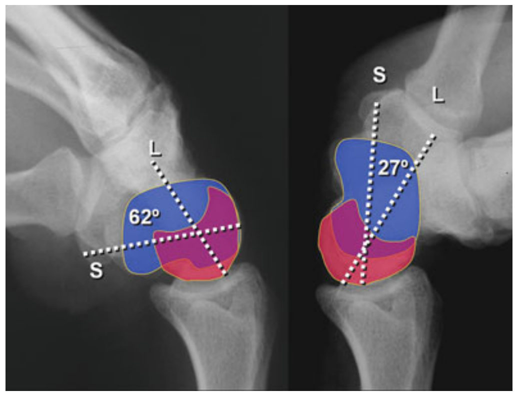

Fig. 3.2 Outlines of the scaphoid and lunate bones obtained from radiographs of a wrist in flexion (*left*) and extension (*right*). The scapholunate angle shows substantial variation from one position to another. This demonstrates that, unlike the distal row bones, there is substantial rotational motion between the bones of the proximal row. In particular, at the scapholunate joint, this rotation occurs around a dorsally located axis represented by the dorsal scapholunate ligament. With permission from [64]

scapholunate (SL) and lunotriquetral (LTq) ligaments is necessary. In the SL joint, there is a "scissor-like" type of rotation around a transverse axis which coincides quite well with the dorsal SL ligament. (Fig. 3.2) [33]. By contrast, the LTq joint axis of flexion–extension coincides with the palmar LTq interosseous ligament [34].

The relative contribution of the radiocarpal and midcarpal joints to the total wrist flexion–extension is controversial. It varies substantially from one column to another. In the central column (radius-lunate-capitate) about a 50 % of the overall flexion–extension occurs at the

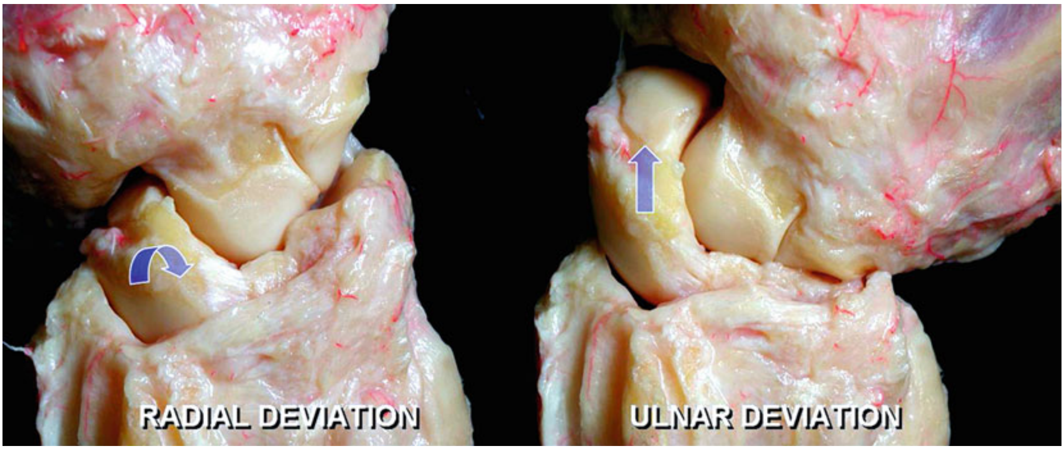

Fig. 3.3 Dorsal view of a dissected specimen demonstrating the two major components of motion exhibited by the proximal carpal bones during radio-ulnar deviation. *Radial deviation* involves flexion and medial translation of the three bones of the proximal row. Contrarily, during wrist *ulnar deviation* the bones of the proximal row rotate into extension while displacing towards the radius. With permission from [64]

proximal radiolunate joint, while the other half occurs at the lunocapitate interval. In the scaphoid column (radius-scaphoid-trapezoid), by contrast, 75 % of flexion and 92 % of extension occurs at the radioscaphoid joint, the scaphoid-trapezium-trapezoid (STT) joint being much less mobile [10, 35, 36].

3.2.2 Radial-Ulnar Deviation

Ulnar deviation (adduction) of the wrist may be described as a rotation that approximates the ulnar aspect of the hand to the medial border of the forearm. The X axis around which this occurs is located at the centre of the head of the capitate, and it is perpendicular to the Y axis of flexion–extension. Radial deviation (abduction) is also a rotation about this axis, but in the reverse direction: the thumb gets closer to the radial aspect of the forearm. All tendons crossing the wrist radial to the X axis bring about a radial deviation, while the tendons located ulnarly are ulnar deviators [30]. The average range of active abduction–adduction is 21° and 38° respectively [31].

As stated for flexion–extension, during wrist radial-ulnar deviation there is almost no rotation between trapezoid, capitate and hamate. The trapezium-trapezoid joint is slightly more mobile, but only in a proximodistal direction: the trapezium tilts proximally when axially loaded by the first metacarpal [37]. This, however does not preclude the distal row to maintain its internal dimensions during motion.

At the level of the proximal row, there is substantial rotation between the three proximal carpal bones during abduction–adduction. From radial deviation to ulnar deviation there is a mean of 10° of SL rotation and 14° of LTq rotation [10] (Table 3.1). Despite differences in rotation, the direction of motion is similar for the three bones: they move synergistically from a flexed position in radial deviation to an extended position in ulnar deviation (Fig. 3.3).

The magnitudes of flexion–extension of the proximal row bones during radioulnar deviation vary between individuals: there is a spectrum of behaviours, all being normal. From wrists with a scaphoid exhibiting almost exclusively flexion–extension, to wrists in which the scaphoid only translates lateromedially, all combinations are possible (Fig. 3.4) [11]. The wrists with a predominant scaphoid flexion–extension component are called “column-type” while the ones with predominant mediolateral translation are “row-type” wrists [16]. The “column-type” wrist appears to be more lax, with a more prominent interfacet ridge than the “row-type”

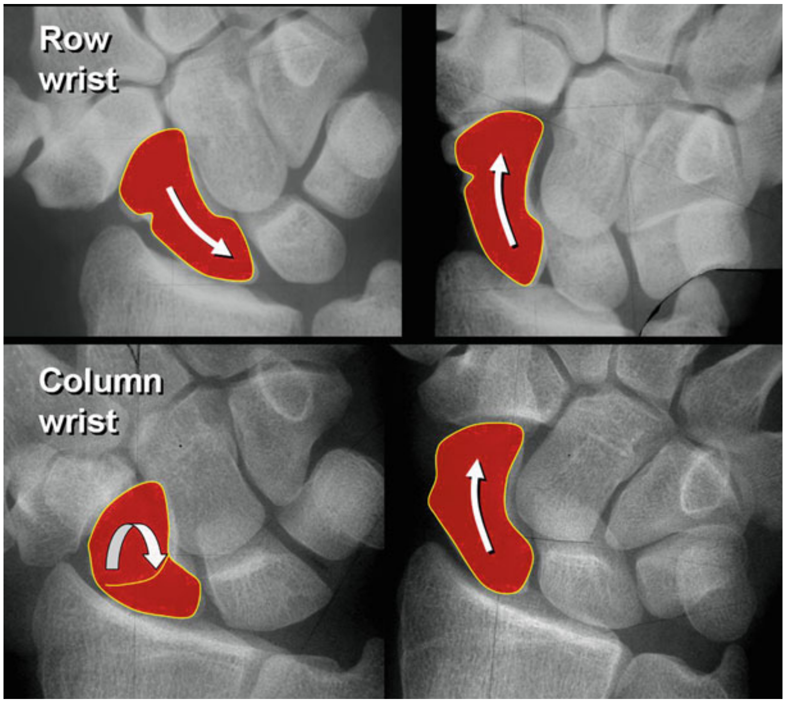

Fig. 3.4 There are different patterns of wrist kinematics. The so-called "row wrists" exhibit little flexion–extension of the scaphoid during radioulnar deviation, while the "column wrists" have substantial out-of-plane motion. With permission from [64]

[38]. Such a complex kinematics is necessary to ensure joint congruency throughout the entire range of wrist motion.

3.2.3 "Dart-Throwing" Motion

It has long been known that the unconstrained wrist seldom rotates along the sagittal or coronal planes [26]. Most actions require a rotation from an extended-radial deviated position to a flexed-ulnar deviated position (Fig. 3.5) [27–29]. It is an oblique plane of motion commonly referred to as the "physiologic" plane of flexion–extension or "dart throwing" plane of rotation [27]. There are several reasons to explain why this oblique plane is so commonly utilized. First, because this rotation is produced by the most

Fig. 3.5 The so-called "physiologic flexion–extension", also known as "dart-throwing" motion, is one of the most usual planes of rotation of the wrist: from extension-radial deviation to flexion-ulnar deviation. This motion mostly involves a rotation of the midcarpal joint. With permission from [64]

powerful muscles of the forearm, the ones with the highest tension fraction: the extensor carpi radialis (longus and brevis) and the FCU [28]. Second, because the midcarpal ball-and-socket articulation is not spherical but ovoid, with an oblique axis oriented towards the anteromedial corner of the wrist. And third, because the distal articular surface of the scaphoid has a ridge which is parallel to the plane of "dart throwing" [33], and guides the distal row towards the anteromedial corner of the wrist.

When the wrist rotates along the "dart throwing" plane, the radiocarpal joint does not move much [12, 14, 29]. When the wrist rotates from radial-extension to ulnar-flexion, the proximal row does not extend, but only translates laterally. The scaphoid does not flex in radial deviation because the concomitant wrist extension prevents that. During ulnar deviation, the proximal row does not extend because is constrained by the flexing distal row. In short: when the wrist rotates along the "dart throwing" plane [39], most motion occurs at the midcarpal level. One of the keys to understand why the proximal row does not move much during this type of motion is the STT ligamentous complex. During radial deviation, the scaphoid tends to rotate into flexion in order to allow the trapezium to approximate to the radial styloid. The STT ligament allows that because is not taut. However, in radial-extension, the trapezium slides down the dorsal slope of the scaphoid, thus pulling the scaphoid into extension by means of the STT ligaments. The equilibrium between the scaphoid flexion tendency and the tensile forces exerted by the STT ligaments explains why the scaphoid remains still during dart-throwing rotations. Likewise, when the wrist ulnarly deviates, the STT ligament becomes taut, thus inducing scaphoid extension. Such scaphoid extension will not happen if the wrist rotates into flexion, in which case the STT ligaments become loose. This may explain why radio-scaphoid-lunate stiffness is so well tolerated. Truly, radiocarpal arthrodeses tend to do better than midcarpal fusions.

3.2.4 Intracarpal Pronosupination Motion

When subjected to a torque along the axial plane, the wrist may be passively displaced in both directions of pronosupination [40]. When unloaded, the mean total rotational laxity of the wrist is 42° [41]. Under load, such displaceability is reduced proportionally to the amount of load being exerted across the wrist. Until recently, it was believed that the wrist could not be actively pronated or supinated, that the muscles with tendons across the wrist could only generate axial compressive forces to the distal row, which eccentricity explained wrist deviations along the coronal or sagittal plane. Recent investigations, however, have demonstrated in the cadaver that the wrist may be actively pronated or supinated depending upon the obliquity of the tendon at the level of the carpus [25]. Certainly, at the level of the carpus, some tendons have an oblique course towards their distal insertion. The abductor pollicis longus (APL), for instance, is located dorsally in the first extensor compartment, but inserts anterolaterally at the base of the first metacarpal. The ECU, by contrast, has an opposite obliqueness from the dorsum of the ulna to the anteromedial corner of the fifth metacarpal. They both are dorsal at the level of the radiocarpal joint, to diverge distally towards either the medial or lateral aspects of the wrist. When these muscles contract, its tendon obliquity is likely to generate pronation or supination moments to the distal row: the medially inserted tendons will induce pronation, while the laterally inserted tendons will induce supination to the distal row. The APL, the extensor carpi radialis longus (ECRL) and the FCU are intracarpal supinators, while the FCR and the ECU are distal row pronators. As it will be stated below, this active pronosupination capability may partly explain how the wrist achieves stability under load.

3.3 Carpal Kinetics

Kinetics is the branch of mechanics that deals with the effects of forces in producing or constraining motion of a mass. Carpal kinetics describes the mechanisms by which the wrist may sustain load without yielding; that is, the mechanisms of carpal stabilization. Unquestionably, most hand activities generate forces and torques that will be transferred proximally across the carpus. Stability is defined as the ability of carry on with such centripetal forces without suffering injury. Although some wrist positions are better prepared to bear loads than others (extension better than flexion) [20], the stable wrist is able to bear load in any given position. A stable wrist is prepared to develop self-locking strategies to facilitate proper transfer of loads. To better understand those strategies, it is important to discuss: (1) what is the magnitude of forces crossing the wrist, (2) how are they distributed among the different carpal articulations, (3) what is the role of ligaments as primary stabilizers, (4) what is the role of mechanoreceptors in the detection of ligaments at risk of being injured, and (5) what is the role of muscles as the ultimate wrist stabilizers.

3.3.1 Magnitude of Forces Transmitted Across the Wrist

The wrist is a load bearing articulation that sustains considerable compressive and shear forces [18]. Wrist loading not only derives from external forces being applied to the hand and transmitted across the wrist onto the forearm, but also from contraction of the muscles that control finger and carpal function. Reaction forces generated in the different stabilizing ligaments also contribute to this (Fig. 3.1). According to a series of mathematical and experimental laboratory studies, the amount of compressive forces that cross each carpometacarpal joint may be as high as 1.5–4.2 times the applied force at the tip of the corresponding fingers. These calculations have been recently validated by Rikli et al. [20] who inserted a pressure-sensor device in the radiocarpal joint space of volunteers. According to these experiments, during motion the pressure sustained by the distal articular surface of the radius varies from 54 N/cm^2 (Newtons per centimetre square) in maximal active extension to 26 N/cm^2 in maximum flexion.

3.3.2 Force Distribution Across the Wrist

Once in the distal row, the axial forces distribute among the different joints following specific patterns. These depend upon direction and point of application of the external loads, position of the wrist, and orientation and shape of the articular surfaces [6]. Most forces concentrate on the SL interval and from there into the radius. Viegas and Patterson [42] found that about 50 % of the load is transferred from the capitate into the scaphoid and lunate, while a 35 % goes across the STT joint. At the radiocarpal level, forces distribute as follows: radio-scaphoid joint, 50–56 %; radio-lunate joint, 29–35 %; and ulnolunate joint 10–21 % [22, 42–44]. These percentages vary with wrist position, the radiolunate fossa being more loaded with ulnar deviation, while the scaphoid resisting more load with radial deviation [20].

3.3.3 Role of Ligaments in the Stabilization of the Carpus

For the wrist to be stable there is a need for a perfect interaction between articular surface geometries and soft-tissue constraints. Not only the ligaments are of importance for a stable function, but also tendons, muscles, capsule, and tendons sheaths contribute to stability. Indeed, carpal stability is a multifactor phenomenon. Of all structures involved, however, the ligaments are the first to react when a load is about to displace bones beyond normal limits. Undeniably, ligaments are the primary stabilizers, the first line of defence against any disturbing force. For the neutrally positioned wrist there are four groups of ligaments that are especially important in stabilizing the different levels of the joint [19]. What follows is a short description of the mechanisms by which these ligaments achieve primary stability:

3.3.3.1 Stabilizing Mechanism of the Distal Row

Once distally emerged from the carpal tunnel, the flexor digitorum tendons have divergent directions. When their corresponding muscles contract, the flexors of the little finger generate a tangential compressive force in an ulnar direction to the hook of the hamate. This force is opposite in direction to the force that generates the FCR to the inner surface of the trapezium. Such opposite forces would tend to open the palmar carpal concavity (the trapezium towards the radial side, the hamate towards the ulnar side) was if not for both the flexor retinaculum and the strong and taut transverse intercarpal ligaments [45]. Their annular disposition appears essential to maintain adequate transverse stability to the carpal pulley. Failure of any one of these structures is likely to create a particular type of instability, called “axial” or “longitudinal”, with the tunnel splitting into two or more unstable columns, displacing in divergent directions [46].

3.3.3.2 Midcarpal Stabilizing Mechanism

Under axial load, the distal carpal row exerts an axial compressive force onto the proximal row bones. Because of its oblique orientation relative to the long axis of the forearm, the axially loaded scaphoid tends to rotate into flexion and pronation [10, 19]. If the ligaments connecting the scaphoid to the distal row, namely the anterolateral STT and the volar scaphocapitate (SC) ligaments [47], are intact, the flexion and pronation moment by the scaphoid will be transmitted to the distal row. The more the trapezium is pulled forward by the STT-SC ligaments, the more the distal row pronates. Excessive distal row pronation, however, could be dangerous for the triquetrum-hamate (TqH) joint. Indeed, being the distal row a rigid structure, the more the capitate pronates, the more the hamate is displaced dorsally. Fortunately, the palmar TqH fascicle of the medial arcuate ligament is strong enough as to prevent such medial midcarpal subluxation. Indeed, the midcarpal crossing ligaments have opposite functions in this regard: the STT-SC ligaments induce pronation to the distal row; the TqH ligament counteracts such pronation vector. Should the latter be insufficient or torn, the distal row would be dragged by the scaphoid into an abnormal flexion-pronation pattern of carpal malalignment, known as “volar intercalated segment instability” (VISI) [7, 48].

3.3.3.3 Stabilizing Mechanism of the Proximal Row

If both the medial and lateral midcarpal crossing ligaments are intact, the proximal carpal row would be subjected to two opposite moments: the scaphoid flexion and pronation moment, and the extension-supination moment induced by the TqH ligament. On theory, if the two moments had equal magnitudes, and if the SL and LTq interosseous ligaments were intact, the scaphoid would rotate into flexion and the triquetrum into extension until a neutral equilibrium would be achieved. In reality, the scaphoid moment predominates over the extension moment of the triquetrum, for not only the scaphoid rotates into flexion and pronation, but also the lunate and triquetrum rotate into flexion and pronation [25, 49]. The scaphoid and triquetrum, however, are not equally constrained by the palmar crossing midcarpal ligaments: the scaphoid is allowed substantial rotation into flexion and pronation, while the triquetrum is tightly controlled by the TqH ligament. Consequently, there are decreasing magnitudes of rotation from lateral to medial. According to Kobayashi et al. [49],

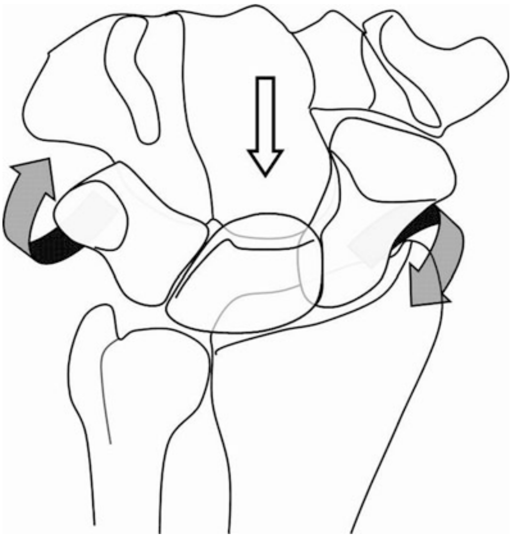

Fig. 3.6 Under axial load (*white arrow*) the proximal row has to cope with two opposite forces (*grey arrows*): one is caused by the scaphoid which tends to draw the entire proximal row into flexion; another is produced by the distal row which extension is transmitted to the triquetrum via the TqH portion of the arcuate ligament. The two opposite moments reach equilibrium provided the transverse intercarpal scapholunate and lunotriquetral interosseous ligaments are intact. With permission from [64]

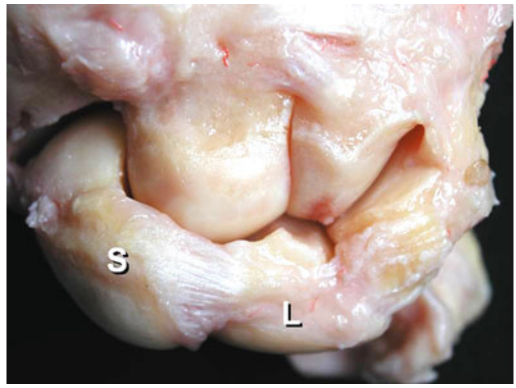

Fig. 3.7 Dorsal view of a dissected wrist demonstrating the obliquely oriented fibres of the dorsal scapholunate interosseous ligament, one important stabilizer of the scaphoid. Its oblique orientation is particularly well adapted to constrain the scaphoid tendency towards collapsing into flexion under load. *S* Scaphoid; *L* Lunate. With permission from [64]

Fig. 3.8 Scapholunate instability resulting from complete rupture of the scapholunate interosseous ligaments. The scaphoid shows the typical rotary subluxation (*curved red arrow*) with increased scapholunate gap formation and slight ulnar translocation of the lunate (*white arrow*). With permission from [64]

when the carpus is isometrically loaded, the scaphoid rotates into flexion an average 5.1° relative to the radius, while the lunate rotates 4.2° and the triquetrum 3.8° [25, 49].

In short, the proximal row is subjected to two opposite moments: a flexion moment generated by the scaphoid and an extension moment transmitted to the triquetrum by the TqH fascicle of the ulnar arcuate ligament (Fig. 3.6). If both the palmar and dorsal SL and LTq ligaments are intact (Fig. 3.7), such opposite moments generate increasing torques at both intercarpal levels resulting in a stable cooptation of the two SL and LTq joints. Such an increased cooptation further contributes to the proximal carpal row stability. Based on this, if the SL ligaments are completely torn, the scaphoid no longer is constrained by the rest of the proximal row, and tends to collapse into an abnormally flexed and pronated posture (the so called "rotatory subluxation of the scaphoid") [6] (Fig. 3.8), while the lunate and triquetrum, under the influence of the ulnar part of the arcuate ligament, are pulled into an abnormal extension, known as a "dorsal intercalated segment instability" (DISI) [47]. The consequence of all these changes is an alteration of the moment arms of all wrist motor tendons, and muscle imbalance [50]. By contrast, if it is not the SL ligaments, but the LTq ligaments the ones that have completely failed, the scaphoid and lunate tend to adopt an abnormal flexed posture VISI, while the triquetrum remains solidly linked to the distal row [34, 51].

3.3.3.4 Radiocarpal Stabilizing Mechanism

The proximal convexities of the scaphoid, lunate and triquetrum are proximally interconnected by fibrocartilaginous membranes, forming what has been called the carpal condyle. Such a biconvex structure does not articulate to a horizontal flat surface but to an ulnarly and palmarly inclined antebrachial glenoid, formed by the distal articular surface of the radius and the distal surface of the triangular fibrocartilage. In such circumstances, the loaded carpal condyle has an inherent tendency to slide down ulnarly and palmarly. This tendency is effectively constrained by both palmar and dorsal radiocarpal ligaments which oblique orientation appears ideal to resist such an ulnar and palmar translation tendency. Failure of these obliquely oriented ligaments is likely to result in a very dysfunctional ulnar and palmar translocation of the carpus relative to the radius [52].

3.3.4 Role of Mechanoreceptors in Carpal Stability

Until recently, all the above mechanisms of ligament stabilization were thought to be the essence of wrist stabilization [6]. Ligaments are the first to detect and react against excessive bone displacement; however, they cannot be the only stabilizers. If they were, they would disrupt easily. Indeed, ligaments are not strong enough to resist the magnitude of strains involved in carpal stabilization. The dorsal SL ligament, for instance, considered by many as one of the most resistant components of the SL ligamentous complex, yields at about 260 N of distraction. The palmar SL ligament fails at 118 N, and the proximal membrane at 63 N [53]. The palmar LTq ligament is thicker and stronger than the dorsal ligament, but still it fails at a mean 301 N while the dorsal LTq ligament disrupts at 121 N [34].

If ligaments were the only means of keeping bones reduced, we would see ligament ruptures very frequently, particularly in certain sports, like gymnastics, where gymnasts land on their wrists after pirouetting in the air. In reality, ligament ruptures are nor that frequent because gymnast's wrists have adequate proprioception, and their sensorimotor system is warned well ahead of time when unusual ligament strains develop. When there is a risk for a ligament to disrupt, the system activates specific muscles that shelter the ligaments against rupture (Fig. 3.9). Indeed, ligaments are protected by muscles, but only if wrist proprioception is fully functional.

Wrist proprioception is more than just conscious perception of joint position. Wrist proprioception is both conscious and unconscious awareness of what occurs within the wrist capsule [8, 9]. Most carpal ligament contain mechanoreceptors able to detect unusually growing strains in the ligaments, and react by sending afferent stimuli to the spinal cord. One of the most active mechanoreceptors in the SL interosseous ligament is the Ruffini corpuscle, a slowly-adapting, low-threshold receptor, constantly active during joint motion, and particularly reactive to axial loading and tensile strain in the ligament, but not to perpendicular compressive load. The afferent stimuli sent by the Ruffini receptor is analyzed at different levels (local, spinal and supraspinal), this triggering the release of efferent (motor) stimuli to specific muscles which contraction will prevent ligament damage. There are different categories of response: from fast joint protective reflexes through monosynaptic spinal control, to more complex plurisynaptic supraspinal responses. In all cases, the faster the muscle response, the better. If the latency time, between ligament aggression and muscle response, is abnormally long, the ligament will suffer more extensive damage than if it is short. Thus, it is important to plan an adequate proprioception training of sportsmen and musicians: by reducing their latency time, injuries are prevented.

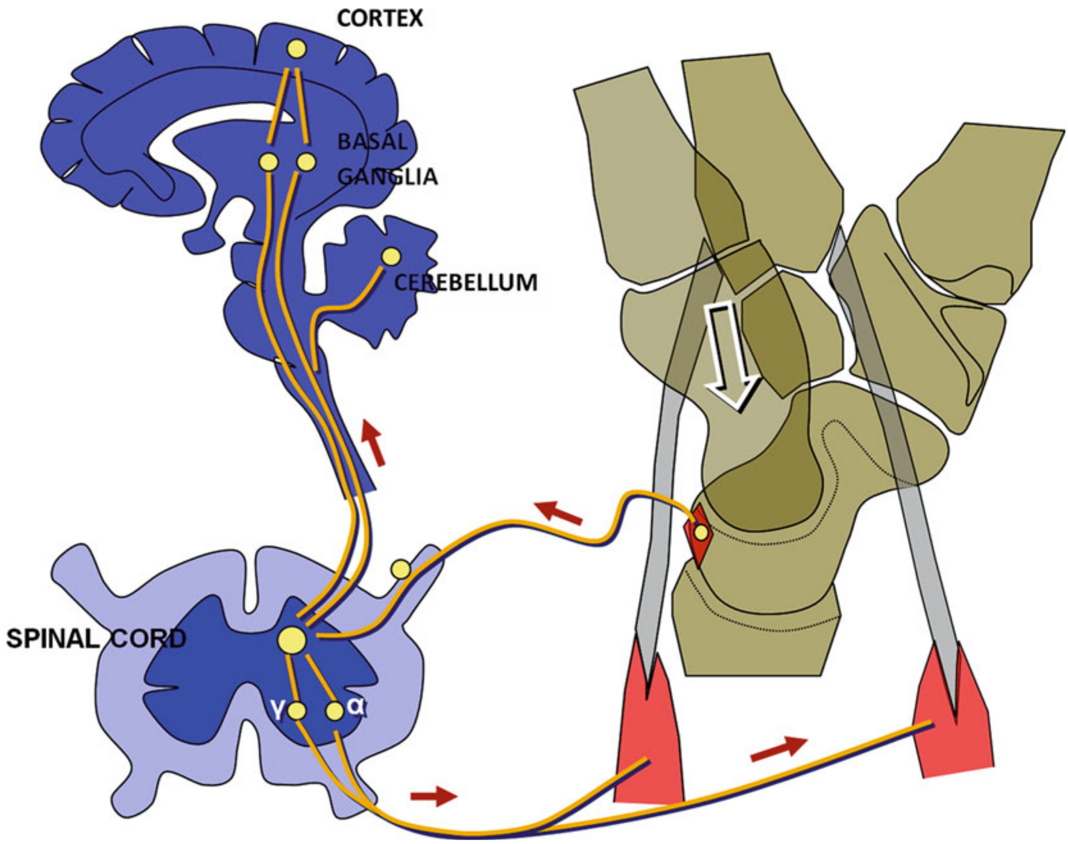

Fig. 3.9 Schematic representation of a ligament-muscle reflex. Under axial load (*white arrow*) the receptors within the dorsal SL ligament send an afferent stimulus (*red arrows*) to the *spinal cord*. The information is forwarded to the supraspinal levels; once analyzed, an efferent (motor) stimuli is sent to specific muscles which contraction will prevent ligament damage. With permission from [64]

Until 1997, it was thought that there were no mechanoreceptors within the carpal capsule. Petrie and associates were the first to demonstrate Golgi organs, Pacinian and Ruffini corpuscles within three palmar wrist ligaments [54]. Since then, several immuno-histo-chemical investigations have been published identifying, qualifying and quantifying sensory receptors in the carpal ligaments [55–57]. The distribution of receptor in the ligaments was not homogeneous: some ligaments are densely innervated while others have almost no innervation [55]. Interestingly enough, with the exception of the dorsal SL ligament, the most poorly innervated ligaments were the ones with the highest yield strength, while the richly innervated ligaments had poorly arranged collagen fibers [55]. In a way, it is reasonable to say that there are mechanically important ligaments, like cables holding bones reduced, and sensorially important ligaments with a predominant proprioceptive role. In general, most ligaments inserted into the triquetrum are richly innervated, while the ones about the scaphoid are mechanically important ligaments. Based on this, it has hypothesized that the triquetrum plays a special role in the detection of abnormal carpal bone displacements, that the triquetrum is the key element in wrist proprioception [55].

In order to prove the existence of ligament-muscle reflexes emanating from inside of the carpal joint, Hagert et al. [58] performed an

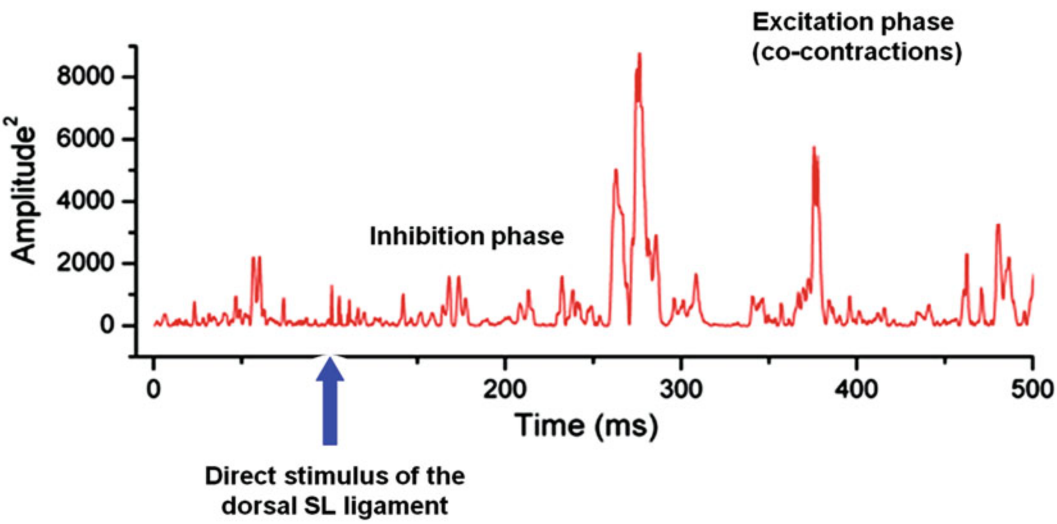

Fig. 3.10 Typical graph demonstrating the changes in muscle activity that occurs in the FCR muscle, 150 ms after the SL ligament was stimulated. Courtesy of Elisabet Hagert, Karolinska Institutet, Stockholm, Sweden. With permission from [64]

interesting experiment. Under ultrasound control, they inserted fine wire electrodes into the depth of the dorsal SL ligament of normal volunteers. The ligament was then electrically stimulated, while surface electromyography sensors documented activity changes in some forearm muscles. The results of that study were conclusive: ligament stimulation was always followed by a muscle response (Fig. 3.10) [58]. In the normal situation, the response was almost immediate (in less than 50 ms after the stimulus) and lasted for 500 ms or sometimes more. The early muscle reaction was interpreted as an attempt to protect the ligaments from suffering injury; while late muscle activity was thought to represent a more elaborated supraspinal response to carpal instability. In all circumstances, the muscle response was not restricted to one muscle, but to several: usually more than three muscles reacted positively for each wrist position. Most often, the response was in the form contraction, except when the muscle could have a destabilizing effect to the joint. In other words, the sensorimotor system is able to discriminate between potential muscle stabilizers and destabilizers; to the first, the system sends an order to contract; to the second, an inhibition order. When a disturbing load risks rupture of the SL ligament, only the muscles able to prevent that injury are asked to contract, while the potential destabilizers are inhibited.

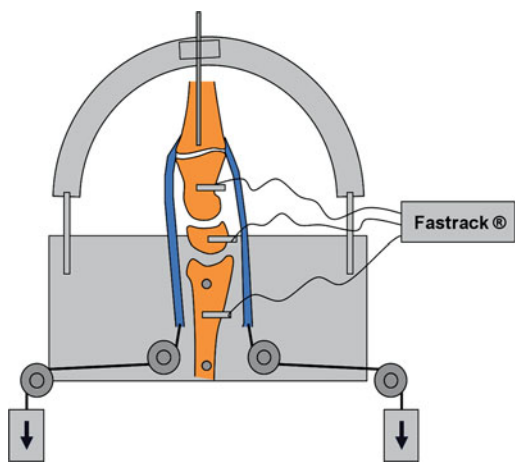

Fig. 3.11 Schematic representation of the experimental setup used by Salvà-Coll to investigate the effects of isometric contraction of muscles on carpal alignment [25, 62, 63]. With permission from [64]

Needless to say, for this to be possible, the nerves carrying afferent stimuli need to be intact. As demonstrated in vivo by Hagert et al. [58, 59] when the posterior interosseous nerve was

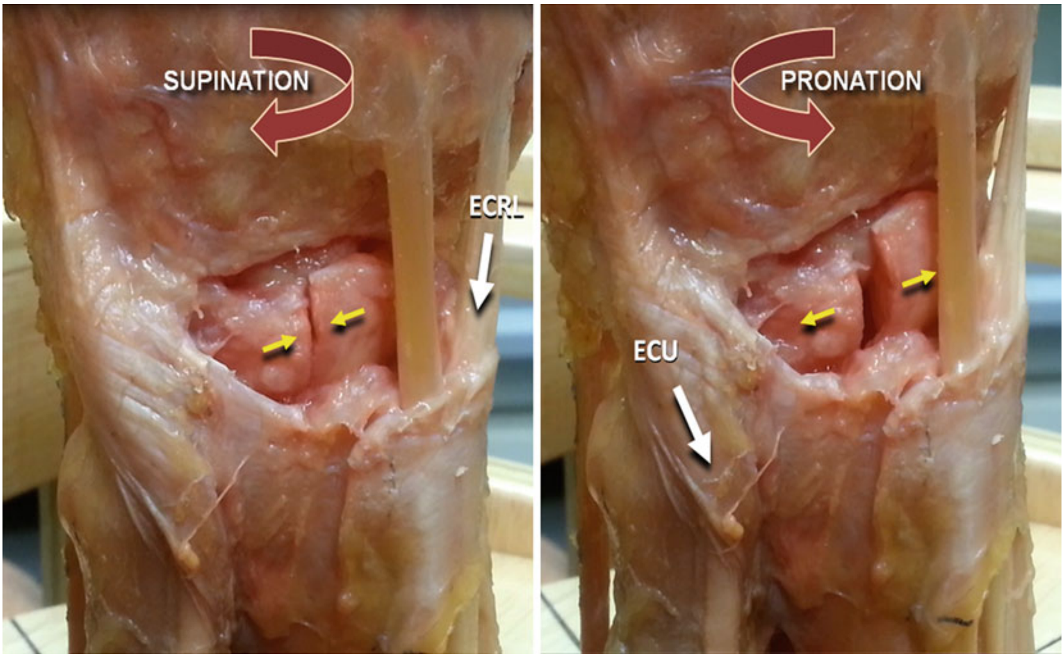

Fig. 3.12 Typical behaviour of the carpus when the SL ligament has been cut and the wrist is subjected to *supination* (*left*) or *pronation* (*right*) torques (*purple curved arrows*). The rotation is produced by pulling tendons with an oblique direction (*white arrows*). When the distal row is torque in supination (*left*), the SL joint becomes reduced (*yellow arrows*). By contrast, when the wrist is pronated, the SL gap increases. From the Department of Anatomy. University of Barcelona. With permission from [64]

anesthetized, stimulation of the SL ligament did not triggered any muscle response. Wrist denervation, therefore, may not influence conscious proprioception (joint position sense) [60, 61], but it may seriously impair unconscious neuromuscle control of carpal stability.

3.3.5 Role of Muscles in Carpal Stability

Until recently, muscles were assumed to have a negative effect on carpal stability [6]. The axial compressive forces generated by their contraction was said to contribute to carpal collapse. Now we know that, in the presence of adequate ligament-muscle reflexes, patients with substantial ligament disruptions may learn to activate unconsciously the beneficial muscles while inhibiting the ones that could destabilize the joint. Indeed, it is not rare to find asymptomatic ligament disruptions.

In order to clarify what muscles are potential stabilizers, in what circumstances and through what mechanism, a number of experiments were conducted by Salvá-Coll et al. [25, 62, 63]. Using a 3D motion tracking device in a cadaver model, the effects of isometric loading of specific wrist motor tendons on carpal bone alignment were analyzed (Fig. 3.11). Despite radius and ulna had been blocked in neutral forearm rotation, some muscles induced pronation to the distal row, while others induced supination. The mechanism by which some muscles are able to supinate or pronate the distal row has been explained above (see Sect. 3.2.4). Interestingly enough, when all forearm muscles contract at once, the distal row always supinates, a displacement that counteracts the natural tendency of the distal carpal row towards pronation (see Sect. 3.3.3.2) [25]. Certainly, if muscles are able to stabilize the carpus is because they are capable of resisting the pronation torque sustained by the carpus under axial load.

According to Salvá-Coll et al. [25] supinator muscles are particularly effective in controlling the symptoms in cases of a dynamic SL dissociation. Indeed, supination constrains the pronation tendency of the scaphoid, and closes the SL gap (Fig. 3.12). Pronator muscles, by contrast, are deleterious in those cases, because they pull the scaphoid away from the lunate, thus widening the SL gap. Certainly, after a dorsal SL ligament repair, contraction of the ECU, a strong pronator, may affect negatively the results by pulling the sutures apart. It is not surprising, therefore, that after stimulation of the SL ligament, the ECU muscle gets an efferent order to relax, to do not contract. Indeed, the ECU is a SL destabilizing muscle, a muscle that can make worse the symptoms of a SL deficient wrist.

As said above (Sect. 3.2.4), there are three muscles that consistently induce supination to the distal row: the ECRL, the APL, and the FCU, and two muscles that generate pronation: the ECU and the FCR. Interestingly enough, the supinator muscles are the ones that generate the "dart-throwing" type of rotation. This explains why patients with dynamic SL dissociation benefit from dart throwing exercises.

The FCR has long been assumed to be a dynamic scaphoid stabilizer [6]. Because the tendon angles around the scaphoid tuberosity, its contraction has been long believed to generate a dorsally directed force that would extend the scaphoid. Recent studies, however, have demonstrated that the FCR muscle does not induce extension to the scaphoid, but flexion and supination, the latter being what makes this muscle beneficial in SL deficient wrists [62]. Indeed, as said above, by supinating the scaphoid, the SL gap is closed.

3.4 The Carpal Pulley

Stiffness of the distal carpal row against dorsopalmar compression is quite high provided that the short and stout transverse intercarpal ligaments are intact. In normal conditions, the flexor retinaculum contributes little to the overall structural stiffness of the carpal arch. As demonstrated by Garcia-Elias et al. [45], when the transverse carpal ligament (the deepest layer of the flexor retinaculum) is experimentally sectioned, the transverse diameter of the carpal arch increases an average 6 mm, whereas the resultant structural stiffness appears to decrease to no more than a 10 %. The role of the flexor retinaculum as a carpal arch stabilizer is minimal as compared to its function as a pulley, and particularly during wrist flexion.

As demonstrated by Kang et al. [23], and later confirmed by Netscher et al. [24], 30° extension of the wrist improves an average 16 % the work efficiency of the flexor tendons, whereas flexing the wrist produces the opposite effect. This is in accordance with the work by O'Driscoll and associates [21] and Li [5], who demonstrated that the most effective wrist position as far as grip strength is concerned involves about 20°–30° of extension and 5°–10° of ulnar deviation.

Section of the transverse carpal ligament tends not to modify the effectiveness of the finger flexor tendons if the wrist is in extension. By contrast, if the wrist is flexed, and the transverse carpal ligament has been removed, greater tendon excursion is required for the same amount of finger flexion to be obtained, mostly due to the bowstringing effect. Since the flexor digitorum muscles have scarce possibilities to increase their tendon excursion, their work efficiency is likely to decrease, as it has been both clinically and experimentally demonstrated. Indeed, section of the transverse carpal ligament results in an average 16 % weakening effect on finger flexion when the wrist is in flexion. The biomechanical importance of the transverse carpal ligament as a true pulley, therefore, cannot be neglected.

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